Automobile Mechanical and Electrical Systems

Tom Denton

Automotive Technology: Vehicle Maintenance and Repair

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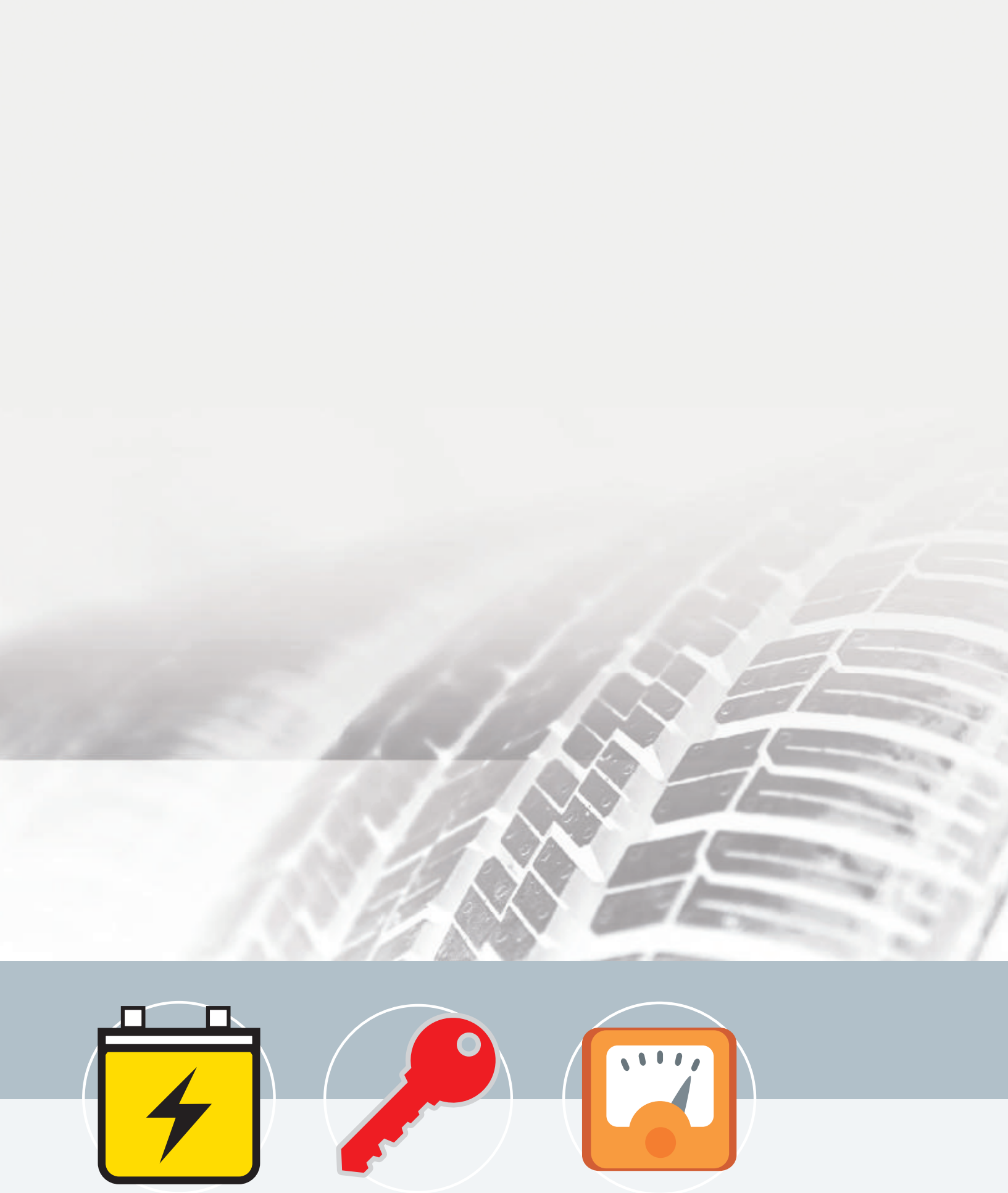

Automobile Mechanical and Electrical Systems

Automotive Technology: Vehicle Maintenance and Repair

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Contents

Preface xi
Acknowledgements xiii

Chapter 1 Overview and introduction 1

1.1 Vehicle categories 1
1.1.1 Layouts 1
1.1.2 Types and sizes 3
1.1.3 Body design 3
1.1.4 Chassis type and body panels 3
1.1.5 Main systems 6
1.1.6 Summary 7

1.2 The motor industry 8
1.2.1 Introduction 8
1.2.2 Types of motor vehicle companies 9
1.2.3 Company structure 11
1.2.4 Role of a franchised dealer 12
1.2.5 Reception and booking systems 12
1.2.6 Parts department 12
1.2.7 Estimating costs and times 13
1.2.8 Jobcards and systems 13
1.2.9 Invoicing 14
1.2.10 Warranties 15
1.2.11 Computerized workshop system 15

1.3 Working safely 18
1.3.1 Introduction 18
1.3.2 The key UK regulations and laws 19
1.3.3 Health and safety law: what you need to know 20
1.3.4 Personal protective equipment (PPE) 23
1.3.5 Identifying and reducing hazards 24
1.3.6 Moving loads 25
1.3.7 Vehicle safety 28
1.3.8 Safety procedures 29
1.3.9 Fire 29
1.3.10 Clean working environment 32
1.3.11 Signage 33
1.3.12 Environmental protection 33

1.4 Basic science, materials, mathematics and mechanics 36
1.4.1 Introduction 36
1.4.2 Units 37
1.4.3 Velocity and acceleration 39
1.4.4 Friction 39
1.4.5 Pressure 39
1.4.6 Centre of gravity or centre of mass 40
1.4.7 Oscillation 40
1.4.8 Energy, work and power 40
1.4.9 Force and torque 42
1.4.10 Mass, weight and force 43
1.4.11 Volume and density 43
1.4.12 Heat and temperature 44
1.4.13 Percentages 44
1.4.14 Fractions 44
1.4.15 Ratios 45
1.4.16 Areas 45
1.4.17 Volumes 45
1.4.18 Indices 45
1.4.19 Drawings 46
1.4.20 Mechanical machines 48
1.4.21 Gears 48
1.4.22 Hydraulics 49
1.4.23 Materials and properties 49

1.5 Tools and equipment 51
1.5.1 Hand tools 51
1.5.2 Test equipment 52
1.5.3 Workshop equipment 53

1.6 Workshop bench skills 54
1.6.1 Introduction 54
1.6.2 Fitting and machining 57
1.6.3 Filing 58
1.6.4 Drilling 59
1.6.5 Cutting 59
1.6.6 Thread cutting 60
1.6.7 Joining 62
1.6.8 Nuts and bolts 63
1.6.9 Adhesives 65
1.6.10 Soldering 66
1.6.11 Brazing 66
1.6.12 Welding 67

1.6.13 Shrinking 68
1.6.14 Compression fitting 68
1.6.15 Riveting 69
1.6.16 Gaskets 69
1.6.17 Sealants 70
1.6.18 Oil seals 70

1.7 Servicing and inspections 71
1.7.1 Introduction 71
1.7.2 Rules and regulations 73
1.7.3 Service sheets 73
1.7.4 Road test 74
1.7.5 Effects of incorrect adjustments 76
1.7.6 Maintenance and inspections 76
1.7.7 Information sources 78

Chapter 2 Engine systems 81

2.1 Engine mechanical 81
2.1.1 Introduction and operating cycles 81
2.1.2 Engine operating details 90
2.1.3 Engine components 109

2.2 Engine lubrication 137
2.2.1 Friction and lubrication 137
2.2.2 Methods of lubrication 140
2.2.3 Lubrication system 140
2.2.4 Oil filters 143
2.2.5 Oil pumps 145
2.2.6 Standards 147

2.3 Engine cooling 151
2.3.1 Introduction 151
2.3.2 System operation 151
2.3.3 Interior heater 166

2.4 Air supply, exhaust and emissions 168
2.4.1 Air pollution and engine combustion 168
2.4.2 Reducing pollution 169
2.4.3 Air supply system 172
2.4.4 Exhaust systems 176
2.4.5 Catalyst systems 179
2.4.6 Emission control systems 181
2.4.7 Turbocharging and supercharging 184

2.5 Fuel systems 189
2.5.1 Introduction 189
2.5.2 Petrol fuel injection systems 194
2.5.3 Diesel fuel injection systems 217
2.5.4 Alternative fuels 231

2.6 Ignition systems 236
2.6.1 Ignition overview 236
2.6.2 Electronic ignition 241
2.6.3 Distributorless ignition system (DIS) 244
2.6.4 Coil on plug (COP) direct ignition system 246
2.6.5 Spark plugs 247

2.7 Hybrid cars 250
2.7.1 Safety 250
2.7.2 Hybrids overview 253

2.8 Formula 1 engine technology 255
2.8.1 Engines overview 255
2.8.2 FIA technical regulations 258

Chapter 3 Electrical systems 259

3.1 Electrical and electronic principles 259
3.1.1 Electrical fundamentals 259
3.1.2 Electrical components and circuits 264
3.1.3 Electronic components 273

3.2 Engine electrical 275
3.2.1 Batteries 275
3.2.2 Starting system 282
3.2.3 Charging system 287

3.3 Lighting and indicators 293
3.3.1 Lighting systems 293
3.3.2 Stoplights and reverse lights 297
3.3.3 Interior lighting 299
3.3.4 Lighting circuits 299
3.3.5 Indicators and hazard lights 301

3.4 Body electrical and electronic systems 305
3.4.1 Washers and wipers 305
3.4.2 Horns 308
3.4.3 Obstacle avoidance 309
3.4.4 Cruise control 310
3.4.5 Seats, mirrors, sunroofs, locking and windows 312

3.4.6 Screen heating 318
3.4.7 Security systems 320
3.4.8 Safety systems 322

3.5 Monitoring and instrumentation 326
3.5.1 Sensors 326
3.5.2 Gauges 329
3.5.3 Global Positioning System (GPS) 332

3.6 Air conditioning 337
3.6.1 Air conditioning fundamentals 337
3.6.2 Air conditioning components 340

3.7 Formula 1 electrical technology 342
3.7.1 Introduction 342
3.7.2 Telemetry 343
3.7.3 FIA technical regulations 344

Chapter 4 Chassis systems 347

4.1 Suspension 347
4.1.1 Overview of suspension 347
4.1.2 Dampers/shock absorbers 356
4.1.3 Suspension layouts 359
4.1.4 Active suspension 364

4.2 Steering 366
4.2.1 Introduction to steering 366
4.2.2 Steering racks and boxes 369
4.2.3 Steering geometry 375
4.2.4 Power steering 383

4.3 Brakes 386
4.3.1 Disc, drum and parking brakes 386
4.3.2 Hydraulic components 394
4.3.3 Brake servo operation 398
4.3.4 Braking force control 400
4.3.5 Anti-lock brake systems 401
4.3.6 Traction control 407

4.4 Wheels and tyres 409
4.4.1 Wheels 409
4.4.2 Tyres 416

4.5 Formula 1 chassis technology (brakes) 422
4.5.1 Brakes overview 422
4.5.2 FIA technical regulations 423

Chapter 5 Transmission systems 425

5.1 Manual transmission clutch 425
5.1.1 Clutch operation 425
5.1.2 Types of clutch 428

5.2 Manual transmission gearbox 434
5.2.1 Gearbox operation 434
5.2.2 Gear change mechanisms 437
5.2.3 Gears and components 441

5.3 Automatic transmission 445
5.3.1 Introduction and torque converter 445
5.3.2 Automatic transmission components 451
5.3.3 Constantly variable transmission 459
5.3.4 Direct shift gearbox 461

5.4 Transmission driveline 467
5.4.1 Propshafts and driveshafts 467
5.4.2 Wheel bearings 472
5.4.3 Four-wheel drive 477

5.5 Final drive and differential 480
5.5.1 Final drive 480
5.5.2 Differential 482

5.6 Formula 1 transmission technology 485
5.6.1 Clutch 485
5.6.2 Gearbox 486
5.6.3 Differential 487
5.6.4 FIA technical regulations 487

Chapter 6 Learning activities 489

6.1 Introduction 489

6.2 Assignments 490

6.3 Tips to help you learn 493

6.4 Practical work 494
6.4.1 Jobcard, jobsheet, repair order 494
6.4.2 Practical task list 494

6.5 Summary 498

Index 499

Preface

One of the things that I find most interesting about automotive technology is how it advances and changes. It is also interesting that ideas from many years ago often return to favour. In this book I have therefore concentrated on core technologies, in other words how the technology works, rather than giving too many examples from specific vehicles. However, I have included some examples of Formula 1 technology, arguably the pinnacle of automotive engineering. Did you know that the 2011 McLaren MP4-26 F1 car is made of 11 500 components? And that's counting the engine as one!

This book is the first in the 'Automotive Technology: Vehicle Maintenance and Repair' series:

- Automobile Mechanical and Electrical Systems
- Automobile Electrical and Electronic Systems
- Automobile Advanced Fault Diagnosis

The first of its type to be published in full colour, this book concentrates on essential knowledge and will cover everything you need to get started with your studies, no matter what qualification (if any) you are working towards. I have written it to be accessible for all, by sticking to the basics. As you want more detailed information, you can move on to the other two books. I hope you find the content useful and informative. Comments, suggestions and feedback are always welcome at my website: www.automotive-technology.co.uk. On this site, you will also find links to lots of free online resources to help with your studies.

Good luck and I hope you find automotive technology as interesting as I still do.

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If I have used any information, or mentioned a company name that is not listed here, please accept my apologies and let me know so it can be rectified as soon as possible.

CHAPTER 1

Overview and introduction

1.1 Vehicle categories

1.1.1 Layouts

This section is a general introduction to the car as a whole. Over the years many unusual designs have been tried, some with more success than others. The most common is, of course, a rectangular vehicle with a wheel at each corner! To take this rather simple idea further, we can categorize vehicles in different ways. For example, by layout (Figs 1.1–1.4), such as:

- front engine driving the front wheels
- front engine driving the rear wheels
- front engine driving all four wheels
- rear engine driving the rear wheels
- mid-engine driving the rear wheels
- mid-engine driving all four wheels.

The following paragraphs and bullet points highlight features of the vehicle layouts mentioned above. Common abbreviations for these layouts are given in Table 1.1.

Figure 1.1 Front-engine, front-wheel drive

Figure 1.2 Front-engine, rear-wheel drive

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Figure 1.3 Rear-engine, rear-wheel drive

Figure 1.4 Mid-engine, rear-wheel drive

Table 1.1 Common abbreviations

FWD	Front-wheel drive
RWD	Rear-wheel drive
AWD	All-wheel drive
4WD	Four-wheel drive

A common layout for a standard car is the front-engine, front-wheel drive vehicle. This is because a design with the engine at the front driving the front wheels has a number of advantages:

- It provides protection in the case of a front-end collision.
- Engine cooling is easier because of the air flow.
- Cornering can be better if the weight is at the front.
- Front-wheel drive adds further advantages if the engine is mounted sideways-on (transversely).
- There is more room in the passenger compartment.
- The power unit can be made as a complete unit.
- The drive acts in the same direction as the steered wheels are pointing.

Rear-wheel drive from a front engine was the method used for many years. Some manufacturers have continued its use, BMW for example. A long propeller shaft from the gearbox to the final drive, which is part of the rear axle, is the main feature. The propshaft has universal joints to allow for suspension movement. This layout has some advantages:

- Weight transfers to the rear driving wheels when accelerating.
- Complicated constant velocity joints, such as used by front-wheel drive vehicles, are not needed.

Four-wheel drive combines all the good points mentioned above but makes the vehicle more complicated and therefore expensive. The main difference with four-wheel drive is that an extra gearbox known as a transfer box is needed to link the front- and rear-wheel drive.

The rear engine design has not been very popular but it was used for the best selling car of all time: the VW Beetle. The advantages are that weight is placed on the rear wheels, giving good grip, and the power unit and drive can be all one assembly. One downside is that less room is available for luggage in the front. The biggest problem is that handling is affected because of less weight on the steered wheels. Flat-type engines are the most common choice for this type of vehicle.

Fitting the engine in the mid-position of a car has one major disadvantage: it takes up space inside the vehicle. This makes it impractical for most 'normal' vehicles. However, the distribution of weight is very good, which makes it the choice of high-performance vehicle designers. A good example is the Ferrari Testarossa. Mid-engine is the term used to describe any vehicle where the engine is between the axles, even if it is not in the middle.

Key fact

In a mid-engine car the distribution of weight is very good.

1.1.2 Types and sizes

Vehicles are also categorized by type and size as in Table 1.2.

1.1.3 Body design

Types of light vehicle can range from small two-seat sports cars to large people carriers or sports utility vehicles (SUVs). Also included in the range are light commercial vehicles such as vans and pick-up trucks. It is hard to categorize a car exactly as there are several agreed systems in several different countries. Figures 1.5–1.13 show a number of different body types.

1.1.4 Chassis type and body panels

The vehicle chassis can be of two main types: separate or integrated. Separate chassis are usually used on heavier vehicles. The integrated type, often called monocoque, is used for almost all cars. The two main types are shown here in Figs 1.14 and 1.15.

Key fact

A vehicle chassis can be of two main types: separate or integrated.

Table 1.2 Common abbreviations and definitions

LV	Light vehicles (light vans and cars) with an MAM of up to 3500 kg, no more than eight passenger seats. Vehicles weighing between 3500 kg and 7500 kg are considered mid-sized
LGV	A large goods vehicle, known formerly and still in common use, as a heavy goods vehicle or HGV. LGV is the EU term for trucks or lorries with an MAM of over 3500 kg
PCV	A passenger-carrying vehicle or a bus, known formerly as omnibus, multibus, or autobus, is a road vehicle designed to carry passengers. The most common type is the single-decker, with larger loads carried by double-decker and articulated buses, and smaller loads carried by minibuses. A luxury, long-distance bus is usually called a coach
LCV	Light commercial vehicle; the formal term in the EU for goods vehicles with an MAM of up to 3.5 tonnes. In general language, this kind of vehicle is usually called a van

MAM: maximum allowed mass; EU: European Union.

Figure 1.5 Saloon car. (Source: Volvo Media)

Figure 1.6 Estate car. (Source: Ford Media)

Figure 1.7 Hatchback. (Source: Ford Media)

Figure 1.8 Coupé. (Source: Ford Media)

Figure 1.9 Convertible. (Source: Ford Media)

Figure 1.10 Concept car. (Source: Ford Media)

Figure 1.11 Light van. (Source: Ford Media)

Figure 1.12 Pick-up truck. (Source: Ford Media)

Figure 1.13 Sports utility vehicle (SUV). (Source: Ford Media)

Figure 1.14 Ladder chassis

Figure 1.15 Integrated chassis

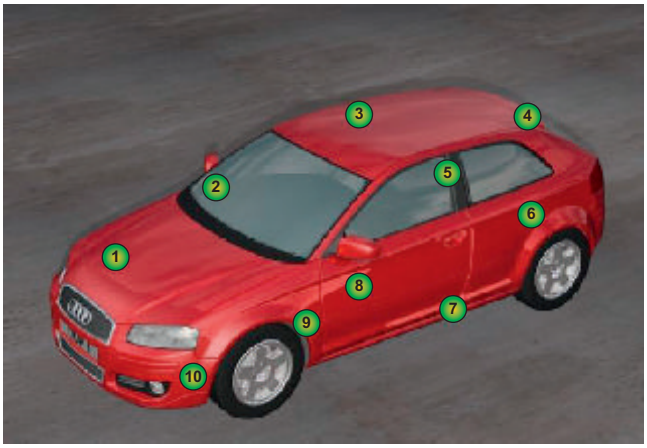

Figure 1.16 Body components: 1, bonnet (hood); 2, windscreen; 3, roof; 4, tailgate; 5, post; 6, rear quarter; 7, sill; 8, door; 9, front wing;10, front bumper/trim

Figure 1.17 Ford Focus engine. (Source: Ford Media)

Most vehicles are made of a number of separate panels. Figure 1.16 shows a car with the main panel or other body component named.

1.1.5 Main systems

No matter how we categorize them, all vehicle designs have similar major components and these operate in much the same way. The four main areas of a vehicle are the engine, electrical, chassis and transmission systems.

1.1.5.1 Engine

This area consists of the engine itself together with fuel, ignition, air supply and exhaust systems (Fig. 1.17). In the engine, a fuel–air mixture enters through an

inlet manifold and is fired in each cylinder in turn. The resulting expanding gases push on pistons and connecting rods which are on cranks, just like a cyclist's legs driving the pedals, and this makes a crankshaft rotate. The pulses of power from each piston are smoothed out by a heavy flywheel. Power leaves the engine through the flywheel, which is fitted on the end of the crankshaft, and passes to the clutch. The spent gases leave via the exhaust system.

1.1.5.2 Electrical

The electrical system covers many aspects such as lighting, wipers and instrumentation. A key component is the alternator (Fig. 1.18) which, driven by the engine, produces electricity to run the electrical systems and charge the battery. A starter motor takes energy from the battery to crank over and start the engine. Electrical components are controlled by a range of switches. Electronic systems use sensors to sense conditions and actuators to control a variety of things – in fact, on modern vehicles, almost everything.

Figure 1.18 A modern alternator. (Source: Bosch Press)

1.1.5.3 Chassis

This area is made up of the braking, steering and suspension systems as well as the wheels and tyres. Hydraulic pressure is used to activate the brakes to slow down or stop the vehicle. Rotating discs are gripped between pads of friction lining (Fig. 1.19). The handbrake uses a mechanical linkage to operate parking brakes. Both front wheels are linked mechanically and must turn together to provide steering control. The most common method is to use a rack and pinion. The steering wheel is linked to the pinion and as this is turned it moves the rack to and fro, which in turn moves the wheels. Tyres also absorb some road shock and play a very important part in road holding. Most of the remaining shocks and vibrations are absorbed by springs in the driver and passenger seats. The springs can be coil type and are used in conjunction with a damper to stop them oscillating (bouncing up and down too much).

Figure 1.19 Disc brakes and part of the suspension system

1.1.5.4 Transmission

In this area, the clutch allows the driver to disconnect drive from the engine and move the vehicle off from rest. The engine flywheel and clutch cover are bolted together so the clutch always rotates with the engine, and when the clutch pedal is raised drive is passed to the gearbox. A gearbox is needed because an engine produces power only when turning quite quickly. The gearbox allows the driver to keep the engine at its best speed. When the gearbox is in neutral, power does not leave it. A final drive assembly and differential connect the drive to the wheels vial axles or driveshafts (Fig. 1.20). The differential allows the driveshafts and hence the wheels to rotate at different speeds when the vehicle is cornering.

Key fact

A gearbox is needed because an engine produces power only when turning quite quickly.

1.1.6 Summary

The layout of a vehicle, such as where the engine is fitted and which wheels are driven, varies, as do body styles and shapes. However, the technologies used in the four main areas of a vehicle are similar no matter how it is described. These are:

- the engine system
- the electrical system
- the chassis system
- the transmission system.

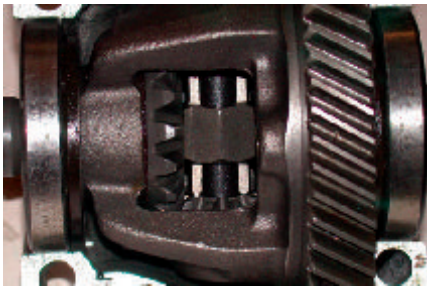

Figure 1.20 Differential and final drive components

These areas are covered in detail and make up the four main technology chapters of this book, but first, let's look at the wider picture of the motor industry.

1.2 The motor industry

1.2.1 Introduction

This section will outline some of the jobs that are open to you in the motor trade and help you understand more about the different types of business and how they operate.

It is easy to think that the operation of a business does not matter to you. However, I would strongly suggest we should all be interested in the whole business in which we are working. This does not mean to interfere in areas we do not understand. It means we should understand that all parts of the business are important. For example, when you complete a job, enter all the parts used so the person who writes the invoice knows what to charge.

The motor trade offers lots of opportunities for those who are willing to work hard and move forwards. There are many different types of job and you will find one to suit you with a little patience and study. To help you get started,some of the words and phrases in common use are listed in Table 1.3.

Table 1.3 Motor industry words and phrases

Customer	The individuals or companies that spend their money at your place of work. This is where your wages come from
Job card/Job sheet	A printed document for recording, among other things, work required, work done, parts used and the time taken. Also known as a job sheet
Invoice	A description of the parts and services supplied with a demand for payment from the customer
Company system	A set way in which things work in one particular company. Most motor vehicle company systems will follow similar rules, but will all be a little different
Contract	An offer which is accepted and payment is agreed. For example, if I offer to change your engine oil for £15 and you decide this is a good offer and accept it, we have made a contract. This is then binding on both of us
Image	This is the impression given by the company to existing and potential customers. Not all companies will want to project the same image
Warranty	An intention that if within an agreed time a problem occurs with the supplied goods or service, it will be rectified free of charge by the supplier
Recording system	An agreed system within a company so that all details of what is requested and/or carried out are recorded. The job card is one of the main parts of this system
Approved repairer	This can normally mean two things. The first is where a particular garage or bodyshop is used by an insurance company to carry out accident repair work. In some cases, however, general repair shops may be approved to carry out warranty work or servicing work by a particular vehicle or component manufacturer
After sales	This is a general term that applies to all aspects of a main dealer that are involved with looking after a customer's car, after it has been sold to them by the sales department. The service and repair workshop is the best example

1.2.2 Types of motor vehicle companies

Motor vehicle companies can range from the very small one-person business to very large main dealers (Figs 1.21–1.26). The systems used by each will be different but the requirements are the same.

Figure 1.21 A Ford main dealer

Figure 1.22 One of the well-known 'quick-fit' companies

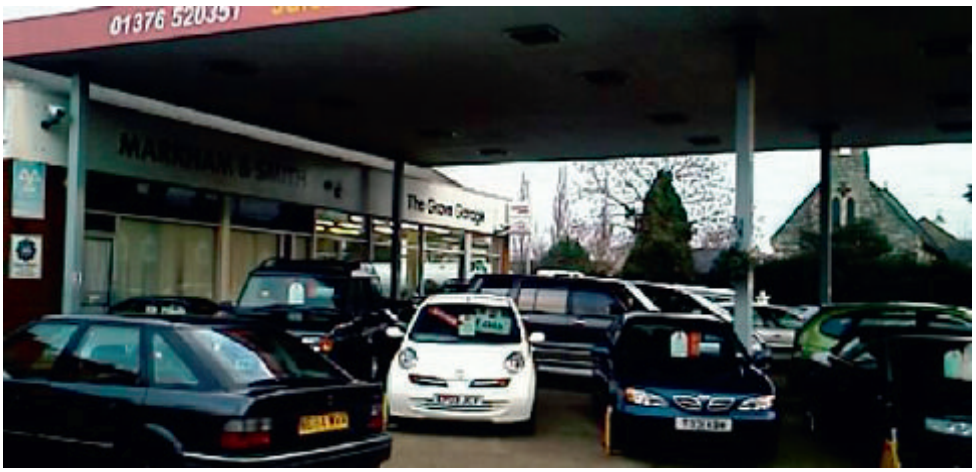

Figure 1.23 An independent garage and car sales business

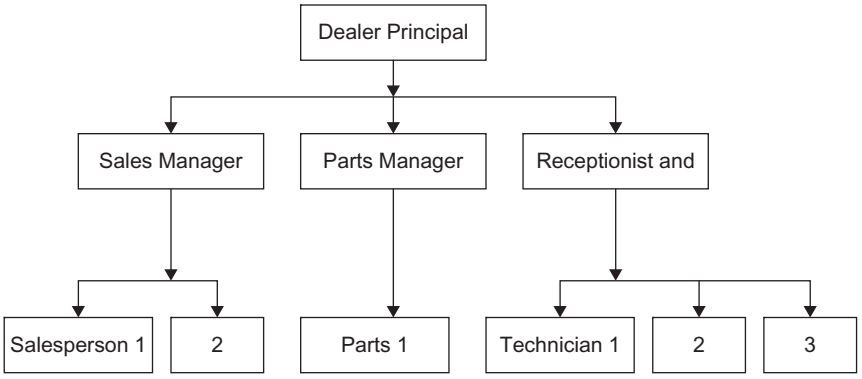

Figure 1.24 One way in which a company could be structured

Figure 1.25 A 'motorists' discount' shop

Figure 1.26 Small specialist companies are often located in units similar to those shown here

A system should be in place to ensure the level of service provided by the company meets the needs of the customer. Table 1.4 shows how diverse the trade is.

Table 1.4 Automotive trades

Mobile mechanics	Servicing and repairs at the owner's home or business. Usually a one-person company
Bodywork repairers and painters	Specialists in body repair and paintwork
Valeters	These companies specialize in valeting, which should be thought of as much more involved than getting the car washed. Specialist equipment and products are used and proper training is essential
Fuel stations	These may be owned by an oil company or be independent. Some also do vehicle repair work
Specialized repairers	Auto-electrical, air conditioning, automatic transmission and in-car entertainment systems are just some examples
General repair workshop or independent repairer	Servicing and repairs of most types of vehicles not linked to a specific manufacturer. Often this will be a small business, maybe employing two or three people. However, there are some very large independent repairers
Parts supply	Many companies now supply a wide range of parts. Many will deliver to your workshop
Fast-fit	Supplying and fitting of exhausts, tyres, radiators, batteries, clutches, brakes and windscreens
Fleet operator (with workshop)	Many large operators such as rental companies will operate their own workshops. A large company that has lots of cars, used by sales reps for example, may also have their own workshop and technicians
Non-franchised dealer	Main activity is the servicing and repairs of a wide range of vehicles, with some sales
Main dealer or franchised dealer	Usually franchised to one manufacturer, these companies hold a stock of vehicles and parts. The main dealer will be able to carry out all repairs to their own type of vehicle as they hold all of the parts and special tools. They also have access to the latest information specific to their franchise (e.g. Ford or Citroën). A 'franchise' means that the company has had to pay to become associated with a particular manufacturer but is then guaranteed a certain amount of work and that there will be no other similar dealers within a certain distance
Multi-franchised dealer	This type of dealer is just like the one above, except they hold more than one franchise (e.g. Volvo and Saab)
Breakdown services	The best known breakdown services in the UK are operated by the AA and the RAC. Others, e.g. National Breakdown and many independent garages, also offer roadside repair and recovery services
Motorists' shops	Often described as motorist discount centres or similar, these companies provide parts and materials to amateurs but in some cases also to the smaller independent repairers

1.2.3 Company structure

A large motor vehicle company will probably be made up of at least the following departments:

- reception
- workshop
- bodyshop and paint shop
- parts department
- MOT bay
- valeting
- new and second user car sales
- office support
- management
- cleaning and general duties.

Key fact

In a large garage it is important that different areas communicate with each other.

Each area will employ one or a number of people. If you work in a very small garage you may have to be all of these people at once. In a large garage it is important that these different areas communicate with each other to ensure that a good service is provided to the customer. The main departments are explained further in the following sections.

1.2.4 Role of a franchised dealer

The role of a franchised dealer (one contracted to a manufacturer) is to supply local:

- new and used franchised vehicles
- franchise parts and accessories
- repair and servicing facilities for franchise vehicles.

The dealer is also a source of communication and liaison with the vehicle manufacturer.

1.2.5 Reception and booking systems

The reception, whether in a large or small company, is often the point of first contact with new customers. It is very important therefore to get this bit right. The reception should be manned by pleasant and qualified people. The purpose of a reception and booking system within a company can be best explained by following through a typical enquiry.

1. The customer enters reception area and is greeted in an appropriate way.
2. Attention is given to the customer to find out what is required. (Let's assume the car is difficult to start, in this case.)
3. Further questions can be used to determine the particular problem, bearing in mind the knowledge of vehicles the customer may, or may not have. (For example, is the problem worse when the weather is cold?)
4. Details are recorded on a job card about the customer, the vehicle and the nature of the problem. If the customer is new a record card can be started, or one can be continued for an existing customer.
5. An explanation of expected costs is given as appropriate. An agreement to spend only a set amount, after which the customer will be contacted, is a common and sensible approach.
6. The date and time when the work will be carried out can now be agreed. This depends on workshop time availability and when is convenient for the customer. It is often better to say that you cannot do the job until a certain time, rather than make a promise you cannot keep.
7. The customer is thanked for visiting. If the vehicle is to be left at that time, the keys should be labelled and stored securely.
8. Details are now entered in the workshop diary or loading chart (usually computer based).

The above list is an example. Your company may have a slightly different system but you can now see the approach that is required.

1.2.6 Parts department

The parts department is the area where parts are kept and/or ordered. This will vary quite a lot between different companies. Large main dealers will have a very large stock of parts for their range of vehicles. They will have a parts manager and in some cases several other staff. In some very small garages the parts department will be a few shelves where popular items such as filters and brake pads are kept.

Even though the two examples given above are rather different in scale the basic principles are the same and can be summed up very briefly as follows:

- A set level of parts or stock is decided upon.
- Parts are stored so they can be easily found.
- A reordering system should be used to maintain the stock.

Security is important as most parts cost a lot of money. When parts are collected from the parts department or area, they will be used in one of three ways:

- for direct sale to a customer
- as part of a job
- for use on company vehicles.

In the first case, an invoice or a bill will be produced. In the second case, the parts will be entered on the customer's job card. The third case may also have a job card; if not, some other record must be kept. In all three cases keeping a record of parts used will allow them to be reordered if necessary. If parts are ordered and delivered by an external supplier, again they must be recorded on the customer's job card.

Key fact

Security is important as most parts cost a lot of money.

1.2.7 Estimating costs and times

When a customer brings his or her car to a garage for work to be carried out, quite understandably he or she will want to know two things:

- How much will it cost?
- When will the car be ready?

In some cases such as for a full service, this is quite easy as the company will have a set charge and by experience will know it takes a set time. For other types of job this is more difficult.

Most major manufacturers supply information to their dealers about standard times for jobs. These assume a skilled technician with all the necessary tools. For independent garages other publications are available. These give agreed standard times for all the most common tasks, on all popular makes of vehicle. To work out the cost of a job, you look up the required time and multiply it by the company's hourly rate. Don't forget that the cost of parts will also need to be included.

1.2.8 Jobcards and systems

The jobcard (Fig. 1.27) is a vital part of the workshop system in a motor vehicle company. Many companies now dispense with the 'paper' altogether and use computer systems. These allow very fast, easy and accurate communication. Whether hand-written job cards or IT systems are used, the principle is the same and consists of a number of important stages. This is often described as the four-part job card system:

- **Reception** – Customers' details and requirements are entered on the job card or computer screen.
- **Workshop control** – Jobs are allocated to the appropriate technician using a loading sheet or again via the computer.
- **Parts department** – Parts used are added to the computer or job card.
- **Accounts** – Invoices are prepared from the information on the job card. Computerized systems may automatically produce the invoice when the job is completed.

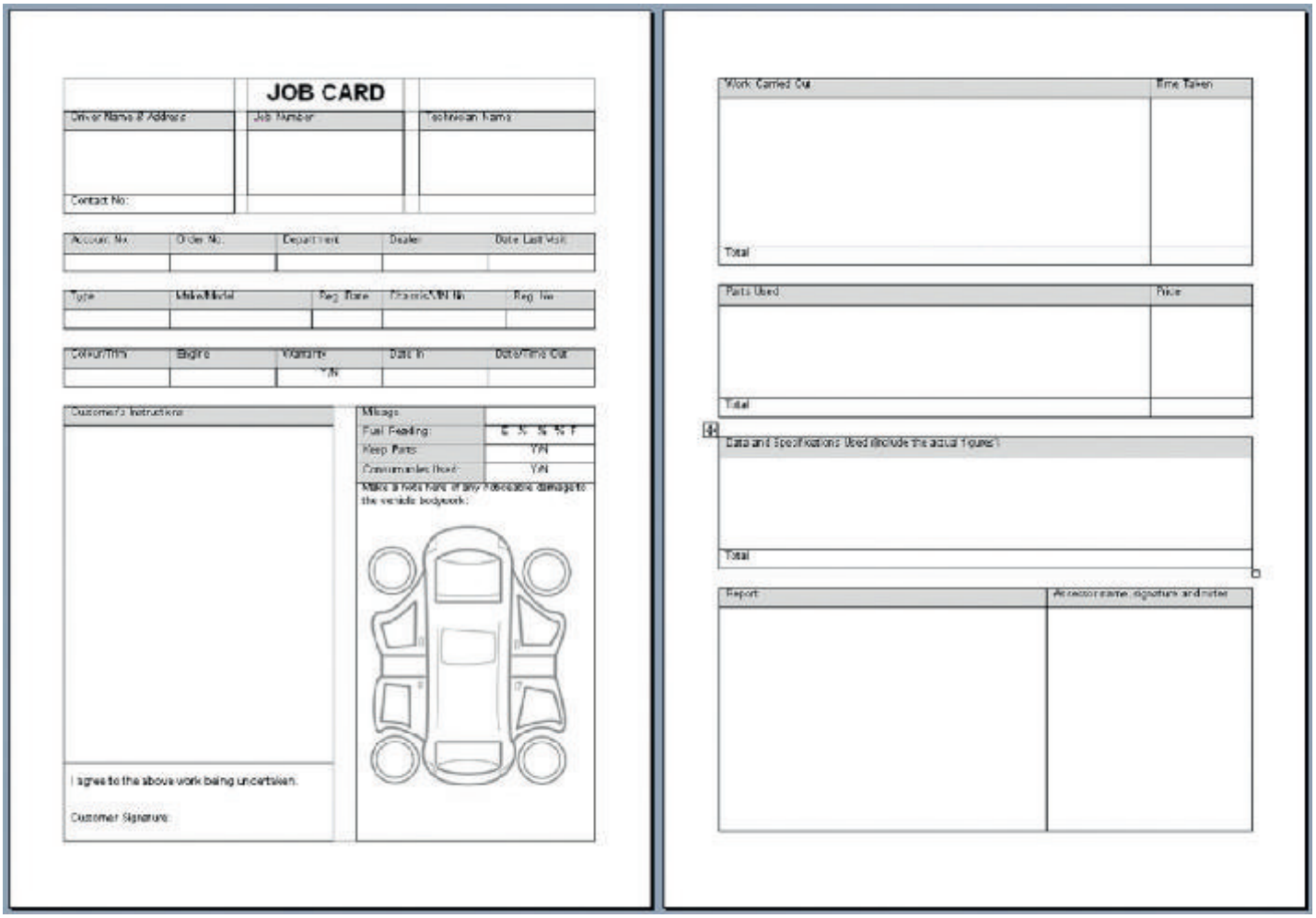

Figure 1.27 An example job card

When a computer system is used each terminal will pass information to all the others. With job cards either the same card must be carried to each stage or copies are kept in each area. The different copies are collected and combined to produce the invoice.

1.2.9 Invoicing

As part of the contract made with a customer, an invoice for the work carried out is issued. The main parts of an invoice are as follows:

- **Labour charges** – The cost of doing the work; usually the time spent times the hourly rate.
- **Parts** – The retail price of the parts or as agreed.
- **Sundries** – Some companies add a small sundry charge to cover consumable items like nuts and bolts, cable ties.
- **MOT (Ministry of Transport) test** – If appropriate. This is separated because VAT is not charged on MOTs.
- **VAT (value added tax)** – Is charged at the current rate, if the company is registered (all but the very small are).

Hourly rates vary quite a lot between different garages. The hourly rate charged by the company has to pay for a lot more than your wages – hence it will be

Definition

Contract
In law, a contract is a binding legal agreement that is enforceable in a court of law or by binding arbitration. That is to say, a contract is an exchange of promises with a specific remedy if broken.

much higher than your hourly rate! Just take a look round in any good workshop: as well as the rent for the premises, some of the equipment can cost tens of thousands of pounds. The money has to come from somewhere.

1.2.10 Warranties

When a vehicle is sold a warranty is given, meaning that it is fit for the purpose for which it was sold. Further to this, the manufacturer will repair the vehicle at no cost to the customer if a problem develops within a set time. For most vehicles this is twelve months, but some periods are now longer. The term generally used for this is 'guarantee'. Quite often manufacturers advertise their guarantee as a selling point.

Key fact

A warranty means that a vehicle is fit for the purpose for which it was sold.

It is also possible to have a warranty on a used vehicle or an extended warranty on a new vehicle. These often involve a separate payment to an insurance company. This type of warranty can be quite good but a number of exclusions and requirements may apply. Some examples are listed:

- Regular servicing must be carried out by an approved dealer.
- Only recommended parts must be used.
- Wear and tear is not included.
- Any work done must be authorized.
- Only recognized repairers may be used in some cases.

The question of authorization before work is carried out is very important for the garage to understand. Work carried out without proper authorization will not be paid for. If a customer returns a car within the warranty period then a set procedure must be followed:

1. Confirm that the work is within the terms of the warranty.
2. Get authorization if over an agreed limit.
3. Retain all parts replaced for inspection.
4. Produce an invoice which relates to standard or agreed times.

Often in the larger garages one person will be responsible for making warranty claims.

1.2.11 Computerized workshop system

Several computer-based workshop management systems are available. Some are specifically designed for main dealers, some for the smaller independent company. This section will outline a system called GDS Workshop Manager, as it is designed for the smaller company yet includes some very powerful features and can be used in larger operations (Figs 1.28–1.31).

The main features of this system are:

- storage of all customer, vehicle and supplier details
- production of jobsheets (job cards), estimates and sales invoices
- creation of documents using menu priced jobs
- invoices that can be split into insurance/excess invoices
- internal billing and cost tracking facilities
- purchase invoices and stock control
- diary/booking planner
- MOT and service reminders
- vehicle registration mark look-up facility
- repair times and service schedules option.

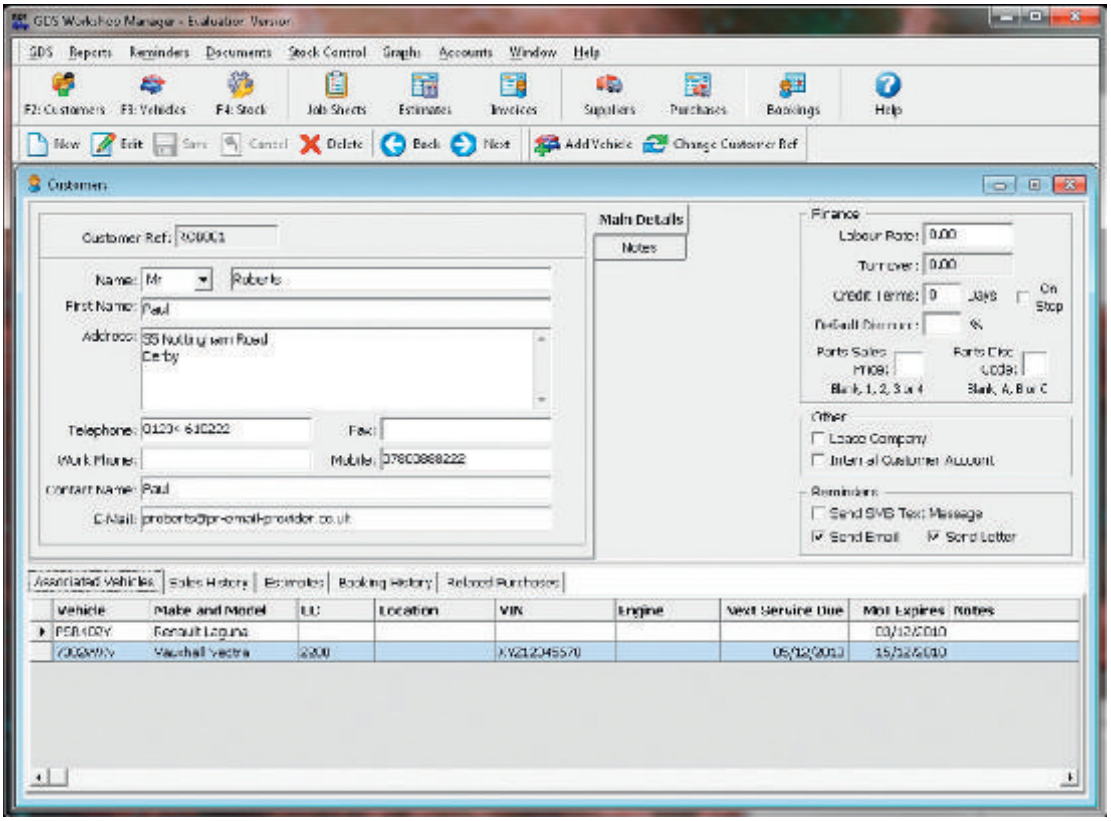

Figure 1.28 Main interface of the GDS program showing the customer screen

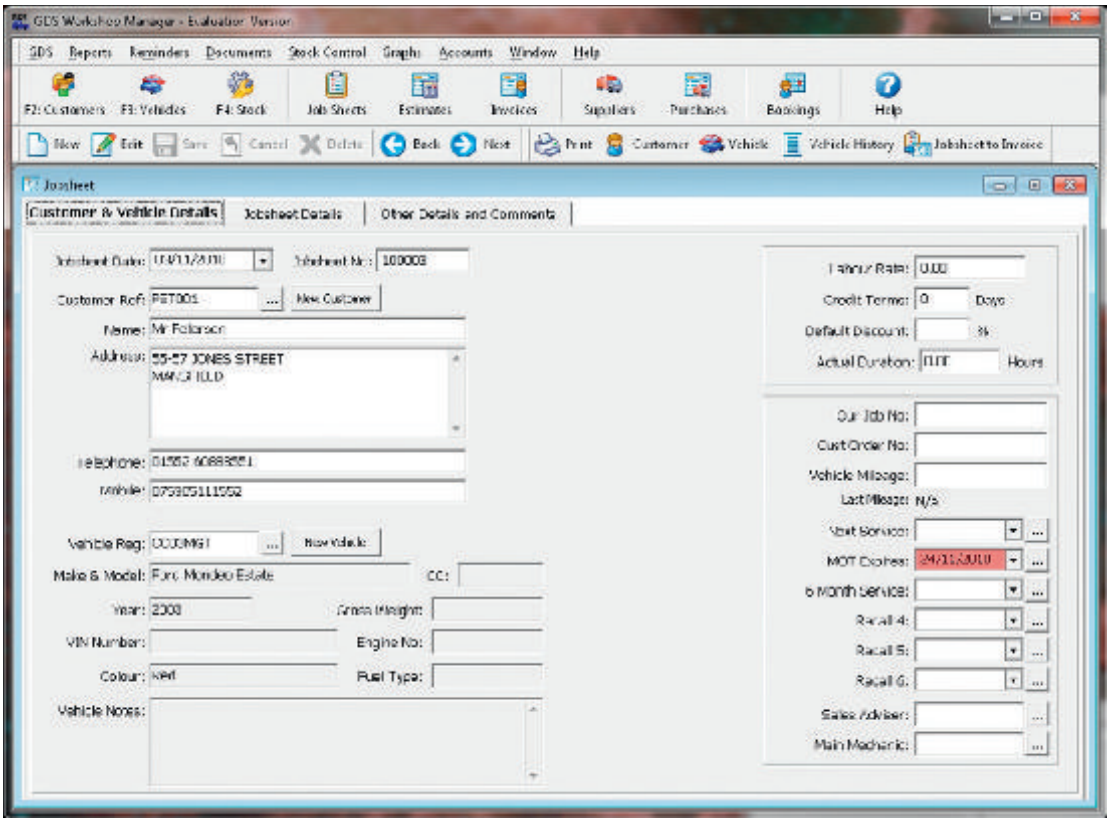

Figure 1.29 Jobsheet screen

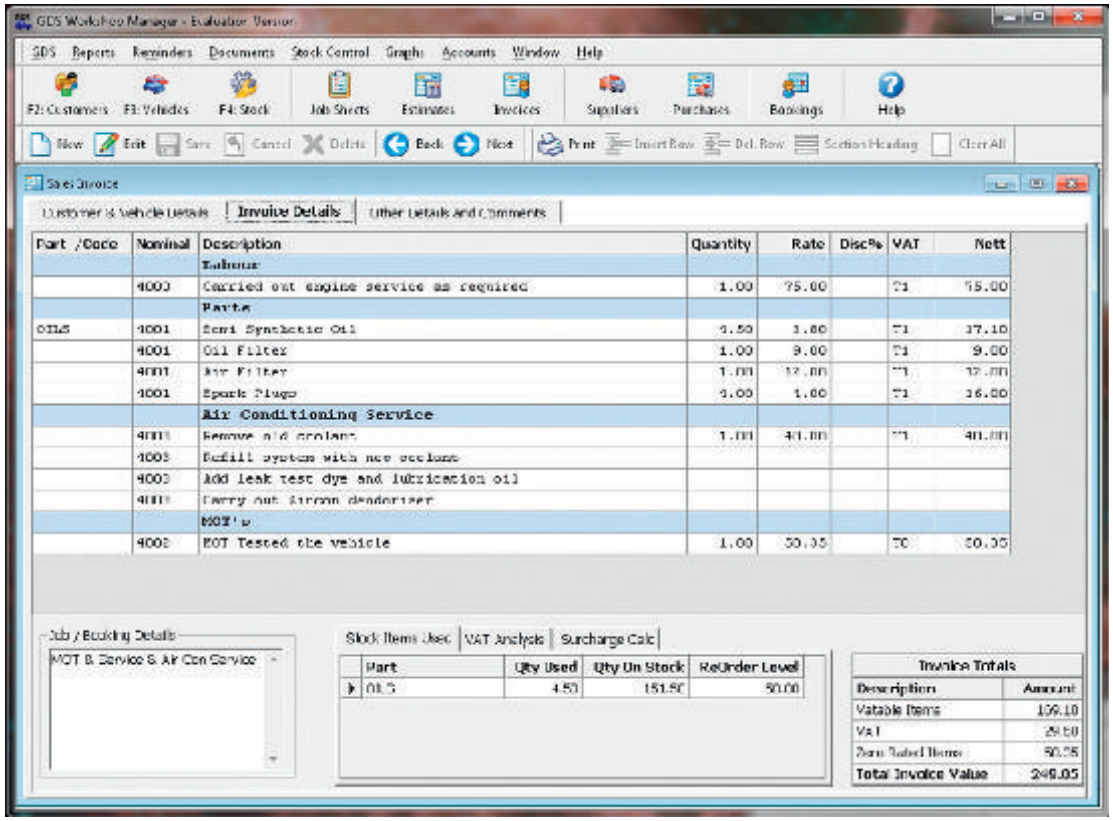

Figure 1.30 Sales invoice screen

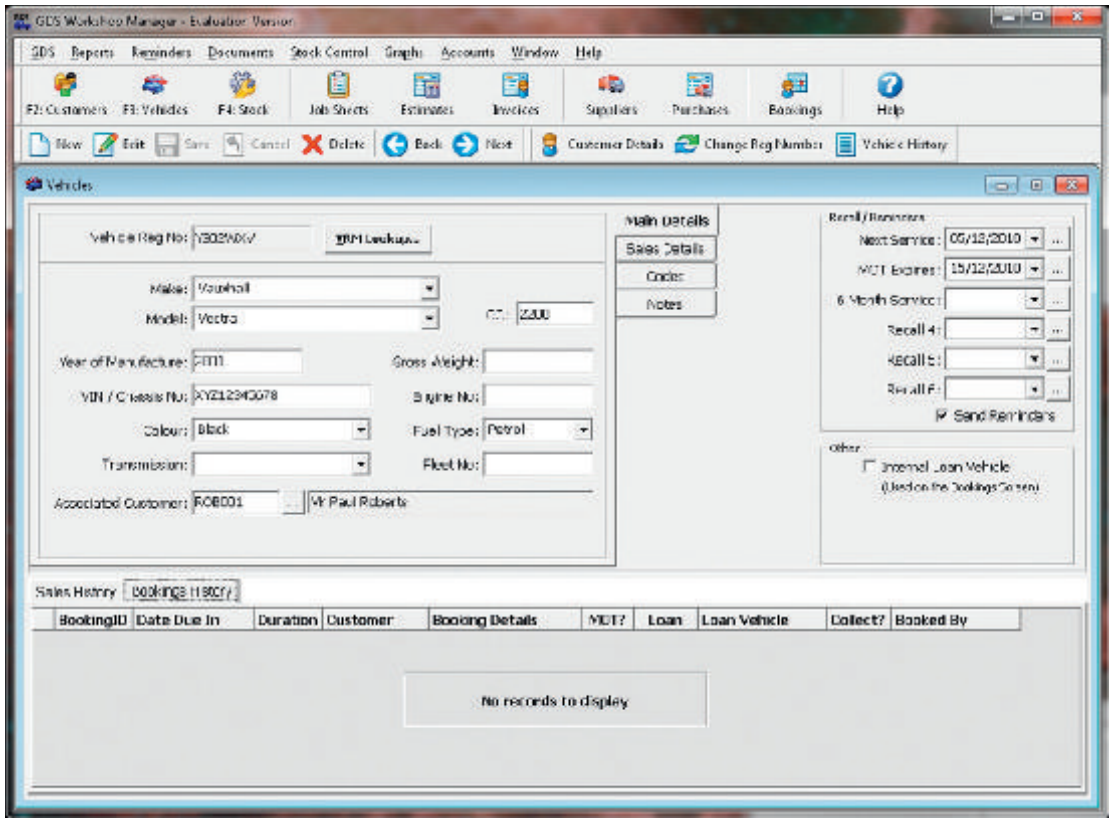

Figure 1.31 Vehicle screen

There are many other features relating to accounts and reports that are beyond the scope of this book but are very useful for managing a business.

The core of this and other systems is the data held about customers, and their vehicles and the work carried out on them. New records can be created from a number of points within the system. The following would be typical of a process:

1. A new customer has a problem with their car and requests an estimate.
2. Customer and vehicle details are added, with the help of postcode and vehicle registration look-up features.
3. The estimate is now created, with the use of repair times look-up if needed, and can be printed.
4. The customer agrees the price and the vehicle is booked in using the booking screen.
5. On the agreed date a jobsheet is printed (or accessed on screen) and the designated technician carries out the work adding parts and comments as needed. A service schedule may also be accessed at this point.
6. An invoice is created and printed (or emailed).
7. In an ideal world, the customer pays as they collect the vehicle.

The above process is just one way the system can be used; for example, the starting point could be the creation of the jobsheet or an invoice. However, in all cases, customer and vehicle details must be added or updated. Existing customer and vehicle records can be easily looked up, making the process of creating an invoice, or whatever, much faster.

The invoice details screen can have lines of detail grouped into relevant sections, such as Parts, Labour, MOT, as required. Sections can be created and stored as menu jobs to automatically fill in an invoice with often used descriptions, quantities and prices. Invoices can automatically update stock quantities for stock Items. Individual items on the invoice can also be linked to customers in order to aid part warranty checks in the future. Purchased parts can be added directly to a sales invoice which maintains a link to the purchase invoice for future reference.

GDS Workshop Manager can optionally include a repair times and service schedules database which can be incorporated directly into the system. Vehicle times and service schedules can be looked up as required, or accessed from within the jobsheet, estimate and invoice screens to allow times to be automatically entered directly onto the document being worked on. Service schedules for cars and light commercial vehicles can be printed.

In summary, a computer-based workshop management system allows the easy creation of all the documentation needed for efficient workshop operation and management. It is now an essential part of a modern garage's tool kit. More information is available from: www.GarageDataSystems.com

Safety first

Health and safety law is designed to protect you.

1.3 Working safely

1.3.1 Introduction

Health and safety law is designed to protect you.

In the UK the Health and Safety Executive (HSE) is the enforcement and legislative body set up by the government. The HSE has a very helpful website where you can get all the latest information, including a document specially developed for the motor industry. The address is: www.hse.gov.uk (Fig. 1.32).

Similarly, in the USA, with the Occupational Safety and Health Act of 1970, Congress created the Occupational Safety and Health Administration (OSHA) to ensure safe and healthful working conditions for working men and women by setting and enforcing standards and by providing training, outreach, education and assistance. The OSHA has a good website at: www.osha.gov (Fig. 1.33).

In Australia there is the office of the Australian Safety and Compensation Council (ASCC), in the Department of Employment and Workplace Relations. Safe Work Australia is an Australian Government statutory agency established in 2009, with the primary responsibility of improving work health and safety and workers' compensation arrangements across Australia. The agency is jointly funded by the Commonwealth, state and territory governments facilitated through an intergovernmental agreement signed in July 2008. Safe Work Australia represents a genuine partnership between governments, unions and industry. Together they work towards the goal of reducing death, injury and disease in the workplace. Their website contains some useful content at: www.ascc.gov.au or http://safeworkaustralia.gov.au (Fig. 1.34).

Now back to the UK's HSE. The emphasis is on preventing death, injury and ill-health in Britain's workplaces. However, the HSE does have the authority to come down hard on people who put others at risk, particularly where there is deliberate flouting of the law. Since 2009, HSE has published new versions of its approved health and safety poster and leaflet. The new versions are modern, eye-catching and easy to read. They are set out in simple terms, using numbered lists of basic points, and what employers and workers must do, and tell you what to do if there is a problem.

Employers can, if they wish, continue to use their existing versions of poster and leaflet until 5 April 2014, as long as they are readable and the addresses of the enforcing authority and the Employment Medical Advisory Service are up to date. Employers must display a poster or give a leaflet to workers. This is in the form of a pocket card that is better suited to the workplace.

Employers have a legal duty under the Health and Safety Information for Employees Regulations (HSIER) to display the poster in a prominent position in each workplace or provide each worker with a copy of the equivalent leaflet outlining British health and safety laws (Figs 1.35 and 1.36).

Employers must meet certain criteria, but health and safety is the responsibility of everyone in the workplace. The reason for the poster and the leaflets is to make everybody aware of this.

Figure 1.32 UK Health and Safety Executive (HSE) logo

Figure 1.33 USA OSHA logo

Safety first

Systems are quite similar, but always check the legislation and law in the country you are working in.

Figure 1.34 Safe Work Australia (SWA) logo

Safety first

Health and safety is the responsibility of everyone in the workplace.

1.3.2 The key UK regulations and laws

There are a number of rules and regulation you need to be aware of. Check the details for the country in which you work. Table 1.5 lists some important areas for the UK.

Figure 1.35 Health and Safety Law poster. (Source: HSE)

1.3.3 Health and safety law: what you need to know

All workers have a right to work in places where risks to their health and safety are properly controlled (Fig. 1.36). Health and safety is about stopping you getting hurt at work or ill through work. Your employer is responsible for health and safety, but you must help. This section is taken from the HSE leaflet for employees.

What employers must do for you:

1 Decide what could harm you in your job and the precautions to stop it. This is part of risk assessment.

2 In a way you can understand, explain how risks will be controlled and tell you who is responsible for this.

HSE

Health and Safety Executive

Health and Safety Law

What you need to know

This is a web-friendly version of pocket card ISBN 978 0 7176 6350 7, published 04/09

All workers have a right to work in places where risks to their health and safety are properly controlled. Health and safety is about stopping you getting hurt at work or ill through work. Your employer is responsible for health and safety, but you must help.

What employers must do for you

1 Decide what could harm you in your job and the precautions to stop it. This is part of risk assessment.
2 In a way you can understand, explain how risks will be controlled and tell you who is responsible for this.
3 Consult and work with you and your health and safety representatives in protecting everyone from harm in the workplace.
4 Free of charge, give you the health and safety training you need to do your job.
5 Free of charge, provide you with any equipment and protective clothing you need, and ensure it is properly looked after.
6 Provide toilets, washing facilities and drinking water.
7 Provide adequate first-aid facilities.
8 Report injuries, diseases and dangerous incidents at work to our Incident Contact Centre: **0845 300 9923**
9 Have insurance that covers you in case you get hurt at work or ill through work. Display a hard copy or electronic copy of the current insurance certificate where you can easily read it.
10 Work with any other employers or contractors sharing the workplace or providing employees (such as agency workers), so that everyone's health and safety is protected.

What you must do

1 Follow the training you have received when using any work items your employer has given you.
2 Take reasonable care of your own and other people's health and safety.
3 Co-operate with your employer on health and safety.
4 Tell someone (your employer, supervisor, or health and safety representative) if you think the work or inadequate precautions are putting anyone's health and safety at serious risk.

Figure 1.36 Health and Safety Law leaflet. (Source: HSE)

3 Consult and work with you and your health and safety representatives in protecting everyone from harm in the workplace.
4 Free of charge, give you the health and safety training you need to do your job.
5 Free of charge, provide you with any equipment and protective clothing you need, and ensure it is properly looked after.
6 Provide toilets, washing facilities and drinking water.
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8 Report injuries, diseases and dangerous incidents at work.
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10 Work with any other employers or contractors sharing the workplace or providing employees (such as agency workers), so that everyone's health and safety is protected.

Table 1.5 UK regulations and laws

Health and Safety Executive (HSE)	The HSE is the national independent watchdog for work-related health, safety and illness in the UK. It is an independent regulator and acts in the public interest to reduce work-related death and serious injury across Great Britain's workplaces. Other countries have similar organizations
Health and Safety at Work etc. Act 1974 (HASAW)	HASAW, also referred to as HASAW, HASAWA or HSW, is the primary piece of legislation covering occupational health and safety in the UK. The HSE is responsible for enforcing the Act and a number of other Acts and Statutory Instruments relevant to the working environment
Control of Substances Hazardous to Health (COSHH)	This law requires employers to control substances that are hazardous to health, such as solvents
Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995 (RIDDOR)	RIDDOR place a legal duty on employers, self-employed people and people in control of premises to report work-related deaths, major injuries or over-three-day injuries, work related diseases and dangerous occurrences (near-miss accidents)
Provision and Use of Work Equipment Regulations 1998 (PUWER)	In general terms, PUWER requires that equipment provided for use at work is: • suitable for the intended use • safe for use, maintained in a safe condition and, in certain circumstances, inspected to ensure this remains the case • used only by people who have received adequate information, instruction and training • accompanied by suitable safety measures, e.g. protective devices, markings, warnings
Lifting Operations and Lifting Equipment Regulations 1998 (LOLER)	In general, LOLER requires that any lifting equipment used at work for lifting or lowering loads is: • strong and stable enough for particular use and marked to indicate safe working loads • positioned and installed to minimize any risks • used safely, i.e. the work is planned, organized and performed by competent people • subject to ongoing thorough examination and, where appropriate, inspection by competent people
Health and safety audit	Monitoring provides the information to let you or your employer review activities and decide how to improve performance. Audits, by company staff or outsiders, complement monitoring activities by looking to see whether your company policy, organization and systems are actually achieving the right results
Risk management and assessment	A risk assessment is simply a careful examination of what, in your work, could cause harm to people. This is done so that you and your company can decide whether you have taken enough precautions or should do more to prevent harm. Workers and others have a right to be protected from harm caused by a failure to take reasonable control measures. It is a legal requirement to assess the risks in the workplace, so you or your employer must put plans in place to control risks. How to assess the risks in your workplace: • Identify the hazards. • Decide who might be harmed and how. • Evaluate the risks and decide on precautions. • Record your findings and implement them. • Review your assessment and update if necessary.
Personal protective equipment (PPE)	PPE is defined in the Regulations as 'all equipment (including clothing affording protection against the weather) which is intended to be worn or held by a person at work and which protects him against one or more risks to his health or safety', e.g. safety helmets, gloves, eye protection, high-visibility clothing, safety footwear and safety harnesses. Hearing protection and respiratory protective equipment provided for most work situations are not covered by these Regulations because other regulations apply to them. However, these items need to be compatible with any other PPE provided

Figure 1.37 Exhaust extraction is an easy precaution to take

Figure 1.38 Eye protection and gloves in use

What you must do:

1. Follow the training you have received when using any work items your employer has given you.
2. Take reasonable care of your own and other people's health and safety.
3. Co-operate with your employer on health and safety.
4. Tell someone (your employer, supervisor, or health and safety representative) if you think the work or inadequate precautions are putting anyone's health and safety at serious risk.

1.3.4 Personal protective equipment (PPE)

Personal protective equipment (PPE) such as safety clothing is very important to protect you (Figs 1.38 and 1.39). Some people think it clever or tough not to use protection. They are very sad and will die or be injured long before you! Some things are obvious; for example when holding a hot or sharp exhaust you would likely be burnt or cut. Other things such as breathing in brake dust, or working in

Safety first

Some people think it clever or tough not to use protection. They are very sad and will die or be injured long before you!

Figure 1.39 Protective clothing for spot welding

Safety first

Breathing in brake dust, or working in a noisy area, does not produce immediately noticeable effects but could affect you later in life.

a noisy area, do not produce immediately noticeable effects but could affect you later in life.

Fortunately, the risks to workers are now quite well understood and we can protect ourselves before it is too late.

Table 1.6 lists a number of items classed as PPE together with suggested uses. You will see that the use of most items involves plain common sense.

1.3.5 Identifying and reducing hazards

Working in a motor vehicle workshop is a dangerous occupation, if you do not take care. The most important thing is to be aware of the hazards and then it is easy to avoid the danger. The hazards in a workshop are from two particular sources: you and your surroundings.

Hazards due to you may be caused by:

- carelessness – particularly while moving vehicles
- drinking or taking drugs – badly affects your ability to react to dangerous situations
- tiredness or sickness – affects your ability to think and work safely
- messing about – most accidents are caused by people fooling about
- not using safety equipment – you have a duty to yourself and others to use safety equipment
- inexperience – or lack of supervision: if in doubt – ask.

The surroundings in which you work may have:

- bad ventilation
- poor lighting
- noise

Table 1.6 Examples of personal protective equipment (PPE)

Equipment	Notes	Suggested or examples where used
Ear defenders	Must meet appropriate standards	When working in noisy areas or if using an air chisel
Face mask	For individual personal use only	In dusty conditions. When cleaning brakes or preparing bodywork
High-visibility clothing	Fluorescent colours such as yellow or orange	Working in traffic, such as when on a breakdown
Leather apron	Should be replaced if it is holed or worn thin	When welding or working with very hot items
Leather gloves	Should be replaced when they become holed or worn thin	When welding or working with very hot items and also if handling sharp metalwork
Life jacket	Must meet current standards	When attending vehicle breakdowns on ferries
Overalls	Should be kept clean and be flameproof if used for welding	These should be worn at all times to protect your clothes and skin. If you get too hot just wear shorts and a T-shirt underneath
Rubber or plastic apron	Replace if holed	Use if you do a lot of work with battery acid or with strong solvents
Rubber or plastic gloves	Replace if holed	Gloves must always be worn when using degreasing equipment
Safety shoes or boots	Strong toe caps are recommended	When working in any workshop with heavy equipment
Safety goggles	Keep the lenses clean and prevent scratches	Always use goggles when grinding or when at any risk of eye contamination. Cheap plastic goggles are much easier to come by than new eyes
Safety helmet	Must be to current standards	When working under a vehicle, in some cases
Welding goggles or welding mask	Check the goggles are suitable for the type of welding. Gas welding goggles are NOT good enough when arc welding	Wear welding goggles or use a mask even if you are only assisting by holding something

- dangerous substances stored incorrectly
- broken or worn tools and equipment
- faulty machinery
- slippery floors
- untidy benches and floors
- unguarded machinery
- unguarded pits.

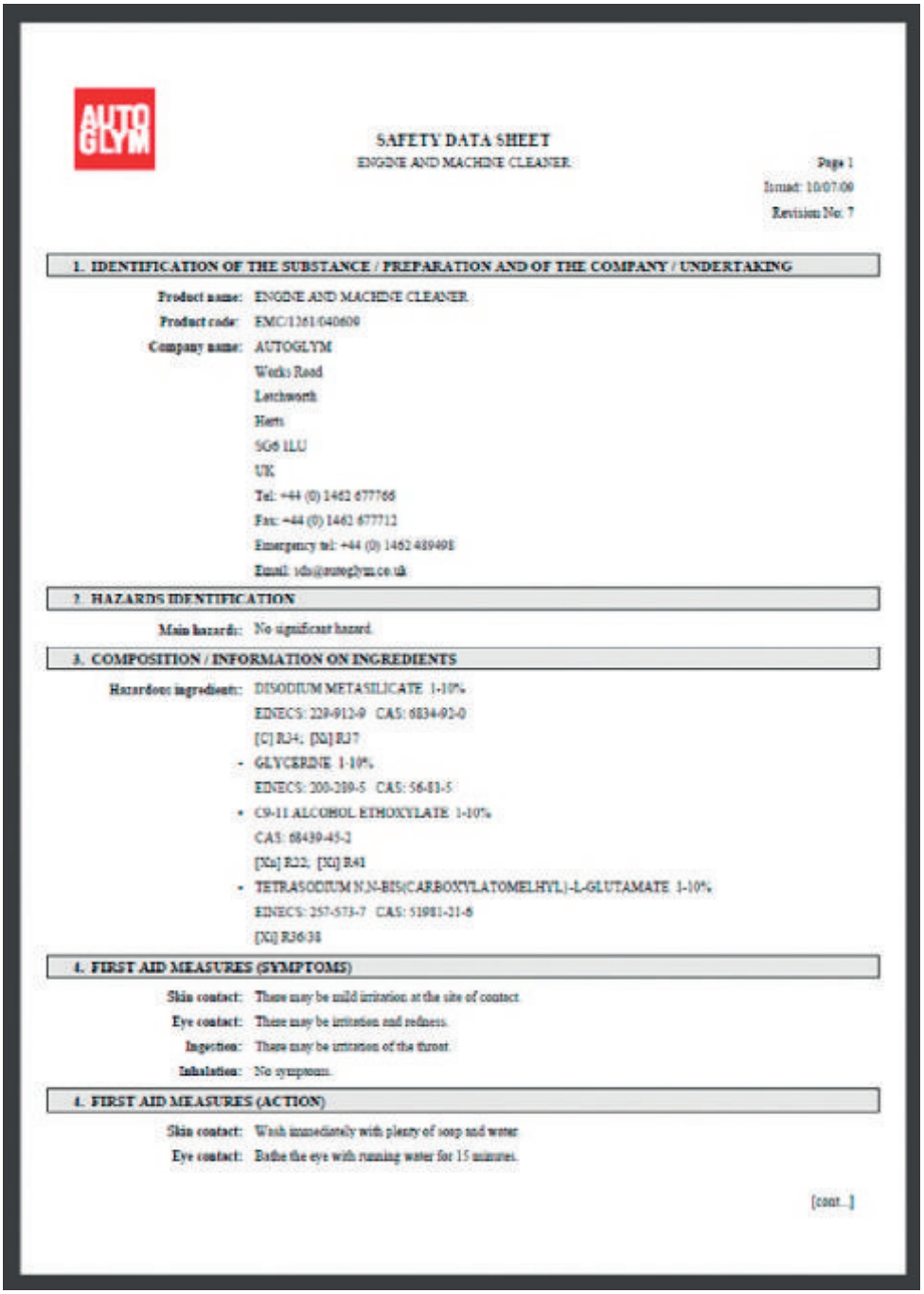
Table 1.7 lists some of the hazards you will come across in a vehicle workshop. Also listed are some associated risks, together with ways they can be reduced. This is called risk management. An example of a safety data sheet is given in Fig. 1.40.

1.3.6 Moving loads

Injuries in a workshop are often due to incorrect lifting or moving of heavy loads. In motor vehicle workshops, heavy and large components, such as engines and

Table 1.7 Hazards and actions to reduce risk

Hazard	Risks	Action
Power tools	Damage to the vehicle or personal injury	Understand how to use the equipment and wear suitable protective clothing, e.g. gloves and goggles
Working under a car on the ramp	1. The vehicle could roll or be driven off the end 2. You could bang your head on hard or sharp objects when working under the car	1. Ensure you use wheel chocks 2. Set the ramp at the best working height; wear protection if appropriate
Working under a car on a jack	The vehicle could fall on top of you	The correct axle stands should be used and positioned in a secure place
Compressed air	Damage to sensitive organs such as ears or eyes. Death, if air is forced through the skin into your bloodstream	Do not fool around with compressed air. A safety nozzle prevents excessive air forces
Dirty hands and skin	Oil, fuel and other contaminants can cause serious health problems, ranging from dermatitis to skin cancer	Use gloves or a good quality barrier cream and wash your hands regularly. Do not allow dirt to transfer to other parts of your body. Good overalls should be worn at all times
Exhaust fumes	Poisonous gases such as carbon monoxide can kill. The other gases can restrict breathing and cause sore throats, and can cause cancer	Only allow running engines in very well-ventilated areas or use an exhaust extraction system
Engine crane	Injury or damage can be caused if the engine swings and falls off	Ensure the crane is strong enough: do not exceed its safe working load (SWL). Secure the engine with good quality sling straps and keep the engine near to the floor when moving across the workshop
Cleaning brakes	Brake dust (especially older types made of asbestos) is dangerous to health	Only wash clean with proper brake cleaner
Fuel	Fire or explosion	Keep all fuels away from sources of ignition. Do not smoke when working on a vehicle
Degreaser solvent	Damage to skin or to sensitive components	Wear proper gloves and make sure the solvent will not affect the items you are washing
Spillage such as oil	Easy to slip over or fall and be injured	Clean up spills as they happen and use absorbent granules
Battery electrolyte (acid)	Dangerous to your skin and in particular your eyes. It will also rot your clothes	Wear protective clothing and take extreme care
Welding a vehicle	The obvious risks are burns, fire and heat damage, but electric welders such as a MIG welder can damage sensitive electronic systems	Have fire extinguishers handy, remove combustible materials such as carpets and ensure fuel pipes are nowhere near. The battery earth lead must also be disconnected. Wear gloves and suitable protective clothing such as a leather jacket
Electric hand tools	The same risk as for power tools, but also the danger of electric shock, particularly in damp or wet conditions. This can be fatal	Do not use electric tools when damp or wet. Electrical equipment should be inspected regularly by a competent person
Driving over a pit	Driving into the pit	The pit should be covered, or you should have another person help guide you and drive very slowly
Broken tools	Personal injury or damage to the car. For example, a file without a handle could stab into your wrist or a faulty ratchet could slip	All tools should be kept in good order at all times. This will also make the work easier
Cleaning fluids	Skin damage or eye damage	Wear gloves and eye protection and also be aware of exactly what precautions are needed by referring to the safety data information. (Fig. 1.40 shows an example)



AUTOGLYM

SAFETY DATA SHEET
ENGINE AND MACHINE CLEANER

Page 1
Issued: 10/07/09
Revision No: 7

1. IDENTIFICATION OF THE SUBSTANCE / PREPARATION AND OF THE COMPANY / UNDERTAKING

Product name: ENGINE AND MACHINE CLEANER
Product code: EMC/1261/040609
Company name: AUTOGLYM
Works Road
Letchworth
Herts
SG6 1LU
UK
Tel: +44 (0) 1462 677766
Fax: +44 (0) 1462 677712
Emergency tel: +44 (0) 1462 489401
Email: sds@autoglym.co.uk

2. HAZARDS IDENTIFICATION

Main hazards: No significant hazard.

3. COMPOSITION / INFORMATION ON INGREDIENTS

Hazardous ingredients: DISODIUM METASILICATE 1-10%
EINECS: 229-912-9 CAS: 6834-92-0
[C] R34; [Xi] R37
- GLYCERINE 1-10%
EINECS: 200-289-5 CAS: 56-81-5
- C9-11 ALCOHOL ETHOXYLATE 1-10%
CAS: 68439-45-2
[Xn] R22; [Xi] R41
- TETRASODIUM N,N-BIS(CARBOXYLATOMELHYL)-L-GLUTAMATE 1-10%
EINECS: 257-573-7 CAS: 51981-21-6
[Xi] R36/38

4. FIRST AID MEASURES (SYMPTOMS)

Skin contact: There may be mild irritation at the site of contact.
Eye contact: There may be irritation and redness.
Ingestion: There may be irritation of the throat.
Inhalation: No symptoms.

4. FIRST AID MEASURES (ACTION)

Skin contact: Wash immediately with plenty of soap and water.
Eye contact: Bathe the eye with running water for 15 minutes.

[cont...]

Figure 1.40 Example of a safety data sheet. (Source: AutoGlym)

gearboxes, can cause injury when being removed and refitted. A few simple precautions will prevent you from injuring yourself, or others.

- Never try to lift anything beyond your capability – get a mate to help. The amount you can safely lift will vary but any more than you feel comfortable with, you should get help.
- Whenever possible use an engine hoist, a transmission jack or a trolley jack (Fig. 1.41).
- Lift correctly, using the legs and keeping your back straight.
- When moving heavy loads on a trolley, get help and position yourself so you will not be run over if you lose control.

The ideal option in all cases is to avoid manual handling where possible.

Safety first

Use lifting equipment where there is risk of injury when moving loads manually.

Figure 1.41 Engine crane. (Source: Blue-Point)

1.3.7 Vehicle safety

Vehicle safety and the associated regulations can be very complicated. However, for our purposes we can consider the issue across two main areas: construction and operation of the vehicle.

1.3.7.1 Construction of the vehicle

Before a vehicle can be constructed a prototype has to be submitted for type approval. When awarded this means the vehicle has passed very stringent tests and that it meets all current safety requirements. Different countries have different systems, which means some modifications to a car may be necessary if it is imported or exported. The European Union (EU) has published many directives which each member country must incorporate into its own legislation. This has helped to standardize many aspects. In the UK the Road Vehicles (Construction & Use) Regulations 1986 is the act which ensures certain standards are met. If you become involved in modifying a vehicle, e.g. for import, you may need to refer to the details of this act. Other countries have similar legislation.

Many other laws exist relating to the motor vehicle and the environment. These are about emissions and pollution. Environmental laws change quite often and it is important to keep up to date.

The Department of Transport states that all vehicles over three years old must undergo a safety check which ensures the vehicle continues to meet the current legislation. First set up by the Ministry of Transport, it continues to be known as the MOT test. This test now includes checks relating to environmental laws.

1.3.7.2 Driving and operating the vehicle

To drive a vehicle on the road you must have an appropriate driving licence and insurance, and the vehicle must be taxed and must be in safe working order.

Table 1.8 Actions in the case of an accident

Action	Notes
Assess the situation	Stay calm: a few seconds to think is important
Remove the danger	If the person was working with a machine, turn it off. If someone is electrocuted, switch off the power before you hurt yourself. Even if you are unable to help with the injury you can stop it getting worse
Get help	If you are not trained in first aid, get someone who is and/or phone for an ambulance
Stay with the casualty	If you can do nothing else, the casualty can be helped if you stay with him. Also say that help is on its way and be ready to assist. You may need to guide the ambulance
Report the accident	All accidents must be reported: by law, your company should have an accident book. This is a record so that steps can be taken to prevent the accident happening again. Also, if the injured person claims compensation, underhanded companies could deny the accident happened
Learn first aid	If you are in a very small company, why not get trained now, before the accident?

1.3.8 Safety procedures

When you know the set procedures to be followed, it is easier to look after yourself, your workshop and your workmates. You should know:

- who does what during an emergency
- the fire procedure for your workplace
- about different types of fire extinguisher and their uses
- the procedure for reporting an accident.

If an accident does occur in your workplace the first bit of advice is: keep calm and don't panic! The HASAW states that for companies above a certain size:

- first aid equipment must be available
- employers should display simple first aid instructions
- fully trained first aiders must be employed.

In your own workplace you should know about the above three points. A guide to how to react if you come across a serious accident is given in Table 1.8.

Safety first

Keep calm and don't panic!

1.3.9 Fire

Accidents involving fire are very serious. As well as you or a workmate calling the fire brigade (do not assume it has been done), three simple rules will help you to know what to do:

1. Get safe yourself, contact the emergency services – and shout FIRE!
2. Help others to get safe if it does not put you or others at risk.
3. Fight the fire if it does not put you or others at risk.

Of course, far better than the above situation is not to let a fire start in the first place.

Figure 1.42 Fire triangle. (Source: Wikimedia)

Safety first

A fire is prevented or extinguished by removing any side of the fire triangle.

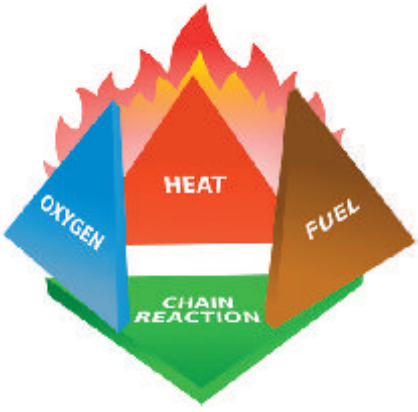


Figure 1.43 Fire tetrahedron. (Source: Wikimedia)

The fire triangle or combustion triangle is a simple model for understanding the ingredients necessary for most fires (Fig. 1.42). The triangle illustrates that a fire requires three elements: heat, fuel and an oxidizing agent (usually oxygen from the air). The fire is prevented or extinguished by removing any one of them. A fire naturally occurs when the elements are combined in the right mixture.

Without sufficient heat, a fire cannot start or continue. Heat can be removed by the application of a substance that reduces the amount of heat available to the fire reaction. This is often water, which requires heat to change from water to steam. Introducing sufficient quantities and types of powder or gas in the flame also reduces the amount of heat available for the fire reaction. Turning off the electricity in an electrical fire removes the ignition source.

Without fuel, a fire will stop. Fuel can be removed naturally, as where the fire has consumed all the burnable fuel, or manually, by mechanically or chemically removing the fuel from the fire. The fire goes out because a lower concentration of fuel vapour in the flame leads to a decrease in energy release and a lower temperature. Removing the fuel therefore decreases the heat.

Without enough oxygen, a fire cannot start or continue. With a decreased oxygen concentration, the combustion process slows. In most cases, there is plenty of air left when the fire goes out, so this is commonly not a major factor.

The fire tetrahedron is an addition to the fire triangle (Fig. 1.43). It adds the requirement for the presence of the chemical reaction which is the process of fire. For example, the suppression effect of a Halon extinguisher is due to its interference in the fire chemical inhibition. Note that Halon extinguishers are only now allowed in certain situations and are illegal for normal use.

Combustion is the chemical reaction that feeds a fire more heat and allows it to continue. When the fire involves burning metals like magnesium (known as a class D fire), it becomes even more important to consider the energy release. The metals react faster with water than with oxygen and thereby more energy is released. Putting water on such a fire makes it worse. Carbon dioxide (CO_2) extinguishers are ineffective against certain metals such as titanium. Therefore, inert agents (e.g. dry sand) must be used to break the chain reaction of metallic combustion. In the same way, as soon as we remove one out of the three elements of the triangle, the fire stops.

If a fire does happen your workplace should have a set procedure so you will know:

- how the alarm is raised
- what the alarm sounds like
- what to do when you hear the alarm
- your escape route from the building
- where to go to assemble
- who is responsible for calling the fire brigade.

There are a number of different types of fire, as shown in Table 1.9.

If it is safe to do so you should try to put out a small fire. Extinguishers and a fire blanket should be provided. Remember, if you remove one side of the fire triangle, the fire will go out. If you put enough water on a fire it will cool down and go out. However, spraying water on an electrical circuit could kill you. Spraying water on a petroleum fire could spread it about and make the problem far worse. This means that a number of different fire extinguishers are needed. Internationally there are several accepted classification methods for hand-held fire extinguishers. Each classification is useful in fighting fires with a particular

Table 1.9 Classification of fires

European/ Australian/Asian	American	Fuel/heat source
Class A	Class A	Ordinary combustibles
Class B	Class B	Flammable liquids
Class C		Flammable gases
Class D	Class D	Combustible metals
Class E	Class C	Electrical equipment
Class F	Class K	Cooking oil or fat

Table 1.10 Australia: fire extinguishers

Type	Pre-1997		Current	Suitable for use on fire class[a]					
Water	Solid red		Solid red	A					
Foam	Solid blue		Red with a blue band	A	B				
Dry chemical (powder)	Red with a white band		Red with a white band	A	B	C		E	
Carbon dioxide	Red with a black band		Red with a black band	(A)	B		D		F
Vaporizing liquid (non-Halon clean agents)	Not yet in use		Red with a yellow band	A	B	C		E	
Halon	Solid yellow		No longer produced	A	B			E	
Wet chemical	Solid oatmeal		Red with an oatmeal band	A					F

[a]Parentheses denote sometimes applicable.

group of fuel. Tables 1.10–1.12 show the differences: study the one that relates to your situation.

In Australia (Table 1.10), yellow (Halon) fire extinguishers are illegal to own or use on a fire, unless an essential use exemption has been granted.

There is no official standard in the USA for the colour of fire extinguishers, though they are typically red, except for class D extinguishers, which are usually yellow, and water extinguishers, which are usually silver, or, if water mist types, white (Table 1.11). Extinguishers are marked with pictograms depicting the types of fires that the extinguisher is approved to fight. In the past, extinguishers were marked with coloured geometric symbols. Some extinguishers still use both symbols.

Fire extinguishers in the UK, and throughout Europe, are red (Fig. 1.44), with a band or circle of a second colour covering between 5 and 10% of the surface area of the extinguisher to indicate its contents (Table 1.12). Prior to 1997, the entire body of the fire extinguisher was colour coded.

In the UK the use of Halon gas is now prohibited except under certain situations such as on aircraft and by the military and police.

Safety first

Study the table on fire extinguishers that relates to your situation.

Table 1.11 USA: fire extinguishers

Fire class	Geometric symbol	Pictogram	Intended use
A	Green triangle	Garbage can and wood pile burning	Ordinary solid combustibles
B	Red square	Fuel container and burning puddle	Flammable liquids and gases
C	Blue circle	Electric plug and burning outlet	Energized electrical equipment
D	Yellow decagon (star)	Burning gear and bearing	Combustible metals
K	Black hexagon	Pan burning	Cooking oils and fats

Figure 1.44 CO_2 and water extinguishers and information posters

1.3.10 Clean working environment

There are three main reasons for keeping your workshop and equipment clean and tidy:

- It makes the workshop a safer place to work.
- It makes it a better place to work.
- It gives a better image to your customers.

Servicing and fixing motor vehicles can be a dirty job, but if you clean up after any job then you will find your workshop a much more pleasant place in which to work.

- The workshop and floor should be uncluttered and clean to prevent accidents and fires as well as maintaining the general appearance.

Table 1.12 UK and Europe: fire extinguishers

Type	Old code		BS EN 3 colour code	Suitable for use on fire class[a]					
Water	Signal red		Signal red	A					
Foam	Cream		Red with a cream panel above the operating instructions	A	B				
Dry powder	French blue		Red with a blue panel above the operating instructions	(A)	B	C		E	
Carbon dioxide (CO_2)	Black		Red with a black panel above the operating instructions		B			E	
Wet chemical	Not yet in use		Red with a canary yellow panel above the operating instructions	A	(B)				F
Class D powder	French blue		Red with a blue panel above the operating instructions				D		
Halon 1211/ BCF	Emerald green		No longer in general use	A	B			E	

[a]Parentheses denote sometimes applicable.

- Your workspace reflects your ability as a technician. A tidy workspace equals a tidy mind equals a tidy job equals a tidy wage when you are qualified.
- Hand tools should be kept clean as you are working. You will pay a lot of money for your tools; look after them and they will look after you in the long term.
- Large equipment should only be cleaned by a trained person or a person under supervision. Obvious precautions are to ensure that equipment cannot be operated while you are working on it and only using appropriate cleaning methods. For example, would you use a bucket of water or a brush to clean down an electric pillar drill? I hope you answered 'a brush'!

In motor vehicle workshops many different cleaning operations are carried out. This means a number of different materials are required. It is not possible to mention every brand name here,but the materials are split into three different types in Table 1.13. It is important to note that the manufacturer's instructions printed on the container must be followed at all times.

1.3.11 Signage

A key safety aspect is first to identify hazards and then to remove them or, if this is not possible, reduce the risk as much as possible and bring the hazard to everyone's attention. This is usually done by using signs or markings. Signs used to mark hazards are often as shown in Tables 1.14 and 1.15.

Safety first

Identify hazards and then remove them. If this is not possible, make others aware of them using signs.

1.3.12 Environmental protection

Environmental protection is all about protecting the environment, on individual, organizational or governmental levels. Owing to the pressures of population and technology the Earth's environment is being degraded, sometimes

Table 1.13 Cleaning materials

Material	Purpose	Notes
Detergents	Mixed with water for washing vehicles, etc. Also used in steam cleaners for engine washing, etc.	Some industrial detergents are very strong and should not be allowed in contact with your skin
Solvents	To wash away and dissolve grease and oil, etc. The best example is the liquid in the degreaser or parts washer which all workshops will have	NEVER use solvents such as thinners or fuel because they are highly inflammable. Suitable PPE should be used, e.g. gloves They may attack your skin Many are flammable The vapour given off can be dangerous Serious problems if splashed into eyes Read the label
Absorbent granules	To mop up oil and other types of spills. They soak up the spillage after a short time and can then be swept up	Most granules are a chalk or clay type material which has been dried out

Table 1.14 Hazard, mandatory and warning signs

Function	Example	Background colour	Foreground colour	Sign
Hazard warning	Danger of electric shock	Yellow	Black	**Figure 1.45** Electricity
Mandatory	Use ear defenders when operating this machine	Blue	White	**Figure 1.46** Wear ear protection
Prohibition	Not drinking water	White	Red/black	**Figure 1.47** Not drinking water

permanently. Activism by the environmental movement has created awareness of the various environmental issues. This has led to governments placing restraints on activities that cause environmental problems and producing regulations.

Table 1.15 Other common signage

Function	Example	Background colour	Foreground colour	Sign
First aid (escape routes are a similar design)	Location of safety equipment such as first aid	Green	White	**Figure 1.48** First aid
Fire	Location of fire extinguishers	Red	White	**Figure 1.49** Extinguisher
Recycling	Recycling point	White	Green	**Figure 1.50** The three Rs of the environment

In a workshop these regulations relate to many items such as solvents used for cleaning or painting, fuels, oil and many other items. Disposal methods must not breach current regulations and, in many cases, only licensed contractors can dispose of certain materials. Failure to comply can result in heavy penalties. Make sure you are aware of your local regulations, as these can change.

Safety first

Disposal methods must not breach current regulations.

Finally, let's consider the three Rs:

- **Reduce** the amount of the Earth's resources that we use.
- **Reuse** – Don't just bin it: could someone else make use of it?
- **Recycle** – Can the materials be made into something new?

And, as we are automotive technicians, maybe there is a fourth: **Repair**?

1.4 Basic science, materials, mathematics and mechanics

1.4.1 Introduction

Key fact

Understanding basic principles will mean that you will be a better technician.

When you want to work on motor vehicles, it is easy to wonder why you should study maths, science, materials, electricity and other similar subjects. The answer is that understanding basic principles will mean that you will be a better technician because you know how things really work – and you will have the skills to figure out how something you have not seen before works.

Often the words used to describe scientific principles can be confusing. Table 1.16 picks out the most important terminology and a simple explanation is given. Some of the terms are described in more detail in later sections.

Table 1.16 Useful terminology

SI units	A set of standard units so we all talk the same language. SI stands for 'Système International'. This is French for 'International System'!
Ratio	The amount of one thing compared to another, e.g. two to one is written as 2:1
Area (m^2)	Amount of surface of anything, e.g. the surface area of a car roof would help you know how much paint would be needed to cover it
Volume (m^3)	Capacity of an object, e.g. 1000 cc (cubic centimetres) or one litre of paint to do the job above
Mass (kg)	The quantity of matter in a body. Volume does not matter, e.g. which has the greater mass, a kilogram of lead or a kilogram of feathers? They both have the same mass, but have different volumes
Density (kg/m^3)	A full paint tin has a greater mass than an empty tin, but the volumes are the same
Energy (J)	The ability to do work or the amount of work stored in something; e.g. petrol contains a lot of energy in chemical form
Force (N)	When you push an object it moves (if you can apply enough force)
Work (J)	Work is done when the force applied to an object makes it move. Work can also be said to be done when energy is converted from one form to another
Power (W)	The rate at which work can be done, e.g. energy used per second
Torque (Nm)	A turning force like a spanner turning a nut. A longer spanner needs less force
Velocity (m/s)	A scientific name for speed; e.g. the UK national velocity limit is 70 mph (not an SI unit!)
Acceleration (m/s^2)	The rate at which velocity changes. If positive then the car, for example, will increase in speed. If negative (or deceleration) such as when braking, the car's speed decreases
Momentum (kg m/s)	The combination of the mass of a body and its velocity. A large goods vehicle has much greater momentum than a car at the same speed. It must have much better brakes or it will take a lot longer to stop
Friction (μ)	When one surface moves over another friction tries to stop the movement. It is interesting to note that without friction a moving object such as a car would not stop!
Heat (J)	This is a measure of the amount of energy in a body. Heat can only transfer from a higher to a lower temperature and this will be by conduction, convection or radiation
Temperature (°C)	A measure of how hot something is, but this must not be confused with the amount of heat energy

(*Continued*)

Table 1.16 (Continued)

Pressure (N/m^2 or Pa)	This is a force per area; e.g. the old tyre pressure measurement for many cars was 28 psi (pounds per square inch). The better unit to get used to is the bar: the tyre pressure would be about 1.8 bar. The SI unit is the pascal or newtons per metre squared (Pa or N/m^2). The pressure in this room is about 1 bar or 1 atmosphere or 100 000 Pa. It may be much more if you have been reading about science for a long time!
Centrifugal force (N)	If you swing a stone on a string round your head it tries to move outwards and you can feel the centrifugal force on the string. The faster you swing it the greater the force. When a car wheel is rotating very quickly a small imbalance in the tyre causes unequal centrifugal force and this makes the wheel wobble
Weight (N)	The mass of an object acted upon by the Earth's gravity gives it a weight. When you next go into outer space, you will find that your weight is zero, or in other words you are weightless. You still have the same mass, however. The word weight is often used incorrectly, but as gravity is the same all over the Earth it doesn't often make any difference
Centre of gravity	The point within an object at which it will balance. All the weight of an object such as a car can be said to act through the centre of gravity. If the force due to gravity and acceleration acting through this point falls outside the wheels of the car, the car will fall over!
Electricity	This is the movement of electrons known as a current flow in a conductor or a wire. Electricity is a very convenient way of transferring energy
Strength	This is hard to define because different materials are strong in different ways. A material can be strong by providing opposition to bending, tension, compression or shear force
Corrosion	Corrosion of materials is by a chemical process; e.g. if iron is left open to the air or water it rusts. The chemical process is that the iron reacts with oxygen in the air and turns into iron oxide (rust)
Machines	A machine is something that converts one form of energy into another; e.g. an alternator converts mechanical energy from the engine into electrical energy
Hydraulics	When fluids are used to do 'work' this is described as hydraulics. The braking system of a car is a good example
Oscillation	If you bounce a mass on a spring (a car on its suspension) it will move up and down (oscillate) until all the mechanical energy in the spring has been converted to another form (mostly heat due to friction). Dampers are used on a car to make this time as short as possible

1.4.2 Units

When I go into a café or a bar and I ask for a pint of beer or half a litre of coke I usually get what I want (Fig. 1.51). This is because I ask by using the correct units. When you blow up the tyres on a car you check the pressure in a book or on a chart and then look at the gauge. It will have the same units, and you can inflate the tyres to the correct pressure.

The easiest units to work with are called SI units, sometimes described as the metric system. Other systems are fine, of course, and whatever is in common use, or whatever is stated in manufacturer's data is what you should use. However, the basic SI units you will need to know are listed in Table 1.17.

Many other units in use are derived from the basic SI units. Some of them are combined and given new names (Table 1.18).

When dealing with some of these units or derived units, we need a way of describing very large or very small quantities. For example, I would not say that I live 24 000 metres away from where I work. I would say I live 24 kilometres away, normally written as 24 km. The 'k' is known as a multiplier and in this case you will see it has the value of 1000.

Definition

SI
SI stands for 'Système International' (often described as the metric system).

Figure 1.51 Mmm!

Table 1.17 SI units

Unit	Abbreviation	Quantity	Example
metre	m	Length	The distance from one point to another
kilogram	kg	Mass	The quantity of matter which makes an object
second	s	Time	About 300 s to boil an egg!
ampere	A	Electric current	The flow rate of electricity through a wire
kelvin	K	Temperature	How hot the radiator of a car is
candela	cd	Luminous intensity	How brightly a headlight shines

Table 1.18 Derived SI units

Unit	Abbreviation	Quantity
joule	J	Energy
newton	N	Force
watt	W	Power
area	m^2	Square metres
volume	m^3	Cubic metres
torque	Nm	Newton metres
velocity	m/s or $m\,s^{-1}$	Metres per second
acceleration	m/s/s or $m\,s^{-2}$	Metres per second per second

Table 1.19 Common multipliers

Prefix	Symbol	Value	Long value
mega	M	10^6	1 000 000
kilo	k	10^3	1000
hecto	h	10^2	100
centi	c	10^{-2}	0.01
milli	m	10^{-3}	0.001
micro	μ	10^{-6}	0.000 001

Likewise, if setting a spark plug gap I could set it at 0.001 metres, or it might be easier to say 1 millimetre, normally written as 1 mm. The 'm' can be thought of as a divider which in this case is 1000 or a multiplier of 0.001. Common multipliers are listed in Table 1.19.

1.4.3 Velocity and acceleration

Velocity is the speed of an object in a given direction. Velocity is a 'vector quantity', meaning that its direction is important as well as its speed. The velocity *v* of an object travelling in a fixed direction may be calculated by dividing the distance *s* it has travelled by the time taken *t*. It is expressed as miles per hour (mph) or m/s (metres per second).

Acceleration is the rate of change of velocity (how quickly speed is increasing or decreasing). It is usually measured in metres per second per second. Newton's second law of motion says that a body will accelerate only if it is acted upon by an outside force. The outside force on a car is either the accelerator to increase speed (accelerate) or the brakes to decrease speed (decelerate). It is usually expressed as metres per second per second or ms^{-2}.

Acceleration due to gravity is the acceleration of an object falling due to the Earth's gravity. The value used for gravitational acceleration or *g* is $9.806\,ms^{-2}$ ($10\,ms^{-2}$ is usually near enough for our calculations).

The average acceleration *a* of an object travelling in a straight line over a time *t* may be calculated using the formula:

$$\text{Acceleration} = \text{Change of velocity/Time taken}$$

Or, if *v* is its final velocity and *u* its initial velocity:

$$a = (v - u)/t$$

A negative answer (less than zero, e.g. $-5\,ms^{-2}$) would mean that the object is slowing down (decelerating).

Definition

Velocity
Velocity = Distance travelled/Time taken ($v = s/t$)

Key fact

The force that opposes the relative motion of two bodies in contact is known as friction.

1.4.4 Friction

The force that opposes the relative motion of two bodies in contact is known as friction. The coefficient of friction is the ratio of the force needed to achieve this motion to the force pressing the two bodies together.

For motor vehicle use friction is greatly reduced in some places by using lubricants such as oil and grease. In other places friction is deliberately increased; for example, brake shoes, pads, drive belts and tyres.

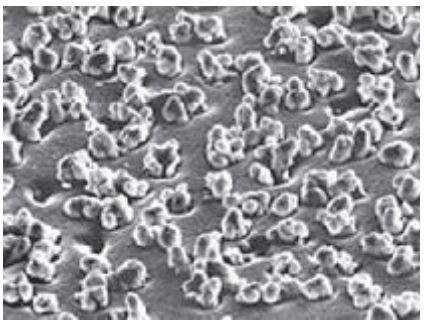


Figure 1.52 Surface of a smooth material magnified thousands of times

1.4.5 Pressure

In a fluid or gas, pressure is said to be the force that acts at right angles per unit surface area of something immersed in the fluid or gas. The SI unit of pressure is the pascal (Pa), equal to a pressure of 1 newton per square metre. In the atmosphere, the pressure decreases as you go higher, from about 101 kPa at sea level to zero, where the atmosphere dwindles into space. The other common units of pressure you will meet are the bar and psi. One bar (100 kPa) is atmospheric pressure, which is also about 14.7 psi (pounds per square inch).

Absolute pressure is measured from a perfect vacuum or zero pressure (Fig. 1.53). Gauge pressure is the difference between the measured pressure and atmospheric pressure. A tyre gauge works like this because it reads zero in atmospheric pressure. When we talk about a vacuum or a depression, what we really mean is a pressure less than atmospheric. It is best to use absolute pressure figures for

Definition

Pressure
The SI unit of pressure is the pascal (Pa), equal to a pressure of 1 newton per square metre.

Definition

Absolute pressure
Absolute pressure is measured from a perfect vacuum or zero pressure.

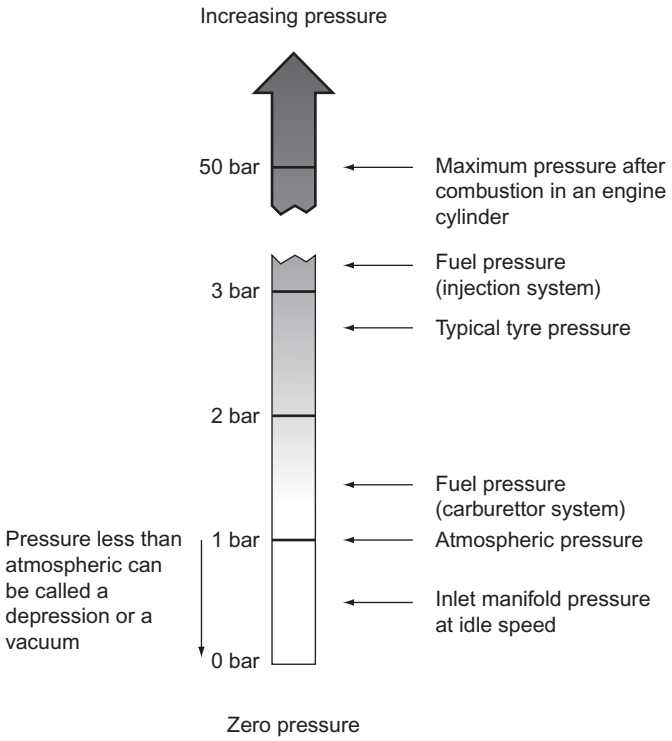


Figure 1.53 Absolute pressure

discussing subjects such as the operation of an engine, or at least make sure you do not confuse the different figures.

1.4.6 Centre of gravity or centre of mass

The centre of gravity (or mass) is a point in or near to an object about which it would turn if it could rotate freely. A symmetrical object, such as a cube or ball, has its centre of mass at its geometrical centre; a hollow object such as a beer glass may have its centre of gravity in the space inside it.

For an object such as a car to be stable, a perpendicular line down through its centre of gravity must run within the boundaries of its wheelbase (Fig. 1.54). If the car is tilted until this line falls outside the wheelbase, it will become unstable and fall over.

Definition

Time period
For any vibration, the time for one complete oscillation.

1.4.7 Oscillation

An oscillation is one complete to-and-fro movement of a vibrating object or system (Fig. 1.55). For any vibration, the time for one complete oscillation is its time period.

The number of oscillations in one second is the frequency. In most mechanical systems in the car, oscillations are damped down. The dampers (shock absorbers) fitted to the suspension help to prevent the springs oscillating.

Key fact

Energy cannot be destroyed, only converted to another form.

1.4.8 Energy, work and power

Energy can be thought of as the ability to do work or the amount of work stored up, and is measured in joules. When you have no energy it's hard to work! Energy

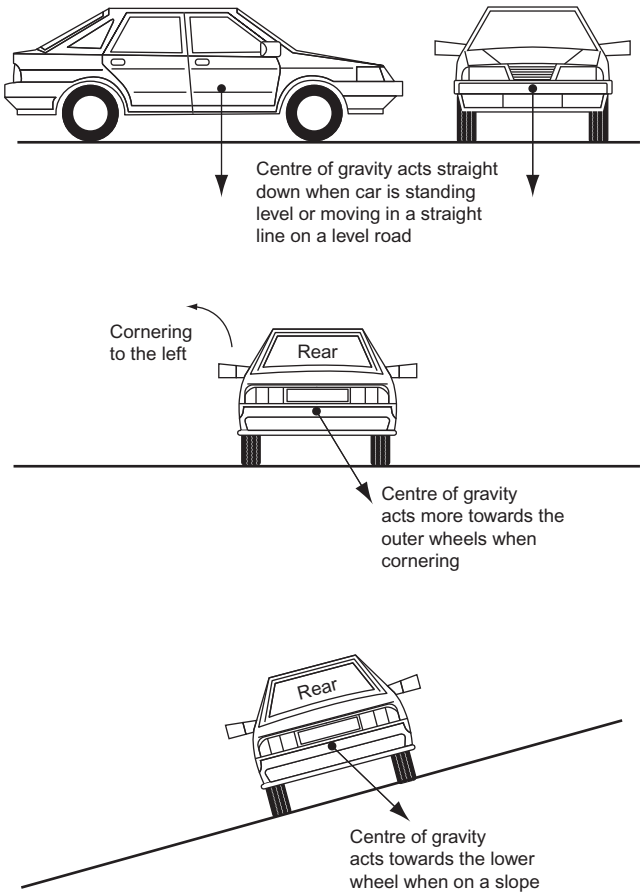


Figure 1.54 Centre of gravity of a car

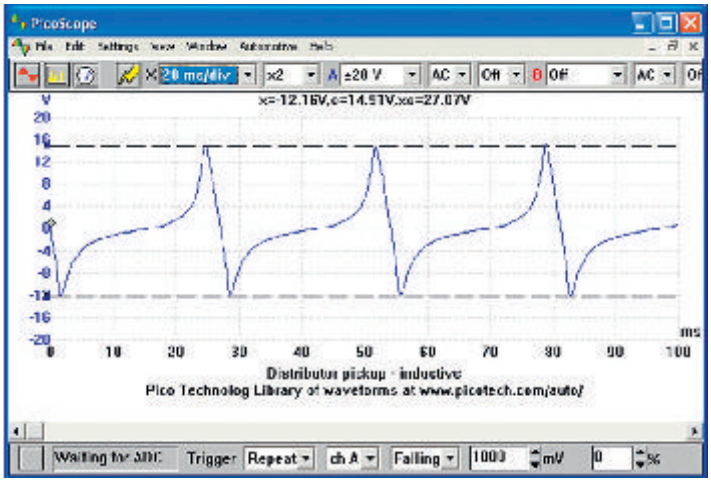


Figure 1.55 Oscillating signal produced by a crank sensor. (Source: PicoScope)

cannot be destroyed, only converted to another form. It can be stored in a number of forms.

Most types of energy are listed here, together with an example (Fig. 1.56):

- kinetic or mechanical energy, e.g. the movement of an engine
- potential or position energy, e.g. when you lift a hammer its potential energy increases

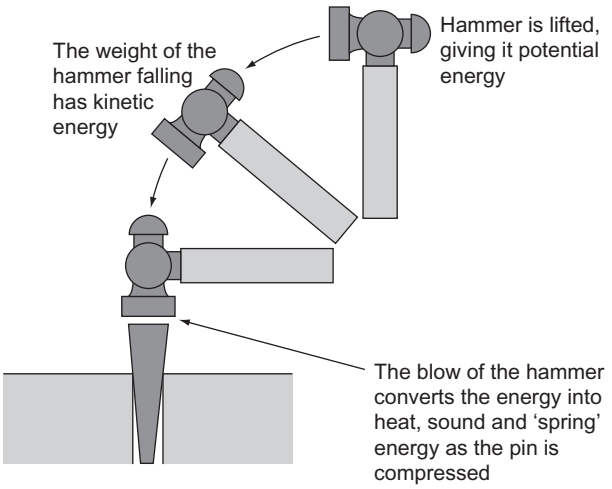


Figure 1.56 Waiting for the hammer to fall

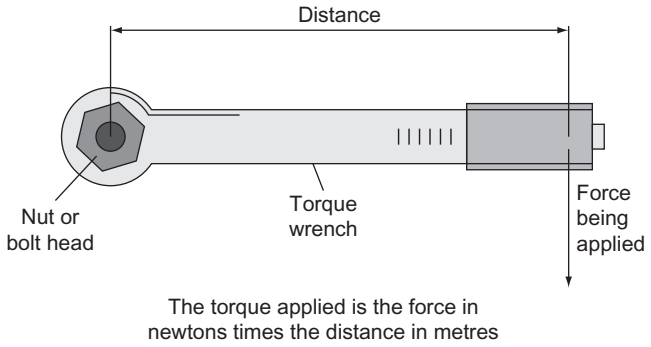


Figure 1.57 Torque wrench

- electrical energy, e.g. that made by an alternator
- chemical energy, e.g. stored in a battery
- heat energy, e.g. from burning a fuel
- nuclear energy – which is not yet used in motor vehicles, fortunately!

Power is the rate of doing work or converting energy. It is measured in watts. If the work done, or energy converted, is E joules in t seconds, then the power P is calculated by:

$$\text{Power} = \text{Work done/Time}$$

$$P = E/t$$

1.4.9 Force and torque

A force is thought of as any influence that tends to change the state of rest or the motion in a straight line of an object, just like braking force slows a vehicle down. If the body cannot move freely it will deform or bend. Force is a vector quantity, which means it must have both size and direction; its unit is the newton (N).

Torque is the turning effect of force on an object (Fig. 1.57). A car engine produces a torque at the wheels. Torque is measured by multiplying the force by its perpendicular distance away from the turning point; its unit therefore is the newton metre (Nm).

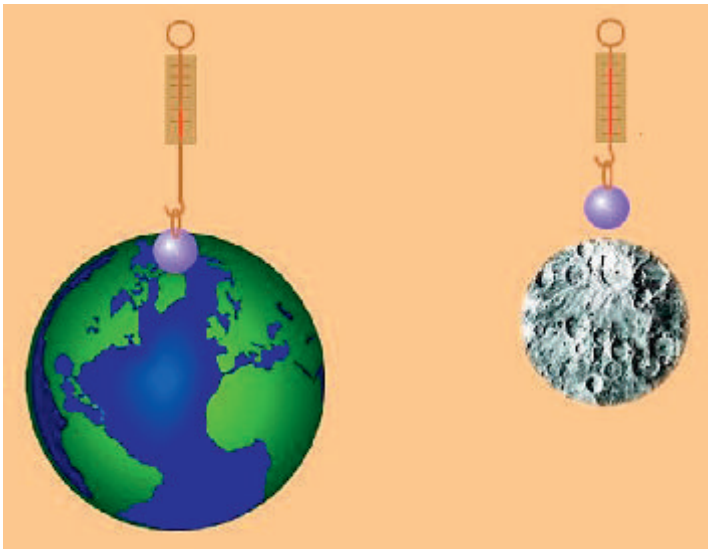


Figure 1.58 Mass on the Earth and Moon remains the same but the weight will change

1.4.10 Mass, weight and force

Mass is the quantity of matter in a body as measured by its resistance to movement. The SI system base unit of mass is the kilogram (kg). The mass of an object such as a car determines how much driving force is needed to produce acceleration. The mass also determines the force exerted on a body by gravity.

Key fact

The mass of an object determines how much driving force is needed to produce acceleration.

The force F, mass m and acceleration a (or g, if due to gravity) can be calculated using:

$$\text{Force} = \text{Mass} \times \text{Acceleration}$$

$$F = ma$$

Or

$$\text{Force (weight)} = \text{Mass} \times \text{Gravity}$$

$$F = mg$$

At a given place, equal masses experience equal gravity, which are known as the weights of the bodies. Masses can be compared by comparing the weights of bodies as long as they are at the same place (Fig. 1.58).

1.4.11 Volume and density

Density is a measure of the compactness of a substance; it is measured in kilograms per cubic metre (kg/m^3 or kg m^{-3}. The density D of a mass m, occupying a volume V, is given by:

$$\text{Density} = \text{Mass/Volume}$$

$$D = m/V$$

Relative density is the ratio of the density of one substance to another. This is useful for testing older types of battery by comparing the density of the electrolyte to that of water (Fig. 1.59). It is sometimes described as specific gravity.

Definition

Relative density
The ratio of the density of one substance to another.

Figure 1.59 Measuring relative density with a hydrometer

1.4.12 Heat and temperature

Heat is a form of energy possessed by a substance by virtue of the vibrating movement or kinetic energy of its molecules or atoms. Heat only flows from a higher temperature to a lower temperature. Its effect on a substance may be simply to raise its temperature, or to cause it to expand. Solids can melt, liquids vaporize and gases if confined will increase in pressure. This is much like ice, water, steam and steam pressure in a boiler.

Quantities of heat are usually measured in units of energy, such as joules (J). The specific heat capacity of a substance is the ratio of the amount of heat energy required to raise the temperature of a given mass of the substance through a given range of temperature, to the heat required to raise the temperature of an equal mass of water through the same range. This is useful for comparing materials.

Heat energy is transferred by conduction, convection and radiation. Conduction is the passing of heat along a medium to neighbouring parts. For example, the whole length of a metal rod becomes hot when one end is held in the flame of a welding torch. Convection is the transmission of heat through a liquid or gas in currents, for example when the air in a car is warmed by the heater matrix and blower. Radiation is heat transfer by infrared rays. It can pass through a vacuum and travels at the speed as light. For example, you can feel radiated heat from a vehicle headlight just in front of the glass.

Definition

Heat
Heat is a form of energy.

1.4.13 Percentages

1.4.13.1 Example 1

If a data book says 30% antifreeze and the cooling system holds 8 litres, how much antifreeze should you add? (Fig. 1.60)

30% means 30/100, which cancels to 3/10

$3/10 \times 8 = 24/10 = 2.4$ litres

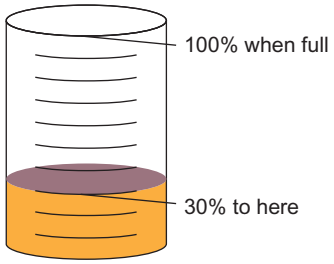


Figure 1.60 Percentage

1.4.13.2 Example 2

If your normal pay rate is £10 per hour, how much will you get if you are given a 22% rise?

22% means 22/100

$22/100 \times £10 = £2.20$

Your new pay rate is £10 + £2.20p = £12.20 per hour

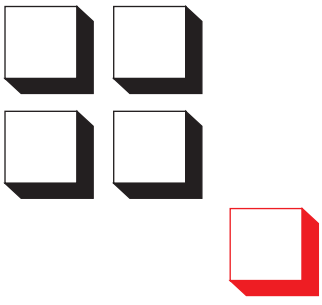


Figure 1.61 The red block is a quarter of the four black ones

1.4.14 Fractions

1.4.14.1 Example 1

If your normal pay rate is £5 per hour, how much will you get if your pay increases by a quarter? (Fig. 1.61)

Time and a quarter means $1\frac{1}{4} \times$ your normal rate

$1\frac{1}{4} \times £5 = 5/4 \times 5/1 = 25/4 = 6.25$

Your overtime pay rate is £6.25 per hour

1.4.14.2 Example 2

If a heater blower circuit has a 2 Ω and a 3 Ω resistor connected in parallel by the speed control switch, what is the combined resistance?

$$\text{The formula is: } 1/R_T = 1/R_1 + 1/R_2$$

$$\text{Which means } 1/R_T = 1/2 + 1/3$$

To add fractions the bottom numbers must be the same:

$$1/R_T = 3/6 + 2/6$$

$$1/R_T = 5/6 \quad R_T = 6/5 = 1.2\,\Omega$$

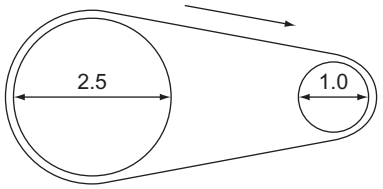
1.4.15 Ratios

1.4.15.1 Example

If the maximum speed an alternator can run at is 15 000 r.p.m. and the top speed of the engine is 6000 r.p.m., why is the pulley ratio 2.5:1? (Fig. 1.62)

$$15000/6000 = 2.5 \text{ (the ratio of the speeds)}$$

Therefore, the alternator can never be driven too fast.



2.5 : 1

Figure 1.62 Pulley ratio

1.4.16 Areas

1.4.16.1 Example

If the car roof is 1.2 m long and 1.1 m wide and the aerosol says it will cover 1.5 m^2, will there be enough paint? (Fig. 1.63)

$$\text{The area is } 1.2 \times 1.1 = 1.32\,m^2$$

So yes, you have got enough paint (for one coat)!

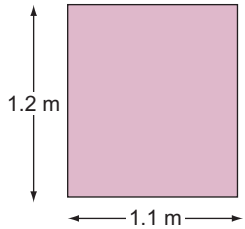


Figure 1.63 Car roof

1.4.17 Volumes

1.4.17.1 Example

If the bore of a four-cylinder engine is 8 cm and the stroke (distance from bottom dead centre to top dead centre) is 6.9 cm, what is the capacity of the engine? (Fig. 1.64)

The volume of a regular solid is the area multiplied by the height. For a cylinder, the area is πr^2, so the volume must be $\pi r^2 h$ (r, the radius, is half the bore diameter; h is the stroke):

$$V = 3.14 \times 4 \times 4 \times 6.9 = 346.66 \text{ (now} \times 4 \text{ cylinders)} = 1386.62 \text{ cc}$$

This engine would be called a 1400 cc or a 1.4 litre engine.

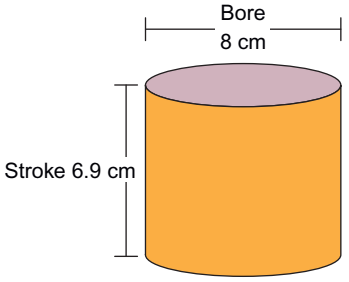


Figure 1.64 Cylinder

1.4.18 Indices

1.4.18.1 Example

A current flow of 1 ampere means that 6 000 000 000 000 000 000 electrons pass a point in one second! It is much easier to write 6×10^{18}, this simply means 6 with 18 zeros after it.

This quantity of electrons is known as a coulomb. It is about enough electricity to work a heavy-duty starter motor for about 0.001 seconds. This could be written as 10^{-3} seconds, where the -3 means moving the decimal point 3 places to the left (dividing by 1000).

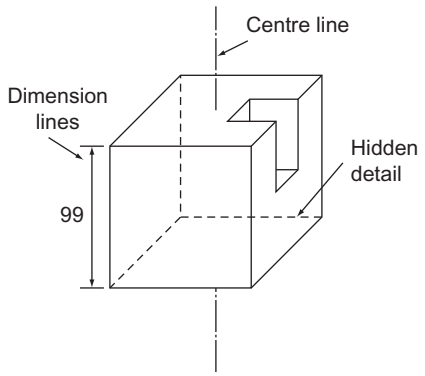


Figure 1.65 A three-dimensional (3D) representation (oblique projection)

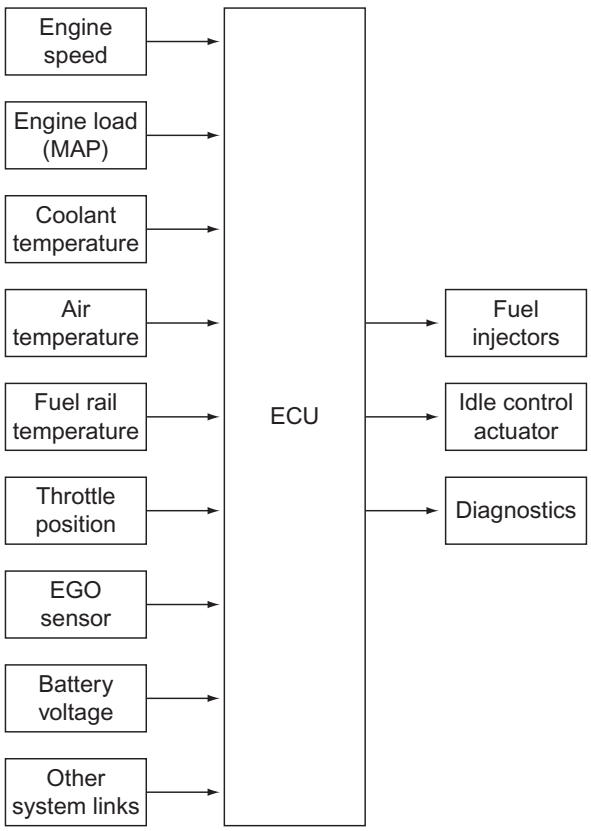


Figure 1.66 Block diagram representing a fuel injection system. MAP, manifold absolute pressure; EGO, exhaust gas oxygen; ECU, electronic control unit

1.4.19 Drawings

Drawings are an ideal way to pass on important information (Figs 1.65 and 1.66). Many manufacturers provide information in the form of drawings. It is essential that you can interpret the details you need and are not put off by the amount of information presented.

To help you do this, some simple standards are used relating to the type of line:

- continuous thick line _____ visible outlines
- continuous thin line _____ projection, dimension and hatching lines
- short thin dashes _ _ _ _ _ _ _ _ hidden details

Table 1.20 Terminology used on drawings

Sections	When the inside details of an object are important it is often convenient to show this by sectioning or cutting the object in a suitable place. A sectioned view of a brake cylinder is a good example
Dimensions	Lines with arrowheads in some cases simply show the size of the object. These are used more for drawings used to make an item than to pass on information for repair
Tolerances and limits	Dimensions can never be completely accurate, although they are very close in some cases. A good example of a tolerance or limit on a motor vehicle drawing is the bore of a cylinder given as 70 ± 0.05 mm
Fits	Two types of 'fit' can be used. Clearance fit is where, say, a pin is slightly smaller than, and therefore slides into a hole. Interference fit is where the pin is very slightly too large and needs pressing into the hole
Projection	A term used to describe the way an object is drawn. You can imagine it as if projected on to a screen from different angles
Line diagram	A simplified diagram showing only the most basic of information
Block diagram	Complicated systems can be simplified by representing, say, the fuel system as one block and the engine as another, and so on
Exploded diagram	This is often used in workshop manuals. It shows a collection of components spread apart to show their details and suggest their original positions

Table 1.21 Sources of drawings and other information

Technical bulletins	Sheets of information sent from manufacturers to the dealers outlining the latest repair information
Parts books	The pictures or drawings in parts books are useful for repair procedures as they often show all the component parts of an object
Textbooks	This one is the best, of course, but a number of other good books are available
Workshop manuals	These are the traditional source of detailed information on specific vehicles and systems
Microfiche	A microfilm is often used to store pictures and information, as a large amount can be stored in a small space. It is like a very small photographic negative read on a viewer. Not used much nowadays
Computer	The computer is increasingly becoming essential in many ways. A large amount of data can be kept on disc and retrieved with a few key strokes
CD and DVD	One DVD can hold a massive amount of information (equivalent to many workshop manuals), which can be accessed quickly and easily by a computer
Online databases	Many sources of information are now available on line. This means that with a computer and modem you can access remote databases

- long thin chain ___ _ ___ _ ___ centre lines
- long chain ___ ___ ___ ___ cutting planes

There are many types of drawing methods and some of these are outlined in Table 1.20. There are many sources of information that use drawings; some are outlined in Table 1.21.

Drawings can be produced in a number of ways. The most ideal for engineering drawings are as follows.

- **Orthographic** projections show three elevations, usually a front, plan and end view.
- **Pictorial** projections, such as isometric and oblique, show a representation of what the item looks like. The isometric view is used often in workshop manuals to show the arrangement of a complicated system.

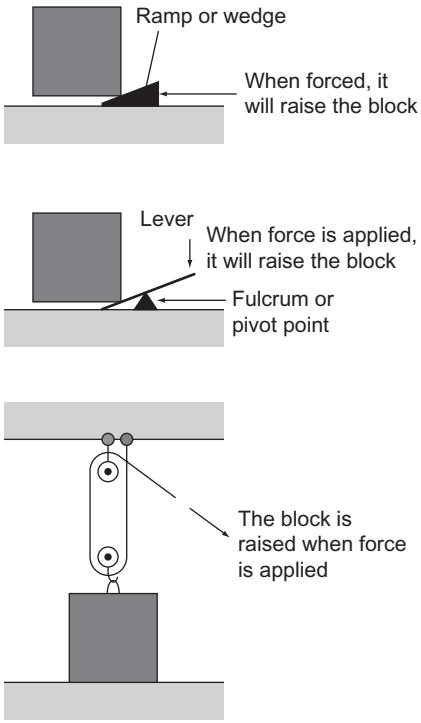


Figure 1.67 The three basic types of machine

Definition

Machine

A simple mechanical machine is a device that allows a small force to overcome a larger force.

A machine is a device that converts one form of energy to another.

1.4.20 Mechanical machines

A simple mechanical machine is a device that allows a small force to overcome a larger force. There are only three basic machines (Fig. 1.67):

- ramps – such as a wedge
- levers – such as a lever!
- wheels and axles – such as pulleys and a belt.

All other machines are combinations of these three. This is a good way of making any complicated machine easier to understand. The main features of a machine are:

- mechanical advantage, which is the ratio of load to effort (think of a car jack)
- velocity ratio, which is the velocity input compared to the velocity output (think of a car gear box)
- efficiency, which is the work output divided by the work input as a percentage.

In a perfect machine, with no friction, the efficiency would be 100%. All practical machines have efficiencies of less than 100% – otherwise perpetual motion would be possible!

1.4.21 Gears

Gears are toothed wheels (with lots of small levers) that transmit the turning movement of one shaft to another. Gear wheels may be used in pairs or in threes if both shafts need to turn in the same direction. The gear ratio, which is the ratio of the number of teeth on the two wheels, determines:

- **the torque ratio** – the turning force on the output shaft compared with the turning force on the input shaft

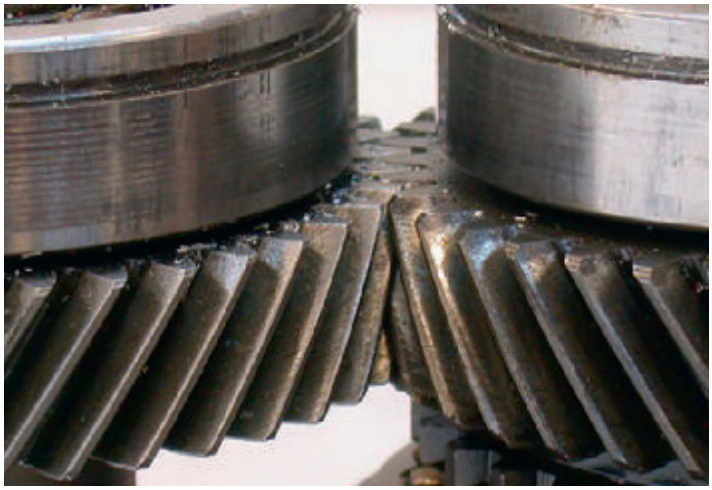


Figure 1.68 Gears in a car gearbox

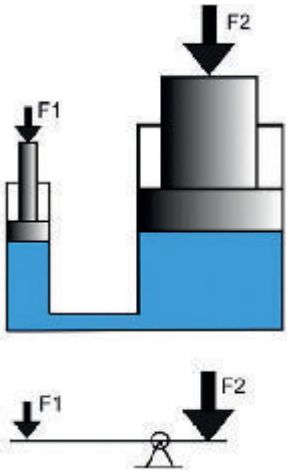


Figure 1.69 A hydraulic system like this one is sometimes called a liquid lever

- **the speed ratio** – the speed of the output shaft compared with the speed of the input shaft.

Gears with the ratio 2:1 (say 20 teeth input and 10 teeth output) will have an output twice the speed and half the torque of the input.

A common type of gear for parallel shafts is the spur gear, with straight teeth parallel to the shaft axis. The helical gear as shown in Fig. 1.68 (most common in car gear boxes) has teeth cut at an angle in a corkscrew shape.

1.4.22 Hydraulics

Hydraulics means using the properties of liquids to transmit pressure and movement (Fig. 1.69). The best known machines of this type are the hydraulic press and the hydraulic jack. The principle of pressurized liquid and increasing mechanical efficiency is also ideal for use on vehicle braking systems.

A basic hydraulic system consists of two liquid-connected pistons in cylinders, one of narrow bore, one of large bore. A force applied to the narrow piston applies a certain pressure to the liquid, which is transmitted to the larger piston.

Because the area of this piston is larger, the force exerted on it is larger. The original force has been increased, although the smaller piston has to move a greater distance to move the larger piston only a small distance. Mechanical advantage is gained in force, but movement is lost.

Definition

Hydraulics
Using the properties of liquids to transmit pressure and movement.

1.4.23 Materials and properties

Different materials are used in different places on motor vehicles because of their properties. For example, cast iron is a fairly obvious choice for use as an exhaust manifold because of the very high temperatures (Fig. 1.70). Plastic would probably melt so would not be used. However, perhaps aluminium could be used instead? This time it is not obvious and more thought is required to decide the most suitable material.

In Table 1.22 are listed several types of material together with important properties. As a very rough guide these are given as a number from 1 (best) to 5 (worst) in a kind of league table. This makes the table easier to use for comparing

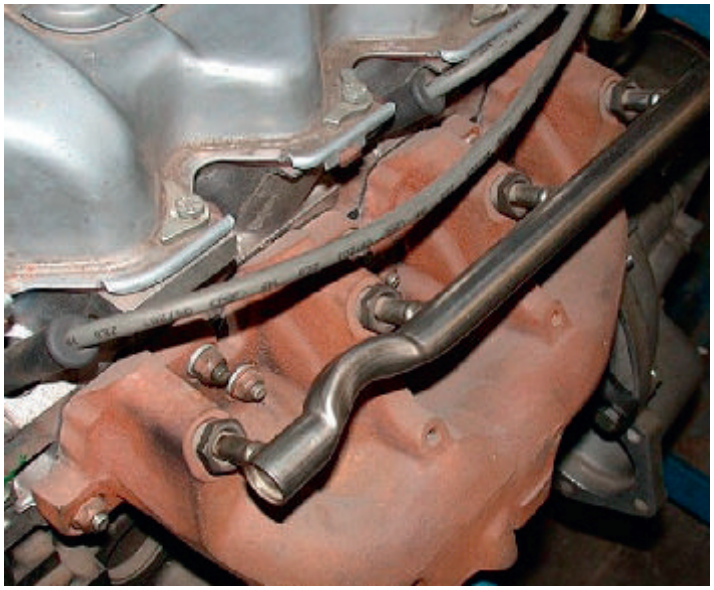


Figure 1.70 Cast iron exhaust manifold

Table 1.22 Comparison of material properties

Material	Ease of shaping	Strength	Resistance to heat	Electrical resistance	Corrosion resistance	Cost	Typical motor vehicle uses
Copper	2	3	2	1	3	4	Wires and electrical parts
Aluminium	2	3	2	1	3	4	Cylinder heads
Steel	3	2	1	1	4	3	Body panels and exhausts
Cast iron	3	2	1	1	4	3	Manifolds and engine blocks
Platinum	3	1	1	1	2	5	Spark plug tips
Soft plastic	1	5	5	5	1	1	Electrical insulators
Hard plastic	1	4	4	5	1	1	Interiors and some engine components
Glass	3	5	2	5	1	2	Screens and windows
Rubber	2	4	5	5	3	2	Tyres and hoses
Ceramics	4	4	1	5	1	4	Spark plug insulators

1 = best; 5 = worst.

one material with another. Note that this table is just to help you compare properties; the league table positions are only rough estimates and will vary with different examples of the same material.

Corrosion is the eating away and eventual destruction of metals and alloys (mixtures of metals) by chemical action (Fig. 1.71). Most metals corrode eventually, but the rusting of ordinary iron and steel is the most common form of corrosion. Rusting of iron or steel takes place in damp air, when the iron

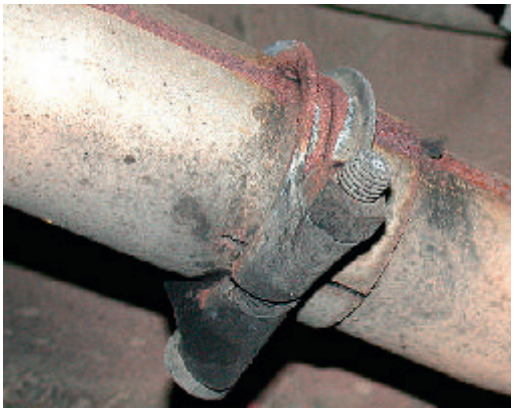


Figure 1.71 Corrosion on an exhaust joint

Table 1.23 Terms used to describe materials

Property	Explanation
Hardness	The ability to withstand indentation (marking)
Softness	Can be easily indented
Toughness	The ability to resist fracture
Brittleness	Breaks or shatters under shock loads (impact)
Ductility	Plastic (deforms and stays that way) under tension or stretching
Malleability	Plastic under compression (squeezing)
Plasticity	The ability to retain a deformation after a load is removed
Elasticity	The ability to return to its original shape when a deforming load is removed
Strength	The ability to withstand a load without breaking

combines with oxygen and water to form a brown deposit known as rust. Higher temperatures make this reaction work more quickly. Salty road and air conditions make car bodies rust more quickly.

Material properties are listed in Table 1.23. Some materials other than metals corrode or perish over a period of time, for example rubber-based materials. Plastics have a great advantage because some appear to last for ever!

1.5 Tools and equipment

1.5.1 Hand tools

Using hand tools is something you will learn by experience, but an important first step is to understand the purpose of the common types (Fig. 1.72). This section therefore starts by listing some of the more popular tools, with examples of their use, and ends with some general advice and instructions.

Practise until you understand the use and purpose of the tools listed in Table 1.24 when working on vehicles.

Figure 1.72 Combination spanners (wrenches)

General advice and instructions for the use of hand tools (taken from advice by Snap-on):

- Only use a tool for its intended purpose.
- Always use the correct size tool for the job you are doing.
- Pull a spanner or wrench rather than pushing whenever possible.
- Do not use a file, or similar, without a handle.
- Keep all tools clean and replace them in a suitable box or cabinet.
- Do not use a screwdriver as a pry bar.
- Look after your tools and they will look after you!

1.5.2 Test equipment

Removing, refitting and adjusting components to ensure the vehicle system operates within specification is a summary of almost all the work you will be doing. The use, care, calibration and storage of test equipment are therefore very important. In this sense, 'test equipment' means:

- measuring equipment, e.g. a micrometer
- hand instruments, e.g. a spring balance
- electrical meters, e.g. a digital multimeter (DMM) (Fig. 1.73) or an oscilloscope.

The operation and care of this equipment will vary with different types. Therefore, you should always read the manufacturer's instructions carefully before use, or if you have a problem. The following list sets out good general guidelines:

- Follow the manufacturer's instructions – at all times.
- Handle with care – do not drop keep the instrument in its box.
- Ensure regular calibration – check for accuracy.
- Understand how to interpret results – if in doubt, ask!

My favourite piece of test equipment is the PicoScope (Fig. 1.74). This is an oscilloscope that works through a laptop or computer. It will test all engine management systems and other electrical and electronic devices. Check out

Table 1.24 Hand tools

Hand tool	Example uses and/or notes
Adjustable spanner (wrench)	An ideal standby tool and useful for holding one end of a nut and bolt
Open-ended spanner	Use for nuts and bolts where access is limited or a ring spanner cannot be used
Ring spanner	The best tool for holding hexagon bolts or nuts. If fitted correctly it will not slip and damage both you and the bolt head
Torque wrench	Essential for correct tightening of fixings. The wrench can be set in most cases to 'click' when the required torque has been reached. Many fitters think it is clever not to use a torque wrench. Good technicians realize the benefits
Socket wrench	Often contains a ratchet to make operation far easier
Hexagon socket spanner	Sockets are ideal for many jobs where a spanner cannot be used. In many cases a socket is quicker and easier than a spanner. Extensions and swivel joints are also available to help reach that awkward bolt
Air wrench	Often referred to a a wheel gun. Air-driven tools are great for speeding up your work but it is easy to damage components because an air wrench is very powerful. Only special, extra strong, high-quality sockets should be used
Blade (engineer's) screwdriver	Simple common screw heads. Use the correct size!
Pozidriv, Phillips and cross-head screwdrivers	Better grip is possible, particularly with the Pozidriv, but learn not to confuse these three very similar types. The wrong type will slip and damage will occur
Torx®	Similar to a hexagon tool like an Allen key but with further flutes cut in the side. It can transmit good torque
Special-purpose wrenches	Many different types are available. As an example, mole grips are very useful tools as they hold like pliers but can lock in position
Pliers	Used for gripping and pulling or bending. They are available in a wide variety of sizes, from snipe nose for electrical work, to engineers' pliers for larger jobs such as fitting split pins
Lever	Used to apply a very large force to a small area. If you remember this you will realize how if incorrectly applied, it is easy to damage a component
Hammer	Anybody can hit something with a hammer, but exactly how hard and where is a great skill to learn!

www.picoauto.com for more information. Figure 1.75 shows a signal from an inductive sensor taken using the PicoScope.

Key fact

An oscilloscope draws a graph of voltage against time.

1.5.3 Workshop equipment

In addition to hand tools and test equipment, most workshops will also have a range of equipment for lifting and supporting as well as electrical or air-operated

Figure 1.73 Digital multimeter in use

Figure 1.74 Automotive PicoScope. (Source: PicoTech Media)

tools (Figs 1.76–1.80). Table 1.25 provides some examples of common workshop equipment together with typical uses.

1.6 Workshop bench skills

1.6.1 Introduction

As well as the obvious skills such as knowledge of the systems and the ability to use normal hand tools for vehicle repairs, bench fitting and in some cases machining skills are also essential.

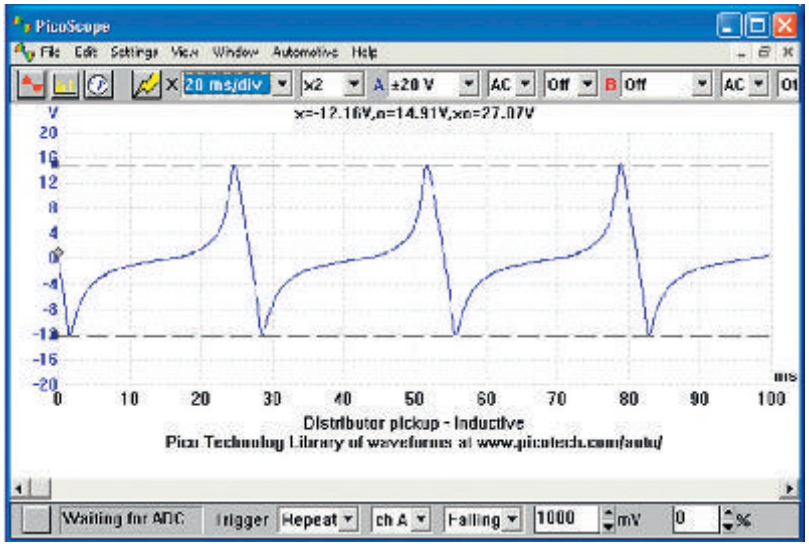


Figure 1.75 Waveform display from the PicoScope

Figure 1.76 Car lift. (Source: asedeals.com)

Figure 1.77 Trolley jack and axle stands. (Source: Snap-on Tools)

Figure 1.78 Welding process. (Source: Wikimedia)

Figure 1.79 Wheel gun. (Source: Snap-on Tools)

Figure 1.80 Transmission jack. (Source: Snap-on Tools)

This usually involves metal cutting operations but it can involve other materials such as wood and plastics. In this sense, the word cutting is a very general term and can refer to:

- sawing
- drilling

Table 1.25 Examples of workshop equipment

Equipment	Common use
Ramp or hoist	Used for raising a vehicle off the floor. A two-post wheel-free type is shown in Fig. 1.76. Other designs include four-post and scissor types where the mechanism is built into the workshop floor
Jack and axle stands	A trolley jack (Fig. 1.77) is used for raising part of a vehicle such as the front or one corner or side. It should always be positioned under suitable jacking points, or axle or suspension mountings. When raised, stands must always be used in case the seals in the jack fail, causing the vehicle to drop
Air gun	A high-pressure air supply is common in most workshops. Figure 1.79 shows a typical wheel gun used for removing wheel nuts or bolts. Note that when replacing wheel fixings it is essential to use a torque wrench
Electric drill	The electric drill is just one example of electric power tools used for automotive repair. Note that it should never be used in wet or damp conditions
Parts washer	A number of companies will supply a parts washer and change the fluid it contains at regular intervals
Steam cleaner	Steam cleaners can be used to remove protective wax from new vehicles as well as to clean grease, oil and road deposits from cars in use. They are supplied with electricity, water and a fuel to run a heater, so caution is necessary
Electric welder	A number of forms of welding are used in repair shops. The two most common are metal inert gas (MIG) (see Fig. 1.94) and manual metal arc (MMA)
Gas welder	Gas welders are popular in workshops as they can also be used as a general source of heat, for example, when heating a flywheel ring gear
Engine crane	A crane of some type is essential for removing the engine on most vehicles. It usually consists of two legs with wheels that go under the front of the car and a jib that is operated by a hydraulic ram. Chains or straps are used to connect to or wrap around the engine
Transmission jack	On many vehicles the transmission is removed from underneath. The car is supported on a lift (perhaps similar to that shown in Fig. 1.76) and then the transmission jack is rolled underneath. An example is shown in Fig. 1.80

- filing
- tapping
- machining.

These aspects will be examined in a little more detail in the following sections.

1.6.2 Fitting and machining

Fitting and machining skills may be needed to complete a particular job (Fig. 1.81). In the context of an automotive engineer, the term ‘fitting’ is often used

Figure 1.81 Repairs using a lathe. (Source: Wikimedia)

as a general description of hand skills usually used on a work bench or similar, to construct an item that cannot be easily purchased – for example, a support bracket for a modified exhaust or a spacer plate to allow the connection of an accessory of some type, such as additional lights.

Machinists usually work to very small tolerances, for example ±0.1 mm, and deal with all aspects of shaping and cutting. The operations most often carried out by machinists are milling, drilling, turning and grinding. To carry out fitting or machining operations you should be familiar with:

- measuring tools, e.g. a micrometer
- hand tools, as found in a standard tool kit
- machine tools, e.g. a bench drill
- work holders, e.g. a vice
- tool holders, e.g. the chuck of a drill
- cutting tools, e.g. saws and files.

1.6.3 Filing

Key fact

Files have forward-facing cutting teeth that cut best when pushed over the workpiece.

Filing is the process of removing material when manufacturing something; it is used mostly for finishing operations. Filing can be used on a wide range of materials as a finishing process. Emery paper may be considered as a filing tool.

Files have forward-facing cutting teeth that cut best when pushed over the workpiece. A process known as draw filing involves turning the file sideways and pushing or pulling it across the work. This catches the teeth of the file sideways and results in a very fine shaving action.

Files come in a wide variety of sizes, shapes, cuts and tooth configurations. The most common cross-sections of a file are: flat, round, half-round, triangular and square. The cut of the file refers to how fine its teeth are. They are described, from roughest to smoothest, as: rough, middle, bastard, second cut, smooth and dead smooth. Figure 1.82 shows three common file cuts. Most files have teeth on all faces, but some flat files have teeth only on one face or edge, so that the file can work against another edge without causing damage.

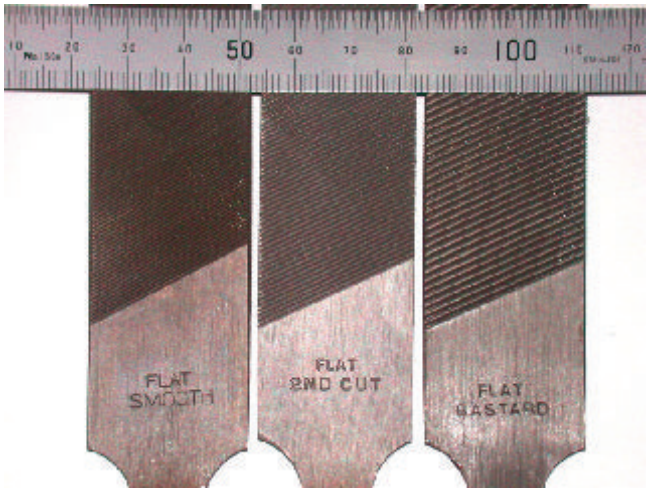


Figure 1.82 Three common types of file. (Source: Glenn McKechnie, Wikipedia)

Figure 1.83 Cutting edges and flutes of a drill bit

1.6.4 Drilling

Drilling is a cutting process that uses a drill bit to cut or enlarge a hole in a solid material. The drill bit cuts by applying pressure and rotation to the workpiece, which forms chips at the cutting edge (Fig. 1.83). The flutes remove these chips.

In use, drill bits have a tendency to 'walk' if not held very steadily. This can be minimized by keeping the drill perpendicular to the work surface. This walking or slipping across the surface can be prevented by making a centring mark before drilling. This is most often done by centre punching. If a large hole is needed, then centre drilling with a smaller bit may be necessary.

Drill bits used for metalworking will also work in wood. However, they tend to chip or break the wood, particularly at the exit of the hole. Some materials such as plastics have a tendency to heat up during the drilling process. This heat can make the material expand, resulting in a hole that is smaller than the drill bit used.

1.6.5 Cutting

A hacksaw is a fine-tooth saw with a blade under tension in a frame. Hand-held hacksaws consist of a metal arch with a handle, usually a pistol grip, with pins

Figure 1.84 Junior hacksaw. (Source: Evan-Amos, Wikipedia)

Figure 1.85 Sawing machine. (Source: Audriusa, Wikipedia)

for attaching a narrow disposable blade. A screw or another mechanism is used to put the blade under tension. The blade can be mounted with the teeth facing toward or away from the handle, resulting in cutting action on either the push or pull stroke. The push stroke is most common.

Blades are available in standardized lengths, usually 10 or 12 inches (15 or 30 cm) for a standard hacksaw. Junior hacksaws are usually half this size (Fig. 1.84). Powered hacksaws may use large blades in a range of sizes (Fig. 1.85).

The pitch of the teeth can vary from eighteen to thirty-two teeth per inch for a hand hacksaw blade. The blade chosen is based on the thickness of the material being cut, with a minimum of three teeth in the material. As hacksaw teeth are so small, they are set in a wave so that the resulting cut is wider than the blade to prevent jamming. Hacksaw blades are often brittle so care needs to be taken to prevent fracture.

1.6.6 Thread cutting

Taps and dies are cutting tools used to create screw threads. A tap is used to cut the female part of the mating pair (e.g. a nut) and a die is used to cut the male portion (e.g. a screw). Cutting threads using a tap is called tapping, and

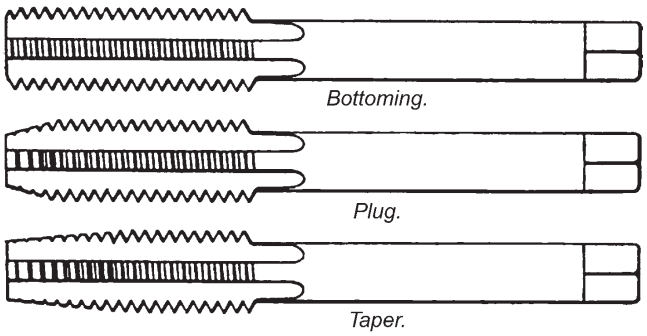


Figure 1.86 Taper, plug and bottoming taps. (Source: Glenn McKechnie, Wikipedia)

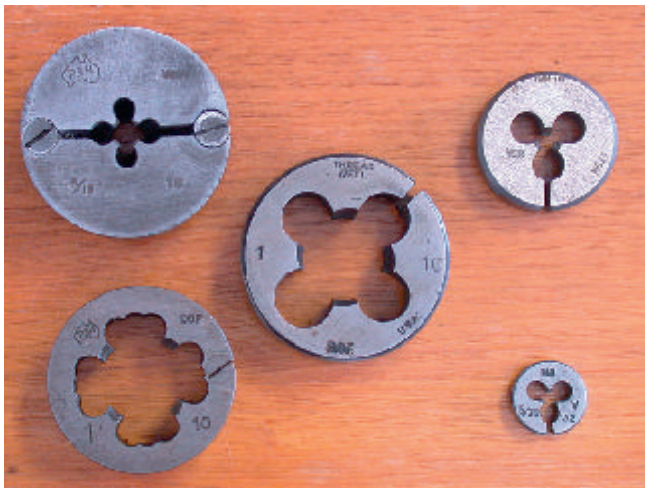


Figure 1.87 Dies. (Source: Glenn McKechnie, Wikipedia)

using a die is called threading. Both tools can also be used to clean a thread, in a process known as chasing. The use of a suitable lubricant is recommended for most threading operations.

Key fact

A lubricant is recommended for most threading operations.

A tap cuts a thread on the inside surface of a hole, creating a female surface which functions like a nut. The three taps in Fig. 1.86 show the three basic types:

- The bottoming tap has a continuous cutting edge with almost no taper, which allows it to cut threads to the bottom of a blind hole.
- The intermediate tap, second tap or plug tap has tapered cutting edges, which assist in aligning and starting it into an untapped hole.
- The taper tap is similar to a plug tap but has a longer taper, which results in a more gradual cutting action.

The process of tapping begins with drilling and slightly countersinking a hole. The diameter of the hole is determined using a drill and tap size chart.

A T-shaped handle is used to rotate the tap. This is often turned in steps of one turn clockwise and about a quarter turn back. This helps to break off the chips, which avoids jamming. With hard materials, it is common to start with a taper tap, because the shallower cut reduces the amount of torque required to make the threads. If threads are to be cut to the bottom of a blind hole, the taper tap is followed by an intermediate (plug) tap and a bottoming tap.

The die (Fig. 1.87) cuts a thread on a cylindrical rod, which creates a male threaded piece that functions like a bolt. The rod is usually just less than the

required diameter of the thread and is machined with a taper. This allows the die to start cutting the rod gently, before it cuts enough thread to pull itself along. Adjusting screws on some types of die allow them to be closed or opened slightly to allow small variations in size. Split dies can be adjusted by screws in the die holder. The action used to cut the thread is similar to that used when tapping.

Die nuts have no split for resizing and are made from a hexagonal bar so that a wrench or spanner can be used to turn them. Die nuts are used to clean up existing threads and should not be used to cut new threads.

1.6.7 Joining

It is very important for the correct methods of joining to be used in the construction and repair of a modern motor vehicle. Joining can cover many aspects, ranging from simple nuts and bolts to very modern and sophisticated adhesives (Figs 1.88 and 1.89).

The choice of a joining method for a repair will depend on the original method used as well as consideration of the cost and strength required. Table 1.26 shows

Figure 1.88 A selection of joining or fastening components

Figure 1.89 Pop rivets

Table 1.26 Joining methods

Joining method	Examples of uses	Notes
Pins, dowels and keys	Clutch pressure plate to the flywheel	Used for strength and alignment in conjunction with nuts or bolts in most cases
Riveting	Some brake shoe linings	Involves metal pegs which are deformed to make the joint. Figure 1.89 shows some pop rivets, which are a popular repair component
Compression fitting	Wheel bearings	Often also called an interference fit. The part to be fitted is slightly too large or small, as appropriate, and therefore pressure has to be used to make the part fit
Shrinking	Flywheel ring gear	The ring gear is heated to make it expand and then fitted in position. As it cools it contracts and holds firmly in place
Adhesives	Body panels and sound deadening	Adhesive or glue is very popular as it is often cheap, quick, easy to apply and waterproof. Also, when two items are bonded together the whole structure becomes stronger
Nuts, screws, washers and bolts	Just about everything!	Metric sizes are now most common but many other sizes and thread patterns are available. This is a very convenient and strong fixing method. Figure 1.88 shows how varied the different types are
Welding	Exhaust pipes and boxes	There are several methods of welding, oxyacetylene and MIG being the most common. The principle is simple, in that the parts to be joined are melted so they mix together and then set in position
Brazing	Some body panels	Brazing involves using high temperatures to melt brass which forms the join between two metal components
Soldering	Electrical connections	Solder is made from lead and tin. It is melted with an electric iron to make it flow into the joint
Clips, clamps and ties	Hoses, cables, etc.	Hose clips, for example, are designed to secure a hose to, say, the radiator and prevent it leaking

some typical joining methods which include the use of gaskets in some cases. Examples of use and useful notes are also given in the table.

Methods of joining are described as permanent or non-permanent. The best example of permanent joining is any form of welding. An example of non-permanent would be nuts and bolts. In simple terms, the permanent methods would mean that some damage would occur if the joint had to be undone.

Definition

Joining methods
Methods of joining are described as permanent or non-permanent.

1.6.8 Nuts and bolts

The nut and bolt is by far the most common method of joining two components together. Figure 1.90 shows some common nuts and bolts. The head of the bolt is usually a hexagon, but an Allen socket or a Torx® drive or a number of other designs can be used. Smaller bolts can have a screwdriver type head such as a slot, cross, Phillips, Pozidriv or some other design.

The material used to make a nut or bolt depends on the application. For example, sump bolts will be basic mild steel, whereas long through bolts on

Figure 1.90 Nuts and bolts

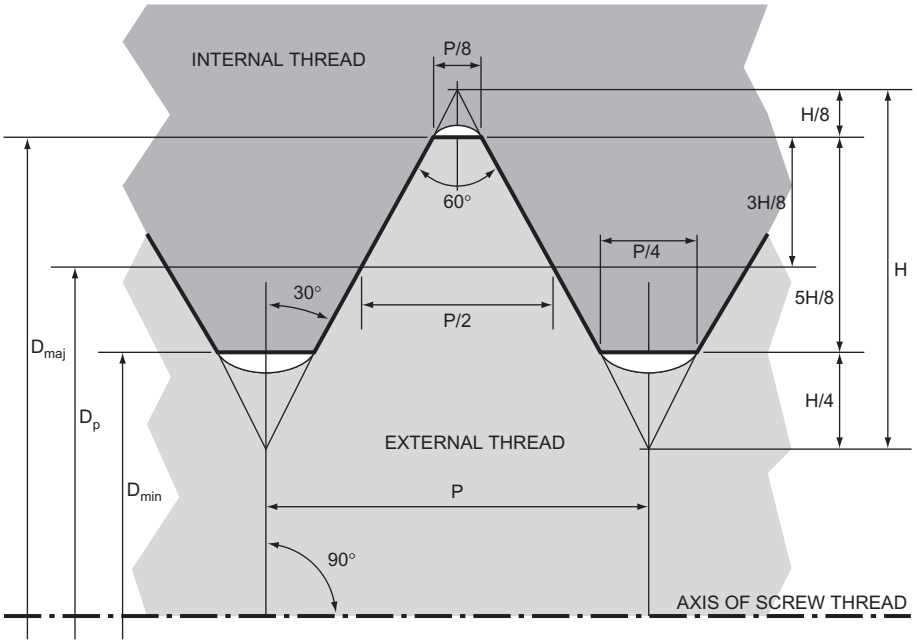


Figure 1.91 ISO metric thread profile

some engines are made from sophisticated high tensile steel so that they will stretch. The size of the nut and bolt will depend on the size of components to be secured. Thread sizes used to be a problem, but fortunately now most nuts and bolts are metric. Figure 1.91 shows a metric thread profile.

Metric nuts and bolts are described as in the following example:

$$M10 \times 1.5$$

The M is metric, the 10 is the bolt diameter and the 1.5 is the pitch of the thread.

When joining with nuts and bolts it is common to find flat washers and in many cases some type of locking device. Metric threads are quite good at locking in position as they are, but for safety, extra devices are often used. Vibration is the main cause of bolts coming loose, as well as their not being tightened to the correct torque in the first place. Figure 1.88 shows a selection of locking devices, including a Nyloc (nylon lock) nut at the top right.

Key fact

Vibration is the main cause of bolts coming loose.

Figure 1.92 Loctite® Threadlocker. (Source: © 2010 Henkel AG & Co. KGaA, Düsseldorf. All rights reserved)

Another common method of securing threads is to use a locking compound such as Loctite®. This is in effect an adhesive which sticks the threads together. When the correct compound is applied with care, it is a very secure way of preventing important components from working loose (Fig. 1.92).

1.6.9 Adhesives

A very wide range of adhesives is used in today's automotive industry. The number of applications is increasing daily and tending to replace older methods such as welding. There are too many types of adhesives to cover here but most of the basic requirements are the same. It is very important to note, however, that manufacturers' instructions must always be followed. This is because of the following:

- Many adhesives give off toxic fumes and must be used with care.
- Most types are highly flammable.
- Adhesives are often designed for a specific application.

Adhesives also have a number of important terms associated with them:

- **Cleanliness** – Surfaces to be joined must be clean.
- **Curing** – The process of setting, often described as 'going off'.
- **Wetting** – The adhesive spreads evenly and fully over the surface.
- **Thermosetting** – Heat is required to cure the adhesive.
- **Thermoplastic** – Melts when heated.
- **Contact adhesive** – Makes a strong joint as soon as contact is made.
- **'Super glue'** – Cyanoacrylate adhesive which bonds suitable materials in seconds, including skin – take care!

Adhesives have many advantages, which is why they are becoming more widely used. These include:

- even stress distribution over the whole surface
- waterproof
- good for joining delicate materials
- no distortion when joining
- a wide variety of materials can be joined
- a neat, clean join can be made with little practice.

Safety first

Manufacturers' instructions must always be followed when working with adhesives.

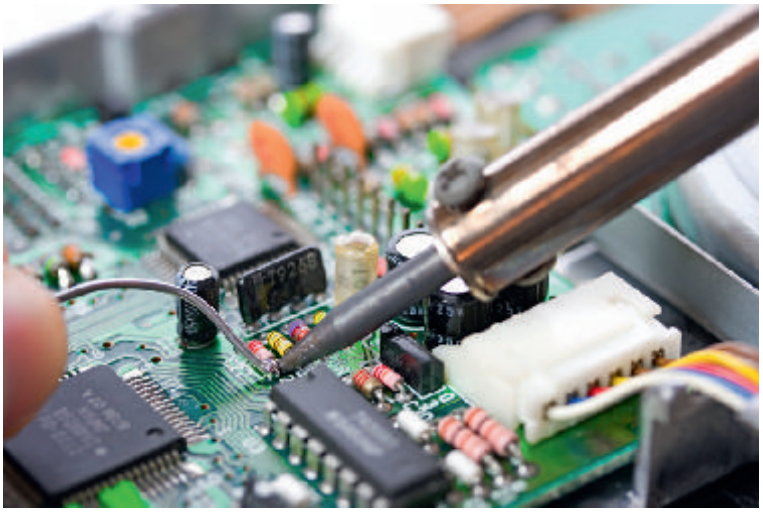


Figure 1.93 Soldering an electronic circuit

As a final point in relation to adhesives, the importance of choosing the correct type for the job in hand must be stressed. For example, an adhesive designed to bond plastic will not work when joining rubber to metal. And don't forget, if the surfaces to be joined are not clean you will make a very good job of bonding dirt to dirt instead of what you intended!

1.6.10 Soldering

Soft soldering is a process used to join materials such as steel, brass, tin or copper. It involves melting a mixture of lead and tin to act as the bond. A common example of a soldered joint is the electrical connection between the stator and diode pack in an alternator. Figure 1.93 shows this process using the most common heat source, which is an electric soldering iron.

The process of soldering is as follows:

1. Prepare the surfaces to be joined by cleaning and using emery cloth or wire wool as appropriate.
2. Add a flux to prevent the surfaces becoming dirty with oxide when heated, or use a solder with a flux core.
3. Apply heat to the joint and add solder so it runs into the joint.
4. Complete the process as quickly as possible to prevent heat damage.
5. Use a heat sink if necessary.

Soldering, in common with many other things, is easy after some practice; take time to do this in your workshop. Note that some materials such as aluminium cannot be soldered by ordinary methods.

1.6.11 Brazing

Brazing is a similar process to soldering except a higher temperature is needed and different filler is used. The materials to be joined are heated to red heat and the filler rod (bronze brass or similar), after being dipped in flux, is applied to the joint. The heat from the materials is enough to melt the rod and it flows into the gap making a good, strong, but slightly flexible, joint. Dissimilar metals such as

Figure 1.94 MIG welding process

brass and steel can also be joined and less heat is required than when fusion welding. Brazing is only used on a few areas of the vehicle body.

1.6.12 Welding

Welding is a method of joining metals by applying heat, combined with pressure in some cases. A filler rod of a similar metal is often used. The welding process joins metals by melting them, fusing the melted areas and then solidifying the joined area to form a very strong bond. Welding technology is widely used in the automotive industry.

The principal processes used today are gas and arc welding, in which the heat from a gas flame or an electric arc melts the faces to be joined. Figure 1.94 shows a welding process in action.

Several welding processes are used:

- Gas welding uses a mixture of acetylene and oxygen which burns at a very high temperature. This is used to melt the host metal with the addition of a filler rod if required (OA or oxyacetylene).
- Shielded metal-arc welding uses an electric arc between an electrode and the work to be joined; the electrode has a coating that decomposes to protect the weld area from contamination and the rod melts to form filler metal (MMA or manual metal arc).
- Gas-shielded arc welding produces a welded joint under a protective gas (MIG or metal inert gas).
- Arc welding produces a welded joint within an active gas (MAG or metal active gas).
- Resistance welding is a method in which the weld is formed by a combination of pressure and resistance heating from an electric current (spot welding).

Other, specialized types of welding include laser-beam welding, which makes use of the intensive heat produced by a light beam to melt and join the metals,

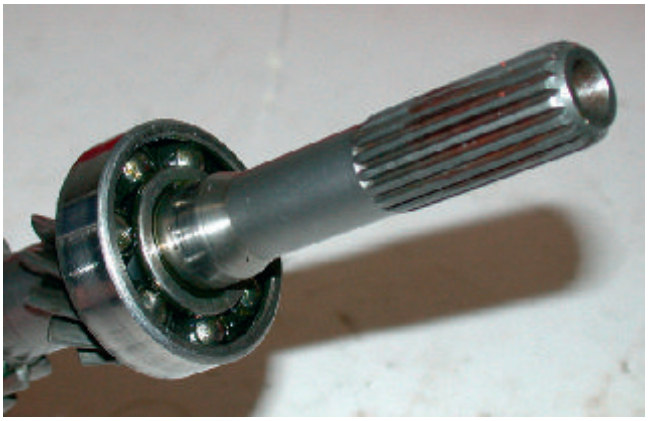


Figure 1.95 This bearing on a gearbox shaft is held in place by compression

and ultrasonic welding, which creates a bond through the application of high-frequency vibration while the parts to be joined are held under pressure.

1.6.13 Shrinking

When parts are to be fitted by shrinking they first have to be heated so they expand, or cooled so they contract. In both cases the component to be fitted must be made to an exact size. If parts fitted in this way are to be removed, it is usual to destroy them in the process. For example, a flywheel ring gear has to be cut through with a hacksaw to remove it.

For a hot shrink fitting, the part will have a smaller internal diameter than the one on which it is to be fitted. It is important not to overheat the components or damage will occur. An oven is best, but a welding torch may be used with great care. When the component has been heated and therefore expanded, it is placed in position at once. It will then cool and make a good tight joint.

Cold shrinking is very similar except the component to be fitted is made very slightly larger than the hole in which it is to be fitted. A cylinder head valve insert is one example. The process is the opposite of hot shrinking. The component is cooled so it contracts, after which it is placed in position where it warms back up and expands, making a secure joint. Cold shrinking is normally a specialist job, but it is possible to buy aerosols of carbon dioxide under pressure which can be used to make a component very cold (dry ice).

1.6.14 Compression fitting

Many parts are fitted by compression or pressure. Bearings are the most common example (Fig. 1.95). The key to compression fitting is an interference fit. This means that the component, say a bearing, is very slightly larger than the hole in which it is to be fitted. Pressure is therefore used to force the bearing into place. Suspension bushes are often also fitted in this way.

The secret is to apply the force in a way that does not make the components go together at an incorrect angle. They must be fitted true to each other.

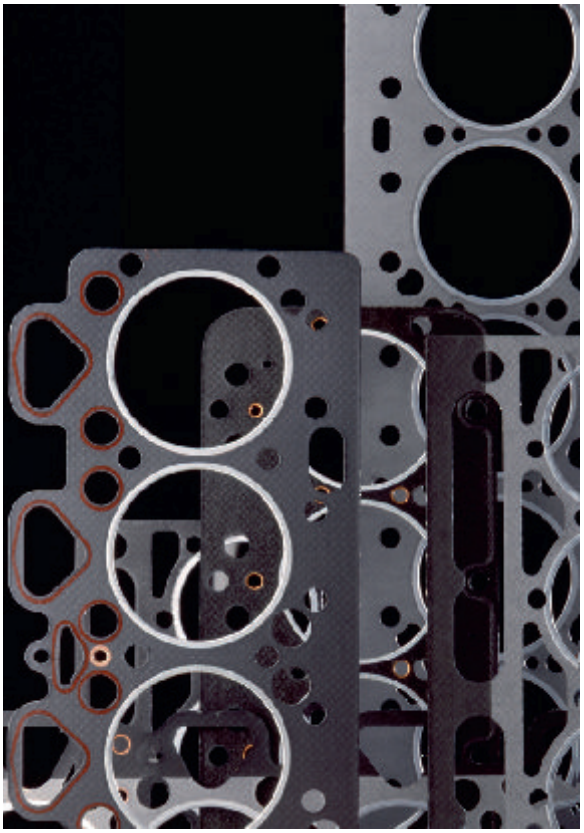


Figure 1.96 Cylinder head gaskets

1.6.15 Riveting

Riveting is a method of joining metal plates, fabric to metal or brake linings to the shoes. A metal pin called a rivet, which has a head at one end, is inserted into matching holes in two overlapping parts. The other end is struck and formed into another head, holding the parts together. This is the basic principle of riveting, but many variations are possible.

Figure 1.89 shows some pop rivets, which are one of the most common for motor vehicle repair. These are hollow rivets which are already mounted on to a steel pin. The rivet is placed through the holes in the parts to be joined and a special rivet gun grips the pin and pulls it with great force. This causes the second rivet head to be formed and when the pin reaches a set tension it breaks off, leaving the rivet securely in place. The great advantage of this method is that you can work blind. In other words, you don't need access to the other side of the hole.

1.6.16 Gaskets

Gaskets are used to make a fluid- or pressure-tight seal between two component faces. The best example of this is the cylinder head gasket, which also has to withstand very high pressures and temperatures (Fig. 1.96). Gaskets are often used to make up for less than perfect surfaces and therefore act as a seal between the surfaces. Also, as temperature changes, the gasket can take up the difference in expansion between the two components. Gaskets are made from different materials depending on the task they have to perform (Table 1.27).

Key fact

Gaskets are used to make a fluid- or pressure-tight seal between two component faces.

Table 1.27 Gaskets and typical uses

Gasket material	Examples of where used
Paper or card	General purpose, such as thermostat housings
Fibre	General purpose
Cork	Earlier types of rocker covers
Rubber, often synthetic	Water pump sealing ring
Plastics, various types	Fuel pump to engine block
Copper, asbestos, or similar	Exhaust flange – note safety issues of asbestos
Copper and aluminium	Head gaskets
Metal and fibre compounds, with metal composites	Head gaskets

The general rules for obtaining a good joint, with a gasket or otherwise, are as follows:

- cleanliness of the surfaces to be joined
- removal of burrs from the materials
- use of the correct materials
- following manufacturers' instructions (such as tighten to the correct torque in the correct sequence)
- safe working (this applies to everything you do).

1.6.17 Sealants

Many manufacturers are now specifying the use of sealants in place of traditional gaskets. The main reason for this is a better quality of joint. Liquid sealants, often known as instant gasket, are a type of liquid rubber that forms into a perfect gasket as the surfaces are mated together. The three major advantages of this technique are:

- It is easier to apply.
- A perfect seal is made with very little space being taken up.
- The adhesive bonding effect reduces fretting due to vibration, and hence the seal is less likely to leak.

Figure 1.97 shows a sealant being applied. A major advantage as far as the repair trade is concerned is that a good selection of jointing sealants means you can manufacture a gasket on the spot at any time! Note the recommendations of the manufacturers, however, as only the correct material must be used.

1.6.18 Oil seals

The most common type of oil seal is the neoprene (synthetic rubber) radial lip seal. The seal is fitted into a recess and the soft lip rubs against the rotating component. The lip is held in place by a spring. Figure 1.98 shows this type of

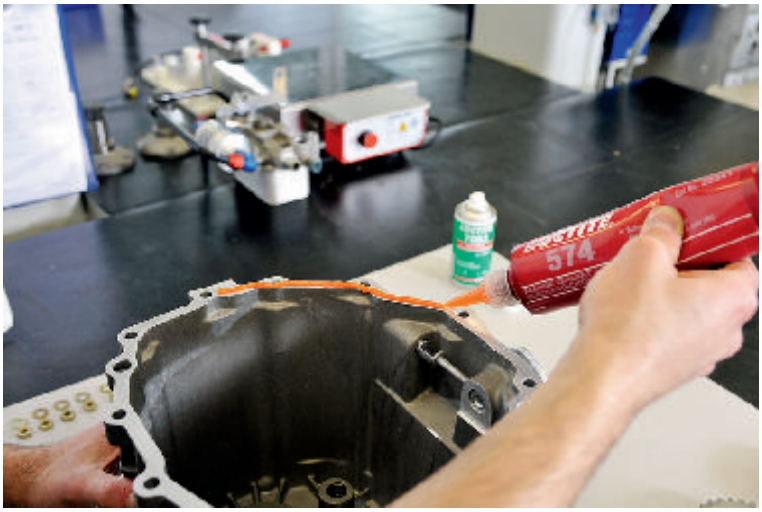


Figure 1.97 Loctite® Sealant. (Source: © 2010 Henkel AG & Co. KGaA, Düsseldorf. All rights reserved)

Figure 1.98 Oil seals. (Source: © 2005 Newsad Energy Company. All Rights Reserved)

seal; note how the lip faces the oil such that any pressure will cause the lip to fit more tightly, rather than allow oil to be forced underneath. Figure 1.98 shows a valve stem oil seal, which prevents oil entering the combustion chamber past the inlet valves.

1.7 Servicing and inspections

1.7.1 Introduction

It is important to carry out regular servicing and inspections of vehicles for a number of reasons:

- to ensure the vehicle stays in a safe condition
- to keep the vehicle operating within tolerances specified by the manufacturer and regulations
- to ensure the vehicle is reliable and to reduce downtime

Table 1.28 Servicing terminology

First service	This service is becoming less common, but some manufacturers like the vehicles to be returned to the dealers after about 1000 miles or so. This is so that certain parts can be checked for safe operation and in some cases oil is changed
Distance-based services	10 000, 12 000 or 20 000 mile intervals are common distances, but manufacturers vary their recommendations. Most have specific requirements at set distances
Time-based services	For most light vehicles, distance-based services are best. Some vehicles though, run for long periods but do not cover great distances. In this case the servicing is carried out at set time intervals. This could be every six months, six weeks or after a set number of hours run
Inspection	The MOT test, which must be carried out each year after a light vehicle is older than three years, is a good example of an inspection. However, an inspection can be carried out at any time and should form part of most services
Records	A vital part of a service, to ensure all aspects are covered and to keep information available for future use
Customer contracts	When you make an offer to do a service, and the customer accepts the terms and agrees to pay, you have made a contract. Remember that this is legally enforceable by both parties

- to maintain efficiency
- to extend components' and the vehicle's life
- to reduce running costs
- to keep the vehicle looking good and to limit damage from corrosion.

To carry out servicing and inspections you should understand how the vehicle systems operate. It is also important to keep suitable records; these are often known as a vehicle's service history. Services and inspections of vehicles vary a little from one manufacturer to another. Servicing data and servicing requirement books are available, as well as the original manufacturer's information. This type of data should always be read carefully to ensure that all the required tasks are completed. Table 1.28 lists some important words and phrases relating to the servicing and inspection.

Key fact

Keep proper records when servicing; these are known as the vehicle's service history.

Clearly, it is important to keep a customer's vehicle in a clean condition (Fig. 1.99). This can be achieved by using:

- seat covers to keep the seats clean
- floor mats to protect the carpets from dirt
- steering wheel covers to keep greasy handprints off the wheel
- wing covers to keep the paintwork clean and to prevent damage.

Figure 1.99 Bodywork protection in use during repairs

1.7.2 Rules and regulations

The three main regulations that cover the repair and service of motor vehicles in the UK are:

- **Road Traffic Act** – this covers things like road signage and insurance requirements. It also covers issues relating to vehicle safety. For example, if a car suspension was modified it may become unsafe and not conform to the law.
- **VOSA regulations** – the main one of these being the annual MOT test requirements. VOSA stands for Vehicle and Operator Services Agency.
- **Highway Code** – which all drivers must follow and forms part of the driving test.

Similar regulations are in place in other countries. The regulations are designed to improve safety.

Some of the main vehicle systems relating to safety are listed in Table 1.29, together with examples of the requirements. Note, though, that these are just examples and that specific data must be studied relating to specific vehicles.

1.7.3 Service sheets

Service sheets are used and records must be kept because they:

- define the work to be carried out
- record the work carried out
- record the time spent
- record materials consumed
- allow invoices to be prepared
- record stock that may need replacing
- form evidence in the event of an accident or customer complaint.

Table 1.30 is an example of a service sheet showing tasks carried out and at what service intervals. Please note once again that this list, while quite comprehensive, is not suitable for all vehicles, and the manufacturer's recommendations must always be followed. Some of the tasks are only

Table 1.29 Safety inspection examples

Brakes	The footbrake must produce 50% of the vehicle weight braking force and the parking brake 16% (this assumes a modern dual-line braking system). The brakes must work evenly and show no signs of leaks
Exhaust	Should not leak, which could allow fumes into the vehicle, and should not be noisy
Horn	Should be noisy! (up to a legal maximum level)
Lights	All lights should work and the headlights must be correctly adjusted
Number plates	Only the correct style and size must be fitted. The numbers and letters should also be correctly spaced and not altered (DAN 15H is right, DANISH is wrong)
Seat belts	All belts must be in good condition and work correctly
Speedometer	Should be accurate and illuminate when dark
Steering	All components must be secure and serviceable
Tyres	Correct tread depth is just one example
Windscreens and other glass	You should be able to see right through this one! No cracks allowed in the screen within the driver's vision

appropriate for certain types of vehicle. The table also lists the work in a recommended order, including the use of a lift.

1.7.4 Road test

Assuming you are a qualified driver, or you are able to tell a driver what you want, then a road test is an excellent way of checking the operation of a vehicle. A checklist is again a useful reminder of what should be done. A typical road test following a service or inspection would be much as follows (but remember to check specific manufacturers' requirements):

- Fit trade plates to vehicle if necessary.
- Check operation of starter and inhibitor switch (automatic).
- Check operation of lights, horn(s), indicators, wipers and washers.
- Check indicators self-cancel.
- Check operation of all warning indicators.
- Check footbrake and handbrake.
- Check engine noise levels, performance and throttle operation.
- Check clutch for free play, slipping and judder.
- Check gear selection and noise levels in all gears.
- Check steering for noise, effort required, free play, wander and self-centring.
- Check suspension for noise, irregularity in ride and wheel imbalance.
- Check footbrake pedal effort, travel, braking efficiency, pulling and binding.
- Check speedometer for steady operation, noise and operation of mileage recorder.
- Check operation of all instruments.
- Check for abnormal body noises.

Table 1.30 Example service sheet

Driving Vehicle into Workshop	
Instrument gauges, warning/control lights and horn	Check operation
Washers, wipers	Check operation/adjust, if necessary
Inside Vehicle	
Exterior and respective control lights; instrument cluster illumination	Check operation/condition
Service interval indicator	Reset after every oil change if applicable
Handbrake	Check operation/adjust, if necessary
Seat belts, buckles and stalks	Check operation/condition
Pollen filter	Renew
Warning vest	Check availability – if applicable
First aid kit	Check availability and expiry date – if applicable
Warning triangle	Check availability – if applicable
Outside Vehicle	
Hood latch/safety catch and hinges	Check operation/grease
Road (MOT) test	Check regarding next road (MOT) test due date – if applicable
Emission test	Check regarding next emission test due – if applicable
Under Bonnet (Hood)	
Wiring, pipes, hoses, oil and fuel feed lines	Check for routing, damage, chafing and leaks
Engine, vacuum pump, heater and radiator	Check for damage and leaks
Coolant	Check antifreeze concentration: °C
Coolant expansion tank and washer reservoirs	Check/top up fluid levels as necessary – in case of abnormal fluid loss, a separate order is required to investigate and rectify
Power steering fluid	Check/top up fluid levels as necessary – in case of abnormal fluid loss, a separate order is required to investigate and rectify
Battery terminals	Clean, if necessary/grease
Battery	Visual check for leaks – in case of abnormal fluid loss, a separate order is required to investigate and rectify
Fuel filter	Drain water, if not renewed – diesel models (with drain facility)
Headlamp alignment	Check – adjust alignment, if necessary
Brake fluid	Check/top up fluid levels as necessary – in case of abnormal fluid loss, a separate order is required to investigate and rectify
Under Vehicle	
Engine	Drain oil and renew oil filter
Steering, suspension linkages, ball joints, sideshaft joints, gaiters	Check for damage, wear, security and rubber deterioration
Engine, transmission	Check for damage and leaks
Pipes, hoses, wiring, oil and fuel feed lines, exhaust	Check for routing, damage, chafing and leaks
Underbody	Check condition of PVC coating
Tyres	Check wear and condition, especially at tyre wall, note tread depth: RF mm, LF mm, LR mm, RR mm, Spare mm
Brake system	With wheels off, check brake pads, discs and linings for wear, and check brake cylinders for condition: check rubber components for deterioration

- Check operation of seat belts, including operation of inertia reels.
- Check handbrake ratchet and hold.
- Position car on lift.
- Recheck tension if drive belts have been renewed.
- Raise lift.
- Inspect engine and transmission for oil leaks.
- Check exhaust system for condition, leakage and security.
- Lower lift: drive vehicle off lift.
- Report on Road Test findings.
- Remove car protection kit.
- Ensure cleanliness of controls, door handles, etc.
- Remove trade plates if fitted.

1.7.5 Effects of incorrect adjustments

Table 1.31 lists a selection of possible incorrect adjustments, together with their effects on the operation of the vehicle. This is intended to be an exercise to help you see why correct adjustments are so important; not so you know how to do it wrong! You must also be able to make a record and tell a customer the effects, if you are unable to make the correct adjustments. This could be due to some parts being worn so that adjustment is not possible.

Remember though, anyone can mess with a vehicle and get it wrong. As a professional you will get it right, the customer and your company will be happy and it *will* affect your pay rates in years to come.

Key fact

It is important that a customer is aware of what will be done, as well as what was done to their vehicle during a service.

One of the problems that can arise after a vehicle has been serviced, is when the customer expected a certain task to be completed, but it was not. For example, on a basic, an interim or even in some cases a full service, little or no work is carried out on the ignition system. This will not therefore rectify a misfire. It is important that the customer is aware of what will be done, as well as what was done to their vehicle. And if you notice a fault during a service, report it.

1.7.6 Maintenance and inspections

The purpose of routine maintenance is simple; it is to keep the vehicle in good working order and in a safe condition. Manufacturers specify intervals and set tasks that should be carried out at these times (Fig. 1.100). It is usually a condition of the warranty that a vehicle should be serviced according to the manufacturer's needs. The main purpose of regular inspection, therefore, is to check for the following:

- malfunction of systems and components
- damage and corrosion to structural and support regions
- leaks
- water ingress
- component and system wear and security.

Inspections are usually:

- aural – listening for problems
- visual – looking for problems
- functional – checking that things work.

Table 1.31 Possible results of incorrect adjustments

Incorrect adjustment	Possible effects						
Brake	Excessive pedal and lever travel	Reduced braking efficiency	Unbalanced braking	Overheating	Skidding and a serious accident		
Drive belts	Overheating	Battery recharge rate slow	Power steering problems	Air conditioning not operating			
Fuel system	Poor starting or non-start	Lack of power or hesitation	Uneven running and stalling	Popping back or backfiring	Running on or detonation	Heavy fuel usage	Fuel leaks and smells
Ignition	Poor starting or non-start	Lack of power	Hesitation	Exhaust emission	Running on		
Plug gaps	Poor starting or non-start	Lack of power	Hesitation	Uneven running	Misfiring	Exhaust emissions	
Steering system	Abnormal or uneven tyre wear	Heavy steering	Pulling to one side	Poor self-centring	Wandering	Steering wheel alignment	Excessive free play
Tyre pressures	Abnormal tyre wear	Heavy steering	Uneven braking	Heavy fuel usage	Reduced tyre lifetime		
Valve clearances	Lack of power	Uneven running	Misfiring	Excessive fuel usage	Exhaust emissions	Noise from valves or camshaft	

Figure 1.100 Checking data and setting up test equipment

The main types of inspection, in addition to what is carried out when servicing, are:

- prework
- postwork
- pre-delivery inspection (PDI)
- used vehicle inspection
- special inspection (e.g. after an accident).

A prework inspection is used to find out what work needs to be carried out on a vehicle. Postwork inspections are done to make sure the repairs have been carried out correctly and that no other faults have been introduced.

A PDI is carried out on all new vehicles to check certain safety items and to, for example, remove any transport packaging such as suspension locks or similar. A used vehicle inspection is done to determine the safety and saleability of a vehicle as well as checking that everything works. After gaining experience you may be asked to carry out an inspection of a vehicle after an accident to check the condition of the brakes, for example.

In all cases, a recommended checklist should be used and careful records of your findings should be kept. Working to timescales, or reporting to a supervisor that timescales cannot be met, is essential:

- When a customer books a car in for work to be done they expect it to be ready at the agreed time. Clearly, if this deadline cannot be met the customer needs to be informed.
- To make the running of a workshop efficient and profitable, a technician will have jobs allocated that will take a certain amount of time to complete. If for any reason this time cannot be met then action will need to be taken by the workshop manager or supervisor.

Definition

PDI
Pre-delivery inspection.

Key fact

A PDI is carried out on all new vehicles.

1.7.7 Information sources

The main sources of information are:

- technical manuals
- technical bulletins

- servicing schedules
- job card instructions
- inspection records
- checklists.

All of the main manufacturers have online access to this type of information. It is essential that proper documentation is used and that records are kept of the work carried out. For example:

- job cards
- stores and parts records
- Manufacturers' warranty systems.

These are needed to ensure that the customer's bill is accurate and that information is kept on file in case future work is required or warranty claims are made.

Results of any tests carried out will be recorded in a number of different ways. The actual method will depend on what test equipment was used. Some equipment will produce a printout, for example. However, results of all other tests should be recorded on the job card. In some cases this may be done electronically but it is the same principle. Remember: always make sure that the records are clear and easy to understand.

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CHAPTER 2

Engine systems

2.1 Engine mechanical

2.1.1 Introduction and operating cycles

The modern motor vehicle engine burns a fuel to obtain power. The fuel is usually petrol (gasoline) or diesel, although liquid petroleum gas (LPG) and compressed natural gas (CNG) are sometimes used. Specialist fuels have been developed for racing car engines. Motor vehicle engines are known as 'internal combustion' engines because the energy from the combustion of the fuel, and the resulting pressure from expansion of the heated air and fuel charge, is applied directly to pistons inside closed cylinders in the engine. The term 'reciprocating piston engine' describes the movement of the pistons, which go up and down in the cylinders. The pistons are connected by a rod to a crankshaft to give a rotary output (Fig. 2.1).

Key fact

Specialist fuels have been developed for racing car engines.

Fuel is metered into the engine together with an air charge for most petrol engines. However, some now use injectors that inject directly into the engine cylinder. In diesel engines, the fuel is injected into a compressed air charge in the combustion chamber. In order for the air and fuel to enter the engine and for the burnt or exhaust gases to leave the engine, a series of ports is connected to the combustion chambers (Figs 2.2 and 2.3). The combustion chambers are formed in the space above the pistons when they are at the top of the cylinders. Valves in the combustion chamber at the ends of the ports control the air charge and exhaust gas movements into and out from the combustion chambers.

Definitions

TDC
Top dead centre.

BDC
Bottom dead centre.

The valves are described as 'poppet' valves and have a circular plate at right angles to a central stem that runs through a guide tube. The plate has a chamfered sealing face in contact with a matching sealing face in the port. The valve is opened by a rotating cam and associated linkage. It is closed and held closed by a coil spring. The opening and closing of the valves and the movement of the pistons in the cylinders follow a cycle of events called the 'four-stroke cycle' or the 'Otto cycle' after its originator (Figs 2.4–2.7).

Key fact

Combustion chambers are formed by the space above the pistons when they are at the top of the cylinders (TDC).

The first stroke of the four-stroke cycle is the induction or intake stroke. This occurs when the piston is moving down in the cylinder from top dead centre (TDC) to bottom dead centre (BDC) and the inlet valve is open. The movement of the pistons increases the volume of the cylinder so that air and fuel enter the engine.

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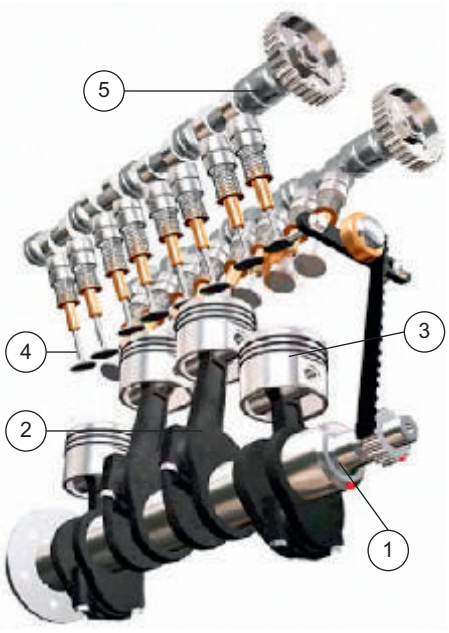


Figure 2.1 Internal combustion engine internal components: 1, crankshaft; 2, connecting rods; 3, pistons; 4, valves; 5, camshafts

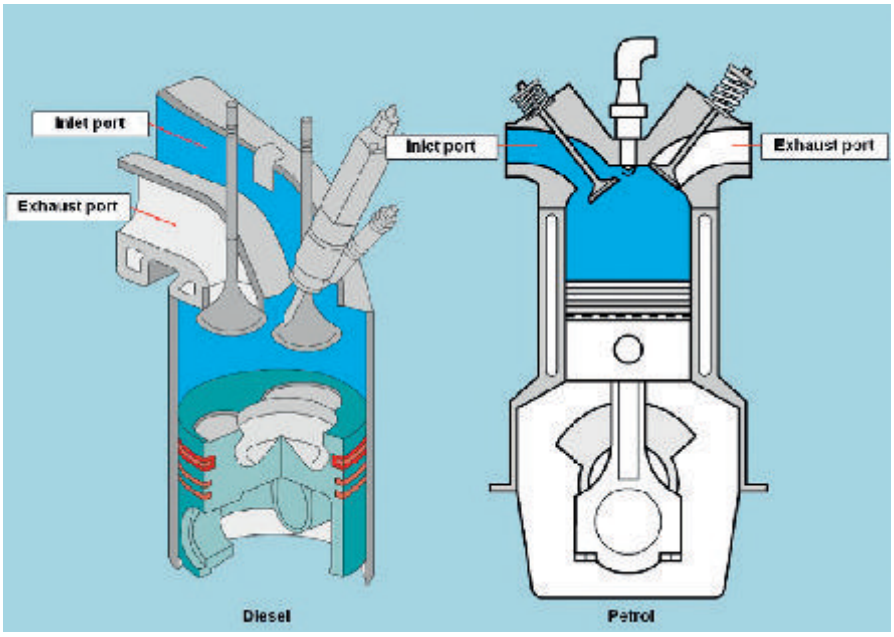


Figure 2.2 Diesel and petrol engine: pistons at bottom dead centre (BDC) before start of the compression strokes

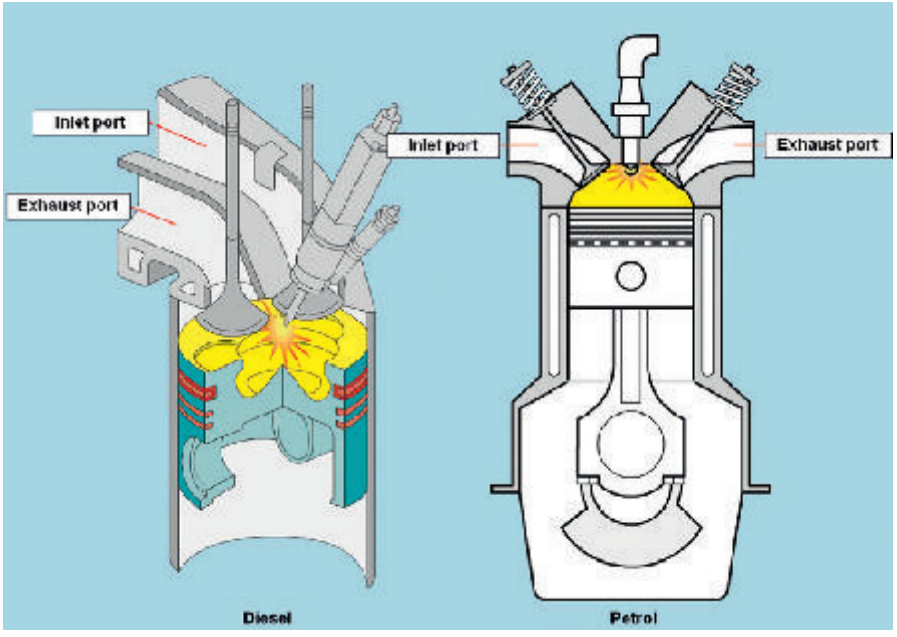


Figure 2.3 Diesel and petrol engine: pistons at top dead centre (TDC) before start of the combustion or power strokes

Key fact

Towards the end of the compression stroke, the fuel is ignited and burns to give a large pressure rise.

The next stroke is the compression stroke, when the piston moves upwards in the cylinder. Both the inlet and exhaust valves are closed and the space in the cylinder above the piston is reduced. This causes the air and fuel charge to be compressed, which is necessary for clean and efficient combustion of the fuel.

Towards the end of the compression stroke, the fuel is ignited and burns to give a large pressure rise in the cylinder above the piston. This pressure rise forces the piston down in the cylinder on the combustion or power stroke.

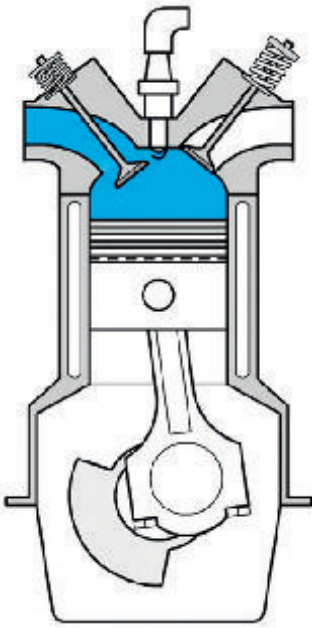


Figure 2.4 Induction or intake: piston moving down

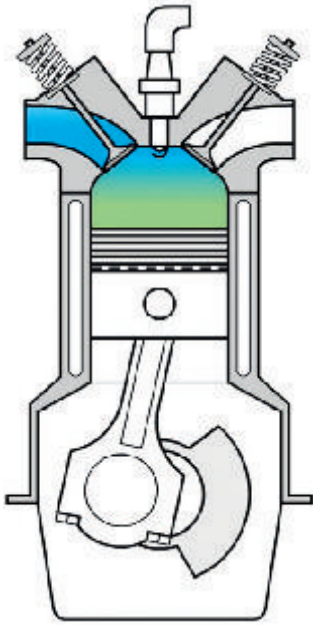


Figure 2.5 Compression: piston moving up

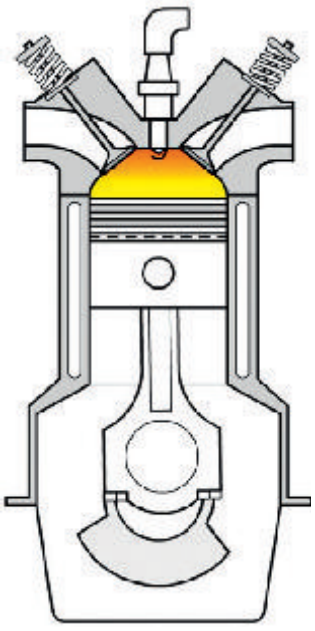


Figure 2.6 Power or combustion: piston is forced down

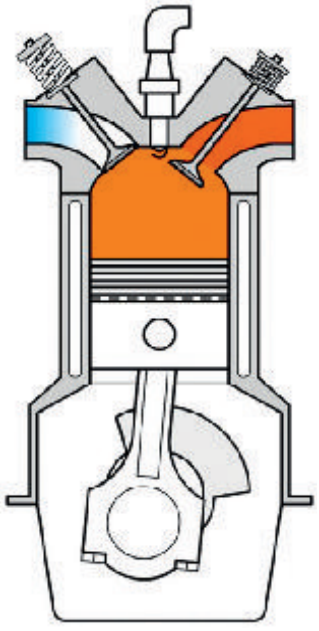


Figure 2.7 Exhaust: piston moving back up

Once the energy from the fuel has been used, the exhaust valve opens so that the waste gases can leave the engine through the exhaust port. To complete the exhausting of the burnt gases the piston moves upward in the cylinder. This final stroke is called the exhaust stroke.

The four-stroke cycle then repeats over and over again, as the engine runs. A heavy flywheel keeps the engine turning between power strokes.

Key fact

The four-stroke cycle is sometimes described as: suck, squeeze, bang, blow ….

On the induction stroke of a petrol engine (most types), air and petrol enter the cylinder so the inlet valve in the inlet port must be open. In diesel, and gasoline (petrol) direct injection (GDi) engines, only air enters the cylinder. A rotating cam on the camshaft provides a lifting movement when it runs in contact with a follower. A mechanical linkage is used to transfer the movement to the valve stem and the valve is lifted off its seat so that the inlet port is opened to the combustion chamber. The air and fuel charge or air charge can now enter the cylinder. The inlet valve begins to open shortly before the piston reaches TDC. The exhaust valve, which is operated by its own cam in the same way as the inlet valve, is beginning to close as the piston passes TDC at the end of the exhaust stroke. Valve overlap helps clear the remaining exhaust gases from the combustion chamber. The incoming air charge fills the combustion chamber as the last quantity of exhaust gas leaves through the exhaust port. This is known as 'scavenging'; it helps cool the combustion chamber by removing hot exhaust gases and gives a completely fresh air charge.

Key fact

Valve overlap helps clear the remaining exhaust gases from the combustion chamber.

The terms TDC and BDC are used to describe the position of the piston and crankshaft when the piston is at the end of a stroke and the axis of the piston and crankshaft bearing journals are in a straight line and at 0° (TDC) and 180° (BDC) of crankshaft revolution. To the abbreviations are added the letters 'A' to indicate degrees 'after' TDC or BDC and the letter 'B' to indicate 'before' TDC or BDC. See Figs 2.2 and 2.3.

Key fact

The camshaft rotates once for the two revolutions of the crankshaft during the four-stroke cycle.

The camshaft (see Fig. 2.1) rotates once for the two revolutions of the crankshaft during the four-stroke cycle. The drive from the crankshaft to the camshaft has a 2:1 ratio produced by the numbers of teeth on the driven and driver gears. Rotational data for the camshaft is usually given as degrees of crankshaft rotation and this should to be considered in relation to the four-stroke cycle. The four-stroke cycle occurs over two full revolutions of the crankshaft, which is a 720° rotational movement.

Looking at the four-stroke cycle and the relationships of the crankshaft rotation, the piston position in the cylinder and the opening and closing of the valves is best observed by looking at a valve timing diagram (Fig. 2.8). This diagram is one method of providing data for valve opening and closing positions.

Valve timing data is given in engine workshop manuals as degrees of crankshaft revolution. This can be as written data or by means of valve timing diagrams.

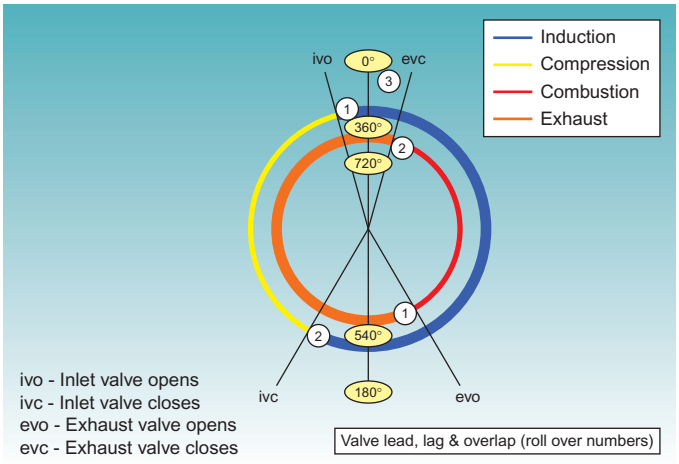


Figure 2.8 Valve timing diagrams: 1, lead; 2, lag; 3, overlap

In the most popular valve timing diagram two circles, one inside the other, are used to represent the 720° of crankshaft rotation through which the crankshaft moves for a complete cycle. Each stroke is represented by an arc of 180° with induction and compression on the outer circle and combustion and exhaust on the inner circle. The valve opening and closing positions are marked and the duration of crankshaft rotation is displayed by a thicker line.

From the valve timing diagrams it can be seen that the valve opening and closing positions do not occur within the 180° of crankshaft rotation for each stroke of the four-stroke cycle. For instance, towards the end of the exhaust stroke, the inlet valve begins to open and this is before the exhaust valve has closed. The exhaust valve finally closes as the piston moves down on the induction stroke. The inlet valve closes as the piston is rising on the compression stroke. The exhaust valve opens before the end of the combustion stroke. The opening and closing positions of the valves are specific to individual engines and are matched to other design and performance requirements.

The terms applied to the valves when opening before and closing after the start of a stroke and when both valves are open together are called ‘lead’, ‘lag’ and ‘overlap’, respectively. The overlap position is often referred to as ‘valves rocking’ and can be used as a rough guide as to when a piston is at TDC.

All internal combustion engines have an induction, compression, expansion and exhaust process. For a four-stroke engine, each of these processes requires half an engine revolution, so the complete engine cycle takes two complete engine revolutions. That is, there is a working and a non-working (gas-exchange) revolution of the engine within the cycle. However, a two-stroke engine combines two of the processes in each half turn of the engine; thus, all processes are complete in one engine revolution and the engine has a power stroke with every revolution (Fig. 2.9). In order to operate, the two-stroke petrol engine uses the crankcase (piston underside) for induction of the fuel/air mixture and transfer into the cylinder via ports in the cylinder barrel.

On the upstroke, the piston moves upwards towards TDC, and fuel/air charge trapped in the cylinder space above the piston is compressed and, around TDC, ignited by a spark. This is the beginning of the power stroke. As the piston rises

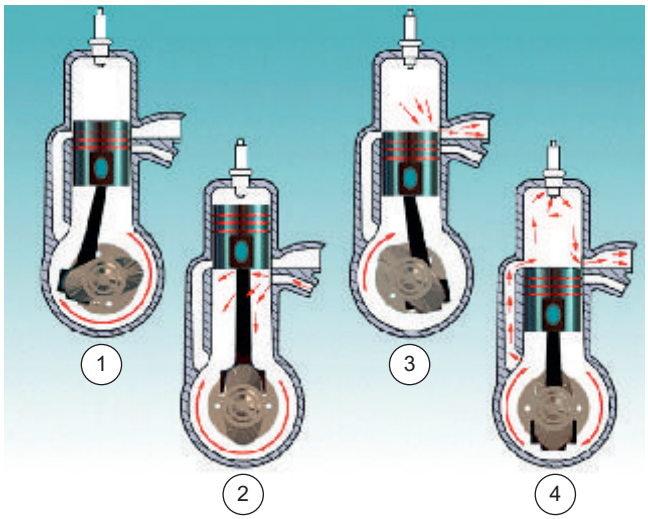


Figure 2.9 Two-stroke operating cycle: 1, compression; 2, induction; 3, combustion (power); 4, exhaust (transfer also taking place)

during the upstroke, the volume in the crankcase increases and atmospheric pressure forces the fresh fuel/air charge into the crankcase (under the piston).

On the downstroke the piston moves towards BDC as the power stroke begins; the expanding gases force the piston down the bore, producing torque at the crankshaft via the connecting rod. At the same time, the crankcase volume decreases and the fuel/air mixture is compressed under the piston. As the piston approaches BDC, the transfer port connecting the cylinder volume to the crankcase volume is uncovered by the piston. On the opposing side of the cylinder, the exhaust port is also uncovered.

This allows the fresh charge in the crankcase volume to transfer and fill the cylinder volume, at the same time forcing the exhaust gases out of the cylinder via the exhaust port. The efficiency of this scavenging process is very dependent on the port exposure timing and the gas dynamics. Often the piston crown has a deflector to assist this process and to prevent losing fresh charge down the exhaust. Note that two-stroke gasoline engines are normally lubricated via the provision of an oil mist in the crankcase. This is provided by oil mixed in with the fuel/air (premixed or injected); hence the oil is burnt in the combustion process, which produces excessive hydrocarbon emissions.

Two-stroke engines are generally more powerful for a given displacement owing to the extra power stroke compared to a four-stroke engine, but the problem is that the expansion stroke is short and volumetric efficiency (how easy it is to get the gases in and out of the engine) is poor, so they are less efficient. In addition, exhaust emissions are higher than from a four-stroke engine.

Some large static diesel engines are often two-stroke types (Fig. 2.10). Note that all four operating processes are executed in one engine revolution (induction, compression, expansion and exhaust). The diesel engine requires a charge of air that is compressed to raise its temperature above the self-ignition point of the fuel. This air charge is supplied by an air pump or pressure charging device (turbo or supercharger). The pressurized air from this device passes into the combustion chamber via ports in the cylinder wall. The exhaust gases leave the

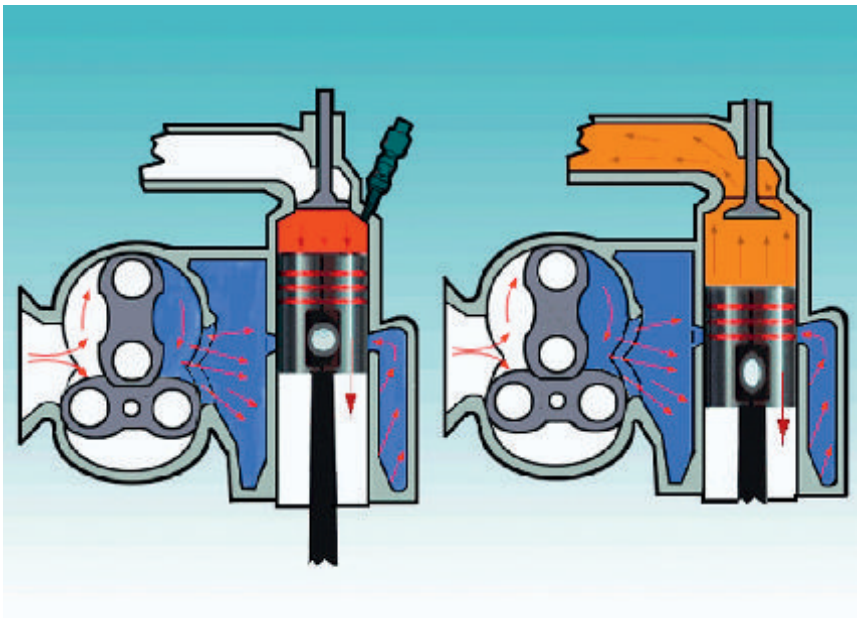


Figure 2.10 Diesel two-stroke cycle

combustion chamber via cam-operated poppet valves. The incoming charge forces the exhaust gases out via these valves (the cylinder scavenging process).

During the downwards movement of the piston, the hot expanding gases are forcing the piston down the bore, producing torque at the crankshaft. This is the expansion process. As the piston approaches BDC, the exhaust valve opens and the remaining pressure in the exhaust gas starts the evacuation of the gases in the cylinder via the open valves. As the piston moves further down to BDC, inlet ports are exposed around the bottom part of the cylinder bore, which allow the pressurized, fresh air charge from the air pump (or turbocharger) to fill the cylinder, evacuating the remaining exhaust gas via the valves and completing the exhaust and induction cycles.

At BDC, the cylinder contains a fresh air charge and the piston then begins to move up the cylinder bore. The inlet ports are closed off by the piston movement and the air charge is trapped and compressed by to the deceasing volume in the cylinder. At a few degrees before TDC, the air temperature has risen owing to the compression process and fuel is injected directly into the combustion chamber, into the hot air charge, where it vaporizes, burns, and generates thermal and pressure energy. This energy is converted to torque at the crankshaft via the piston, connecting rod and crankshaft during the downstroke.

Another variation on engine operation is the Wankel (the name of the inventor) or rotary engine (Fig. 2.11). This engine has been used in a limited number of passenger car applications. The engine uses a complex geometric rotor that moves within a specially shaped housing. The rotor is connected to the engine crankshaft and turns within the housing to create working chambers. These are exposed to inlet and exhaust ports to allow a fuel/air charge in, compress it and expand it (thus extracting work), then evacuate the waste gases and restart the cycle (Fig. 2.12). The rotor has special tips to provide a gas-tight seal between the working chambers. The movement of the rotor in this engine follows a path know as an epitrochoid.

Definition

Epitrochoid
A roulette traced by a point attached to a circle rolling around the outside of a fixed circle.

No matter what design of engine, it has to be positioned in the vehicle. There are various configurations that manufacturers have used in the configuration of their vehicle powertrains. The engine can be front, mid or rear mounted and can be installed in-line (along the vehicle axis) or transverse (across the vehicle axis) (Fig. 2.13).

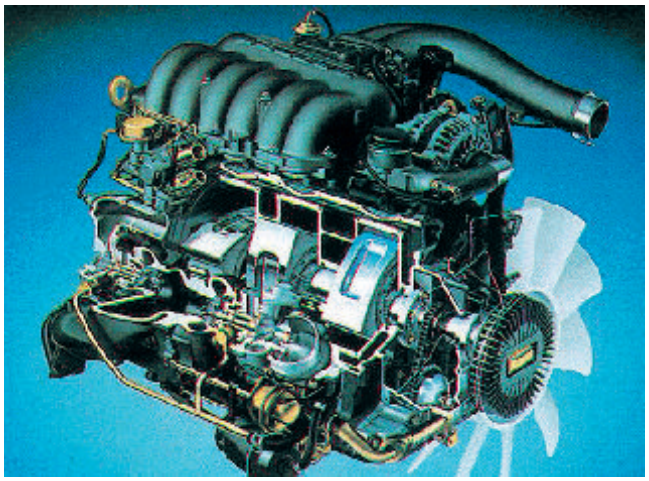


Figure 2.11 Rotary engine. (Source: Mazda Media)

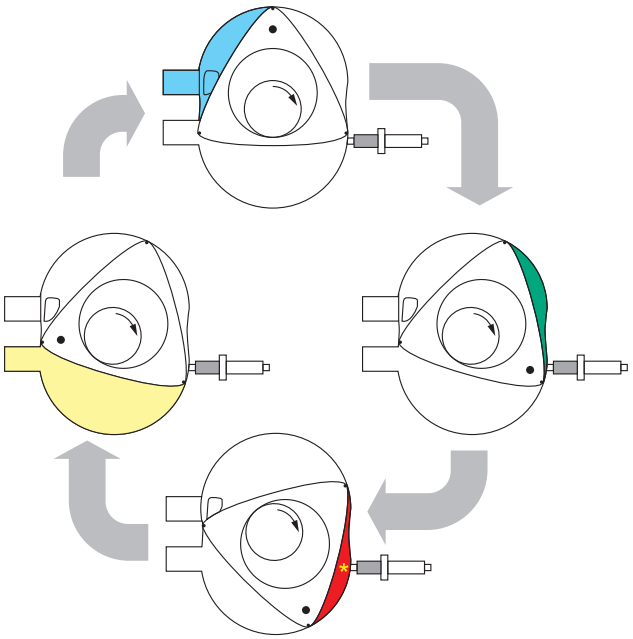


Figure 2.12 Rotary engine cycle: starting with the top image, induction, compression, power, exhaust. (Source: Wikimedia)

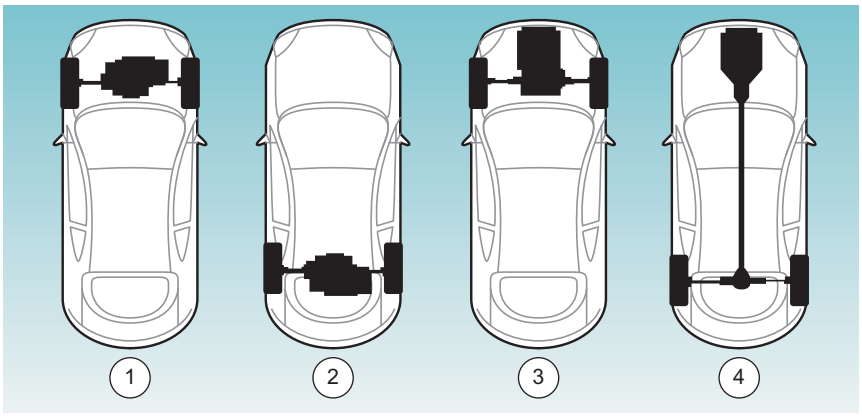


Figure 2.13 Typical positions for the engine: 1, front transverse engine FWD; 2, rear transverse engine RWD; 3, front longitudinal engine FWD; 4, front longitudinal engine RWD

Key fact

The mounting system has to isolate the vehicle from the engine vibrations.

The engine mounting system is important as it supports the weight of the engine in the vehicle. In addition, it counteracts the torque reaction under load conditions. The mounting system has to isolate the vehicle from the engine vibrations. The engine mounts consist of steel plates with a rubber sandwich between to provide the vibration isolation (Fig. 2.14). The mountings have appropriate brackets and fittings to fix to the engine and vehicle frame.

For a front-engine, rear-drive powertrain layout, the engine mounts are often at the centre position of the engine side, approximately at the engine centre of gravity (Fig. 2.15). The engine mounts bear compression and shear forces in supporting the engine weight and torque. The rear of the engine is bolted to the transmission, which in turn is supported at the rear end via a rubber mounting system. This three-point mounting is very common for this powertrain configuration.

For a front-wheel drive, transverse powertrain layout (Fig. 2.16), the mounting system has to cope with weight of the engine, plus the torque reaction of the

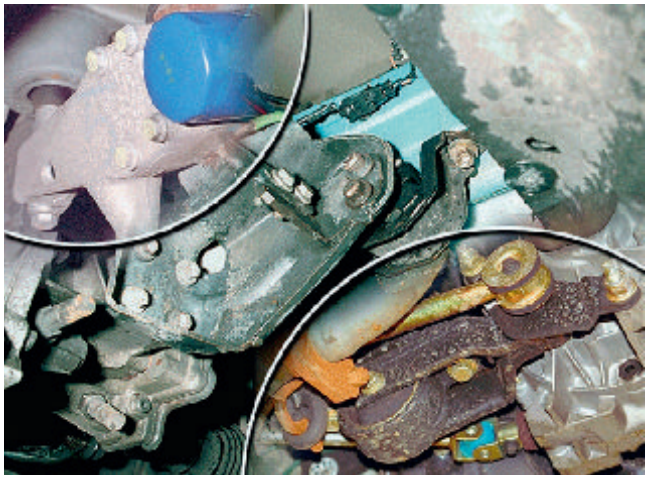


Figure 2.14 Engine mountings

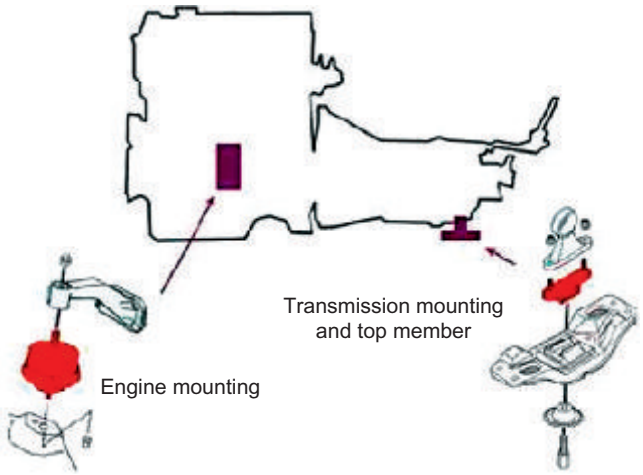


Figure 2.15 Typical engine mountings for front-engine RWD

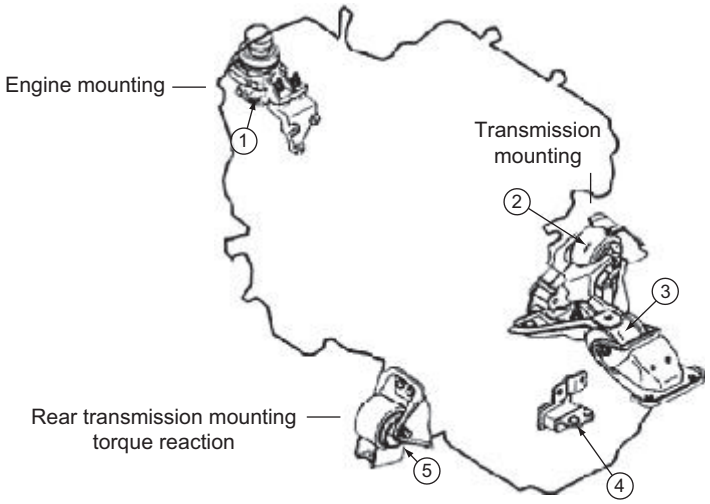


Figure 2.16 Five typical engine mountings for front-engine FWD

wheel torque. The mounting system therefore includes mountings to support weight and counteract torque separately. These are mounted at the top or bottom of the engine, respectively.

2.1.2 Engine operating details

The air above the Earth's surface is like a fluid that exerts a pressure on all points around it because of the Earth's gravitational force pulling it down. This creates a pressure known as atmospheric pressure and is 101.325 kPa, 760 mmHg, 29.92 inches Hg, 14.696 psi or 1013.25 millibars (let's stick with approximately 1 bar or 15 psi).

Definition

Naturally aspirated engine
An engine that does not use forced induction by a supercharger or turbocharger.

A naturally aspirated engine (one that does not use forced induction by a supercharger or turbocharger) relies on atmospheric pressure to charge the cylinder with gas (air or air/fuel mixture) ready for the combustion process. As the piston moves down the cylinder (from TDC to BDC), the volume increases and this causes the pressure in the cylinder to reduce, becoming lower than atmospheric pressure. This creates a pressure difference between the inside and outside of the cylinder, and as a result the atmospheric pressure (the higher pressure) forces gases into the cylinder (where there is lower pressure) until the pressure is balanced. Note that any restriction to the flow of gas will reduce the effectiveness of the cylinder charging process.

Definition

Volumetric efficiency
A measure of the efficiency of the cylinder charging process during the induction stroke.

Volumetric efficiency is a measure of the efficiency of the cylinder charging process during the induction stroke. Theoretically, the cylinder should be completely filled with a mass of gas, but in practice this never happens owing to flow losses and inefficiencies. Therefore, the volumetric efficiency is a measure of the actual amount of gas induced compared to the theoretical amount (which is the mass required to completely fill the cylinder volume) and is expressed as a percentage (Fig. 2.17). It is calculated as:

$$(\text{Actual mass of air}/\text{Theoretical mass of air}) \times 100\%$$

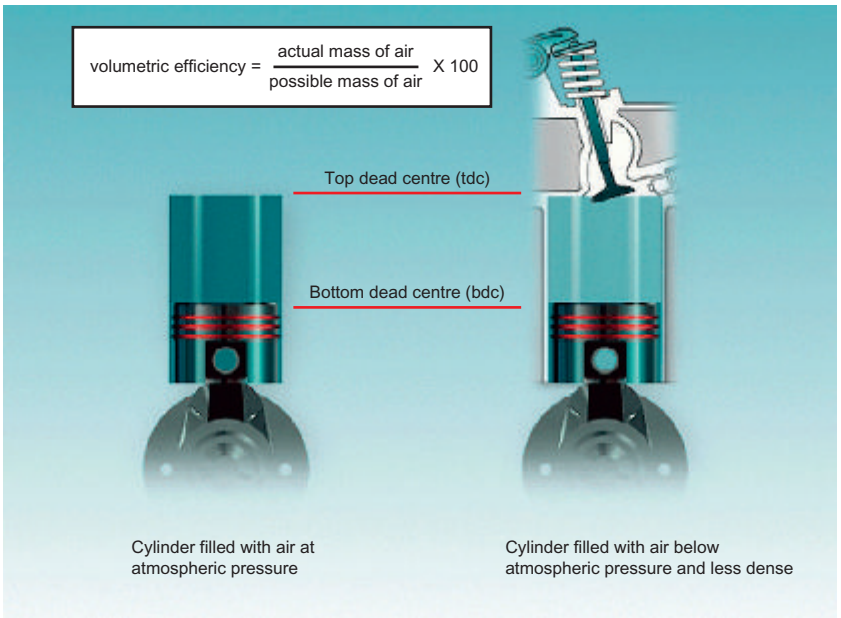


Figure 2.17 Volumetric efficiency

The more efficiently the engine cylinders can fill with gas, the more air, or fuel/air, is available for the combustion process and this improves overall engine efficiency (Fig. 2.18). The process of getting gases into and out of the engine is known as 'aspiration' or 'engine breathing'.

Combustion in the engine cylinder takes place because of a chemical reaction between the carbon and hydrogen in the fuel and the oxygen in the air. This reaction releases energy from the fuel in the form of heat that generates pressure in the cylinder to force movement of the piston. To achieve efficient combustion, the quality of the fuel/air mixture is important; that is, how evenly mixed the fuel droplets are in the induced air. Movement of the air as it enters the cylinder is important for this process and the requirements are different for petrol and diesel engines. The required air movements for each engine type are created by careful design of the components that form the inlet tract and combustion chamber.

Key fact

Combustion in the engine cylinder takes place because of a chemical reaction between the carbon and hydrogen in the fuel and the oxygen in the air.

The inlet valve opens and closes according to piston position and controls the incoming gas charge into the engine. It generally remains open for a small period after the piston has reached BDC (i.e. beyond the end of the inlet stroke). This allows the energy of the moving gas column in the inlet tract to assist in the cylinder charging process, which helps to increase volumetric (and engine) efficiency.

After the combustion chamber has been charged with gas (air or fuel/air) during the induction stroke, the cylinder inlet and exhaust valves are both closed and seal the combustion chamber. The piston begins to rise in the cylinder, thus reducing the volume of the cylinder space and hence increasing the pressure of the trapped gas charge in the cylinder before combustion. The opening and closing of the valves is executed in sequence via the engine valve gear, synchronized with the four-stroke cycle and piston position.

It is important that the closed cylinder is sealed properly to maintain the appropriate pressures in the cylinder during the working cycle. Any losses in pressure would significantly reduce the efficiency of the engine. To seal the piston and bore, piston rings are fitted into radial groves near the top of the piston and provide a gas-tight seal between the moving piston and the cylinder bore. When the cylinder volume is reduced during the compression stroke,

Figure 2.18 This very efficient engine produces 98 g of CO_2/km. (Source: GM Media)

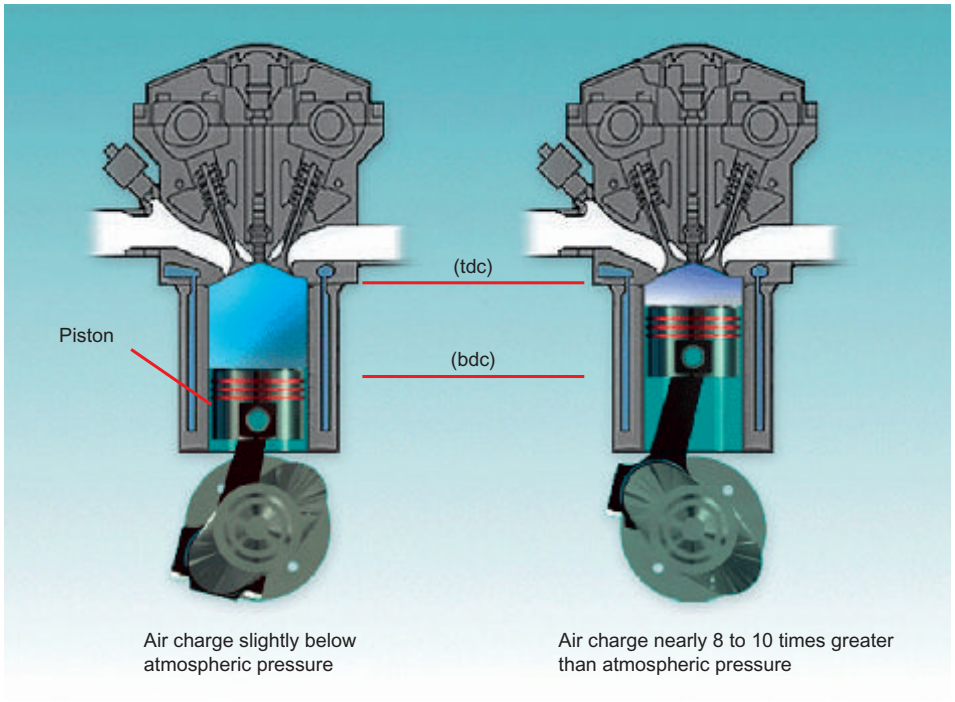


Figure 2.19 Compression

Key fact

Most spark ignition engines have a compression ratio of 8:1 to 10:1.

the trapped gas is compressed and the amount of compression is known as the compression ratio. Compressing the charge before combustion allows more oxygen or fuel/oxygen in the cylinder than would otherwise have been available without compression and this improves combustion efficiency. Most spark ignition engines have a compression ratio of 8:1 to 10:1. This means that the cylinder volume reduces by eight or ten times during the compression stroke (Fig. 2.19).

2.1.2.1 Spark ignition (SI)

During compression of the fuel/air mixture in a petrol engine, heat energy and kinetic energy (due to gas movement) are imparted into the mixture owing to the reducing volume and rising pressure. This creates a significant temperature increase and the magnitude of this increase depends upon the speed of the compression process and the amount of heat rejected to the surroundings (via the cylinder combustion space, walls, head, etc.). The temperature rise elevates to a point just below the self-ignition temperature of the fuel/air charge, which will combust at or above the flashpoint when ignited via an external source (i.e. the spark plug). Note that if the temperature of the mixture was too high, spontaneous self-ignition could occur and this would be a limiting factor for the maximum compression ratio in a petrol engine.

After compression of the inlet charge, combustion of the fuel creates heat and pressure energy, which is imparted on the piston to generate mechanical work. In a petrol engine, this process is initiated by the high-voltage arc at the spark plug electrodes in the cylinder.

Combustion in the cylinder of an engine is a chemical reaction process between carbon and hydrogen in the fuel and oxygen present in the induced air. The carbon and oxygen combine to form carbon dioxide (CO_2), and the hydrogen combines with oxygen to form water (H_2O). Nitrogen passes through the engine as long as the combustion chamber temperatures remain below critical limits.

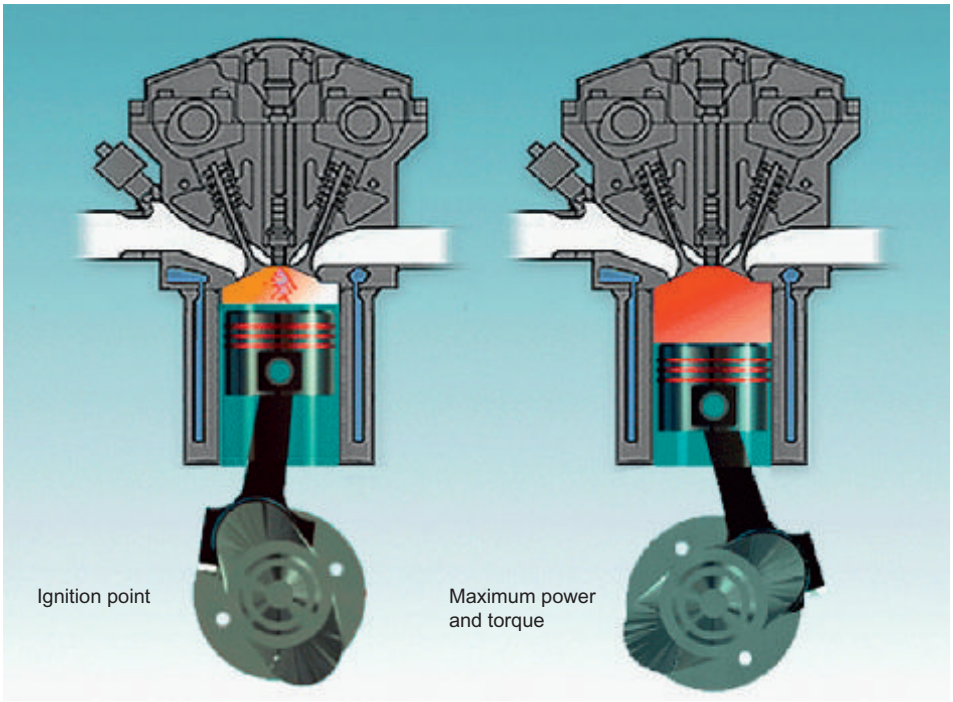


Figure 2.20 Ignition timing for best torque

If the combustion process is not efficient, incomplete combustion will result and this produces carbon monoxide (CO). If combustion chamber temperatures are high, oxides of nitrogen (NO_x) are produced. These are harmful pollutants and their emissions from motor vehicles are closely regulated and controlled by environmental protection agencies and bodies around the world.

The combustion process should occur in a rapid but controlled manner. The flame propagation and energy release in the cylinder should have a predictable, stable behaviour depending on the engine operating conditions. The timing of the spark ignition is critical to achieve appropriate energy release for maximum efficiency in the energy conversion process that takes place in the combustion chamber. The burn duration of the fuel varies according to engine conditions; therefore, the spark must be adjusted to occur at the correct time, according to these conditions, to obtain the optimum torque from the engine. The optimum spark advance for a given engine condition is known as minimum spark advance for best torque (MBT) (Fig. 2.20).

Definition

MBT
Minimum spark advance for best torque.

The quality of petrol (gasoline) is measured by a parameter called the octane rating, which gives an indication of the fuel's resistance to engine 'knock' or uncontrolled, spontaneous combustion, which causes engine damage. Fuels with a higher octane rating burn more slowly and in a more controlled manner, and hence have a greater resistance to knock. The octane rating of the fuel determines the limit of ignition advance for a given engine speed and load condition. Therefore, it is particularly important to operate the engine on the correct fuel, to prevent damage to the engine due to knocking.

A chemically correct air and fuel ratio mixture must exist to ensure that sufficient oxygen is present to completely combust all of the fuel. This is known as mixture strength and is the ratio of air mass to fuel mass (Fig. 2.21). For petrol, the correct ratio is approximately 14.7 air mass to 1 part fuel mass. If more air is present then the mixture strength is known as 'weak'. If less than a 14.7 air/fuel

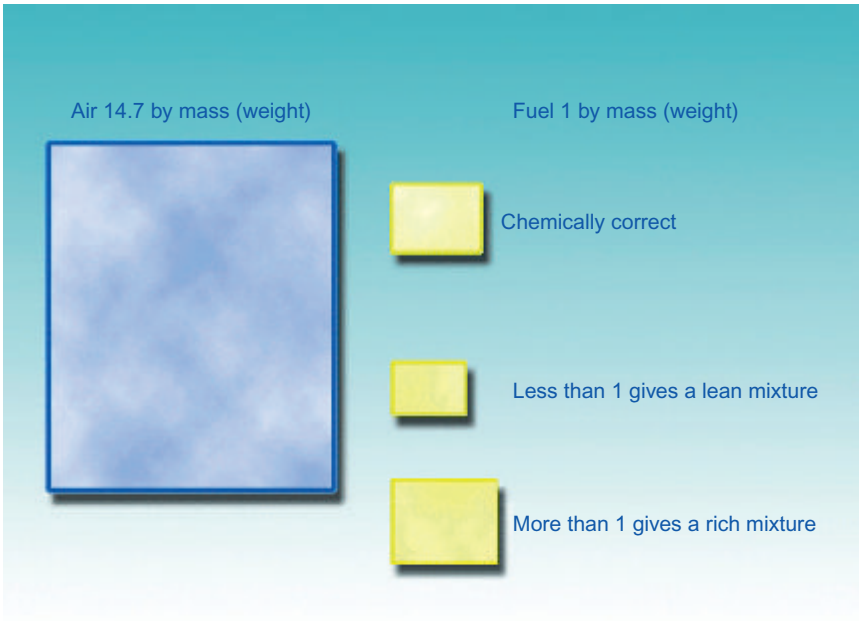


Figure 2.21 Mixture ratio

Definition

Stoichiometric ratio
For petrol, the correct ratio is approximately 14.7 air mass to 1 part fuel by mass.

ratio, then the mixture strength is known as 'rich'. Weak and rich mixtures are less than optimum for the engine, although under certain conditions the mixture strength is adjusted by the engine control system according to demand. For example, for full power a slightly rich mixture is needed and this is provided when the engine is at full throttle. Extended running on rich or weak mixtures reduces engine efficiency and can cause damage to the engine and its subsystems.

The combustion process creates energy within the cylinder in the form of heat from the burning fuel/air mixture. Owing to the enclosed nature of the cylinder, this heat energy creates a pressure rise in the cylinder above the piston. This pressure, applied over the piston area, in turn, creates a force pushing down on the piston and turning the crankshaft via the connecting rod, thus producing torque at the crankshaft. The pressure in the cylinder is shown plotted against cylinder volume in Fig. 2.22. This is known as an indicator diagram.

The torque at the crankshaft is a function of the cylinder pressure and crankshaft angle; the maximum torque is produced when the connecting rod and crankshaft main/big-end bearings are at right angles (i.e. 90° crank rotation from TDC position). Note that at TDC, any pressure on the piston produces no work as there is no turning moment (torque), just a force pushing down on the bearings.

The ignition and fuel settings of an engine are set by the manufacturer at the optimum position to achieve the best compromise of performance, economy and minimal exhaust emissions. With respect to combustion, it is important that the maximum cylinder pressure and energy release occur at the correct angle. Damage to the engine can occur if this happens too early or late in the engine cycle (Fig. 2.23). An example is early or advanced ignition, which causes engine knock and damages the piston if allowed to occur for any significant period. This is a characteristic noise caused by preignition or early ignition of the fuel/air mixture. Advanced or early ignition causes an early pressure rise that is applied to the piston at TDC. At this crank angle, no engine torque can be produced and this means that all the combustion energy is applied directly to the engine mechanical components (piston crown, bearings, etc.), causing them to generate

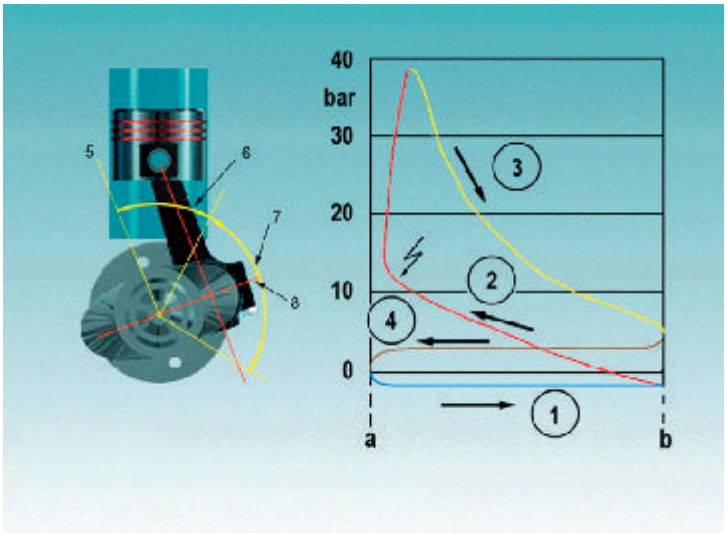


Figure 2.22 Petrol engine indicator diagram. Diesel figures are approximately double: 1, introduction; 2, compression; 3, power; 4, exhaust

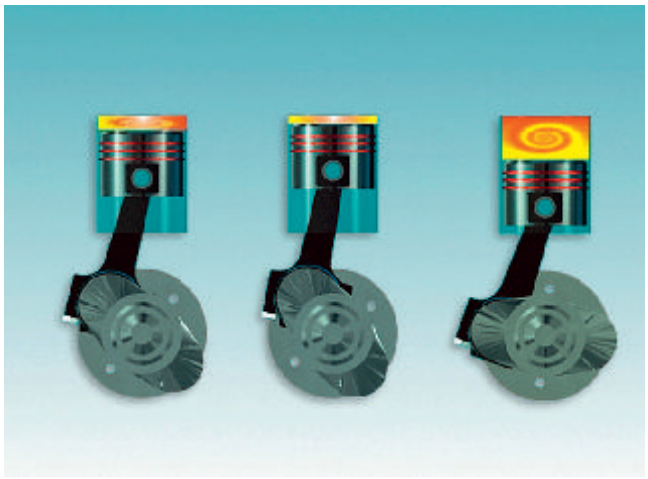


Figure 2.23 Ideal, retarded and advanced ignition point

the 'pinking' noise. Although the noise is quite subtle, the forces are massive and cause considerable damage to the engine.

When pinking occurs, the combustion energy precipitates through the engine components, causing damage. In addition, heat is generated that is not dissipated normally and this causes excessive temperature of engine components (e.g. pistons, valves and valve seats) and consequent heat-related damage.

Overretarded ignition causes incorrect timing of the energy release from the fuel that, in turn, means less energy to do work and therefore more energy to dissipate via the cylinder boundaries. This causes an increase in engine temperatures, damages components and reduces overall engine efficiency. This excess energy also has to be rejected via the exhaust and this causes increased exhaust gas temperatures that can damage exhaust valves and seats, as well as exhaust gas components (catalytic converter).

Key fact

Overadvanced (early) or retarded (late) ignition can cause serious damage.

2.1.2.2 Compression ignition (CI)

In a diesel engine, the compression process must create sufficient energy to cause the temperature of the compressed gas (air) to rise above the

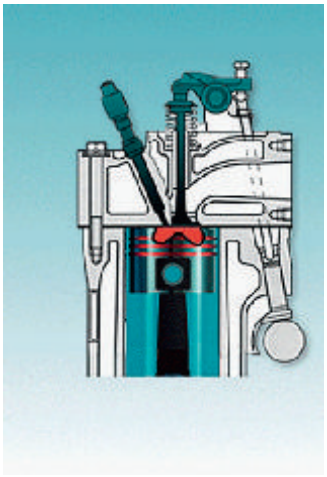


Figure 2.24 Direct diesel injection

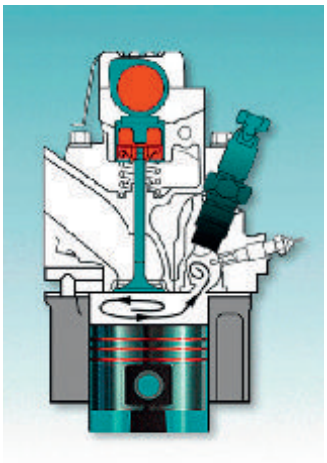


Figure 2.25 Indirect diesel injection

self-ignition temperate of the fuel that is injected into the cylinder at the end of the compression stroke.

Inlet charge movement is particularly important in a diesel engine, to ensure that the fuel droplets have sufficient oxygen for complete combustion. The required air flows during the induction and compression processes are created by the design of the inlet tract and combustion space. There are two designs of combustion chamber in common use and these are named after the position in the chamber where the fuel is introduced. They are known as direct and indirect injection (Figs 2.24 and 2.25).

Key fact

A direct injection combustion chamber has a 'bowl' formed in the piston crown.

A direct injection combustion chamber has a 'bowl' formed in the piston crown. This is designed to promote a tumble movement of the incoming air mass; this helps to ensure good distribution of the fuel in the cylinder and reduced soot emissions.

The indirect type combustion chamber incorporates a precombustion chamber within the cylinder head (Fig. 2.26). The compressed inlet charge is forced into this chamber at high velocity and pressure. This creates a swirl movement that ensures complete mixing of fuel droplets with air for maximum combustion

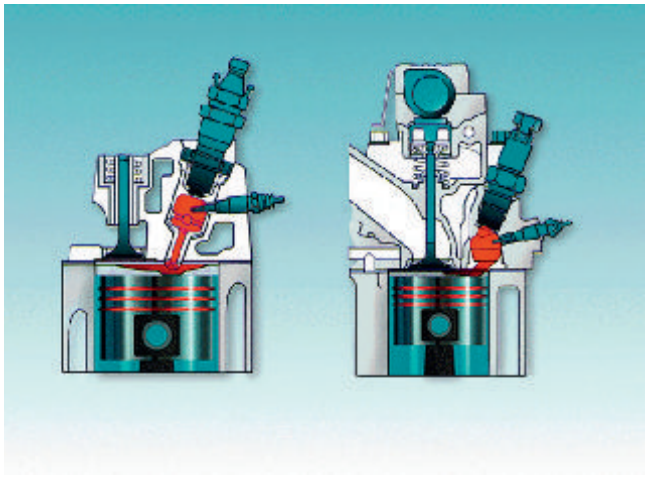


Figure 2.26 Precombustion chamber and swirl chamber (indirect injection)

efficiency. During the combustion process, the burning gases are ejected from this chamber with high pressure and energy. This ensures sufficient turbulence in the main combustion chamber for efficient combustion.

The compression ratio of a direct injection engine is typically between 16:1 and 21:1. This is sufficient to raise the induced charge temperature for self-ignition of the fuel under all engine operating conditions without creating excessive combustion noise (or diesel knock). Indirect injection engines have higher compression ratios of 22:1 to 25:1. This is necessary to generate the extra heat energy required due to losses via the increased surface area of the cylinder head. Diesel knock is less apparent in indirectly injected engines as the energy release is more controlled and less spontaneous.

Key fact

The compression ratio of a direct injection engine is typically between 16:1 and 21:1.

The diesel engine is designed to produce compression pressures that generate sufficient heat in the cylinder to ignite the fuel as it is injected into the combustion chamber. This is known as compression ignition (CI). Petrol engines are generally known as spark ignition (or SI) engines. During the combustion stroke, the engine power output or work is generated, hence the name ‘power’ stroke in the four-stroke cycle of induction, compression, power and exhaust. Engine combustion is a fundamental process in the operation of the engine. This process must be efficiently executed and controlled via the engine subsystems (fuel, air, ignition, etc.) to ensure best efficiency and performance, with minimum harmful exhaust emissions.

Combustion in a diesel engine begins very rapidly as the fuel is being injected into the combustion chamber and heated. This causes a rapid energy release that generates the characteristic ‘diesel’ engine noise. For this reason, a simple diesel engine is noisier than the equivalent petrol engine. The combustion process is most rapid in a direct injection diesel engine (Figs 2.27 and 2.28) and, because of this, combustion losses are minimal and these are the most fuel-efficient type of internal combustion engine seen in road vehicles. Combustion is not fully completed in the prechamber before the combustion gases are expelled into the cylinder and continue the combustion process in the main combustion chamber. The increased surface area means that more heat from combustion is lost to the cylinder boundaries (walls, head, etc.) than in the direct injection type. Indirect injection engines are however, quieter in operation because of the longer, slower combustion process.

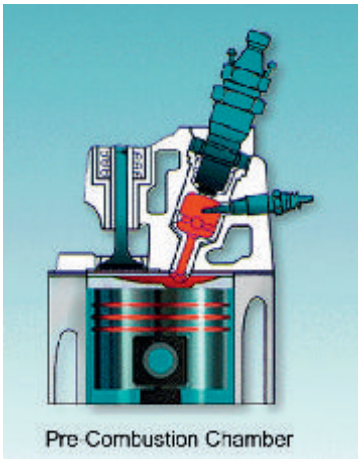


Figure 2.27 Indirect diesel injection

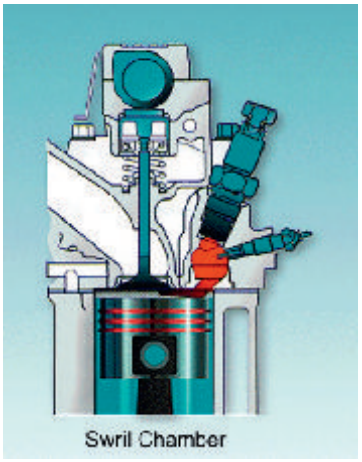


Figure 2.28 Swirl chamber

Diesel engines always operate with excess air (or weak mixture) and with high exhaust gas temperatures. This oxygen combines with nitrogen to form the pollutant NO_x (oxides of nitrogen). Exhaust gas recirculation (EGR) is often used to reduce cylinder temperatures and to reduce the amount of oxygen in the cylinder air charge, thus preventing the formation of NO_x (Figs 2.29 and 2.30).

For diesel engines, there are three main phases in the combustion process (Fig. 2.31). The first is the delay phase as the fuel absorbs heat from the cylinder air charge and vaporizes. The next phase occurs when the fuel has reached a sufficient temperature to self-ignite. This causes combustion and the flame front propagates rapidly out across the piston crown. This is where the rapid energy release occurs and causes the characteristic diesel engine noise. Once initial burning of the fuel takes place, continued injection of fuel provides a controlled burning and energy release to provide sustained pressure on the piston and good torque generation at the crankshaft.

Efficient and effective combustion promotes an engine with good power output and with minimal harmful emissions. This can only be achieved when the engine mechanical parts are in good condition and the engine control systems for fuel delivery, ignition and emission control are correctly optimized and set.

Key fact

For diesel engines, there are three main phases in the combustion process:

1 start of injection and delay
2 start of combustion and flame spread
3 controlled combustion.

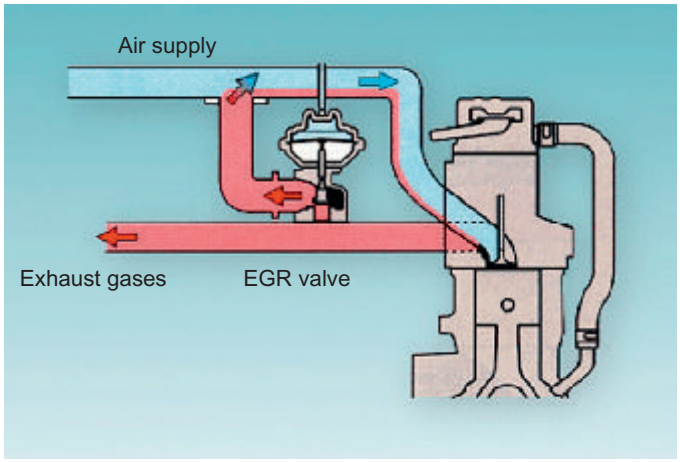
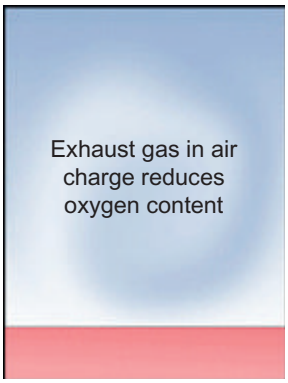


Figure 2.29 Exhaust gas recirculation (EGR)



Cylinder charge with exhaust gas recirculation

Figure 2.30 Reduced oxygen

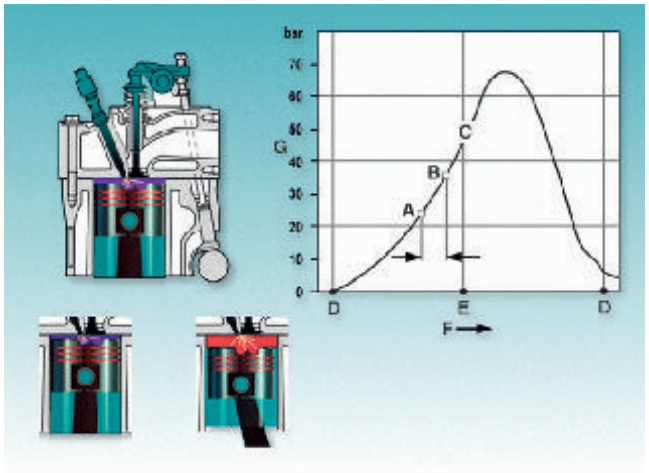


Figure 2.31 Phases of combustion, diesel engine: A, start of injection; B, start of combustion; C, controlled phase; D, bottom dead centre; E, top dead centre; F, piston travel; G, combustion chamber pressure (A – B is the delay phase)

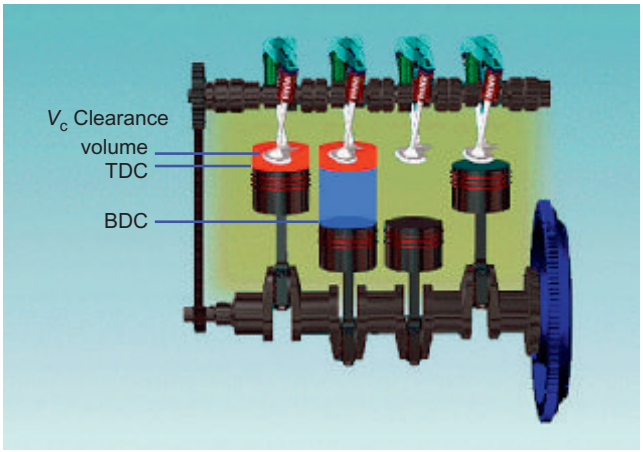


Figure 2.32 Clearance and swept volumes

2.1.2.3 Engine terminology and methods

The following are some of the technical terms that are used to describe features of the engine:

- ***Engine capacity***–the total, combined, displaced volume of all engine cylinders as a single value stated in units of cubic capacity. This is generally given in cubic centimetres (cm^3) or litres. In America, engine capacity is normally stated in cubic inches (in^3).
- ***Swept volume***–the volume of a cylinder bore between the TDC and BDC piston positions, excluding the volume above the piston at TDC (Fig. 2.32).
- ***Clearance volume***–the volume above the piston at TDC. Note that it is the volume of the combustion chamber itself (Fig. 2.32).
- ***Bore***–the diameter of the engine cylinder.
- ***Stroke***–the total linear distance travelled by the piston in the bore between TDC and BDC positions. Note that it is twice the crankshaft throw.
- ***Compression ratio***–the total volume of the cylinder at BDC (swept + clearance volume), expressed as a ratio of the volume of the cylinder at TDC (clearance volume).

The information on cylinder dimension can generally be found in workshop or manufacturer manuals. In addition, these values can be measured directly or derived via calculations.

Swept volume can be calculated via the formula:

$$(l\pi d^2)/4$$

where d is cylinder bore and l is stroke. Note that units of bore and stroke must be consistent. Engine volume is mostly stated in litres by manufacturers, but remember that 1000 cc (cubic centimetres) equals 1 litre. The total engine displacement is the sum of all cylinders' individual displacements.

The formula used to calculate the compression ratio is:

$$CR = (V_s + V_c)/V_c$$

where CR is compression ratio, V_s is swept volume, and V_c is clearance volume.

Note the correct order of preference when carrying out this calculation (remember or google BODMAS).

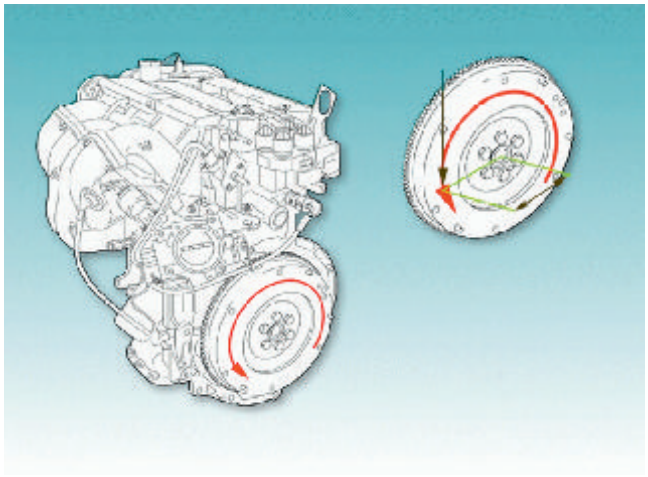


Figure 2.33 Torque and power measured at the flywheel

Two common terms used when expressing engine performance characteristics are ‘torque’ and ‘power’. Torque is an expression relating to work and is a measure of the turning force provided by the engine. Torque output can vary independently of engine speed and is a measure of the load on the engine. The SI units of torque are newton metres (Nm) and the imperial units are pounds/foot (lb/ft). Power is a derived unit and relates to the rate of work done, or the work done per unit of time. For an engine, the power is a product or torque and speed. Power output is given in kilowatts (kW) or horsepower (HP). Engine power is normally stated as measured at the flywheel, via a dynamometer or brake, hence the term ‘brake horsepower’ (Fig. 2.33).

Engine manufacturers often publish performance data in a graphical form showing torque and power curves against speed. Two examples are shown in Figs 2.34 and 2.35. Note that a petrol engine generally produces more power, at higher speed. A diesel engine produces more torque at lower speeds.

The optimum size of an individual engine cylinder is a compromise of a number of technical factors. The optimum displacement for a cylinder is generally between 250 and 600 cm^3 for road vehicle applications. In this range, the combustion chamber size, surface area and individual components size (pistons, valves, etc.) produce an engine with optimum efficiency with respect to fuel consumption and emissions. Typically, engines with total displacements in the range of 1–2.5 litres have four cylinders (Fig. 2.36).

The number of power strokes per revolution can be found by dividing the number of engine cylinders by two (for a four-stroke engine). The greater the number of cylinders, the smoother the torque delivery owing to reduced peak torque firing pulses from each cylinder and the increased number of firing strokes per revolution. Over 2 litres, six-cylinder engines give smooth power delivery with optimum cylinder displacement sizes. An in-line six cylinder has a relatively long crankshaft that can be difficult to accommodate in a transverse engine installation layout; therefore by using two banks of three cylinders in a ‘V’ configuration, total length is reduced and torsional rigidity of the crankshaft is improved (Fig. 2.37).

The engine’s flywheel acts as an energy buffer owing to its inertia. Energy stored in the flywheel maintains rotation between firing pulses and acts as a damper to smooth torque peaks as each cylinder fires.

Definitions

Torque
The turning force produced by an engine. It is not affected by time.

Power
The rate at which energy is being converted. It is therefore related to time.

Or how about this version?
Power is how hard you hit a tree. Torque is how far you move it.

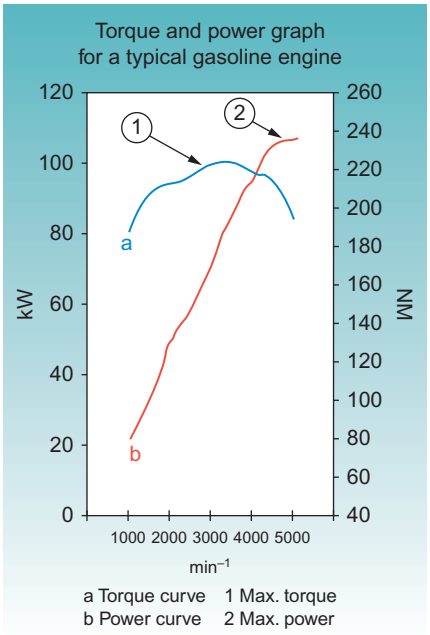


Figure 2.34 Spark ignition (SI) engine

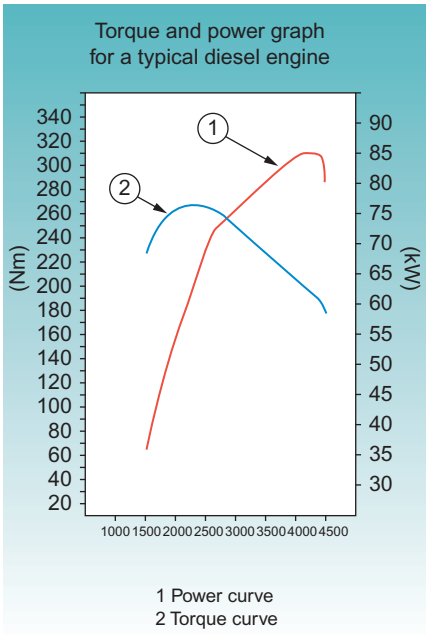


Figure 2.35 Compression ignition (CI) engine

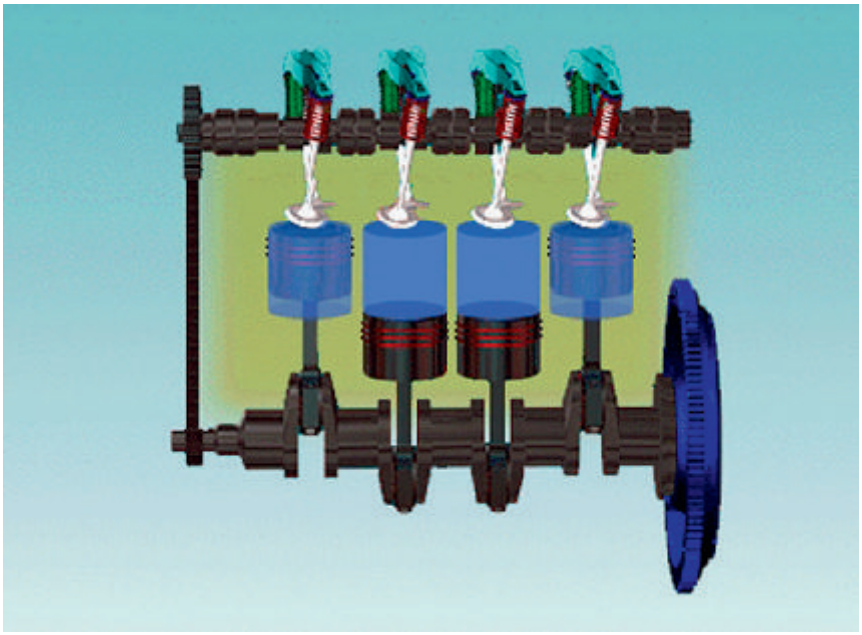


Figure 2.36 Displacement

There are numerous engine configurations with respect to the arrangement of the engine cylinders, the number of cylinders, position and firing order (Fig. 2.38). In addition, combustion chamber designs and valve train layout all dictate the basic properties of an engine. Engine installation and orientation is another important factor to be considered in a road vehicle. There are also two-stroke and rotary engine designs with their own particular characteristics, all of which are explained in this section.

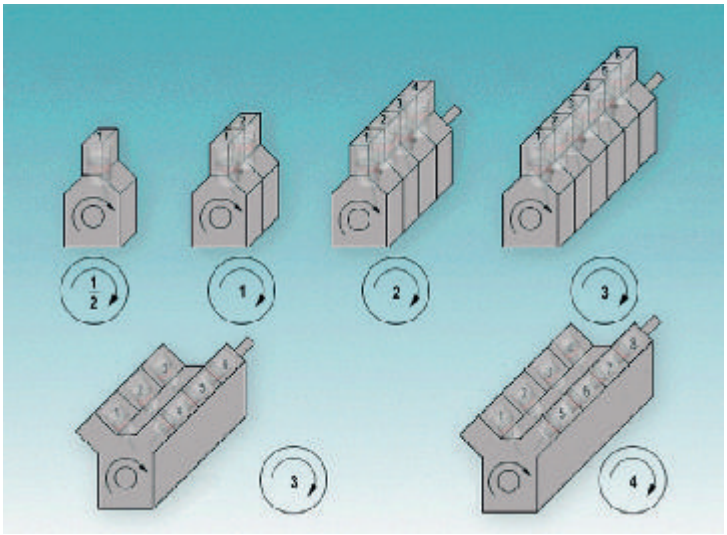


Figure 2.37 Cylinder layouts and power strokes per engine revolution

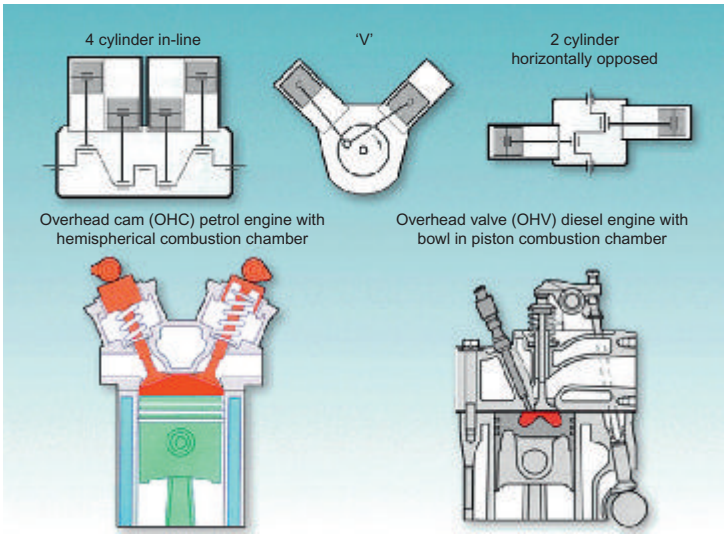


Figure 2.38 Engine designs

2.1.2.4 Engine design variations

The following section outlines some of the many design variations that are or have been used for engines. The configuration of the engine depends on the number of cylinders, their relative position, the engine layout and the firing order, as well as combustion chamber design, fuel type, valve train design, engine location and mounting position. Further parameters are engine type (reciprocating, rotary) and stroke (two or four).

The simplest engine design is the single cylinder, normally found in small engine applications (Fig. 2.39). If the engine is a single-cylinder four-stroke, then the engine fires only once every other engine revolution. This gives a large variation in the torque delivery at the engine crankshaft and hence torsional vibration is significant and the engine is not very smooth. Increasing engine capacity does not increase power output directly as there are other factors that contribute to the efficiency of the engine (heat and pressure losses); therefore, there is an

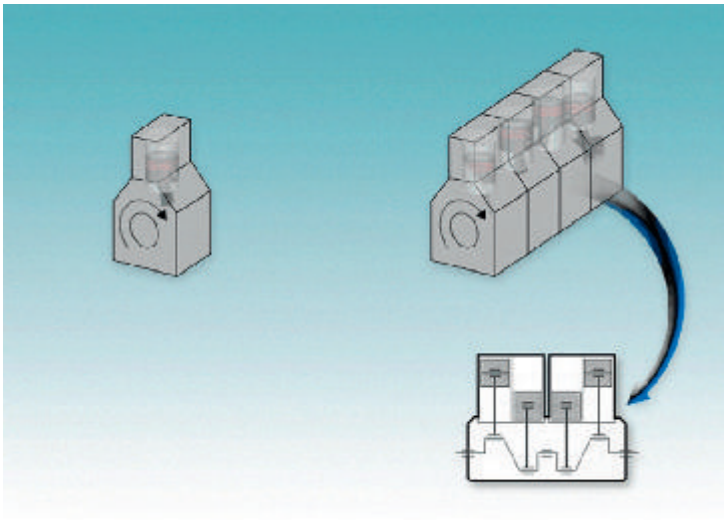


Figure 2.39 A single- (left) and four-cylinder (right) engine

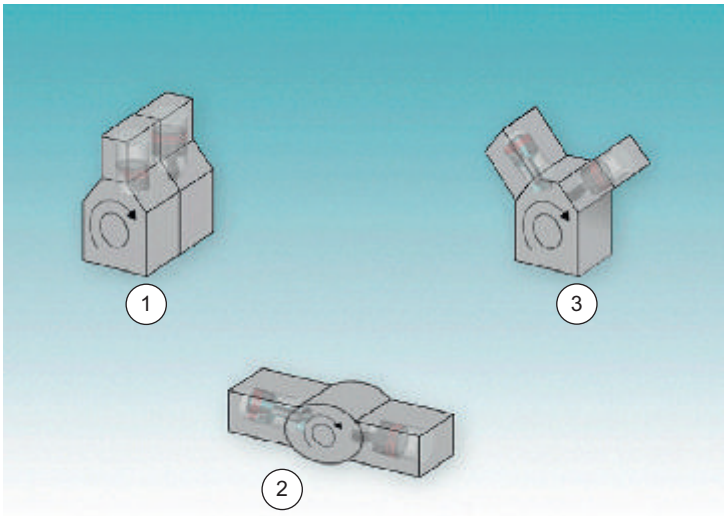


Figure 2.40 Twin-cylinder engines. 1, In-line; 2, horizontally opposed; 3, V type

optimum cylinder capacity that provides the best compromise of surface and valve area for maximum efficiency, which is approximately 0.5 litre displacement volume. For this reason, increasing the engine capacity is normally done by adding extra cylinders.

Twin-cylinder engines can be configured as in-line, horizontally opposed or V types (Fig. 2.40). These engines have been used in car applications but are more commonly found in motor cycles. In-line engines have been built with both pistons operating in parallel and on alternate strokes; often, this depends on whether they are two- or four-stroke engines. Horizontally opposed cylinders have pistons that move out and return in opposing directions. They are well balanced as the forces generated by the reciprocating masses (pistons, con-rod, etc.) cancel out exactly. Various V engine configurations have been used.

Three-cylinder in-line engines of around 1 litre displacement have been used by some manufacturers in car and motor cycle applications. The three-cylinder V

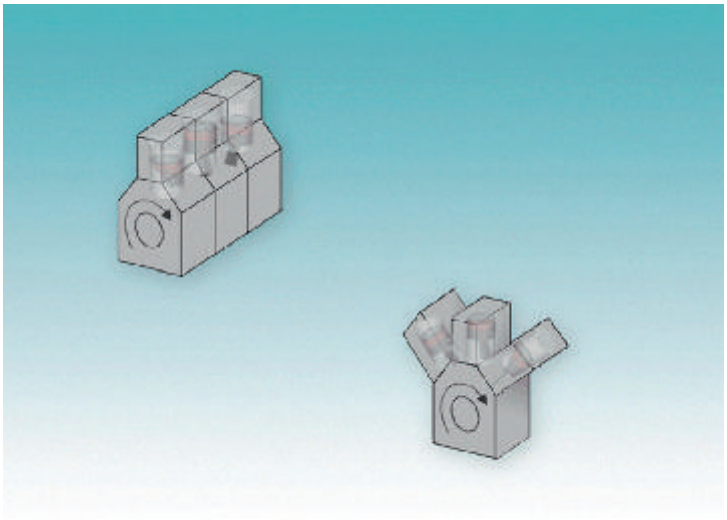


Figure 2.41 Three-cylinder engines

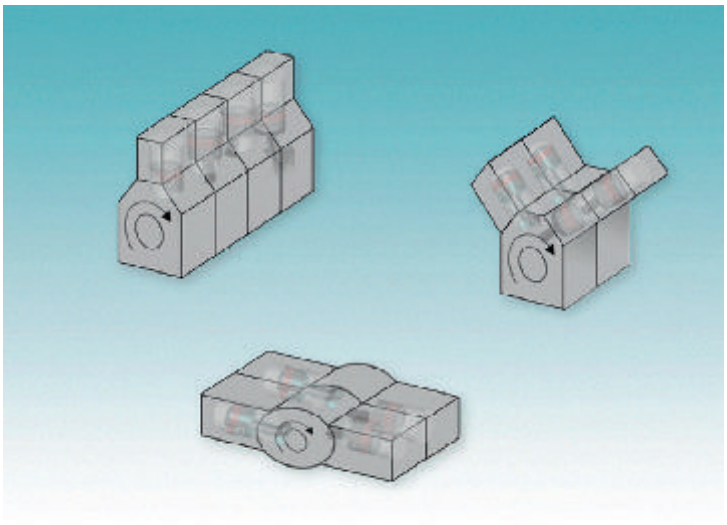


Figure 2.42 Four-cylinder in-line engines

engine is a possible design being considered as it has a very compact form (Fig. 2.41).

Four-cylinder in-line engines (Fig. 2.42) are commonly used as they provide a good compromise of performance, efficiency and smoothness with optimized individual cylinder displacements where the total engine displacement is in the range of 1–2.5 litres. This range is extremely common for passenger car applications. Another well-established design for this application is the opposed cylinder; less common is the V4 engine.

Where five-cylinder engines (Fig. 2.43) have been designed and used, they are generally of in-line construction only. There is an example of a V5 engine with a very narrow V-angle, two cylinders on one bank and three on the other. The main advantage of a five-cylinder engine is that the reciprocating forces are well balanced and this provides a smooth power delivery. The V5 cylinder engine has the added advantage that the overall length of the engine is reduced (compared to the in-line design) and this allows for a transverse engine powertrain layout.

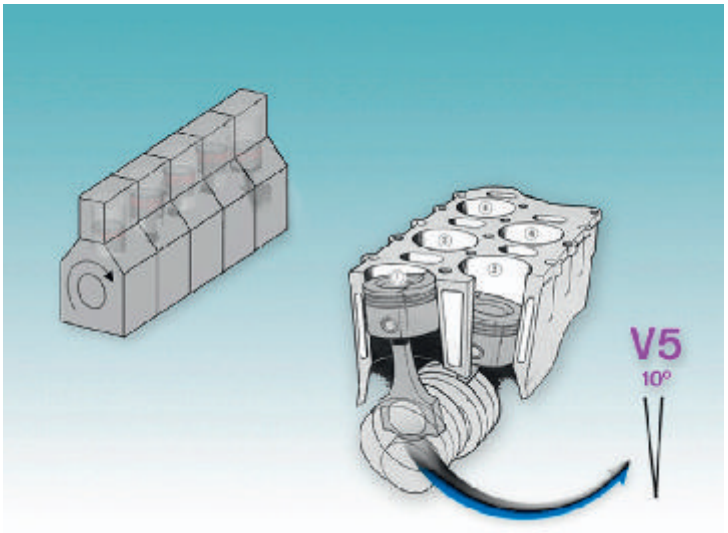


Figure 2.43 Five-cylinder in-line engines

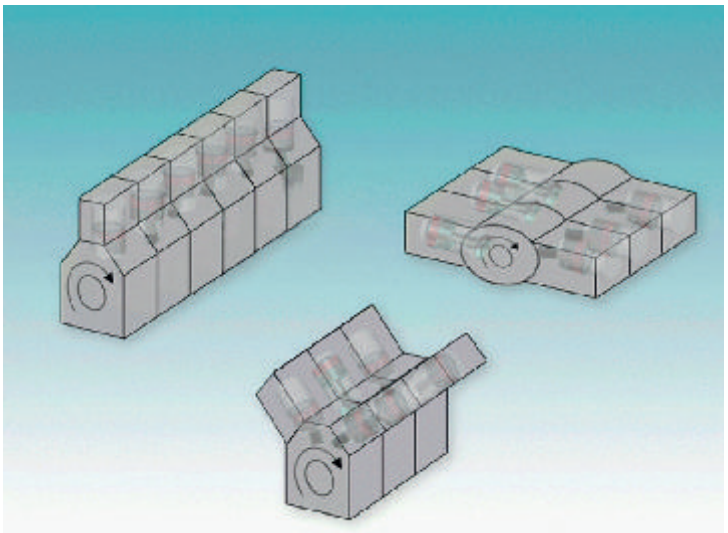


Figure 2.44 Six-cylinder engines

Six-cylinder engines (Fig. 2.44) are very common and have been built with in-line, horizontally opposed and V layouts. The construction and manufacturing costs of a six-cylinder engine are higher but they are well balanced and offer smoother power delivery than the equivalent four-cylinder engine. If greater engine capacity is necessary, then a six-cylinder engine is necessary to keep the individual cylinder displacements in the optimum range.

Horizontally opposed and V engines (Fig. 2.45) have shorter crankshafts and overall length than the equivalent in-line engines. This makes them appropriate for transverse or overhung installation in the powertrain. The optimum angle for a V6 cylinder engine is 60°.

Eight, ten, twelve and higher V configuration engines are manufactured but less common in vehicle applications (Fig. 2.46). V8 engines are very common and used in most countries on larger vehicles. There are petrol and diesel engine designs that employ this layout with engine capacities greater than 3 litres. The optimum V-angle for cylinder banks in an eight-cylinder V engine is 90°.

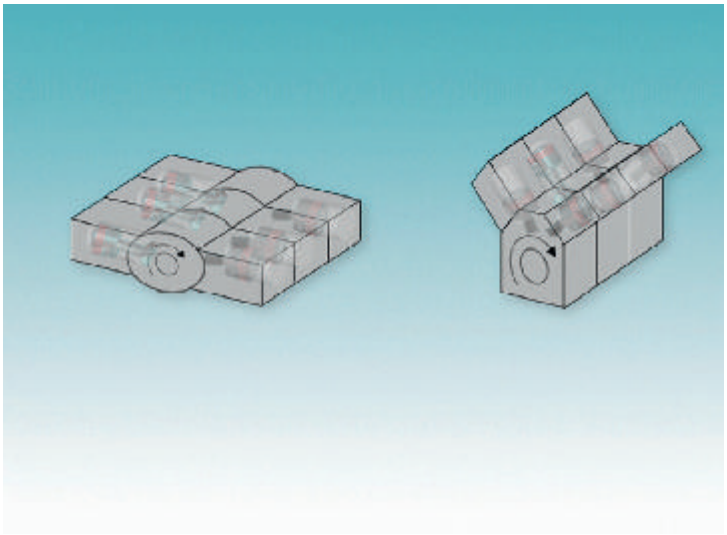


Figure 2.45 Flat and 'V' engines

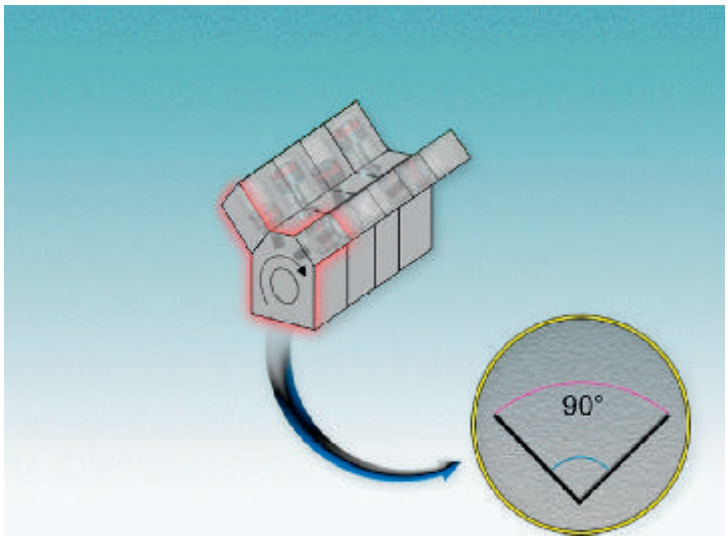


Figure 2.46 Multiple cylinders. V engine shown

For multicylinder engines, the firing order, the crankshaft big-end journal positions and the direction of rotation must be considered together in the engine design. In general, in-line four-cylinder engine crankshafts have cylinders numbered 1 and 4, and 2 and 3, paired and 180° apart. This gives two possible firing orders of 1-3-4-2 and 1-2-4-3 with alternate firing from each pair, giving a power stroke every 180° crank angle. In-line six-cylinder engine cylinders are paired; 1 and 6, 2 and 5, and 3 and 4. The big-end journals are positioned at 120° intervals and this gives the most common firing order of 1-5-3-6-2-4 (Fig. 2.47).

In a V6 engine (Fig. 2.48), the big-end journals carry two connecting rods each, one from each cylinder bank. The journals are positioned at 120° intervals and are either a single journal or offset journals with the two big-end crank pins offset to match the connecting rod angle to the journal.

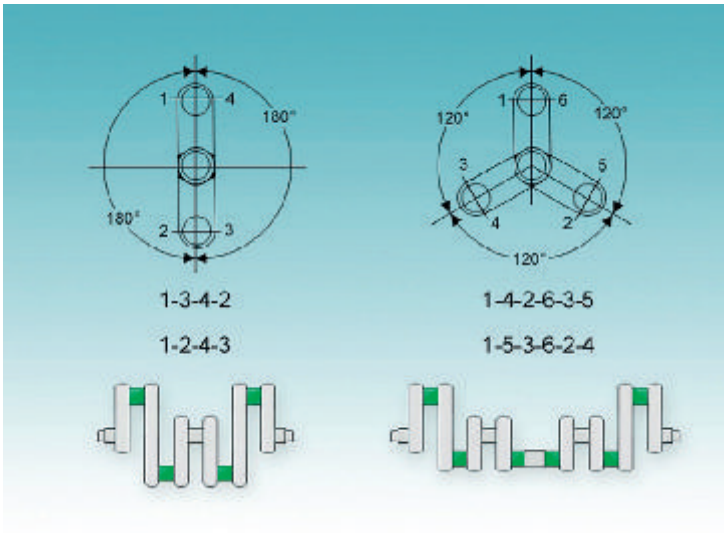


Figure 2.47 Firing order: 4-cylinder (left) and 6-cylinder (right) engines

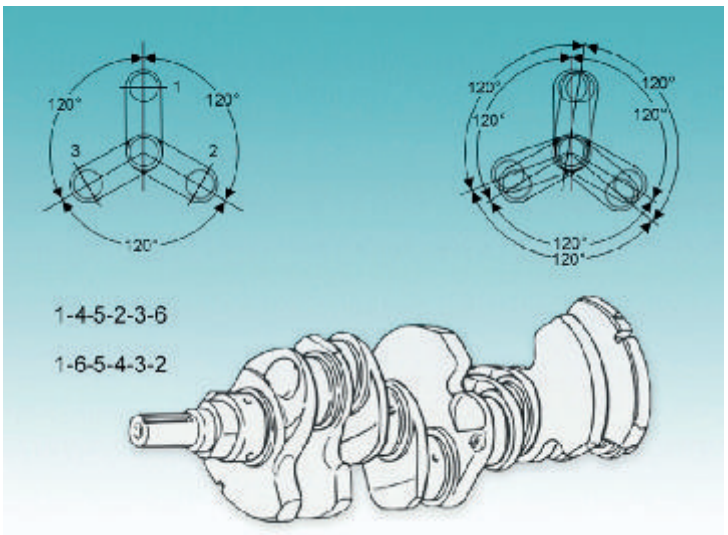


Figure 2.48 V6 crank

V6 engine cylinder numbering is generally implemented in one of two ways. The first is that one bank has 1, 2 and 3 and the other bank has 4, 5 and 6. The alternative numbering sequence uses alternate banks with 1, 3 and 5 on one side and 2, 4 and 6 on the other. The firing orders are either one bank followed by the alternate bank or one cylinder from one bank followed by a cylinder from the other bank.

A V8 engine has four paired journals placed at 90° intervals to each other (Fig. 2.49). Each journal carries one connecting rod from each of the opposite banks. The cylinders can be numbered in a similar method to the six-cylinder engines with either odd numbers on one side and even numbers on the other, or 1–4 on one cylinder bank and 5–8 on the other bank. Typical firing orders are shown in Fig. 2.50.

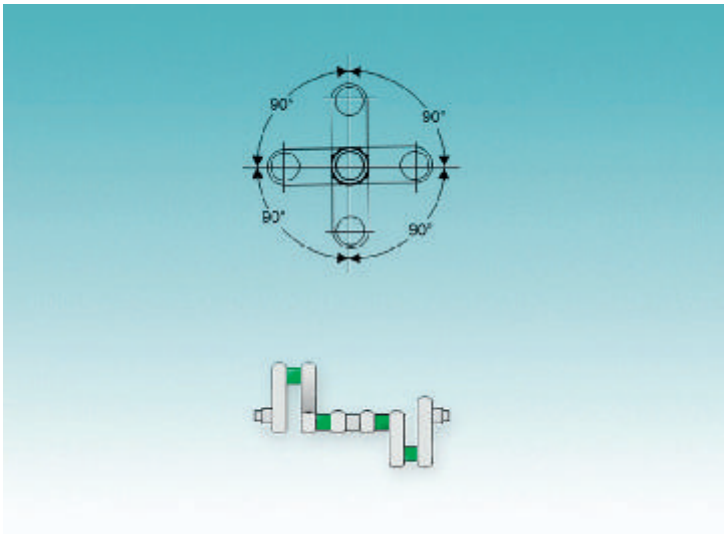


Figure 2.49 V8 crank

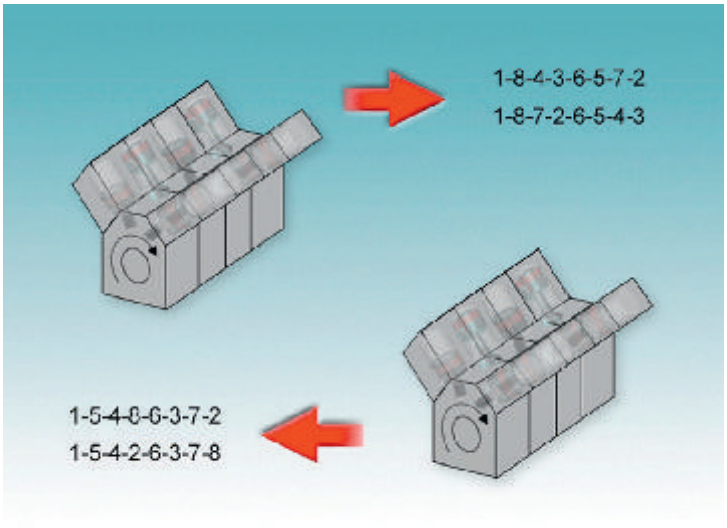


Figure 2.50 Typical firing orders – V8 engine

2.1.3 Engine components

This section explores various different engine designs and components found on modern road vehicles (Fig. 2.51).

2.1.3.1 Engine block and liners

Engine cylinders, when cast in a single housing, are known as the engine block. Usually, the engine block is manufactured from cast iron (Fig. 2.52) or aluminium alloy. In the latter case, cast iron or steel liners form the cylinder bore. The engine block forms the major component of a 'short' motor.

The cylinder bores are formed via a machining process with a boring tool to give the correct form to the cylinder within closely specified tolerances. Cast iron is a mixture of iron with a small amount of carbon (2.5–4.5% of the total). The carbon added to the iron gives a crystalline structure that is very strong in compression. In addition, it is slightly porous and this helps to retain a film of lubricating oil on

Figure 2.51 Engines vary, here is a four cylinder inline design. (Source: Ford Media)

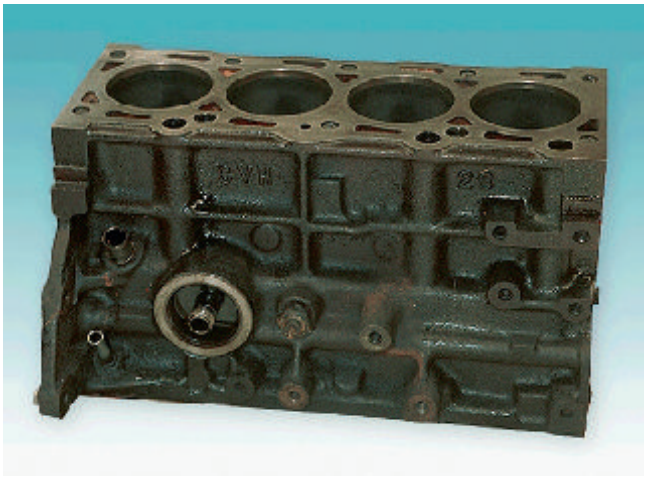


Figure 2.52 Cast iron engine block

working surfaces. This property makes cast iron particularly suitable for cylinder bores that can be machined directly into the casting. On many engines cylinder liners are used.

Cylinder liners fall into two main categories, wet and dry (Fig. 2.53). Wet liners are installed such that they are in direct contact with the coolant fluid. They are fitted into the block with seals at the top and bottom and are clamped into position by the cylinder head. Spacers are fitted at the bottom to adjust the protrusion of the liner to achieve the correct clamping force.

Dry liners are not in direct contact with the coolant. In general, they are fitted into the casting mould and retained by shrinkage of the casting via an interference fit. Alternatively, they can be pressed into place in a precast cylinder block. When repairing or reconditioning the engine, the former type can be rebored whereas the latter type is replaceable.

Definition

Cast iron
A mixture of iron with a small amount of carbon (2.5–4.5% of the total).

Key fact

Cylinder liners fall into two categories, wet or dry.

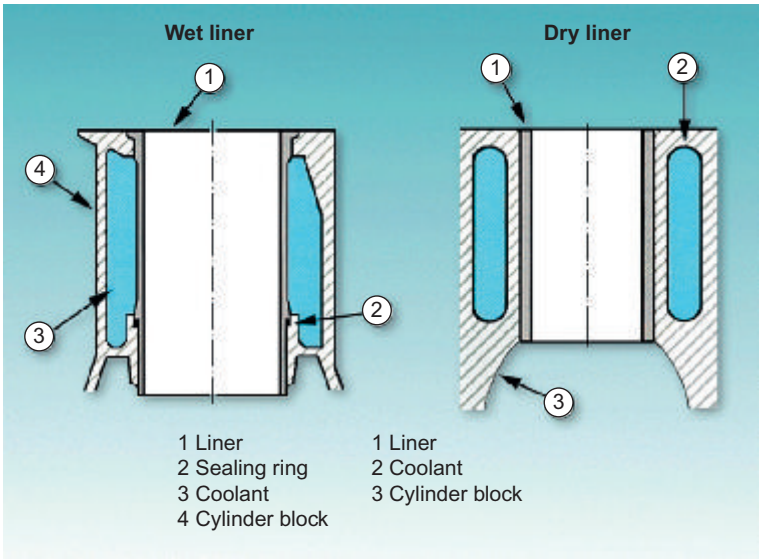


Figure 2.53 Wet and dry liners

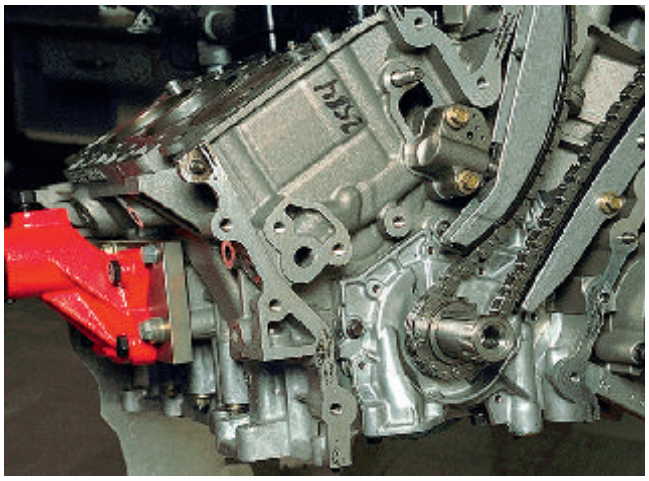


Figure 2.54 Modern engine block

Most modern engines (Fig. 2.54) have specific treatments applied to the cylinder bores and, as such, cannot be rebored or honed. Replaceable liners mean that the liner and piston assembly can be replaced without the need for specialist reboring equipment. Commercial vehicle engines often use replaceable liners to reduce repair times.

Cast iron has been used for cylinder block construction in the past as the cylinders can be bored directly into the material; in addition, these bores can be remanufactured or repaired by reboring oversize. Cast iron is porous and hence the cylinder bore is capable of retaining lubricating oil for lubrication of the contact surfaces. The disadvantage of cast iron is weight. Modern engines use aluminium and can achieve the same strength and stiffness as cast iron via advanced design techniques.

Aluminium alloy cannot provide a suitably durable surface for piston ring contact. Therefore, cylinder liners or sleeves, made from cast iron or steel, are normally fitted into an aluminium cylinder block (Fig. 2.55).

Key fact

Aluminium alloy cannot provide a suitably durable surface for piston ring contact, so liners made from cast iron or steel are used.

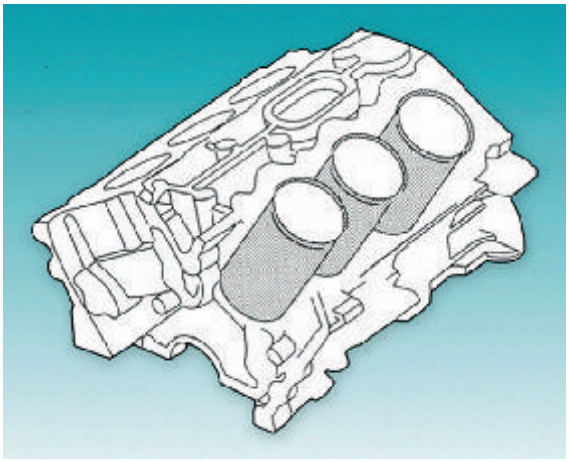


Figure 2.55 Liners in an aluminium block

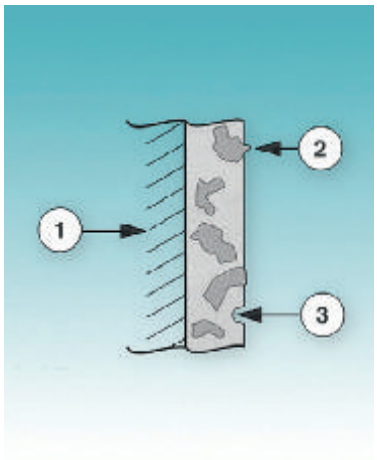


Figure 2.56 Cylinder coating: 1, engine block; 2, silicon carbonate; 3, nickel phosphate

Recent developments in material technology have produced a coating of nickel phosphate and silicon carbonate which provides a suitably durable surface for the cylinder bores (Fig. 2.56). Note that these bores cannot be rebored, so if excessive wear occurs the block must be replaced.

A crankcase is usually integrated into the cylinder block and is machined in-line to form the crankshaft main bearings. This process is known as line boring. The main bearings are split in two halves; one half locates in the block, the other in the bearing cap. The bearing caps are secured before the machining process and thus each cap is matched in position with its opposite half. It is important to note this when disassembling and reassembling the bearings. The caps are located via dowels and fastened via high-tensile steel bolts (Fig. 2.57). It is important to follow manufacturer guidance if the bolts are removed and refitted; replacement of the bolts and tightening procedures must be followed if specified.

Between the cylinder walls and the outside surface of the cylinder block, voids and channels are formed during the casting process; this is known as the water jacket (Fig. 2.58) and is used for engine cooling purposes. A sand former creates this space during casting and when the cast block has cooled, the sand is evacuated via holes in the side of the block. These holes are then sealed using core plugs (Fig. 2.59).

Figure 2.57 Main bearing bolts

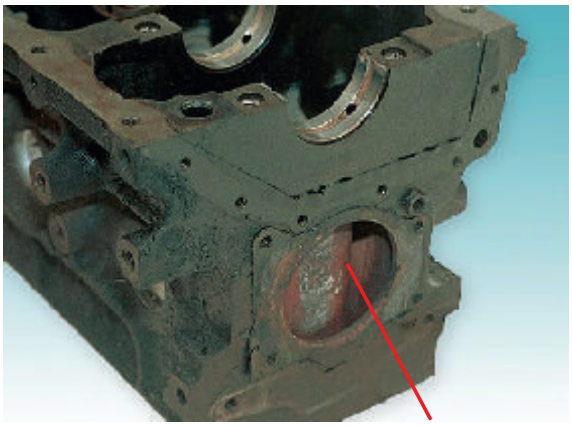


Figure 2.58 Water jacket

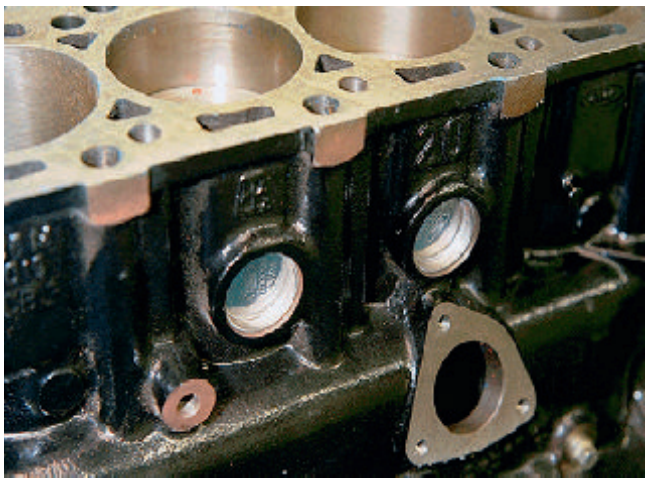


Figure 2.59 Core plugs

In order to supply pressurized oil to the engine moving surfaces, an oil gallery is formed along the length of the cylinder block (Fig. 2.60). This has drillings to supply oil directly to the bearings in the block, crankshaft and cylinder head. Additional drillings connect the oil pump and pressure control valve to complete

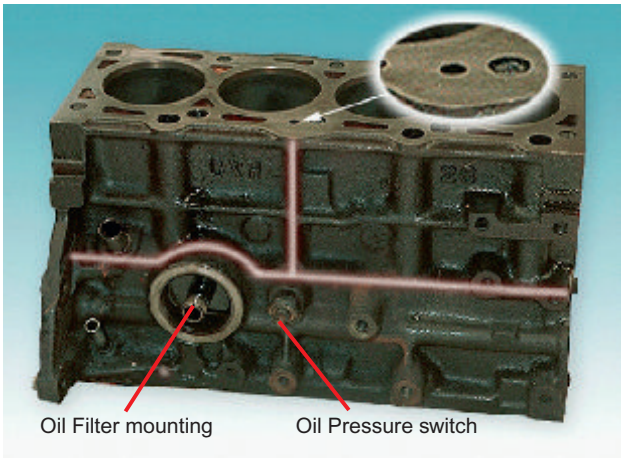


Figure 2.60 Oilways

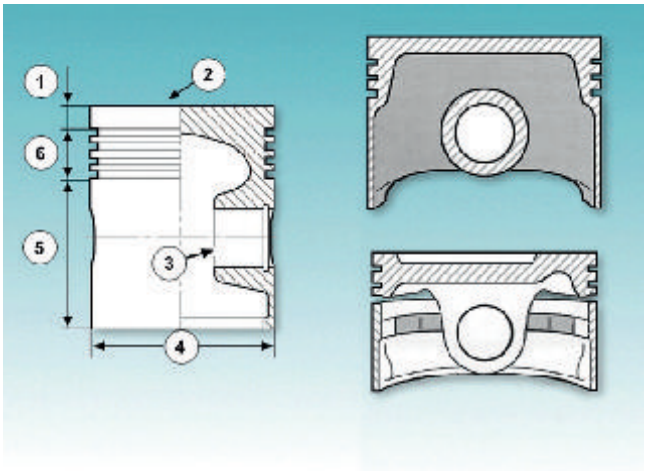


Figure 2.61 Piston features: 1, fire land; 2, crown; 3, piston pin bore; 4, skirt diameter; 5, skirt; 6, piston rings

Key fact

Pistons are generally manufactured from an aluminium alloy which reduces weight and increases heat dissipation.

the oil supply system. The block is prepared, drilled and threaded to attach additional components such as the oil sump pan and oil pump assembly.

2.1.3.2 Pistons and connecting rod

Pistons are generally manufactured from an aluminium alloy, which reduces weight and increases heat dissipation. There are numerous designs to accommodate thermal expansion according to engine type and application (Fig. 2.61).

Aluminium has greater thermal expansion than cast iron used for the block and cylinder liners. This means that the piston expands more than the block as the engine temperature increases. When the engine is cold, the working tolerances are greater to allow for expansion. The piston has design features to allow for expansion and correct tolerances at running temperatures; for example, a cold piston is slightly oval and tapered inwards towards the crown (Fig. 2.62).

The piston pin or gudgeon pin has an offset by a small amount toward the thrust face of the cylinder bore which allows the thrust forces at the piston crown to maintain the piston against the cylinder wall (Fig. 2.63). This has an effect when the engine is cold by reducing piston movement due to excessive clearance,

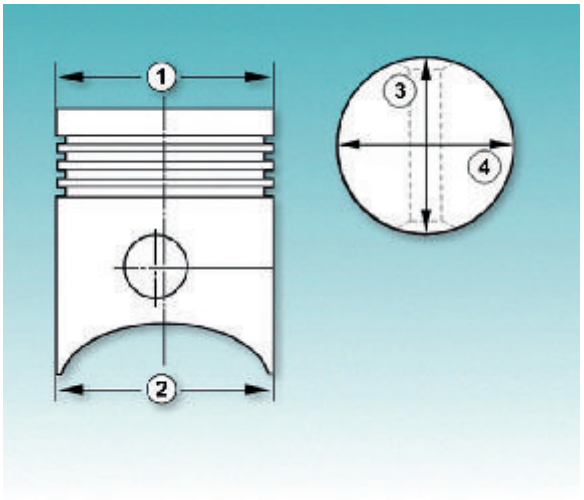


Figure 2.62 Piston dimensions: 1, crown diameter; 2, skirt diameter; 3, diameter in piston pin direction; 4, diameter at right angles to the pin

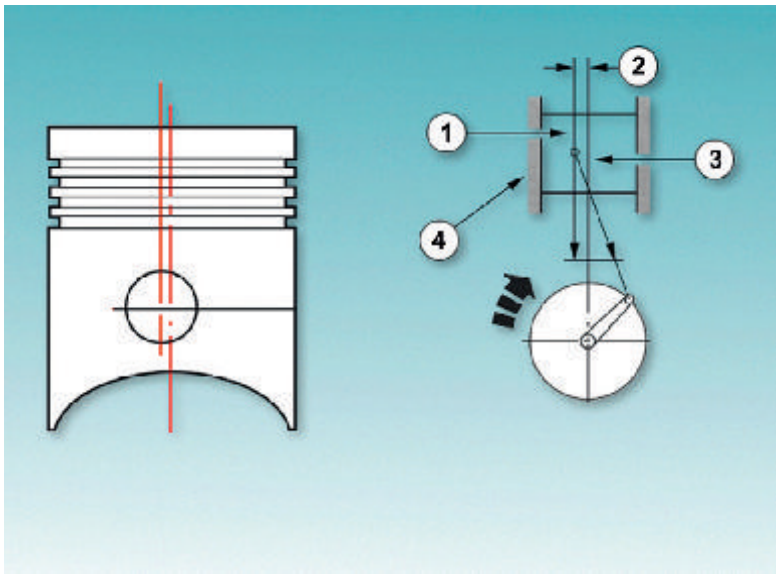


Figure 2.63 Piston design features: 1, piston; 2, offset; 3, centre line; 4, block thrust face

which creates a noise known as 'piston slap'. Note that pistons are marked so that they can be installed correctly and this should be carefully observed.

Around the upper portion of the piston, grooves are cut to accommodate sealing rings, known as piston rings (Fig. 2.64). In general, there are three or four grooves and rings, the lowest of which is known as the oil control ring and is used to control the amount of lubricant remaining on the cylinder bore surface to lubricate the piston. The upper rings are known as compression rings and these provide the gas-tight seal, maintaining the cylinder pressures that create force to move the piston.

Piston rings seal the combustion chamber to prevent the escape of combustion gases and loss of cylinder pressure; these are known as 'compression rings' (Fig. 2.65). In addition, the piston rings must control the oil film on the cylinder bore surface, and these are known as 'oil control rings'. Combustion pressure

Key fact

Piston rings seal the combustion chamber to prevent the escape of combustion gases.

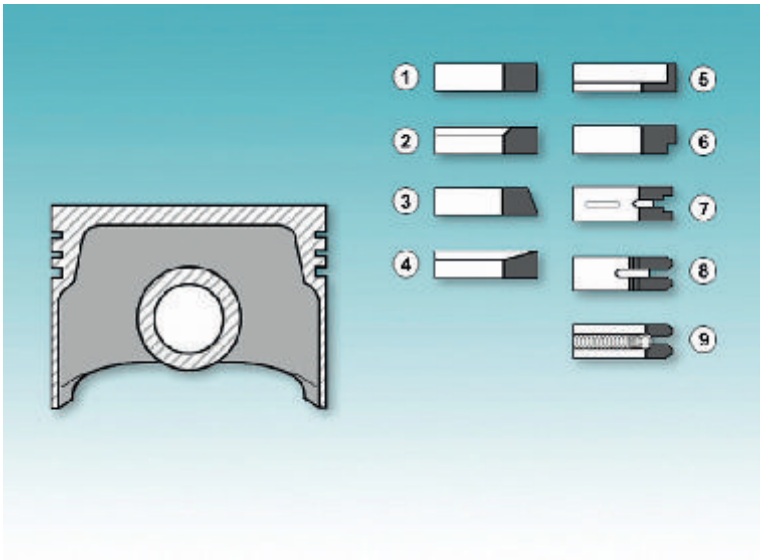


Figure 2.64 Piston rings: 1, rectangular; 2, internally chamfered; 3, taper faced; 4, trapezoidal; 5, L shaped; 6, stepped; 7, slotted oil control; 8, oil ring with expander; 9, oil ring with spiral expander

Figure 2.65 Compression and oil control rings

is allowed to act on the back of the cylinder-sealing compression rings to help maintain a gas-tight seal of the piston assembly.

Compression rings are manufactured from cast iron, with a surface coating to promote fast bedding in. This means that the rings quickly wear in to give a gas-tight seal against the cylinder pressures. It is important not to damage this coating during fitting. Note that rings have different cross-sections according to their mounting position on the piston (Fig. 2.66).

Oil control rings can be one of two designs. A multipart ring consists of two thin alloy rings used in conjunction with an expander between them. A cast iron ring has a groove and slot arrangement to allow oil flow back to the sump via the ring and piston.

The piston pin or gudgeon pin bore is machined into the piston to accept the piston pin, also known as the gudgeon pin (Fig. 2.67). The fixing mechanism of the piston pin to the piston and the connecting rod can vary (Fig. 2.68). It can

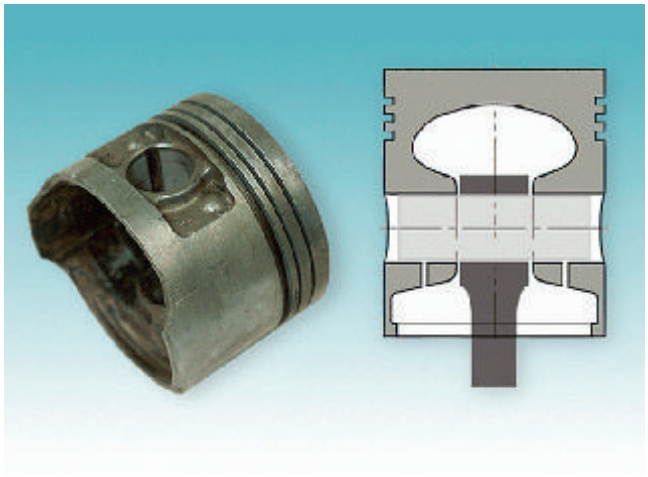


Figure 2.66 Cross-section of a piston

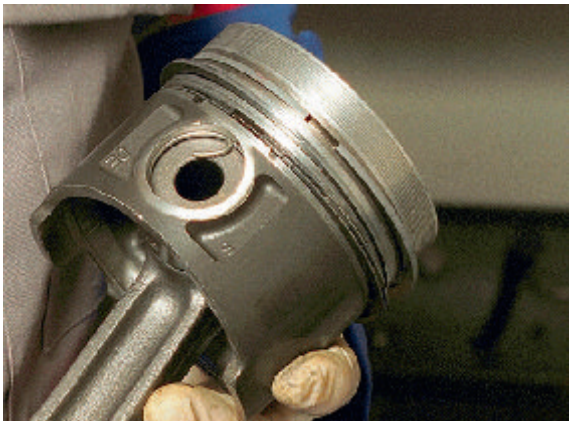


Figure 2.67 Piston pin (gudgeon pin)

Figure 2.68 Con rod and pin

be an interference fit in the connecting rod, or a push fit in both the piston and connecting rod end. If the piston pin is clamped in the connecting rod, the piston pin bore is smooth (Fig. 2.69). Circlip grooves are formed in the piston pin bore when a push fit piston pin is used.

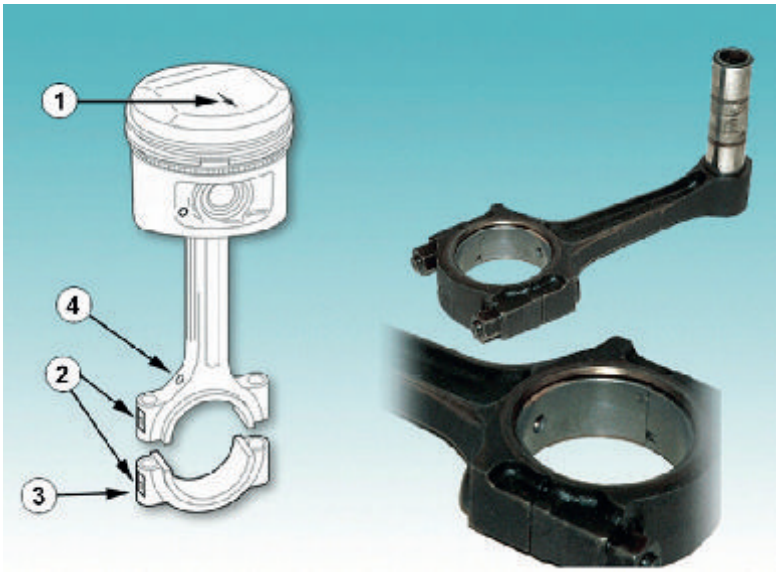


Figure 2.69 Con rod features: 1, front of engine; 2, identification marks; 3, big end cap; 4, oil spray hole for cylinder wall lubrication

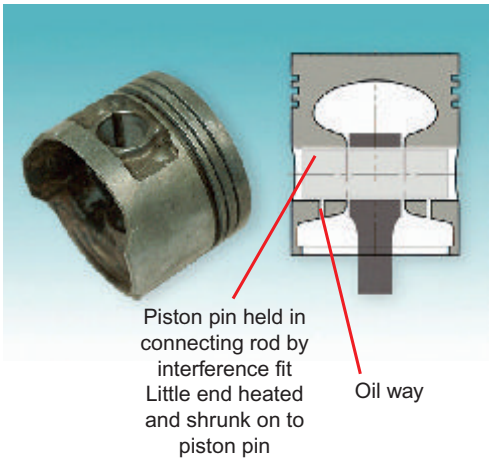


Figure 2.70 Piston pin in position

The piston crown forms part of the combustion chamber and experiences the full cylinder pressure applied by the expanding gases. Many different design are available depending on engine type. Complex shapes can be formed in the piston crown to allow for valve movements and to create an effective combustion chamber space, promoting the correct charge motion for efficient combustion.

The piston or gudgeon pin provides the mechanical link between the piston and connecting rod. The pin locates in the piston body and the little end of the connecting rod (Fig. 2.70). The pin can be a clearance fit into the little-end bearing or bush, and hence a corresponding interference fit, or located via circlips, in the piston.

An alternative to circlips is that the pin is an interference fit in the little end, or is clamped by the connecting rod. In this case, the piston pin bore is the bearing surface and there are appropriate drillings in the piston to allow for lubrication.

The main purpose of the connecting rod is to transfer the linear force from the piston and apply it to the rotating crankshaft (Fig. 2.71). It is generally

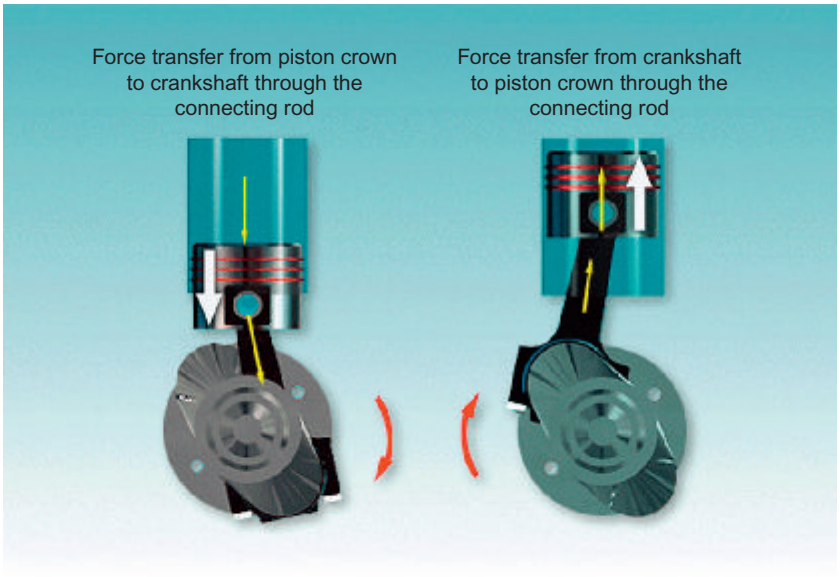


Figure 2.71 Force transfer

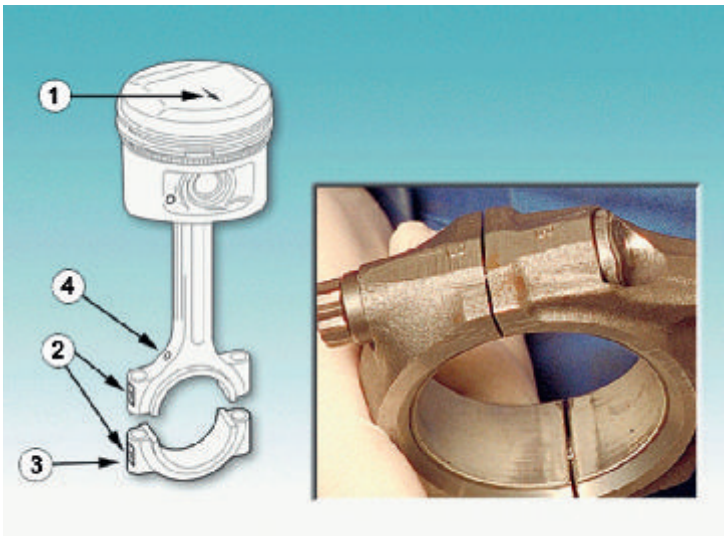


Figure 2.72 Big end bearing: 1, front of engine; 2, identification marks; 3, big end cap; 4, oil spray hole for cylinder wall lubrication

manufactured from carbon steel in a process known as drop forging to form the required shape and profile.

The connecting rod is designed specifically with a high resistance to bending, compressive and tensile forces via an I-section profile. The piston end, known as the little end, has an appropriate bush, bearing or clamping arrangement for the piston pin. The crankshaft end of the connecting rod is known as the big end (Fig. 2.72). This consists of a split bearing with a removable bearing cap. The bearing cap is attached to the connecting rod via bolts or nuts.

It is important to note that the connecting rod and bearing cap are machined as one unit, and hence, the parts are matched. Therefore, they must always be reassembled as a pair and fitted correctly oriented.

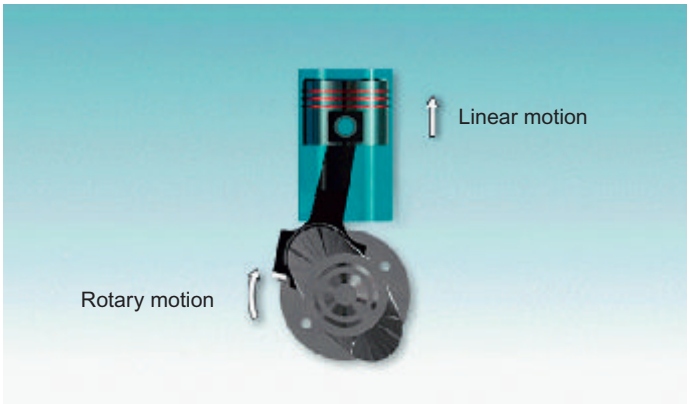


Figure 2.73 Conversion of linear to rotary motion: 1, engine block; 2, silicon carbonate; 3, nickel phosphate

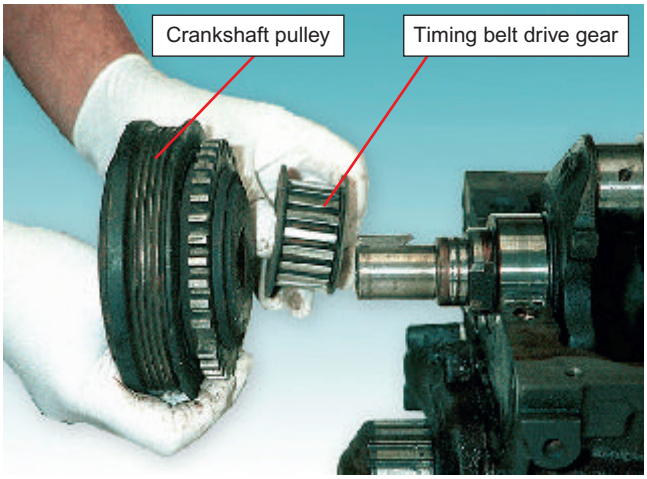


Figure 2.74 Crankshaft pulleys

The crankshaft receives the linear force of the pistons, via the connecting rods, and converts this force into a rotating torque (Fig. 2.73). The crankshaft is generally manufactured from cast iron or steel alloy via a forging or casting process.

Key fact

The crankshaft of a four-cylinder engine generally has five main bearings.

2.1.3.3 Crankshaft

The crankshaft of a four-cylinder engine usually has five main bearings. At the front of the crankshaft provision is made to locate and drive the crankshaft pulley and timing gear via keyways and securing bolts (Fig. 2.74). Behind this, the oil pump drive is located, and then the first or front main bearing.

The big-end bearing for the first cylinder is fitted in between the crankshaft webs radiating from the main bearing journals (Figs 2.75 and 2.76). These webs form counter-balance weights to the big-end journal. One of the main bearings is usually fitted with an thrust washer to control axial movement of the crankshaft.

At the rear of the main bearing journal, at the back of the engine, a machined face is formed on the crankshaft as a mating surface for a sealing ring. This is the main oil seal at the back of the engine (Fig. 2.77). In addition, there is a

Figure 2.75 Crankshaft: 1–5 main journals

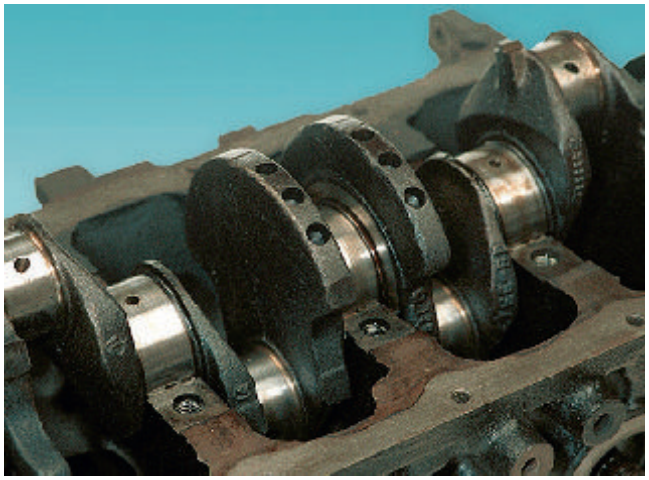


Figure 2.76 Journals in position in the engine block

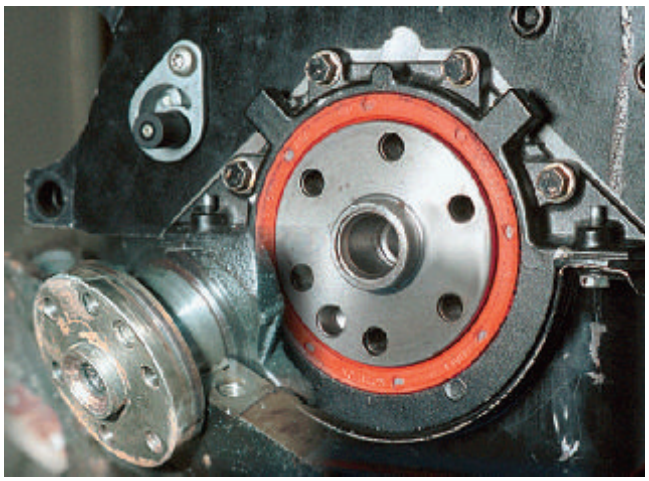


Figure 2.77 Radial lip oil seal

machined, threaded flange surface to accommodate mounting of the flywheel. For a four-cylinder engine, the big-end journals are paired and set and 180°. For most four-cylinder engines the firing order is 1, 3, 4, 2.

The crankshaft bearings are split-type, steel-backed shells with an alloy or coated bearing surface (Fig. 2.78). Correct bearing types to engine

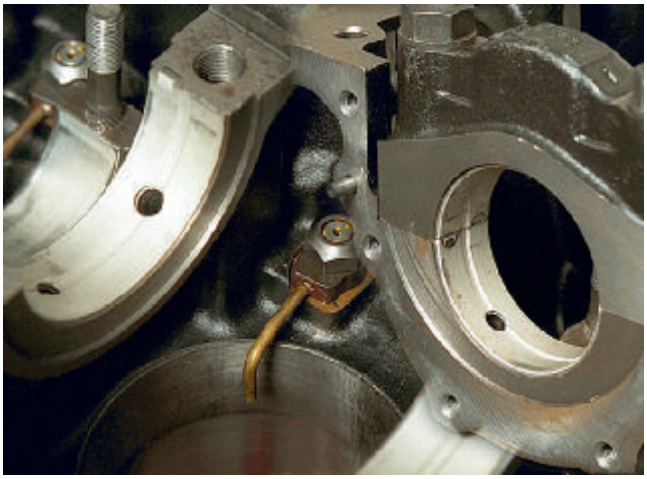


Figure 2.78 Bearings

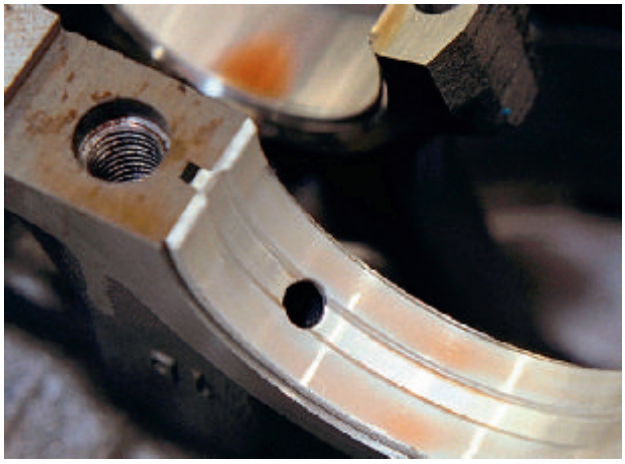


Figure 2.79 Signs of 'nip'

Key fact

Bearing shell halves, when correctly fitted and tensioned in the bearing caps, form a perfectly round profile.

manufacturers' original specification must always be fitted. Bearing shell halves, when correctly fitted and tensioned in the bearing caps, form a perfectly round profile with equidistant clearance around the bearing journal. The bearings are 'nipped' and held in position when fitted into the tightened bearing caps (Fig. 2.79). The bearing shell is also fitted with a locating lug on the back that mates with a slot in the bearing locating 'half-bores' (Fig. 2.80). This ensures that the bearing cannot rotate. Oil supply holes and slots are machined in the bearing surface to supply appropriate lubrication.

Axial displacement of the crankshaft is controlled by thrust bearings to limit the axial movement. These are fitted at a main bearing journal either as two semi-circular rings or as part of a main bearing shell.

Key fact

A dual-mass flywheel splits the mass of the flywheel into two parts and reconnects them by damping springs to reduce vibration.

A flywheel is fitted on the end of the crankshaft to reduce vibration by maintaining the engine rotation between power strokes. The clutch on a manual transmission vehicle is mounted on the flywheel. On automatic transmission vehicles the torque converter also works as a flywheel. Particularly on modern small but high-torque diesel engines, a dual mass flywheel can be used as shown in Fig. 2.81. Vibration on these systems is reduced considerably by splitting the mass of the flywheel into two parts and connecting them by damping springs.

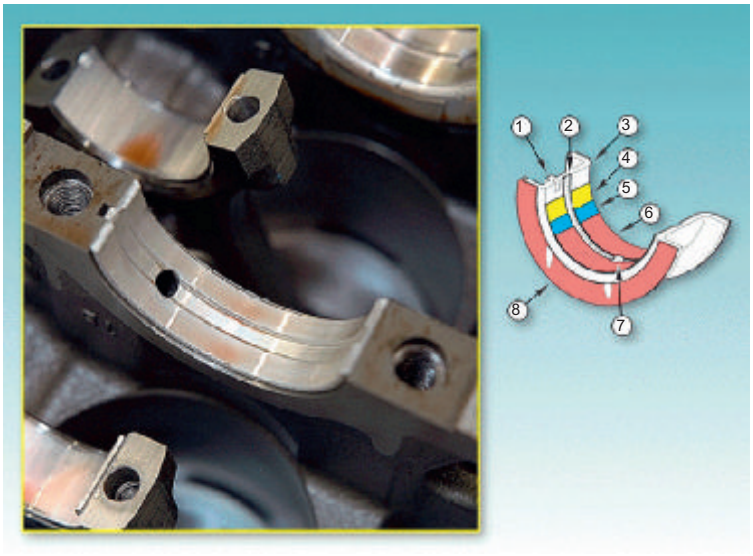


Figure 2.80 Details of the bearing: 1, locating lug; 2, oil groove; 3, steel support shell; 4, support coating; 5, nickel coating; 6, surface coating; 7, oil bore; 8, thrust flange

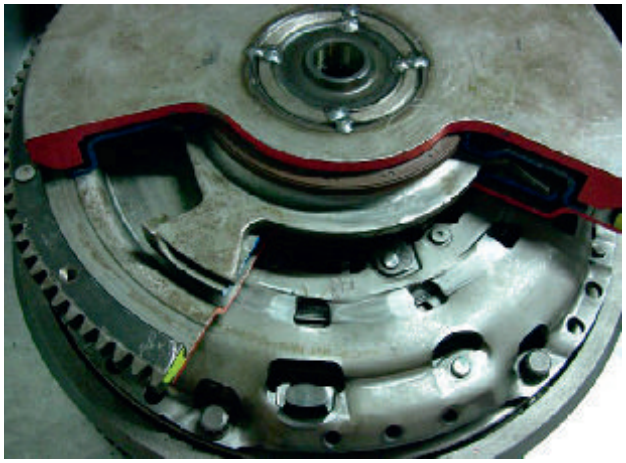


Figure 2.81 Dual-mass flywheel

2.1.3.4 Cylinder heads

The cylinder head gasket has to form a gas-tight seal at the interface between the cylinder head and the cylinder bores. In addition, it must seal and separate the cooling water supply jacket and the oil supply and return drillings. Traditional head gaskets were constructed from copper and asbestos. Modern material technologies allow head gaskets to be made from composite materials which have superior sealing and heat transfer performance (Fig. 2.82).

Key fact

Modern head gaskets are made from composite materials.

Head gaskets must always be replaced when the cylinder head is removed and refitted. In addition, when refitting a cylinder head, it is important that the manufacturer's information is sought and applied with respect to replacement of cylinder head bolts where necessary. Correct torque and a tightening sequence of cylinder head bolts must be followed (Fig. 2.83).

Cylinder heads are cast from aluminium alloy or iron. Aluminium alloy is lighter but cast iron or steel valve seats and guides must be installed in the head (Fig. 2.84). Cast iron heads generally have valve seats and guides formed directly in the head material.

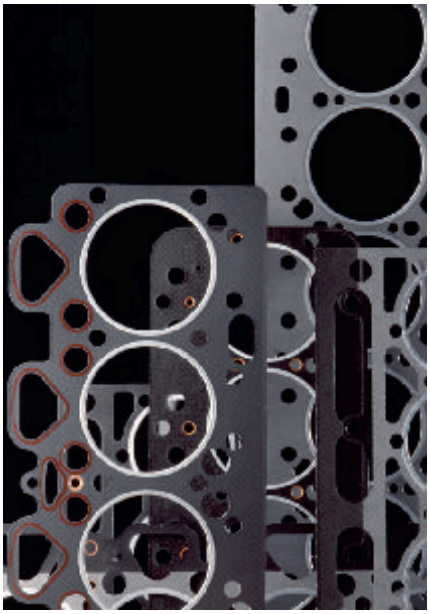


Figure 2.82 Head gaskets

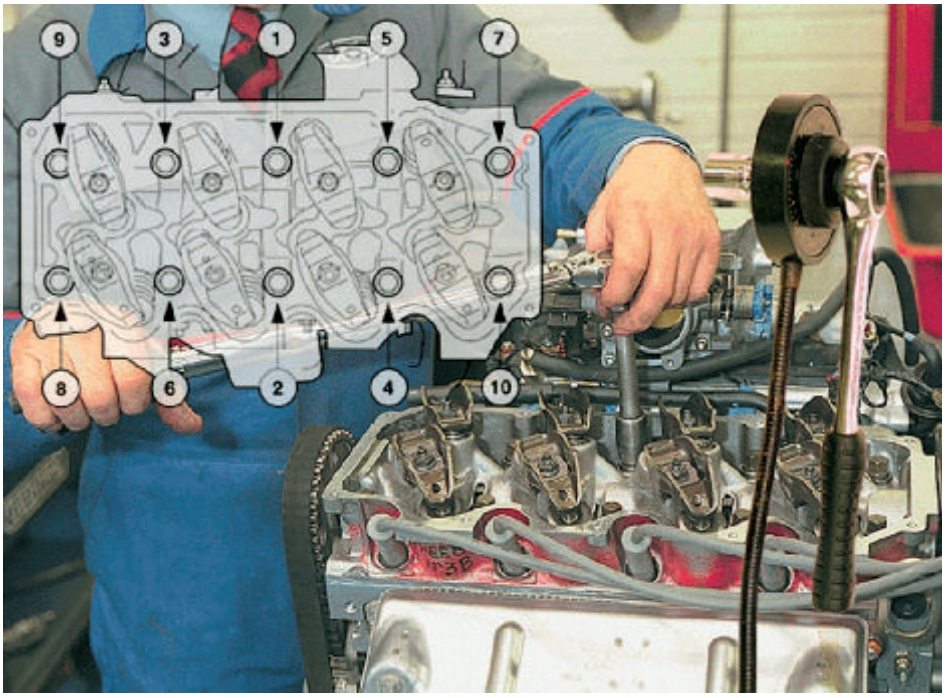


Figure 2.83 Tightening sequence

Figure 2.84 Valve seats

The combustion chamber (Fig. 2.85) is formed in the cylinder head such that, on assembly, it is located directly over the cylinder bore in the engine block. There are numerous designs in use depending on engine type, optimization parameters and application. The evolution of petrol engines can be seen in the design of combustion chambers that has been developed over the years to improve efficiency.

The next major development was overhead valve (OHV) engines (Fig. 2.86). These used in-line valves and bath-tub combustion chambers over the piston. Improved combustion and flame propagation could be achieved with a wedge-shaped chamber (Fig. 2.87). This had the valves offset from the vertical position. A problem associated with the wedge design is combustion knock, also known as pinking (Fig. 2.88). This is caused by uncontrolled ignition of the end gases prior to ignition from the advancing flame front. It occurs as a result of compression of the end gases in the thin end of the wedge. This generates pockets of combustion with high pressures that damage the piston crown and area above the compression ring.

Key fact

A problem associated with the wedge design is combustion knock, also known as pinking.

Figure 2.85 Inside the combustion chamber

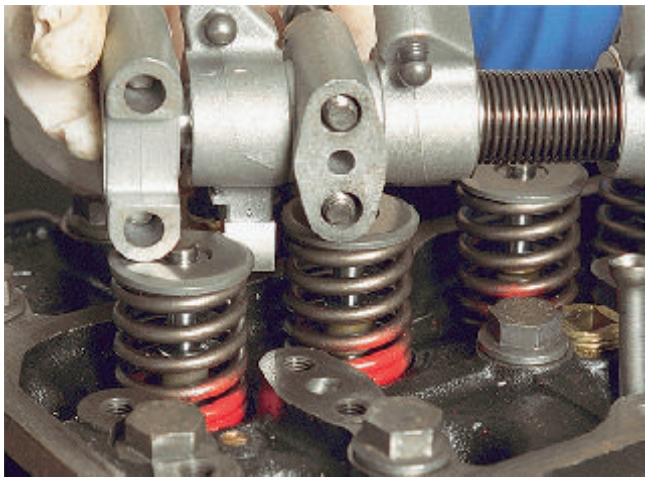


Figure 2.86 Overhead valve (OHV) head

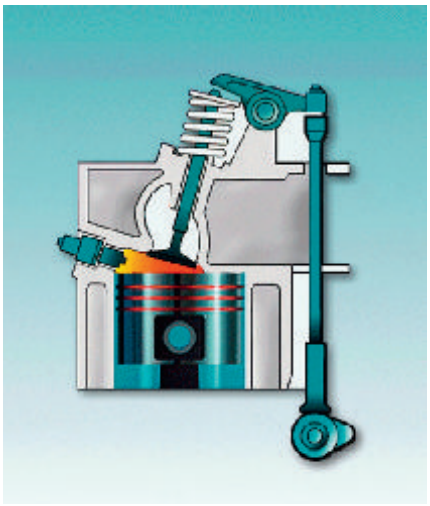


Figure 2.87 Combustion chamber wedge design

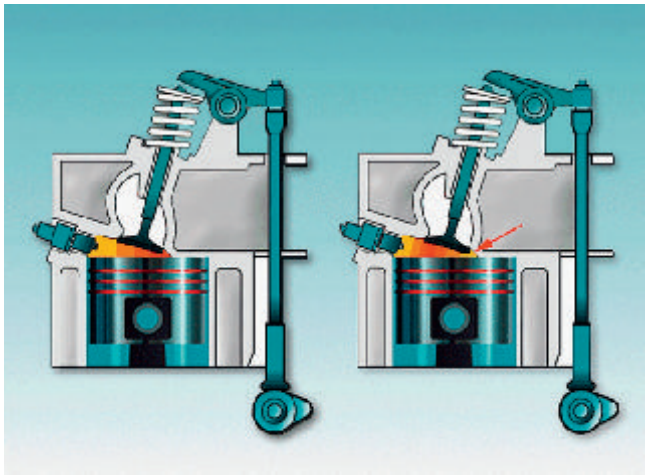


Figure 2.88 Engine knock can cause damage

It is possible for inlet and exhaust ports to be on the same or opposite sides of the cylinder head, known as precross-flow or cross-flow. In addition, two cylinders can share a common inlet port and this is known as a siamese port. When a single inlet for each port is used, this is known as parallel ports.

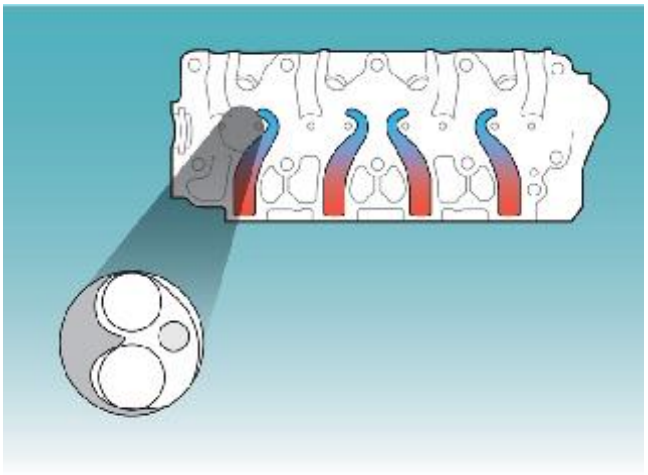


Figure 2.89 The need for a good mixture is why port and valve design is important

Key fact

Most modern petrol engines use a hemispherical or pent roof combustion chamber design.

Most modern petrol engines use a hemispherical or pent roof combustion chamber design. This shape provides the best compromise of surface to volume ratio; this reduces heat energy loss during the expansion stroke, which in turn improves the thermal efficiency of the engine. The combustion chamber design allows single- or dual-inlet and exhaust ports with cross-flow engine breathing. This design easily accommodates two to five valves per cylinder.

The correct design of the inlet tract, including manifold, head and valves, is essential to provide the charge motion as the gases enter the cylinder during the induction stroke (Fig. 2.89). Charge motion is important to speed up the combustion process sufficiently in order to prevent excessive exhaust emissions.

One arrangement of combustion chamber and valves uses a hemispherical design with two valves per cylinder positioned opposite each other for cross-flow movement of the intake and exhaust gases. It is known as compound valve hemispherical (CVH). The valves are inclined such that they sit in the curved profile of the combustion chamber space. The spark plug is mounted as close to centric as possible in the combustion chamber via an appropriate drilling (Fig. 2.90). It is sealed by a compressible washer or conical sealing face.

Key fact

The combustion chambers are surrounded by cooling water passages that are connected to the water jacket in the cylinder block.

The combustion chambers are surrounded by cooling water passages that are connected to the water jacket in the cylinder block (Fig. 2.91). The water jacket casting holes are sealed by core plugs in a similar way to the cylinder block. On the upper surface of the cylinder head, bearing journal surfaces are formed to locate the valve operating camshafts and mechanism. Oil supply drillings ensure adequate lubrication for the camshaft bearings and valve train components.

Key fact

Hardened valve seat inserts are required in aluminium heads.

Hardened valve seat inserts are required in aluminium heads (Fig. 2.92). Certain cast iron heads will also use these. They are necessary to increase the durability of the head such that it can resist the heat of the exhaust gases. In older engines, which ran on leaded fuel, the lead fuel additive provided an element of protection.

For some engines the cam followers and push rods are encouraged to rotate and this helps to extend their life and reduce wear (Fig. 2.93). In addition, in many engine designs, the valves rotate for the same reason. Rotation is promoted by a slight offset or taper on the tappet or rocker face in contact with the cam lobe. Some engines may be fitted with valve rotating mechanisms which are integral with the spring retainer. These are in two parts with opposing angle faces and rollers to provide a rotational drive as the valve is operated.

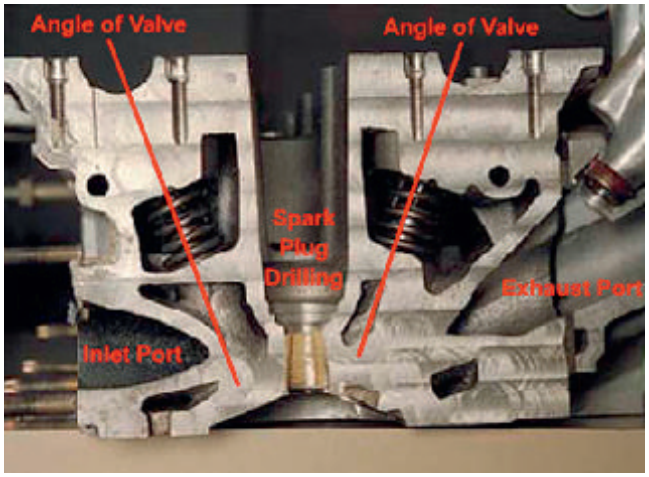


Figure 2.90 Cross-section of a cylinder head

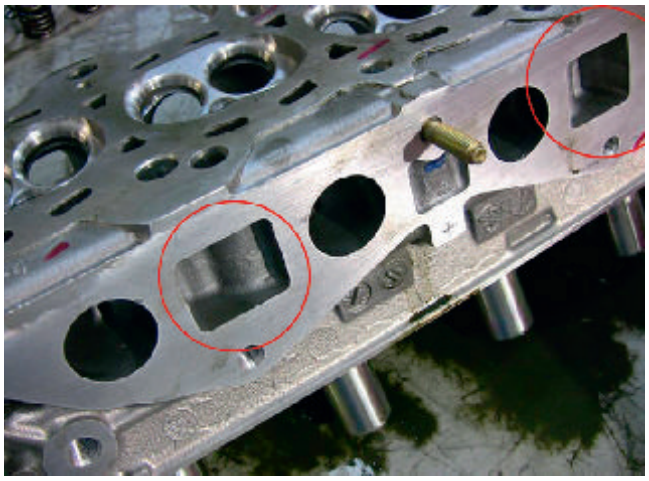


Figure 2.91 Engine coolant passages

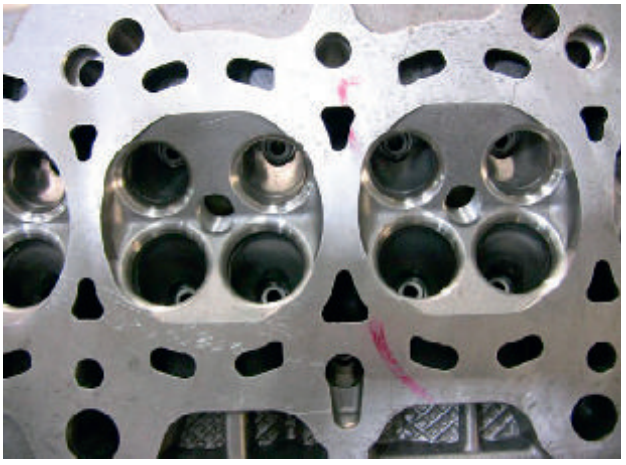


Figure 2.92 Hardened seats in an aluminium head

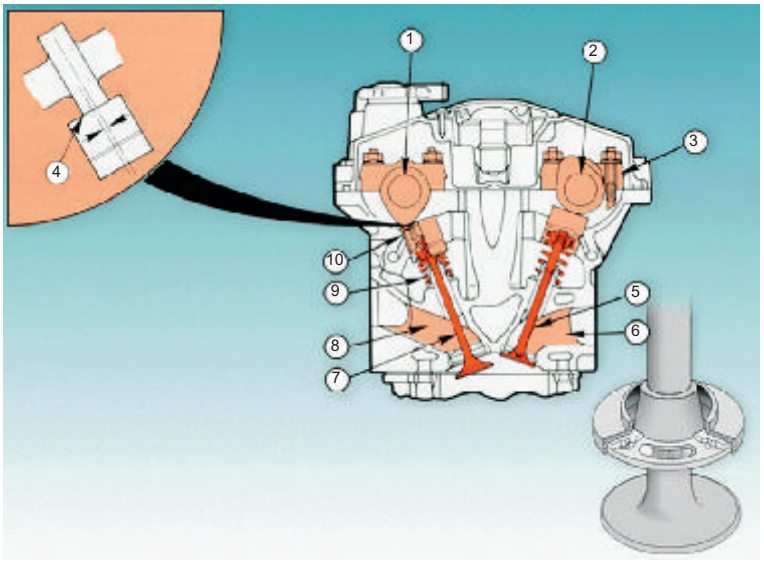


Figure 2.93 OHC value rotator features: 1, exhaust cam; 2, inlet cam; 3, cam bearings; 4, rotator; 5, inlet valve; 6, inlet port; 7, exhaust valve; 8, exhaust port; 9, spring; 10, follower

Figure 2.94 Valves in position on a cutaway engine. (Source: Ford Media)

2.1.3.5 Valves

Inlet and exhaust valves are poppet-type valves with a circular sealing face recessed in the cylinder head (Fig. 2.94). The valves are located via the stem and slide inside valve guides mounted in the cylinder head. Valve heads are exposed to full, combustion chamber temperatures and pressures; the temperature of the exhaust valve can be as high as 800°C. The incoming gas charge has a cooling effect on the intake valve but, generally, heat dissipation from the valves is via the stem and guides to the cylinder head. Combustion and fuel deposits can cause problems on the valve; this can be avoided by the use of good quality fuels and oils.

The total valve opening area is always greater for the inlet valves; this is to increase the volumetric efficiency of the engine since the pressure difference across the inlet valve, when charging the cylinder, is much lower than the pressure difference

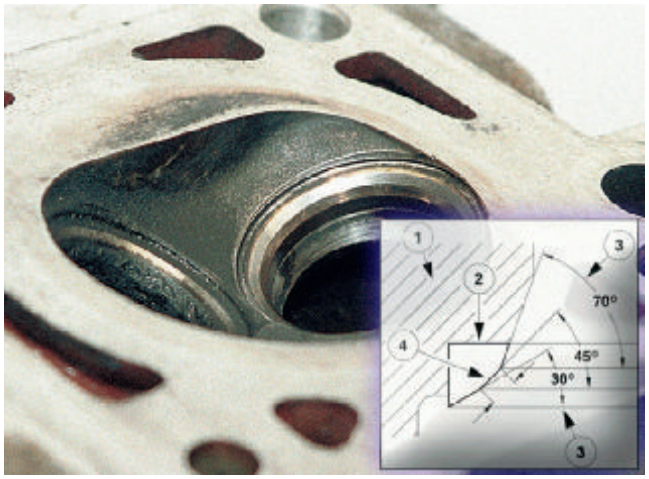


Figure 2.95 Seat angles: 1, head; 2, valve seat; 3, possible angles; 4, valve insert angle where contact is made

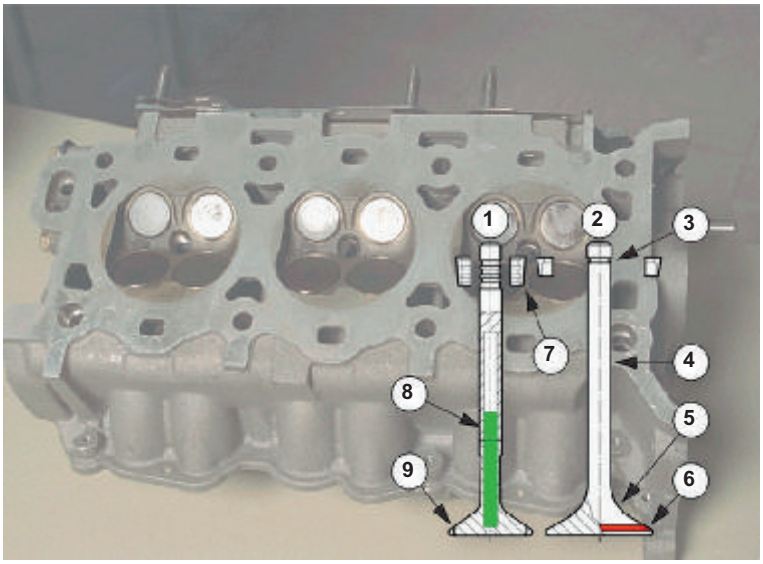


Figure 2.96 Valve details: 1, bimetallic valve; 2, single metal valve; 3, collet groove; 4, stem; 5, head; 6, face; 7, collets; 8, sodium filling; 9, armouring

across the exhaust valve, when evacuating the cylinder. Hence, a larger valve is needed to reduce restrictions to gas flow during the inlet stroke.

Valves seats and the valve sealing face are cut at slightly different angles (Fig. 2.95). This is to ensure that a complete seal is made under working conditions as, when the valve is installed and at running temperatures, the valve head will deform slightly, causing the sealing faces to meet correctly and seal efficiently. The angle of the sealing face is approximately 45°. The valves open via the force applied from the cam and valve gear and are held in the closed position by spring force. The springs are connected to the valve via a retainer and split collets as this allows removal and refitting. In operation, the valve head rotates and this helps to maintain the sealing face.

Some valve stems are hollow and contain sodium, which melts when the valve is hot and assists in transferring heat from the valve face to the valve stem for dissipation via the valve guides (Fig. 2.96). Cooling of the valve head can be

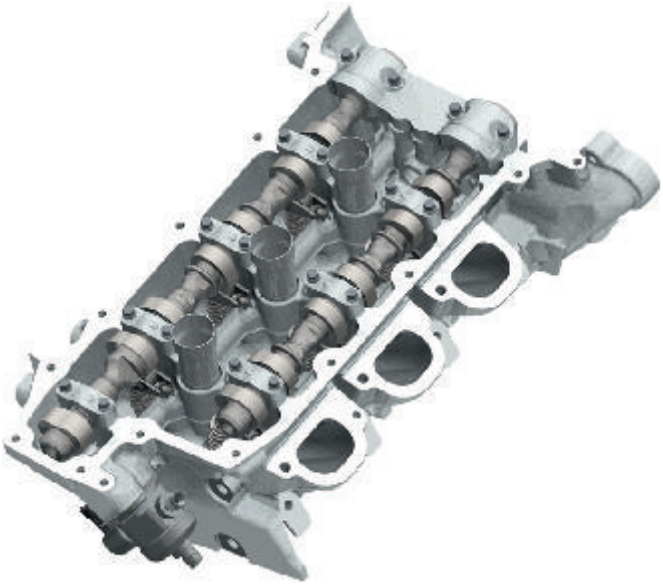


Figure 2.97 V6 cylinder head with two cams in position. (Source: GM Media)

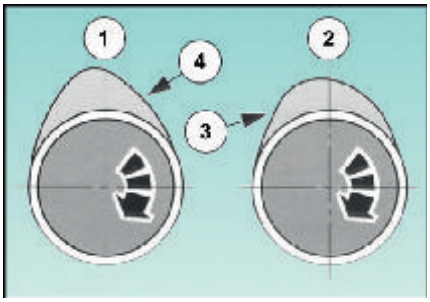


Figure 2.98 Cam profiles: 1, pointed cam; 2, cam with steep profile; 3, trailing face; 4, leading face

improved significantly via a temperature reduction of up to 100°C. These valves are also known as bimetal type. Note that a sodium-filled valve of this type must be handled with care as sodium exposed to air is flammable and will self-ignite.

Key fact

The camshaft has cam lobes for each valve. To ensure the correct sequence of valve timing, the camshaft is timed and synchronized with the crankshaft position.

2.1.3.6 Camshaft

The camshaft, on most modern engines, is mounted in bearings formed into the cylinder head via an in-line boring process (Fig. 2.97). The camshaft is forged from steel or cast iron and the bearings and cam surfaces are a smooth, machined finish. The camshaft has cam lobes for each valve and to ensure the correct sequence of valve timing, the camshaft is timed and synchronized with the crankshaft position.

The cam lobes have a specific profile that consists of a base circle and lobe to provide the correct valve opening and closing characteristics (Fig. 2.98). The cam profile is not necessarily symmetrical and the profile may allow progressive opening of the valve but with a sharp closing action depending on the characteristics and optimization parameters of the engine.

Overhead valve (OHV) is used to describe an engine where the valves and operating mechanism are located in the cylinder head. The valve gear transfers reciprocating motion from the cam followers and camshaft. It is then passed to

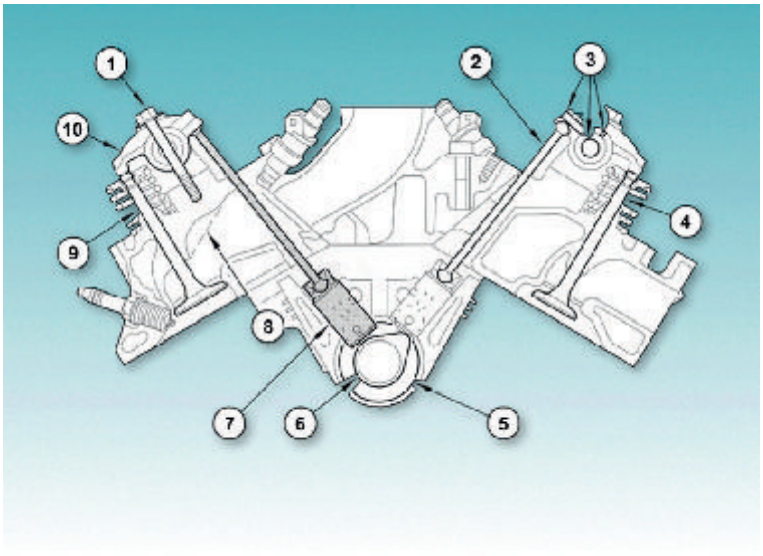


Figure 2.99 Overhead valves (OHV): 1, rocker shaft bolt; 2, push rod; 3, lubrication passages; 4, exhaust valve; 5, cam bearing journal; 6, cam lobe; 7, hydraulic tappet; 8, turbulence ramp; 9, inlet valve; 10, rocker

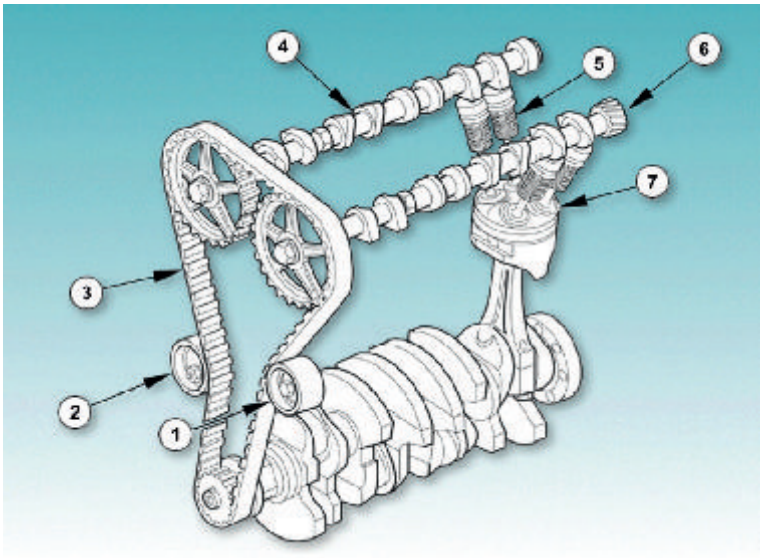


Figure 2.100 Double overhead camshaft engine (DOHC): 1 and 2: tensioner wheels; 3, timing belt; 4, inlet cam; 5, exhaust cam; 6, distributor drive; 7, valve

the valves via push rods and a rocker assembly, which acts on the valve stems (Fig. 2.99).

Overhead cam (OHC) refers to the position of the camshaft in the engine; that is, it is positioned in the cylinder head. There are various designs using direct or indirect mechanisms to convert the rotating cam motion into a reciprocating motion, and then transfer this motion to the valve stems. These designs are proposed to facilitate a close tolerance in operating clearances.

A further development, now employed extensively, is the use of twin or double overhead camshafts (DOHC) (Fig. 2.100). These can use direct or indirect valve actuation and are well suited to multivalve engine designs, including those with variable valve timing.

Key fact

Overhead cam (OHC) refers to the position of the camshaft in the engine.

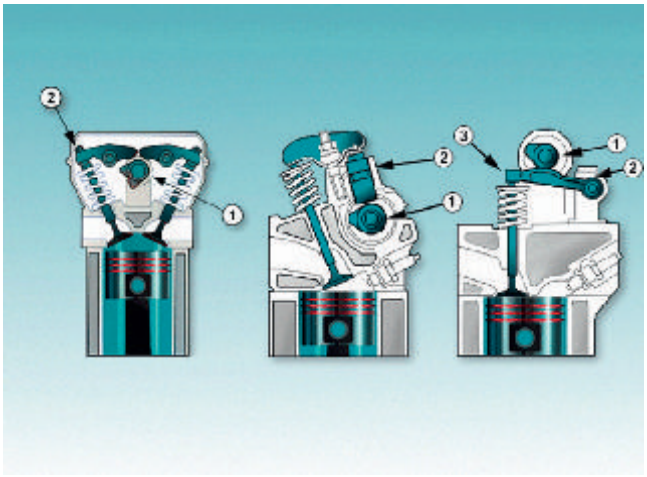


Figure 2.101 Valve operating mechanisms. Left, 1, cam; 2, adjusting screw in direct acting rocker. Centre, 1, cam; 2, hydraulic follower. Right, 1, cam; 2, pivot and adjuster; 3, finger follower

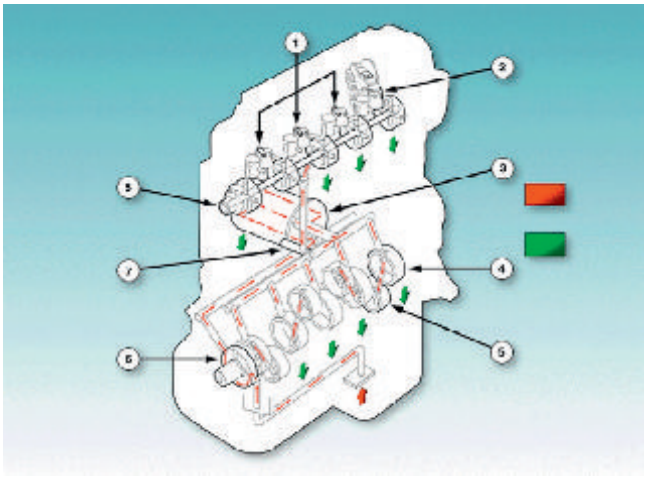


Figure 2.102 Hydraulic tappets and components: 1, oil to rocker arms, hydraulic tappets; 3, filter; 4, crank main bearings; 5, big end bearings; 6, crank driven oil pump; 7, oil under pressure; 8, camshaft

Indirect, rocker arm-type valve actuators incorporate close tolerance adjusters. Two systems are commonly seen, a rocker shaft and pivot stud, or a rocker arm supported on a pedestal at one end and the valve stem at the other, the cam acting between these two points (Fig. 2.101). A hydraulic pedestal can be used for self-adjustment of the mechanism.

Figure 2.102 shows a typical engine oil lubrication circuit that feeds the self-adjusting followers with pressurized oil to maintain the correct valve clearances. Always refer to manufacturers' data for the service requirements of the valve train system. Often, special procedures are required when replacing and recommissioning self-adjusting valve mechanisms, and these must be followed to prevent engine damage (Fig. 2.103).

Many engines now employ variable camshaft timing to optimize the inlet valve timing with respect to engine speed and load conditions (Fig. 2.104).

As air enters the engine through the inlet manifold this forms a column of moving air that possesses kinetic energy (Fig. 2.105). The pulsating nature of the engine's

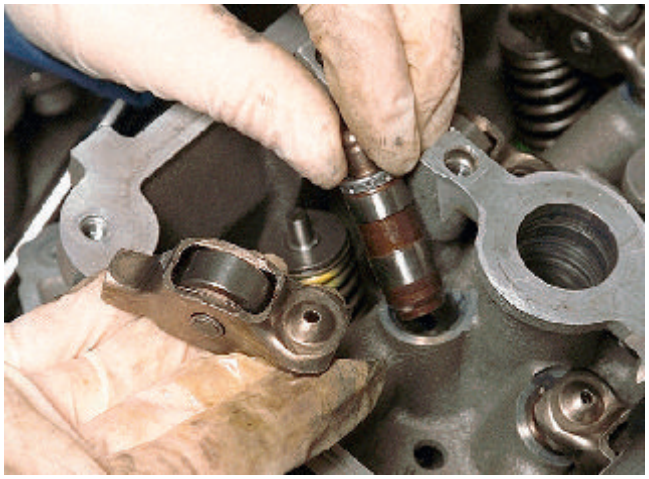


Figure 2.103 Hydraulic lifters

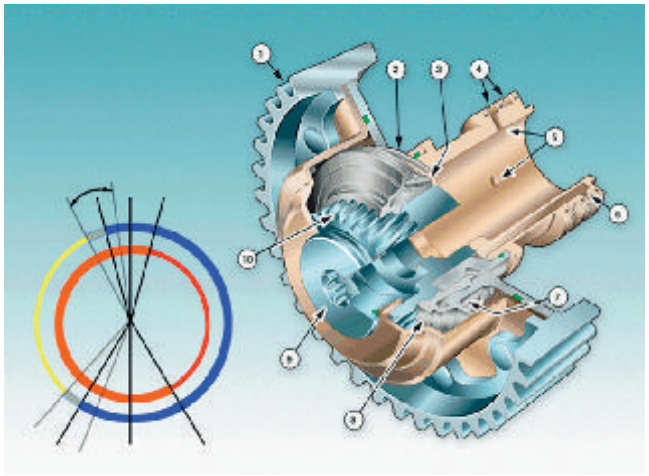


Figure 2.104 Timing is changed under electronic control: 1, camshaft gear; 2, spring; 3, outer helical teeth; 4, adapter with ring grooves; 5, oil supply to front chamber via hollow bolt (not shown); 6, oil supply to rear chamber; 7, rear chamber; 8, front chamber; 9, blanking plug; 10, inner helical teeth

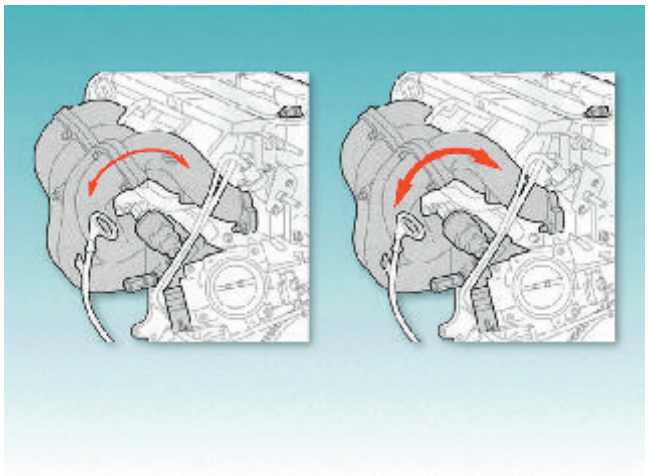


Figure 2.105 Inlet manifolds

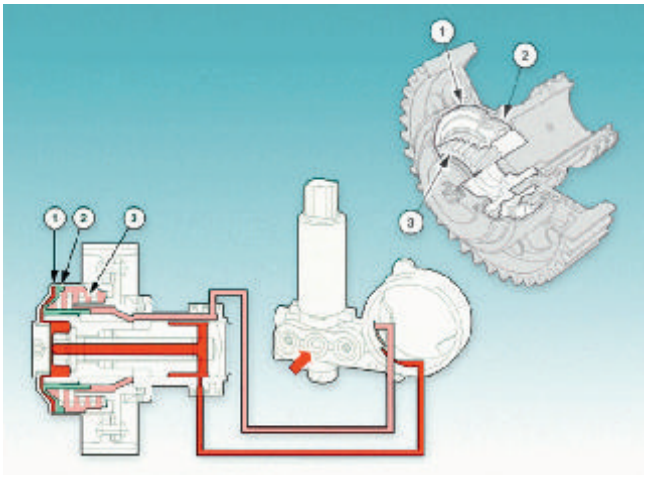


Figure 2.106 Electrohydraulic variable cam control method: 1, adjusting piston with inner and outer helical teeth; 2, outer helical teeth connected to camshaft pulley; 3, inner helical teeth connected to the camshaft

Figure 2.107 Variable cam timing. (Source: Ford Media)

Key fact

Variable valve timing (VVT) optimizes the valve opening point to increase engine torque and power at various points in the operating speed range.

air consumption creates pressure waves in this air column. The energy in these pressure waves can be harnessed to assist in charging the cylinder, increasing the volumetric efficiency of the engine. In order to do this, the valve opening point must be optimized according to the engine condition, and with variable valve timing this can be achieved to increase engine torque and power at various points in the operating speed range.

There are various technologies available to provide the required phase angle between the cam drive and the camshaft for variable valve timing (Figs 2.106 and 2.107). It can be generated via a hydraulic mechanism in the cam wheel that is controlled via a valve assembly from the engine's electronic control unit (ECU). Cam wheel actuators can employ a 'helix' or pressure differential actuation principle. In addition, some engines have employed valve mechanisms with alternative cam profiles where the engine switches over to a different cam lift profile at certain engine speeds.

The camshaft-driven gearwheel has twice as many teeth as the crankshaft drive gearwheel. The camshaft is therefore driven at half engine speed. Various drive mechanisms are used.

Figure 2.108 Cam drive belt in position on the Duratec engine; not to be confused with the serpentine alternator drive belt. (Source: Ford Media)

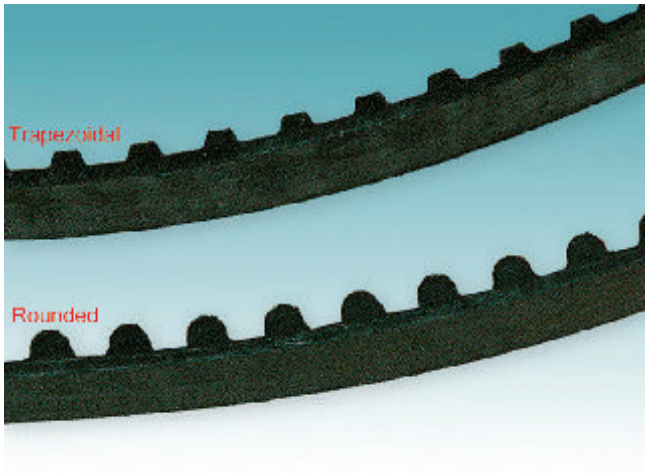


Figure 2.109 Two types of cam belt

For many engines, a toothed belt is used to drive the camshaft (Fig. 2.108). The belt is manufactured from a durable, synthetic rubber with reinforcing fibres. The teeth moulded on the inside of the belt mate with the corresponding teeth on the crankshaft and camshaft pulley wheels. The teeth formed on the belt can be trapezoidal or rounded (Fig. 2.109). Note that they are not interchangeable and it is important to fit the correct type when replacing the belt.

Correct tension of the timing belt is imperative for maximum belt life. The belt is generally tensioned by adjustable tensioner wheels (Fig. 2.110). It is important to note that manufacturer- and engine-specific information must be sought when making adjustments in service. The advantages of timing belts are that they are cheap and run quietly.

Key fact

The advantages of timing belts are that they are cheap and run quietly.

Drive gears (Fig. 2.111) are not used on many applications but have the advantage of a very positive drive because they have little backlash compared with belts and chains (Fig. 2.112).

Covers are fitted to enclose moving parts and retain oil (Fig. 2.113). The sump or oil pan is fitted on the underside and holds the oil capacity. The cover that

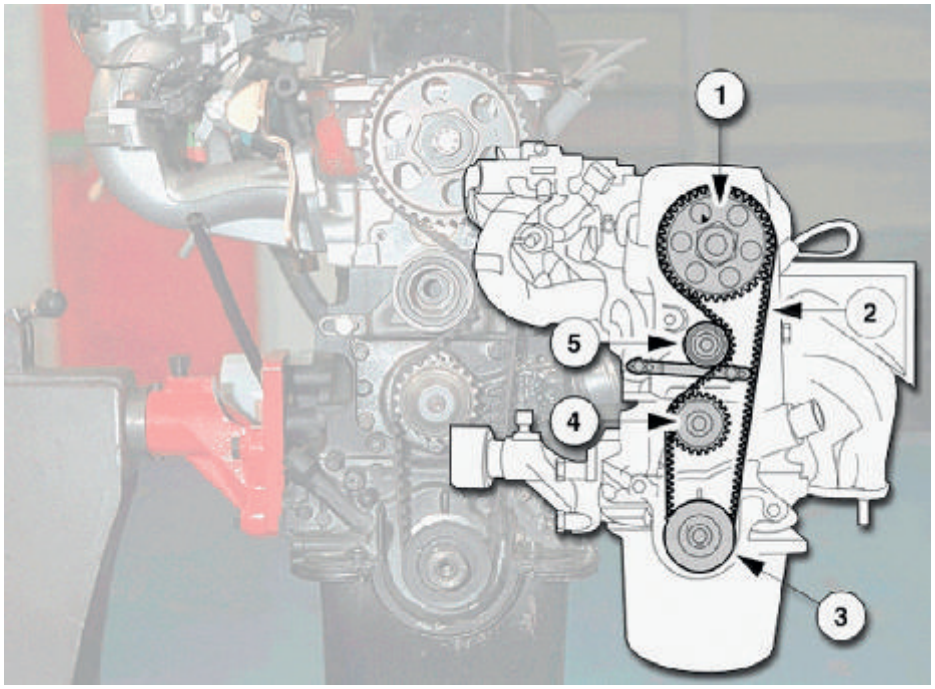


Figure 2.110 Belt drive components: 1, cam gear; 2, belt; 3, crank gear; 4, water pump; 5, tensioner

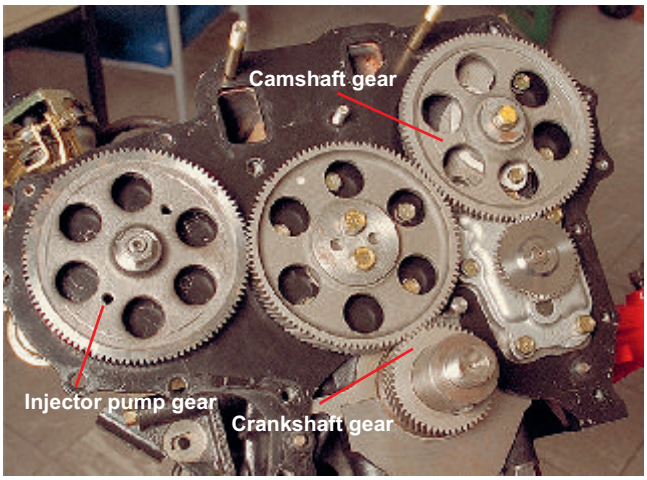


Figure 2.111 Cam drive gears

Figure 2.112 Cam drive chain in position on the 2012 Focus engine. (Source: Ford Media)

encloses the valve gear is known as the rocker or cam cover. Generally, it incorporates the oil filler cap and part of the engine breather system.

At the front of the engine, there is a casing that retains the crankshaft oil seal. In addition, a cover is fitted to enclose and protect the camshaft drive belt. At the

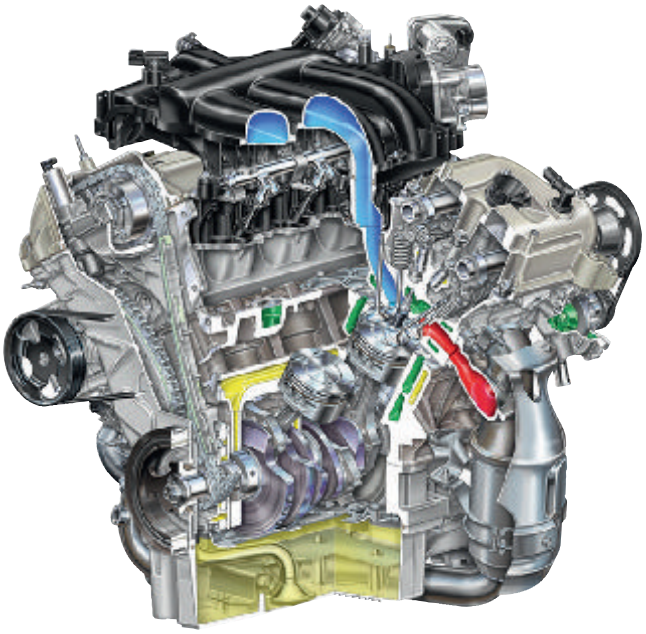


Figure 2.113 There are a variety of covers on all engines. On this diagram yellow represents the oil sump and other areas, green coolant passages, red exhaust ports and blue inlet air. (Source: Ford Media)

rear of the engine, another crankshaft oil seal is fitted to a casing that is bolted to the engine and located by dowels.

The sump contains baffles to prevent excessive oil movement or surge. This maintains a good supply of oil around the area of the oil pick-up.

Attached around the engine are auxiliary components and subsystems for lubrication, cooling, ignition, fuel, air, exhaust and electrical systems.

2.2 Engine lubrication

2.2.1 Friction and lubrication

Lubrication is the introduction of a substance, called a lubricant (e.g. oil to create an oil film), between two moving contact surfaces, to reduce friction. This reduction of friction greatly reduces the wear of the surfaces and thus lengthens their service life. It also reduces the energy required for the movement. Lubrication is important in all moving parts of the vehicle but the engine has the greatest need.

Under a microscope, even the smoothest engine components have a surface that looks very rough. If these surfaces made contact they would rub together, overheat and destroy themselves. To prevent this happening, engines have a lubrication system that pumps or drips a constant supply of oil on all the moving metal components.

Key fact

Under a microscope, even the smoothest engine components have a surface that looks very rough.

Although the basic function of a lubricant is to reduce friction and wear, it may also perform a number of other functions. It carries off generated heat and it helps to form a gas-tight seal between piston rings and cylinders. It also carries away harmful combustion waste products. Lubrication helps to control corrosion by coating parts with a protective film. A detergent added to the lubricant helps to removes sludge deposits.

Some engine oils are refined from crude oil to which are added viscosity index enhancers, reduced friction enhancers, antioxygenates, sludge, lacquer and corrosion inhibitors, and cleaning agents for carbon, acids and water. Synthetic and semi-synthetic oils have improved performance for environmental or special purposes. Multigrade oils have been developed to modify the viscosity index and give thin oils at low temperatures that do not become excessively thin at higher temperatures (Fig. 2.114).

Definition

Viscosity
A measure of resistance to flow.

Viscosity is a measure of an oil's resistance to flow (Fig. 2.115). Thin oil will flow more easily than thicker oil. A viscosity index is the measure of a change in an oil's flow rate with a rise in temperature. The higher the viscosity index, the smaller the change in viscosity. Manufacturers' recommended viscosity ratings generally reflect the lowest temperature at which the vehicle is being used and may be different for summer and winter use. The viscosity rating is an indicator not of oil quality but of oil flow under particular conditions. Some low-grade oils carry recommendations that limit the use of the vehicle, particularly for high engine speeds, heavy loads and long journeys.

Engine oils are not normally biodegradable and should not be allowed to enter the environment as either vapour or liquid. Total loss lubrication systems used

Figure 2.114 Oils

Figure 2.115 Viscosity is the resistance to flow

on small two-stroke engines, such as those on motorbikes and outboard motors, use a 'petroil' mixture of petrol and a specially formulated biodegradable oil. Other types of oil should not be used.

Several international standards (described in a later section) describe the properties of an oil, but some original equipment manufacturers (OEMs) are now specifying their own. The safest advice on what oil to use is always to follow manufacturers' recommendations.

If a film of lubricant is used between the surfaces, the process is called boundary lubrication (Fig. 2.116). This type of lubrication is introduced between the moving surfaces by splash feed or an oil mist. The best example is on the side of the pistons but all sliding components use this method.

Boundary lubrication also commonly occurs on some bearings during starting of the engine. Pressure is generated once the engine is moving as a result of the shape and motion of the surfaces. This is known as hydrodynamic lubrication. For example, the rotation of the crankshaft in a bearing forces lubricant into the wedge-shaped space between the shaft and the bearing (Fig. 2.117). The clearance between the bearing and the shaft, the load on the shaft, the speed of rotation and the viscosity of the lubricant have a marked effect on this process.

Figure 2.116 Boundary lubrication uses the oil to prevent two rough surfaces from touching

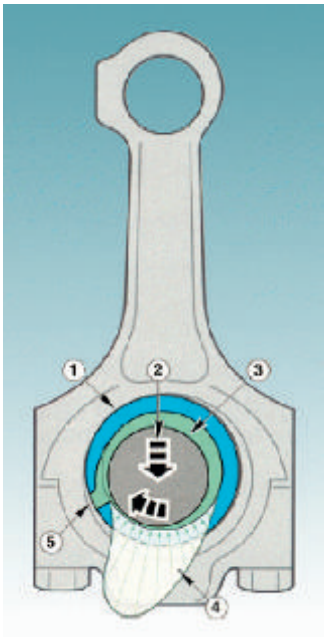


Figure 2.117 Con rod big end lubrication: 1, bearing shell; 2, load; 3, shaft; 4, lubrication pressure; 5, oil supply

2.2.2 Methods of lubrication

Bath lubrication or splash lubrication (used in gearboxes and rear axles) may be used for gears, chains, bearings and other moving parts that can be partly submerged in an oil reservoir. In the bath system the gear simply picks up oil as it dips into the reservoir and sprays or carries it to other parts along its path. The splash system increases the efficiency by attaching a special splash ring to a moving part so that the oil is splashed against other parts that need to be lubricated. This is similar to oil-mist lubrication, created by the oil escaping from the engine's rotating crankshaft, in which the oil is atomized in a stream of air.

Force-feed lubrication uses an oil pump to force the oil under pressure to the parts to be lubricated, normally the engine crankshaft and camshaft. On some high-performance vehicles the mainshaft in the gearbox is pressure fed. Some parts are self-lubricating and require no external lubrication; the lubricant may be sealed in against loss as in sealed ball bearings, or a porous material such as porous bronze can be used so that oil impregnated in the material can penetrate to the point of contact of the moving parts through pores in the material. In small two-stroke gasoline engines the oil is mixed in with the fuel to bring it to the moving parts inside the engine.

Key fact

Force-feed lubrication uses an oil pump to force the oil under pressure to the parts to be lubricated, normally the engine crankshaft and camshaft.

Although lubricating oil is used elsewhere in a car, the lubrication of the engine is of greatest importance because it reduces the friction and wear between moving metal parts and also removes heat from the engine. A supply of oil is kept in the engine crankcase. An oil pump, which is powered by the engine, forces oil from the crankcase under pressure to the cylinder block main oil gallery. Passages in the engine block channel the oil to various moving parts, such as the crankshaft and camshaft, and the oil eventually drains back down in the crankcase. An oil filter is fitted in the oil circuit to filter out metal shavings, carbon deposits and dirt. Because the filter is not completely effective, and because of prolonged exposure to high temperatures, the oil eventually becomes contaminated, decomposes and loses its lubricating qualities. This is why routine maintenance calls for changing the oil and oil filter at regular intervals.

2.2.3 Lubrication system

From the sump reservoir under the crankshaft oil is drawn through a strainer into the pump (Fig. 2.118).

Oil pumps have an output of tens of litres per minute and operating pressures of over 5 kg/cm^2 at high speeds. A pressure relief valve limits the pressure of the lubrication system to between 2.5 and 4 kg/cm^2. The pressure relief valve is a spring-loaded conical, or ball, valve that opens when the pressure in the oil exceeds the spring force acting on the valve seat (Fig. 2.119). When the valve opens, a return drilling is uncovered and the excess oil flows through this to return to the sump. This control is needed because the pump would produce excessive pressure at high speeds. After leaving the pump, oil passes into a filter and then into a main oil gallery in the engine block or crankcase (Fig. 2.120).

Drillings connect the gallery to the crankshaft bearing housings and when the engine is running, oil is forced under pressure between the rotating crank journals and the main bearings. The crankshaft is drilled so that the oil supply from the main bearings is also to the big-end bearing bases of the connecting rods.

The connecting rods are often drilled near the base so that a jet of oil sprays the cylinder walls and the underside of the pistons (Fig. 2.121). In some cases the

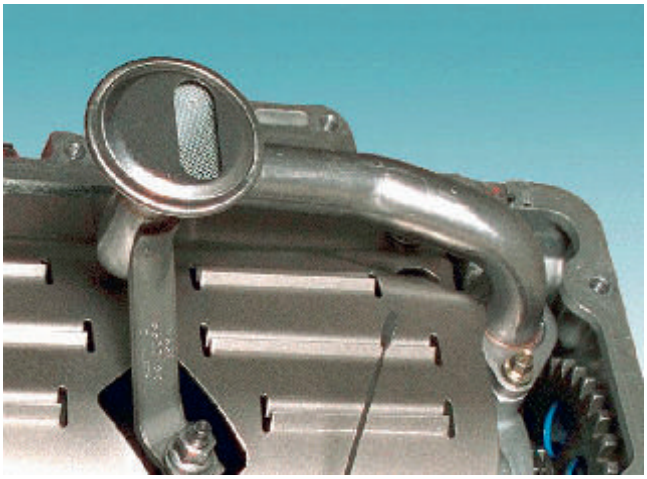


Figure 2.118 Pick-up pipe and strainer

Figure 2.119 Plunger and spring

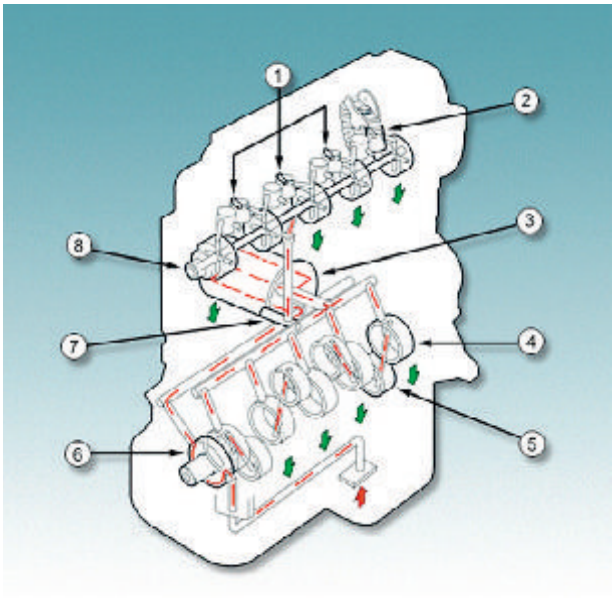


Figure 2.120 Oil flow: 1, oil to rocker arms; 2, hydraulic tappets; 3, filter; 4, crank main bearings; 5, big end bearings; 6, crank driven oil pump; 7, oil under pressure; 8, camshaft

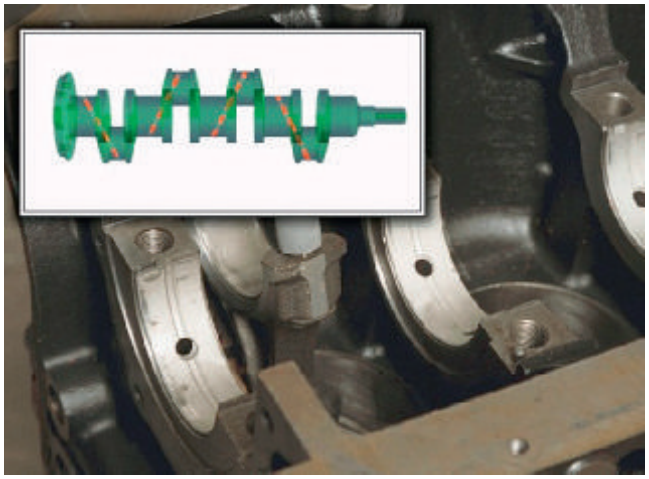


Figure 2.121 Drillings in the block and crank

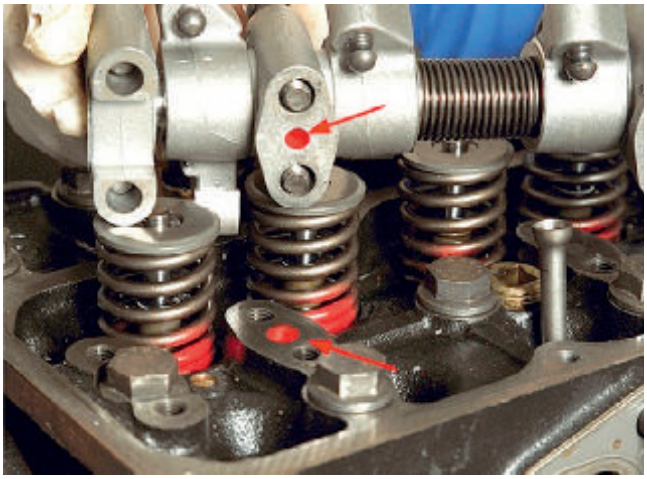


Figure 2.122 Oil drillings for the valve gear

Figure 2.123 Oil cooler for a racing car. (Source: www.prcracing.com Media)

connecting rod may be drilled along its entire length so that oil from the big-end bearing is taken directly to the gudgeon pin (small end). The surplus then splashes out to cool the underside of the piston and cylinder.

The camshaft operates at half crankshaft speed, but it still needs good lubrication because of the high-pressure loads on the cams (Fig. 2.122). It is usual to supply pressurized oil to the camshaft bearings and splash or spray oil on the cam lobes. On overhead camshaft engines, two systems are used. In the simplest system the rotating cam lobes dip into a trough of oil. Another method is to spray the cam lobes with oil. This is usually done by an oil pipe with small holes in it alongside the camshaft. The small holes in the side of the pipe aim a jet of oil at each rotating cam lobe. The surplus splashes over the valve assembly and then falls back into the sump.

On cars where a chain drives the cam, a small tapping from the main oil gallery sprays oil on the chain as it moves past, or the chain may simply dip in the sump oil.

Some specialized vehicles use an oil cooler (Fig. 2.123). The oil cooler commonly used is an air radiator similar to an engine-cooling radiator, with tubes and fins to transfer heat from the oil to the passing air stream. This cooler is fitted next

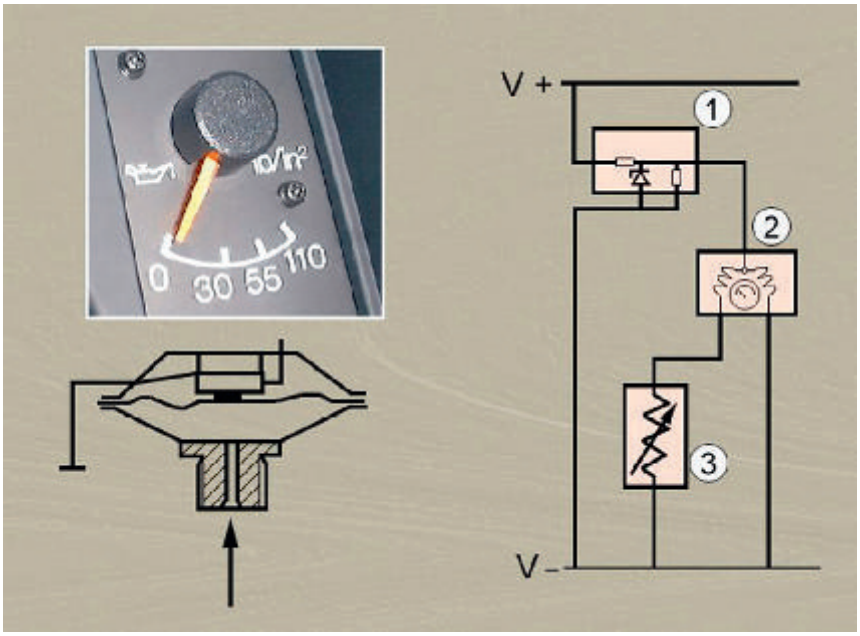


Figure 2.124 Gauge and circuit: 1, voltage stabilizer; 2, gauge; 3, sender unit

to the cooling-system radiator at the front of the vehicle. Pipes from the filter housing carry oil to and from the oil-cooler radiator.

A key component of the lubrication system is the dipstick. No matter how clever the system is it will not work if the oil level is low. The dipstick is marked to show the maximum and minimum acceptable levels.

Key fact

A key component of the lubrication system is the dipstick!

Many modern engines are now also fitted with an electronic sensor that supplies information to the driver on the level of oil in the engine (low oil pressure indicating low oil level). A warning light, or a gauge in the instrument panel, indicates whether the oil level is within acceptable levels (Fig. 2.124). The sensor is fitted into the sump or the engine block. Some engines now have oil quality sensors to indicate when the oil should be changed.

To warn the driver about low oil pressure, a pressure-sensitive switch is fitted into the main gallery. It makes an electrical contact when the pressure is below about 0.5 bar (7 psi). The switch may be fitted in the same circuit as the oil level warning lamp. When the switch contacts make a connection, the lamp lights, and this should occur before the engine is started. Once the engine is running, oil pressure builds up and the switch contacts separate and the warning lamp will go out. This indicates that a minimum oil pressure is being maintained in the system. Oil pressure gauges are also used and employ a piezoelectric pressure sensor fitted into the main gallery and a gauge unit.

2.2.4 Oil filters

Even new engines can contain very small particles of metal left over from the manufacturing process or grains of sand that have not been removed from the crankcase after casting. Old engines continually deposit tiny bits of metal worn from highly loaded components such as the piston rings. To prevent any of these lodging in bearings or blocking oil ways, the oil is filtered (Fig. 2.125).

The primary filter is a wire mesh strainer that stops particles of dirt or swarf from entering the oil pump. This is normally on the end of the oil pick-up pipe. An

Figure 2.125 Oil filters

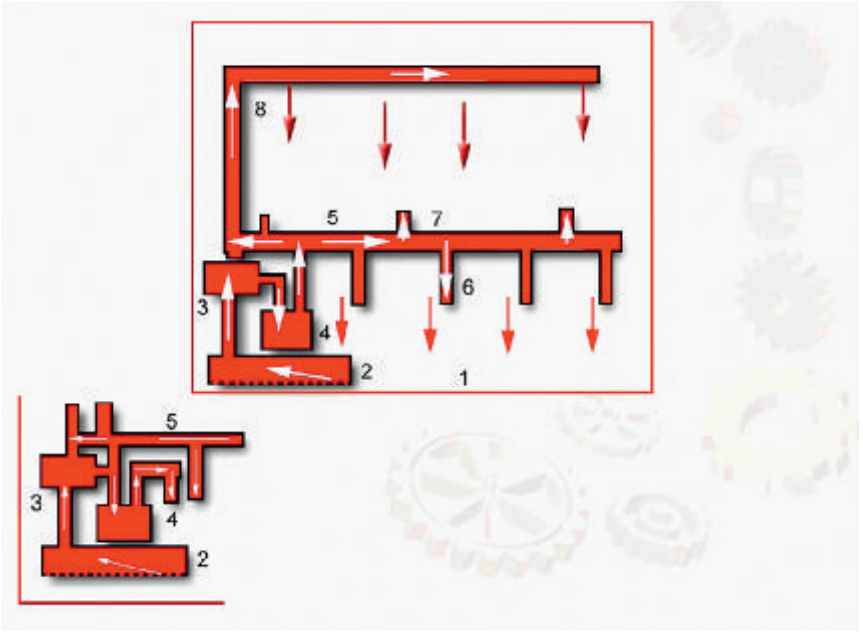


Figure 2.126 Oil circuits: 1, full flow (bottom left bypass flow); 2, sump; 3, pump; 4, filter; 5, main gallery; 6, main bearings; 7, big ends; 8, camshaft

extra filter is also used that stops very fine particles. The most common type has a folded, resin-impregnated paper element. Pumping oil through it removes all but smallest solids from the oil.

Most engines use a full-flow system to filter all of the oil after it leaves the pump (Fig. 2.126). The most popular method is to pump the oil into a canister containing a cylindrical filter. From the inner walls of the canister, the oil flows through the filter and out from the centre to the main oil gallery. Full-flow filtration works well provided the filter is renewed at regular intervals. If it is left in service too long it may become blocked. When this happens the build-up of pressure inside the filter forces open a spring-loaded relief valve in the housing and the oil bypasses the filter. This valve prevents engine failure, but the engine will be lubricated with dirty oil until the filter is renewed. This is better than no oil!

Key fact

Most engines use a full-flow system to filter all of the oil after it leaves the pump.

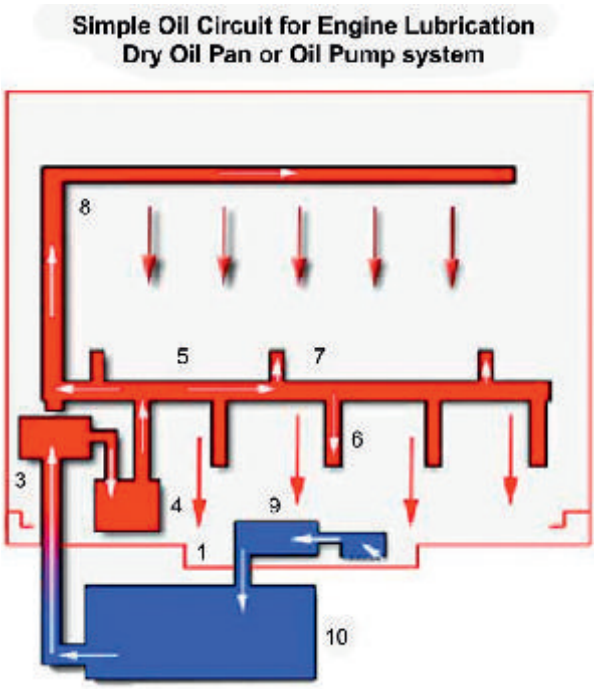


Figure 2.127 Dry sump: 1, small collection area; 2, not shown; 3, pump; 4, filter; 5, main gallery; 6, main bearings; 7, big ends; 8, camshaft; 9, return pump; 10, remote tank

A bypass filtration system was used on some vehicles (Fig. 2.126, bottom left). This system only filters a proportion of the oil pump output. The remainder is fed directly to the oil gallery. At first view this seems a strange idea but all of the oil does eventually get filtered. The smaller amount through the filter allows a higher degree of filtration.

For many high-performance applications, a larger oil supply is needed so that engine heat can be removed by the engine oil as well as by the engine-cooling system (Fig. 2.127). A separate reservoir of oil is held in a remote tank and drawn into the main oil pump for distribution throughout the engine in the same way as a wet-sump system. The oil returns to a small sump below the engine. A scavenge pump, with a pick-up pipe in the sump, draws oil out of the sump and delivers it back to the reservoir. An oil cooler is usually fitted in this return circuit.

2.2.5 Oil pumps

The oil pump is the heart of the system. It pumps oil from the sump into the engine. The main types of oil pump are gear, rotor, gerotor, vane and crescent. The gear type uses two gears in mesh with each other (Fig. 2.128). Drive is made to one gear which, in turn, drives the other. The housing has a figure-of-eight internal shape, with one gear in each end. Ports are machined in the housing and align with the areas where the teeth move into, and out of, mesh. As the teeth separate, the volume in the inlet side of the housing increases and atmospheric pressure in the sump is able to force oil into the pump. The oil is carried around inside the pump in between the teeth and the side of the housing. When the teeth move back into mesh, the volume in the outlet side of the housing is reduced, the pressure rises and this forces the oil out into the engine.

Key fact

The main types of oil pump are gear, rotor, gerotor, vane and crescent.

The rotor-type pump uses the same principle of meshing but with an inner rotor with externally formed lobes that mesh with corresponding internal profiles on the inside of an external rotor (Fig. 2.129). The inner rotor is offset from the centre

Figure 2.128 Gear pump

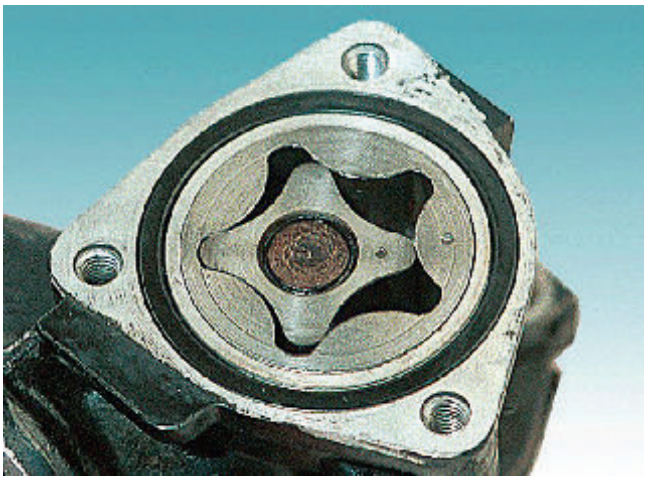


Figure 2.129 Rotor pump

of the pump and the outer rotor is circular and concentric with the pump body. As the rotors rotate, the lobes mesh to give the outlet pressure of the oil supply, or move out of mesh for the intake of oil from the sump.

The gerotor (gear rotor pump) is a variation on the smaller rotor pump (Fig. 2.130). The gerotor pump is usually fitted around, and driven by, the crankshaft. There are inner and outer rotors, with the inner rotor externally lobed and offset from the internally lobed outer rotor. During rotation, the pumping and carrying chambers are formed by the relative positions of the lobes.

The crescent pump is named after the solid block in the gear body. This pump is a variation on the gear pump, and also uses gear teeth to create the pumping chambers and to carry oil from the inlet port to the outlet port of the pump. The operation of this pump is based on the meshing of the gear teeth, the positioning of the ports in the housing and alignment at each end of the crescent where the teeth move in and out of mesh. Oil is carried from the inlet port to the outlet port in the spaces between the teeth and the crescent. This type of pump is used for engine lubrication and for automatic transmissions.

The vane-type pump uses an eccentric rotor with vane plates set at right angles to the axis of the rotor and sitting in slots in the rotor (Fig. 2.131). As the rotor

Figure 2.130 Gerotor pump driven by the crankshaft

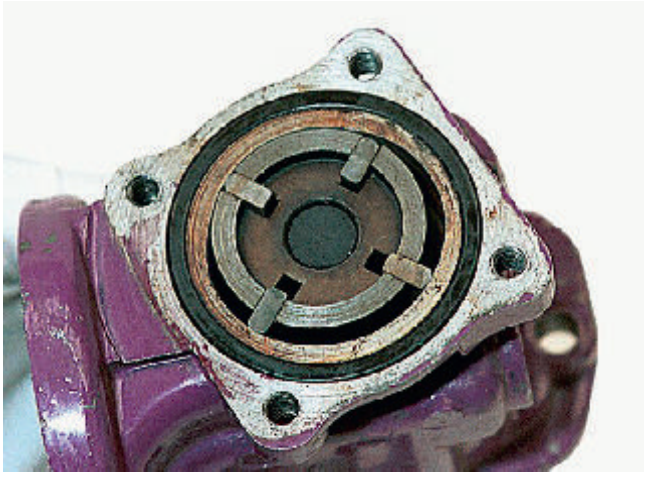


Figure 2.131 Vane pump

rotates, the vanes sweep around inside the pump housing. The pump chambers increase in volume as the vanes move away from the housing walls, and reduce in volume as the vanes approach the walls. Oil is carried between the vanes and the pump housing from the inlet port to the outlet port.

Most modern engines now use the crankshaft to give a direct drive to the oil pump. These pumps are of the gerotor or crescent design, and are fitted around the front of the crankshaft. This arrangement is used on many overhead camshaft engines because it provides a low position for the pump.

Key fact

Most modern engines now use the crankshaft to give a direct drive to the oil pump.

2.2.6 Standards

2.2.6.1 SAE

The Society of Automotive Engineers (SAE) (Fig. 2.132) has established a numerical code system for grading motor oils according to their viscosity characteristics. SAE viscosity grades include the following, from low to high viscosity: 0, 5, 10, 15, 20, 25, 30, 40, 50 or 60. The numbers 0, 5, 10, 15 and 25 are suffixed with the letter W, designating their 'winter' or cold-start viscosity, at lower temperature. The number 20 comes with or without a W, depending

Figure 2.132 Society of Automotive Engineers (SAE) logo

Figure 2.133 Castrol Magnatec multigrade engine oil. (Source: www.castrol.com, where you can also find a useful feature that recommends the correct grade for any vehicle by entry of the registration number)

on whether it is being used to denote a cold or hot viscosity grade. Viscosity is graded by measuring the time it takes for a standard amount of oil to flow through a standard orifice, at standard temperatures. The longer it takes, the higher the viscosity and thus the higher the SAE code.

Note that the SAE has a separate viscosity rating system for gear, axle and manual transmission oils, which should not be confused with engine oil viscosity. The higher numbers of a gear oil (e.g. 75W–140) do not mean that it has higher viscosity than an engine oil.

A single-grade engine oil does not use a polymeric viscosity index improver additive (also described as a viscosity modifier). For some applications, such as when the temperature ranges in use are not very wide, single-grade motor oil is satisfactory; for example, lawn mower engines, industrial applications, and vintage or classic cars. However, multigrade oil is far more common. The temperature range the oil is exposed to in most vehicles can be wide, ranging from cold temperatures in the winter before the vehicle is started up, to hot operating temperatures when the vehicle is fully warmed up in hot summer weather.

Key fact

A specific oil will have high viscosity when cold and a lower viscosity at the engine's operating temperature.

A specific oil will have high viscosity when cold and a lower viscosity at the engine's operating temperature. To bring the difference in viscosities closer together, special polymer additives called viscosity index improvers (VIIs) are added to the oil. These additives are used to make the oil a multigrade motor oil (Fig. 2.133). The idea is to cause the multigrade oil to have the viscosity of the base grade when cold and the viscosity of the second grade when hot. This enables one type of oil to be generally used all year. The SAE designation for multigrade oils includes two viscosity grades; for example, 10W–30 is a common

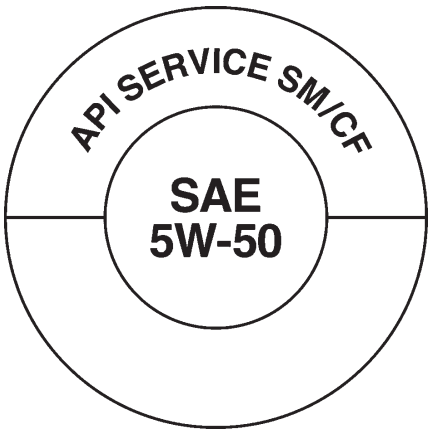


Figure 2.134 API service symbol example (donut)

multigrade oil. The two numbers used are individually defined by SAE for single-grade oils. Therefore, an oil labelled as 10W–30 must pass the viscosity grade requirement for both 10W and 30 grades.

2.2.6.2 API

The American Petroleum Institute (API) sets a minimum for performance standards for lubricants. Lubricant base stocks are categorized into five groups by the API. Group I base stocks, for example, are composed of fractionally distilled petroleum which is further refined with solvent extraction processes to improve certain properties such as oxidation resistance and to remove wax. Other groups describe further refinements and bases. Group III relates to synthetic oils and group V is used for anything that does not fit into the other groups.

The API service classes use two general classifications: S for 'service' (originating from spark ignition) and C for 'commercial' (originating from compression ignition). Engine oil that has been tested and meets the API standards may display the API Service Symbol, also known as the 'donut' (Fig. 2.134).

The latest API service standard designation is SN for gasoline automobile and light truck engines. The SN standard refers to a group of laboratory and engine tests, including the latest series for control of high-temperature deposits. Current API service categories include SN, SM, SL and SJ for petrol/gasoline engines.

There are six current diesel engine service designations: CJ-4, CI-4, CH-4, CG-4, CF-2 and CF. In addition, API created a separated CI-4 PLUS designation in conjunction with CJ-4 and CI-4 for oils that meet certain extra requirements, and this marking is located in the lower portion of the API service symbol.

Some oils conform to both the petrol/gasoline and diesel standards. It is the norm for all diesel-rated engine oils to carry the corresponding gasoline specification.

2.2.6.3 ILSAC

The International Lubricant Standardization and Approval Committee (ILSAC) also has standards for motor oil. Introduced in 2004, GF-4 applies to SAE 0W–20, 5W–20, 0W–30, 5W–30 and 10W–30 viscosity grade oils. A new set of specifications, GF-5, took effect in October 2010. The industry has one year to convert their oils to GF-5 and in September 2011, ILSAC will no longer offer licensing for GF-4. In general, ILSAC works with API in creating the newest oil

specification, with ILSAC adding an extra requirement of fuel economy testing to its specification. To help consumers recognize that an oil meets the ILSAC requirements, API developed a 'starburst' certification mark (Fig. 2.135).

2.2.6.4 ACEA

The Association des Constructeurs Européens d'Automobiles (ACEA) classifications A3/A5 tests used in Europe are arguably more stringent than the API and ILSAC standards. The Co-ordinating European Council is the development body for fuel and lubricant testing in Europe and beyond, setting the standards via industry groups.

2.2.6.5 JASO

The Japanese Automotive Standards Organization (JASO) has created its own set of performance and quality standards for petrol engines of Japanese origin. For four-stroke petrol engines, the JASO T904 standard is used, and is particularly relevant to motorcycle engines. The JASO T904-MA and MA2 standards are designed to distinguish oils that are approved for wet clutch use, and the JASO T904-MB standard is not suitable for wet clutch use.

For two-stroke gasoline engines, the JASO M345 (FA, FB, FC) standard is used, and this refers particularly to low ash, lubricity, detergency, low smoke and exhaust blocking. These standards, especially JASO-MA and JASO-FC, are designed to address requirement issues not addressed by the API service categories.

2.2.6.6 OEM

By the early 1990s, many European original equipment manufacturers (OEMs) felt that the direction of the American API oil standards was not compatible with the needs of a motor oil to be used in their engines. As a result, many leading European motor manufacturers created and developed their own oil standards.

Recently, very highly specialized oils have been developed so that a petrol engine can now go up to two years or 30 000 km (18 600 miles), and a diesel engine can go up to two years or 50 000 km (31 000 miles) before requiring an oil change. Volkswagen, BMW, GM, Mercedes and PSA all have their own similar 'long-life' oil standards.

Because of the real or perceived need for motor oils with unique qualities, many European cars will demand a specific OEM oil standard and may make no reference to ACEA or API standards, or SAE viscosity grades.

Figure 2.135 ILSAC service symbol example (donut)

2.3 Engine cooling

2.3.1 Introduction

Heat is a form of energy that can be sensed by a change in temperature. The engine uses chemical energy in the fuel and converts it into heat and then into movement. The energy conversion process in an engine is not very efficient and only about 30% is converted into movement energy. Of the remaining heat, up to 50% goes out of the exhaust and the rest heats the engine. Excessive heating of the engine must be controlled to prevent damage. Components expand with heat and, at high temperatures, this expansion can cause seizure, and burning of pistons and valve seats. High temperature would also produce rapid deterioration of the engine oil.

Cooling systems are designed to maintain engines at an optimum temperature. This allows the design of components that expand on heating to form very tight fits and running tolerances. The adjustment of ignition and fuel settings is equated to the optimum temperature required for the clean and efficient combustion of fuel. Because a cold engine produces high levels of unwanted exhaust emissions, a rapid warm-up is needed to keep emissions to a minimum. The 'normal' running engine coolant temperature is maintained at about the boiling point of water, which enables efficient combustion. A further reduction in harmful exhaust emissions is achieved by keeping the warm-up time to a minimum. There are two types of cooling system.

Key fact

Cooling systems are designed to maintain engines at an optimum temperature.

Air-cooled systems have the air stream passing directly over the cylinder heads and cylinders to remove heat from the source (Fig. 2.137). Fins are cast into the cylinder heads and cylinders to increase the surface area of the components, thus ensuring that sufficient heat is lost.

Liquid-cooling systems use a coolant to carry heat out of the engine and dissipate the heat into the passing air stream (Fig. 2.138). The liquid coolant is contained in a closed system and is made to circulate almost continuously by the impeller on the water pump. Heat is collected in the engine and dissipated from the radiator into the passing air stream. Almost all modern cars and light vehicles use liquid cooling systems.

2.3.2 System operation

The coolant is a mixture of water, antifreeze and inhibitors. The antifreeze is usually ethylene glycol, which needs inhibitors to prevent corrosion and foaming. These inhibitors have a lifespan of about two years, which means that the

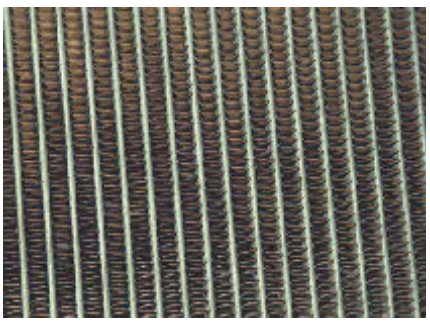


Figure 2.136 Elements of a radiator; a key component in the cooling system

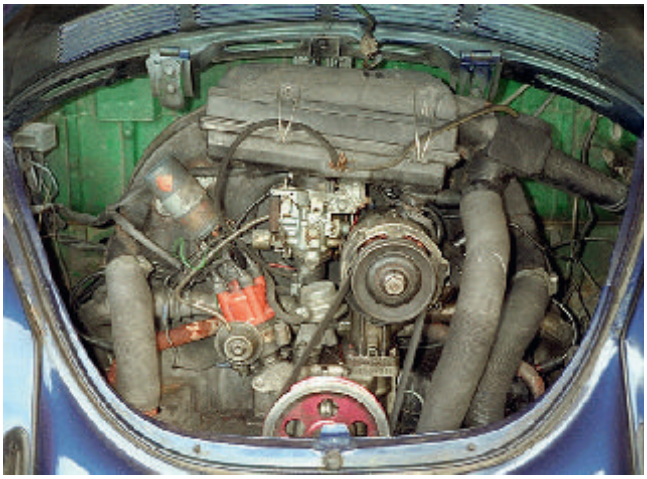


Figure 2.137 Air-cooled system

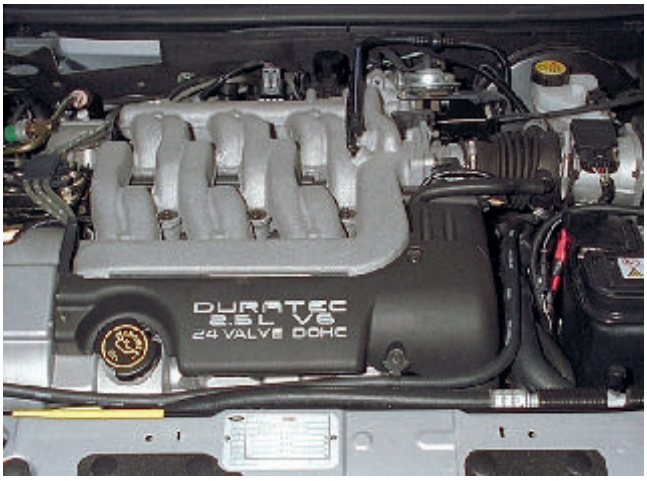


Figure 2.138 Water-cooled system

coolant should be changed at these intervals. Selection of the correct coolant mixture must be made to meet the manufacturer's specifications. Aluminium-alloy engines are more prone to corrosion than cast-iron engines.

Antifreeze is mixed to a specified ratio with water. Many manufacturers specify a 50/50 mixture of water and antifreeze, which allows higher engine temperatures before the coolant boils and prevents freezing. An ethylene glycol antifreeze solution has an added advantage. It forms a semi-solid wax solution prior to solidification and this enables any expanding ice crystals to move within the water passages.

A 50/50 coolant mixture will increase the boiling point to about 105°C (222°F) and provide protection down to −34°C (−30°F). For colder temperatures down to −65°C (−90°F), a maximum mixture of 65% ethylene glycol can be used. Higher concentrations begin to freeze at higher temperatures and therefore no more than 65% ethylene glycol should be used.

Many areas have 'hard' water that contains calcium or chalk. This separates from the water when it is heated. Deposits can form inside the water jacket or radiator where they can block small water passages. Frequent topping up with tap water in hard-water areas should be avoided. In some areas, it may be recommended to use distilled water, or water from outside the area.

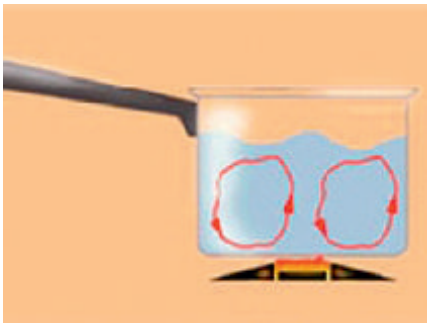


Figure 2.139 Convection

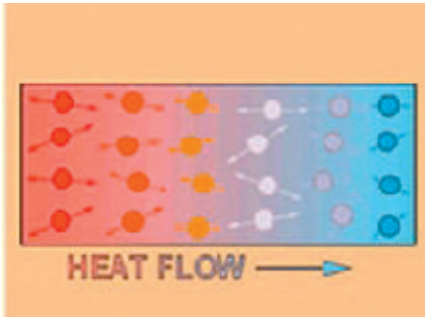


Figure 2.140 Conduction

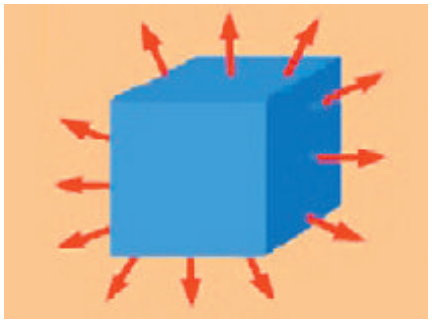


Figure 2.141 Radiation

All three forms of heat transfer are used in the cooling system:

- Convection occurs in the water jacket, creating flows of internal coolant from the cylinder block to the cylinder head (Fig. 2.139).
- Conduction occurs through the cylinder and combustion chamber surfaces as heat passes to the coolant (Fig. 2.140).
- Radiation of heat occurs from the radiator and cooling fins when heat is dissipated to the atmosphere (Fig. 2.141).

The amount of heat transfer is dependent on four main factors:

- the temperature difference between the engine and coolant
- the temperature difference between the coolant and the air stream passing through the radiator
- the surface area of the radiator tubes and fins
- the rate of flow of air and coolant through the radiator.

Key fact

Modern engines use water cooling because this is capable of giving the precise engine temperature control needed for exhaust emission regulations.

Modern engines use water cooling because this is capable of giving the precise engine temperature control needed for exhaust emission regulations. Warming up to the optimum temperature as quickly as possible is important, because it helps not only to reduce exhaust emissions, but also to prevent the formation of water particles in the combustion chamber and exhaust when the engine is cold. Any water that does not evaporate can enter the engine and contaminate the engine oil, or remain in the exhaust system and cause premature corrosive damage.

The water jacket is cast into the cylinder block and cylinder head (Fig. 2.142). Casting sand is used to shape the inside, or core, of the casting for the water passages. The sand is removed after casting through a series of holes in the sides, ends and mating faces of the cylinder block and head.

The holes in the sides and ends of the block and head are machined to provide accurate location for core plugs. The holes in the mating faces are aligned to allow coolant flow from the cylinder block to the cylinder head. These components are also machined for the fitting of the water pump and a water outlet to the radiator.

The internal designs of the head and block vary to give different coolant flow patterns (Fig. 2.143). An even flow to all areas of the engine is very important.

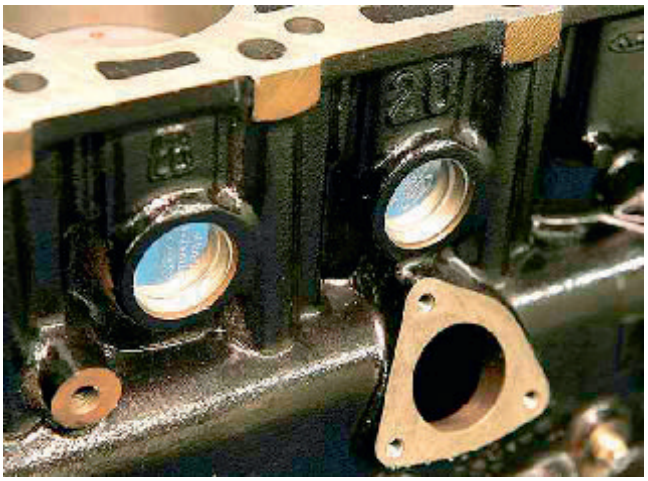


Figure 2.142 Engine block water jacket and core plugs

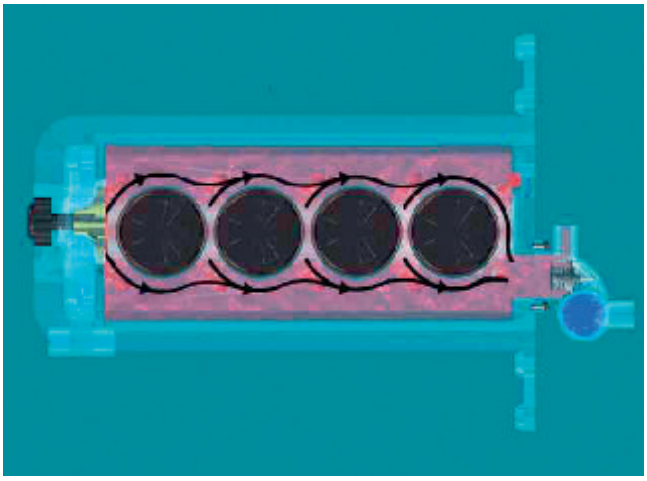


Figure 2.143 Coolant flow and temperature variations across the block

The main areas where cooling is needed are around the combustion chambers and the upper cylinder walls (Fig. 2.144). The need for inlet ports, exhaust ports and valves makes cooling of these regions difficult. These areas are prone to cracking and other deterioration from overheating, freezing and the use of incorrect, or old, antifreeze solutions.

Developments in coolant circulation give improved control of engine temperature (Figs 2.145 and 2.146). Mixing cold and hot water as it enters the engine achieves this, as opposed to the cold fill of earlier systems.

Many engines use a heated inlet manifold that has a coolant flow from the engine water jacket running continuously through it (Fig. 2.147). As soon as an engine is started, some heat is produced and this rises into the inlet manifold very quickly. The heat vaporizes the fuel in the air stream into the engine. This improves atomization and fuel distribution in the new air and fuel charge.

Liquid cooling systems traditionally used a thermostat in the outlet to the top hose to control engine temperature. A thermostat is a temperature-sensing valve that opens when the coolant is hot and closes as the coolant cools down.

Key fact

The internal designs of the head and block vary to give different coolant flow patterns.

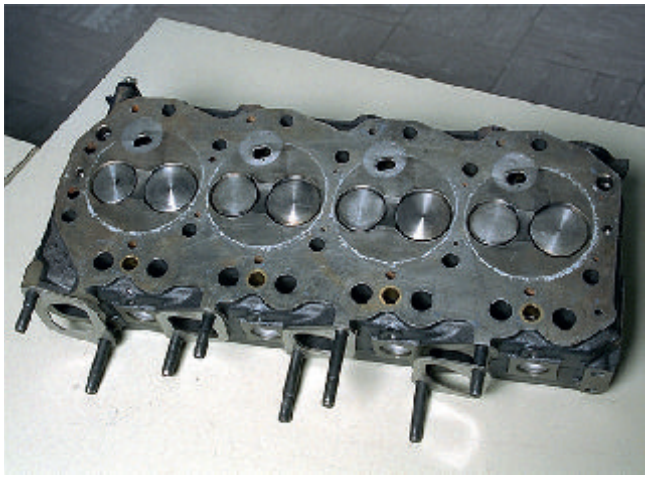


Figure 2.144 Cylinder head coolant passages

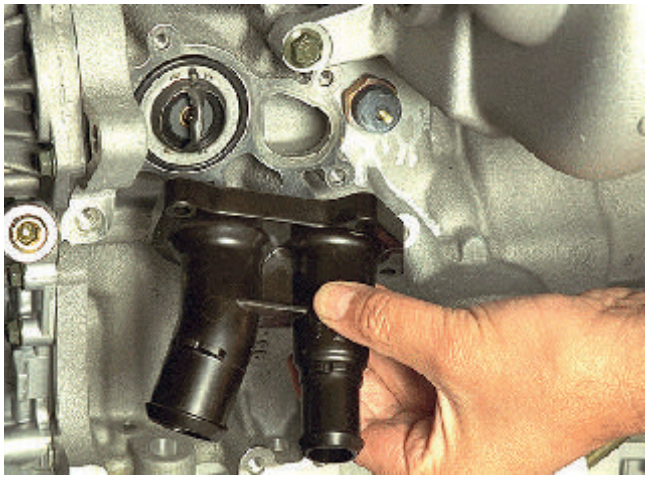


Figure 2.145 Engine coolant ports with a thermostat in position

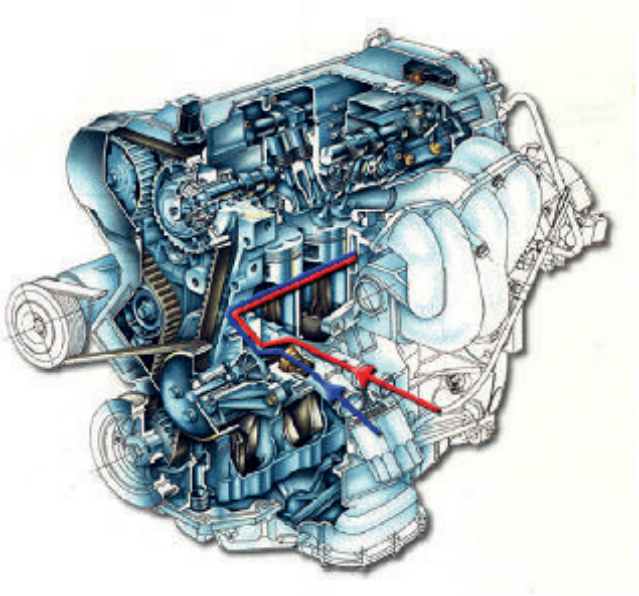


Figure 2.146 Engine coolant circuit (red is hot water, blue is cooler water)

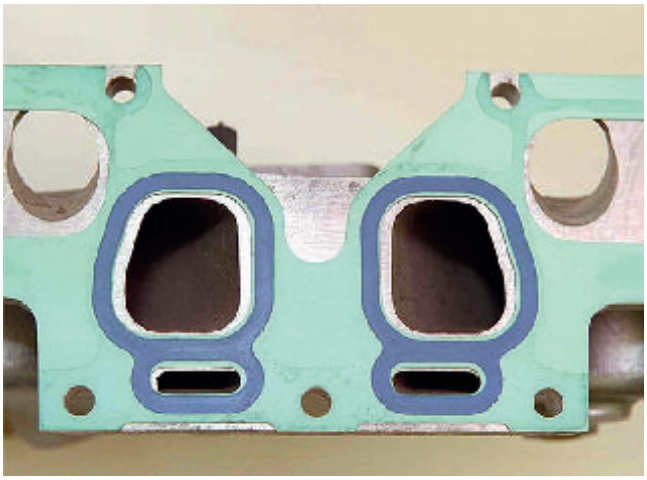


Figure 2.147 Inlet manifold

This allows hot coolant to flow from the engine to the radiator, where it cools down and returns to the engine. The cooled coolant in the engine acts on the thermostat and it closes.

The coolant reheats in the engine, the thermostat opens, and the cycle of hot coolant flow to the radiator and cool coolant returning to the engine repeats itself (Fig. 2.148). Although this system provides a reasonably effective method of engine temperature control, it produces a fluctuating temperature. However, a steady temperature is required for very clean and efficient combustion.

Many engine designers are moving towards a system with the thermostat in the radiator bypass channel (see Figs 2.145 and 2.146). When the thermostat opens, it allows cold water from the radiator to mix with the hot-water flow in the bypass as it enters the water pump. This system provides a steady engine temperature and prevents the fluctuating temperature cycle of the earlier system. The modern system is shown in Fig. 2.146 with arrows indicating the coolant flow.

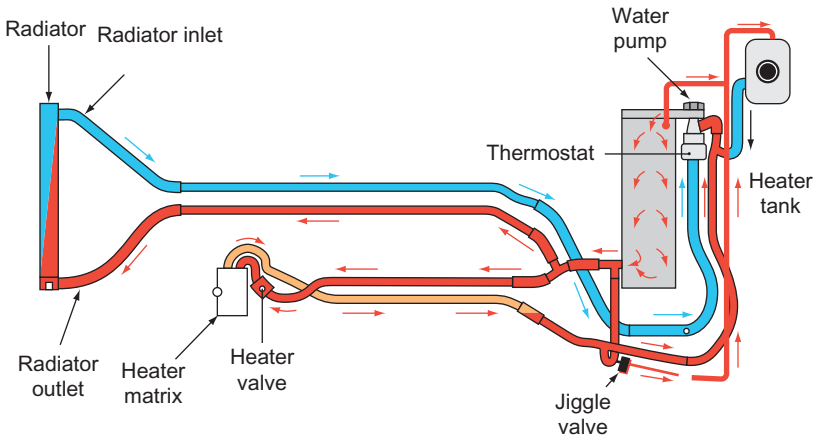


Figure 2.148 Basic cooling system

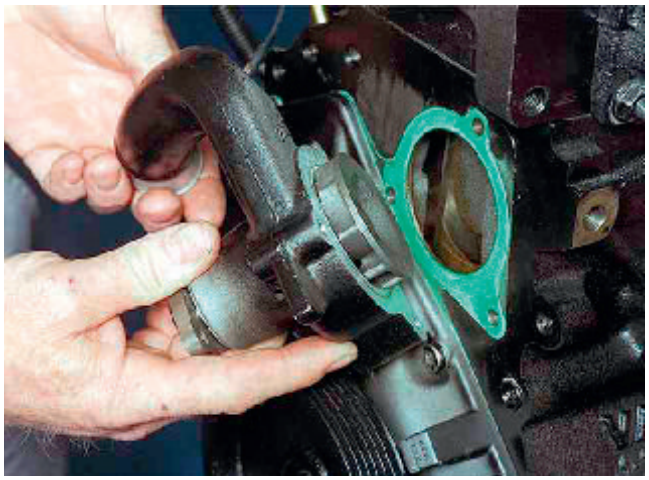


Figure 2.149 Water pump and its position in the engine block

The heat distribution within the engine needs to be controlled. The temperature around all cylinders and combustion chambers should be identical. The heat removed by the cooling system has, therefore, to be consistent for all areas of the engine. All modern engines have a fairly rapid coolant circulation within the engine so that an even temperature distribution is achieved.

The water (or coolant) pump draws the coolant through a radiator bypass channel when the engine is cold and from the radiator when the engine is hot (Fig. 2.149). The impeller on the water pump drives the coolant into the engine coolant passages or water jacket. Water-jacket passages are carefully designed to direct the coolant around the cylinders and upwards over and around the combustion chambers.

The density of coolant falls as it heats up and, as the temperature approaches boiling point, bubbles begin to form. These bubbles can create areas in the water jacket where the coolant is at a lower density and the actual mass of coolant in those areas is reduced. The reduced mass of coolant therefore cannot effectively absorb heat efficiently to cool the engine.

To overcome this problem, all liquid cooling systems are pressurized. When hot, most modern systems have an operating pressure equivalent to about one atmosphere (1 bar, or 100 kPa). The pressure is obtained by restricting the loss of

Key fact

The density of coolant falls as it heats up and, as the temperature approaches boiling point, bubbles begin to form.

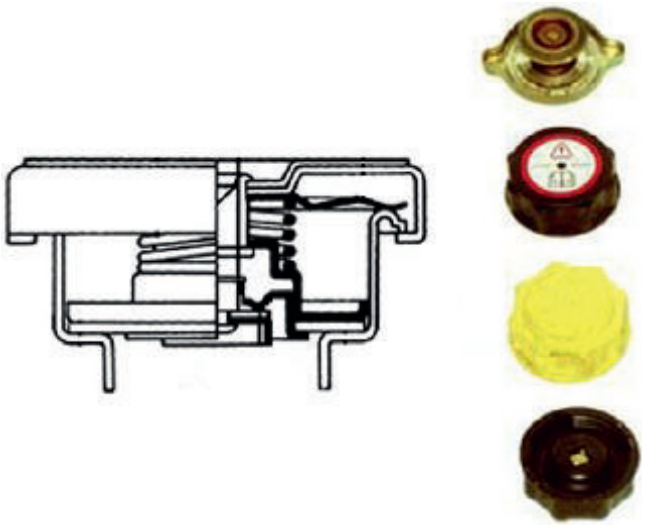


Figure 2.150 Pressure caps

air above the coolant in a radiator header tank or an expansion tank. As coolant heats up it expands. If the air above the coolant has less space to occupy, and it cannot immediately escape, it increases in pressure. A pressure-sensing valve in the radiator or header tank cap allows excess pressure to escape but retains the operating pressure.

The pressure cap was traditionally called the radiator cap because it was fitted to the radiator. On most vehicles, the cap is fitted to the expansion tank. There are many different designs and operating pressures. Vehicles are often fitted with a plastic, or nylon, cap that is specific to one manufacturer.

Key fact

The main parts of all pressure caps are the sealing ring, pressure valve, vacuum valve and a bayonet, or screw, fitting.

The main parts of all pressure caps are the sealing ring, pressure valve, vacuum valve and a bayonet, or screw, fitting (Fig. 2.150). The pressure valve consists of a spring-loaded seal that rests on a seat, either in the filler neck or in the cap. The vacuum valve allows air to return to the system as it cools to prevent a pressure lower than atmospheric. It is fitted in the centre of the pressure valve. Both the pressure valve and the vacuum valve are one-way valves and operate in opposite directions. The pressure valve allows air out and the vacuum valve allows air in. The advantages of a pressurized system are more efficient cooling with a higher safe operating temperature. It can also be used at high altitudes without the need for modification.

In a liquid-cooling system, the coolant carries heat from the engine to the radiator. Air flow through the radiator dissipates the heat into the atmosphere. Air is forced through the radiator by the forward movement of the vehicle, or is assisted by a fan fitted behind the radiator.

The fan can be driven by an electric motor (Fig. 2.151) or by a belt from the crankshaft. Early engines had the fan mounted on the front of the water pump with a 'V' belt driving the fan and pump. Fan designs that have been used include variable-pitch (to reduce noise) and viscous-hub types.

Key fact

The thermostat uses a wax pellet that expands with temperature.

The thermostat uses a wax pellet in an enclosed cup (Figs 2.152 and 2.153). Inside the wax is a rubber sleeve enclosing a pin. The pin is connected to a plate that acts as the valve. All these components are held in the thermostat body, together with a spring to hold the valve closed when the coolant is not hot. The thermostat body includes a flange that fits into a housing in the coolant outlet from the cylinder head, or a radiator-bypass channel.

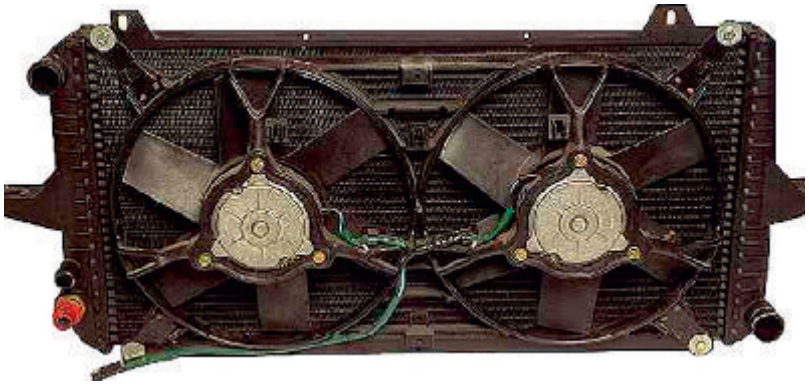


Figure 2.151 Twin electric fans

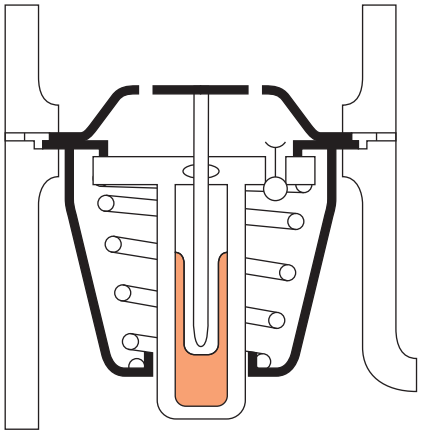


Figure 2.152 Thermostat closed

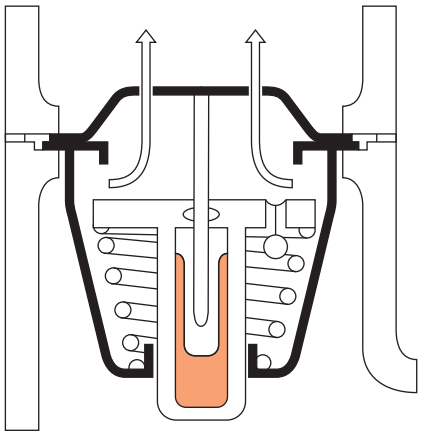


Figure 2.153 Thermostat open

When the temperature of the coolant acting on the wax pellet reaches the operating temperature, there is sufficient heat to cause the wax to expand, press on the pin, and force it out of the cup to open the valve. Coolant is then free to flow through the valve.

The wax pellet must always be fitted so that it sits on the hot side of the coolant flow through the thermostat (Fig. 2.154).

Some thermostat flanges are fitted with a small subvalve to allow air to flow through the thermostat as the system is filled with coolant (Fig. 2.155). This small valve must

Figure 2.154 Thermostat with its wax pellet in the hot-coolant area

Figure 2.155 Thermostats

be fitted towards the top if the thermostat is fitted on its side. Some manufacturers fit the thermostat in a radiator hose. The thermostat may also be fitted directly into its own housing and, if so, has to be replaced as a complete assembly.

The various designs and manufacturing materials used for radiators (Fig. 2.156) all consist of a series of small tubes through which the coolant flows (Fig. 2.157). Very thin sheets of metal are used to form a large surface area surrounding the small tubes. This large surface area makes radiators efficient heat exchangers for engine-cooling purposes.

The radiator tubes are fitted to tanks at each end, and these tanks are fitted with connections for the top and bottom or cross-flow hoses. The traditional radiator had the core tubes set vertically and the coolant flowing downward from the header tank to the bottom tank (Fig. 2.158). The air space required for expansion of the coolant could be either in the header tank or in a separate expansion tank.

However, because of the lower frontal area of most modern cars and light vehicles, a different radiator layout is needed. The cross-flow radiator has tubes and thin sheet fins forming the core (Fig. 2.159). The core tubes run across the vehicle and the coolant flows from one side to the other. The tanks at each end of the radiator are joined to the core and have connections for the hoses.

Key fact

Cross-flow radiators usually have a remote expansion tank to which the pressure cap is fitted.

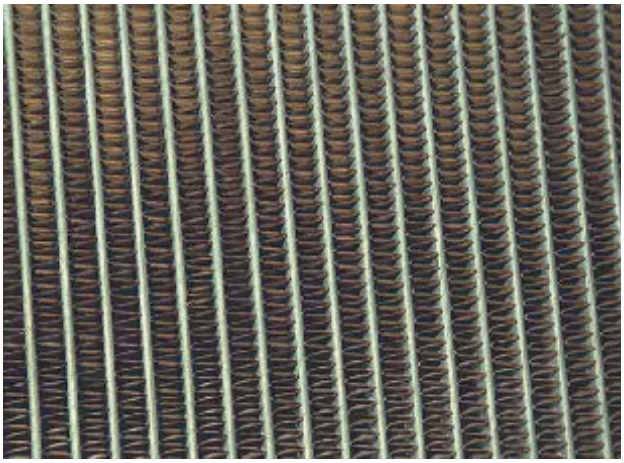


Figure 2.156 Radiator core construction

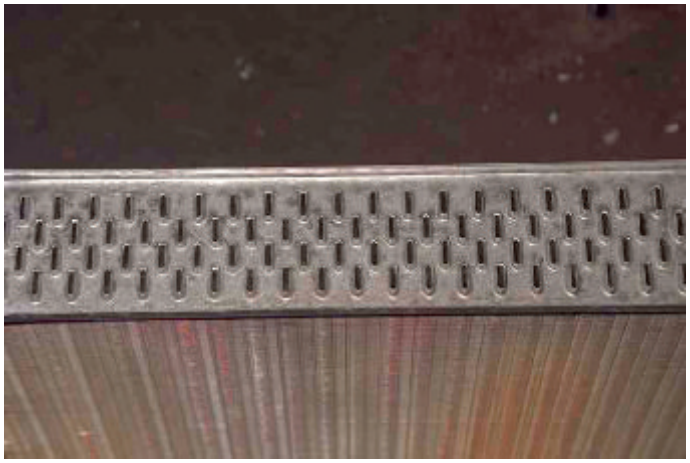


Figure 2.157 Radiator tubes

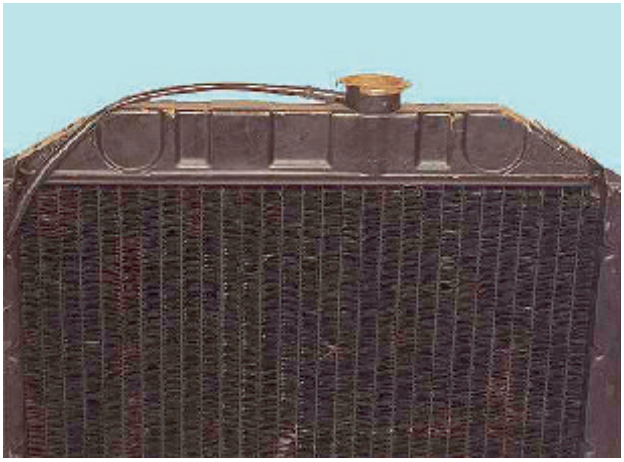


Figure 2.158 Traditional radiator

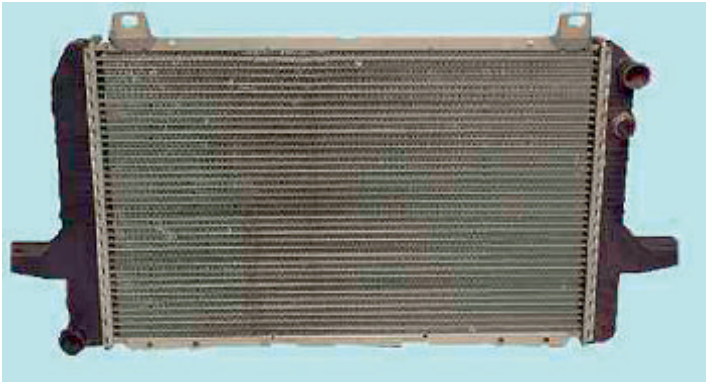


Figure 2.159 Cross-flow radiator

Cross-flow radiators usually have a remote expansion tank to which the pressure cap is fitted (Fig. 2.160).

Modern radiators are constructed from an aluminium core with nylon, or plastic end-tanks that are cinched together (Figs 2.161 and 2.162). This is a method of

Figure 2.160 Remote expansion tank (on the left)

Figure 2.161 Aluminium and plastic radiator

Figure 2.162 The heater matrix (radiator) is similar to the main radiator but smaller

folding the edges of the radiator core ends over a sealing ring and a lip on the end-tank. Aluminium radiators are lighter and cheaper to produce than traditional copper/brass radiators.

The water pump is usually fitted into the water jacket of the cylinder block (Fig. 2.163). However, there have been some engines where it has been fitted into the cylinder head. An external water pump is used on some engines and connected to the water jacket by pipes or hoses (Fig. 2.164). The water pump is driven from the engine crankshaft by a belt.

Figure 2.163 Water pump in water jacket

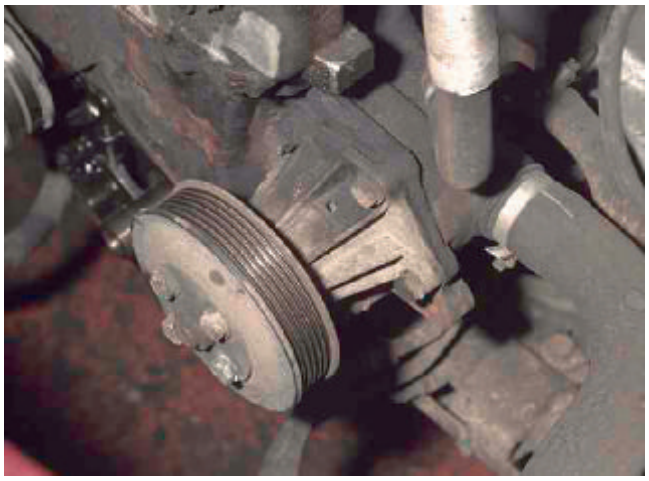


Figure 2.164 External water pump

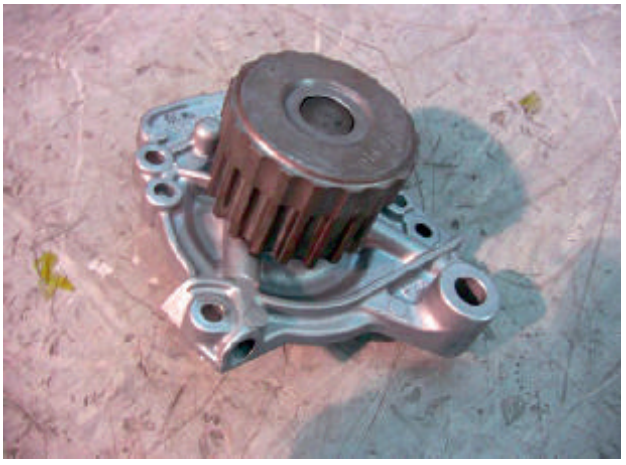


Figure 2.165 Water pump drive gear (cam belt)

Running through the centre of the water pump is a spindle mounted on a bearing. The bearing is prepacked with grease, and fitted with seals for retaining the grease and keeping the coolant in the engine. The drive pulley is fitted to the spindle on the outside of the pump. The movement of the impeller assists coolant flow through the water jacket. Water pumps are supplied as a replacement part fully assembled in a housing holding the bearing, spindle, impeller and drive flange for the pulley (Figs 2.165 and 2.166).

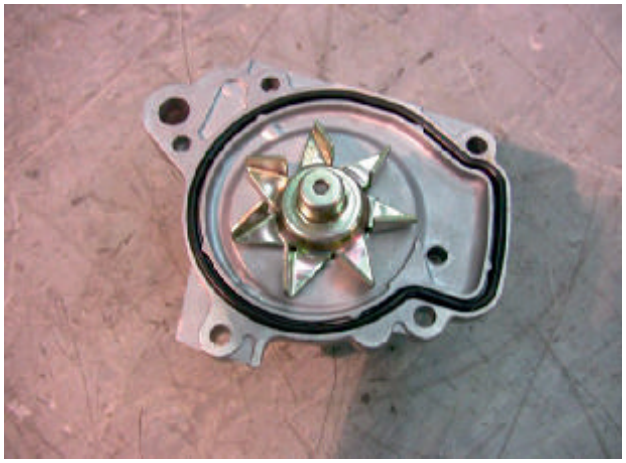


Figure 2.166 Water pump impeller

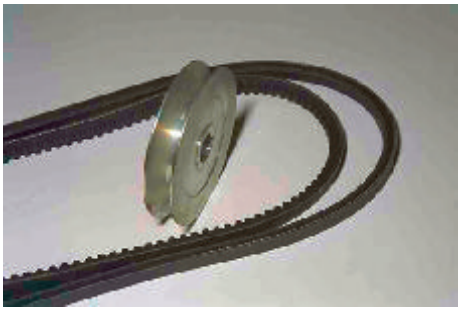


Figure 2.167 'V' belt and pulley

Figure 2.168 Multi-V belt and pulley

The drive components for the water pump on earlier cars consisted of a 'V' belt that also drove the alternator (Fig. 2.167). On many other vehicles multi-V belts are also in common use (Fig. 2.168). An adjuster for the belt is provided on the alternator mounting, or as a separate tensioner. The toothed camshaft drive belt is used to drive the pump on some vehicles (Fig. 2.165).

A fan is used to ensure an adequate air flow through the radiator when this is not provided by the forward speed of the vehicle. The fan was traditionally fitted to the front of the water pump and attached with the same bolts as the drivebelt pulley. Some longitudinal engines still use this system, but the fan, formerly a pressed-steel component, now incorporates a thermostatic viscous hub and nylon fan blades (Figs 2.169 and 2.170). The viscous hub is a fluid clutch using silicon oil. The operation of the clutch is temperature controlled with a bimetallic valve. When the air flow temperature over the viscous hub is cool, the valve

Figure 2.169 Viscous-fan hub on an earlier engine

Figure 2.170 Viscous-fan hub

Figure 2.171 Motor-driven fan

remains closed and the clutch is inoperative. When the air flow temperature over the viscous hub increases, the valve in the hub opens and the viscous fluid is driven outwards by centrifugal force. The increased force in the fluid locks the plates in the hub together to engage the clutch drive to the fan.

An improved temperature-sensing arrangement is for the fan to be driven by an electric motor mounted on a cowl frame attached to the radiator (Fig. 2.171). A plastic fan is fitted to the motor spindle and operates when a temperature-sensitive switch closes. The electrical supply to the motor is connected through a relay.

Key fact

Many vehicles, particularly those fitted with air conditioning, have two-speed fan circuits.

Many vehicles, particularly those fitted with air conditioning, have two-speed fan circuits. These have a control circuit to switch the motor (or motors) to half speed at 95°C, and full speed at 100°C. This arrangement can be also be operated by the engine management system.

Cooling system hoses are manufactured from fabric-reinforced rubber, and are moulded to suit the vehicle application. Connectors are cast, or formed, with a raised lip on the pipes leading into, and out of, other components. The hoses are held with round clips that can be drawn tight to give a watertight seal (e.g. jubilee clips).

2.3.3 Interior heater

The vehicle interior heater is made from an air box with a heat exchanger inside. The heat exchanger, called a heater matrix or a heater radiator (Fig. 2.172), is very similar to the cooling radiator in that it consists of a similar series of tubes and fins. Hot coolant from the engine flows through the matrix, thus heating the tubes and fins. Air flows across the outside and collects some of the heat for distribution inside the vehicle.

Air is drawn into the heater through ducts on the vehicle exterior. The design of the ducts provides a dust and water trap, and usually the ducts have an outlet hose for water drainage. Many vehicles have a pollen filter fitted in the air-intake ducts (Fig. 2.173). The filter is a microporous paper element that traps pollen and dust particles.

Figure 2.172 Heater radiator

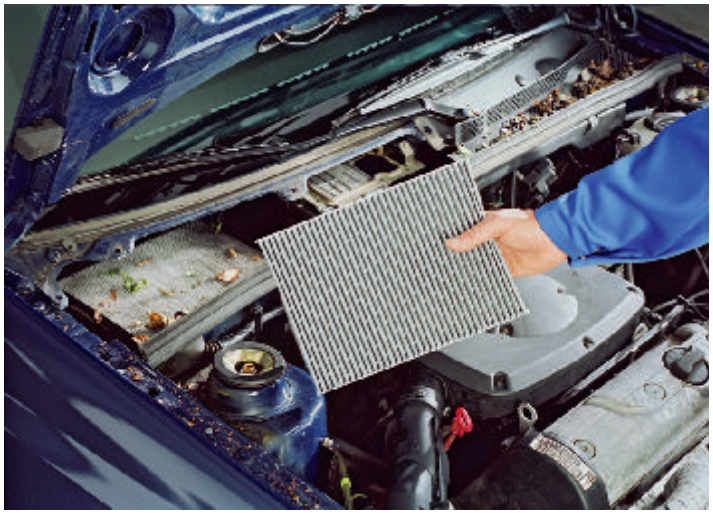


Figure 2.173 Heater intake with pollen filter

The distribution of air inside the vehicle is provided by a series of ducts and outlets. These are positioned on the underside of the fascia, at fascia level, and adjacent to the front and side screens (and in the doors on some cars). The outlets can be selected by operating the controls to the required positions (Fig. 2.174). The controls are connected to flaps in the heater air box by a cable, a vacuum system or an electrical actuator. The flap position directs air to the appropriate outlet.

On older vehicles, temperature selection was achieved by regulating the coolant flow through the heater, by means of a valve. More often now it is by a flap in the heater air box that directs how much air flows through the heater matrix (Fig. 2.175). The flap is controlled in the same way as the air direction flaps. Thermostatic devices are used to control air temperature on some vehicles.

A blower motor in the air-intake duct boosts air flow through the heater system (Fig. 2.176). The motor may be fitted with a series of resistors or be electronically controlled to provide a range of speeds.

Most modern heaters are linked with an air conditioning system. This is covered in Chapter 3.

Figure 2.174 Air flow and heater controls

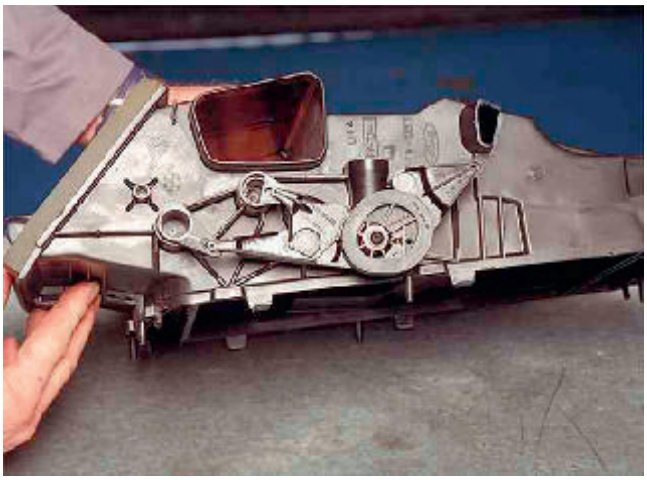


Figure 2.175 Heater control with flaps

Figure 2.176 Heater motor fan

2.4 Air supply, exhaust and emissions

2.4.1 Air pollution and engine combustion

Key fact

The rapid burning of fossil fuels during the past century increased carbon dioxide levels in the atmosphere.

Atmospheric pollution has become a serious problem to the health of people and to the environment. Many urban areas are heavily polluted, with people suffering medically from the effects of vehicle exhaust pollution. There have been many changes in climatic conditions in the world. Many of these have occurred over a long period and animals and plants have adapted to the changes naturally. However, the rapid burning of fossil fuels during the past century has increased carbon dioxide (CO_2) levels in the atmosphere.

Carbon dioxide allows the sun's heat in, but reduces the ability of the heat to radiate outward, causing the Earth to warm up. Many studies of the warming process indicate that the rate of Earth warming is increasing too quickly and preventing animals and plants from adapting. Vehicle exhaust gas also includes other toxic components (Fig. 2.177). Environmental regulations are now in place to find safer alternatives, or to reduce the production and use of the most harmful pollutants. Other regulations and agreements are seeking to reduce the production of carbon dioxide by improving the efficiency of fossil fuel burners.

Lead was at one time used as an additive in petrol to slow down the combustion process. This was to eliminate knocking or pinking in the engine. It made engines more efficient but the lead did not burn and was, instead, passed into the atmosphere from the exhaust and produced airborne concentrations that were capable of causing many physical disabilities, including brain damage. For this reason, lead additives are no longer used and modern engines are now designed to run on lead-free fuel.

Another naturally occurring substance in fossil fuels, particularly diesel, is sulphur. This does not burn but, during combustion, chemically reacts with oxygen in the air to form sulphur dioxide (SO_2). This passes from the engine exhaust into the atmosphere, where it combines with water to form sulphuric acid (H_2SO_4) and falls back to Earth as acid rain, which destroys trees, plants, other vegetation and

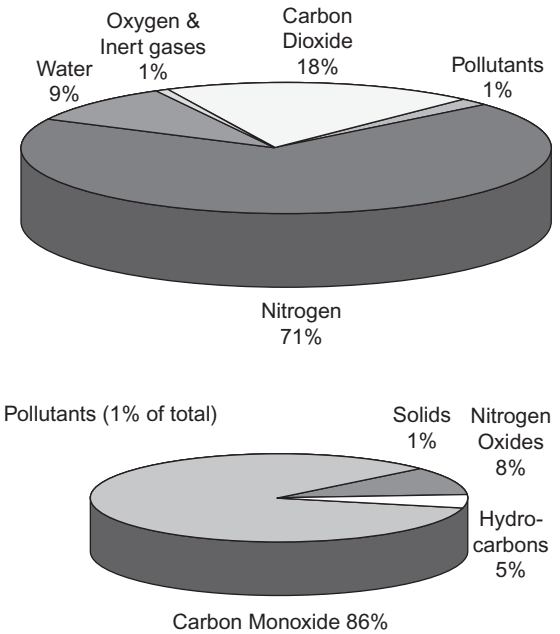


Figure 2.177 Approximate composition of vehicle exhaust gases

aquatic life in streams, rivers and lakes. Fuel suppliers now remove, or significantly reduce, the amount of sulphur during the refining process.

Air consists of about 80% nitrogen which, under normal circumstances, is an inert gas. An inert substance is one that has very little chemical reactivity and does not burn, or mix easily with other chemicals. Nitrogen, however, will mix with oxygen at high temperatures to form nitrogen oxides (NO_x). These combine in exceptional geographical and meteorological conditions to form smog, acids and increases in low-level ozone. This serves to make a very unpleasant atmosphere in which to live. Many respiratory and asthmatic fatalities occur under these conditions.

Definition

Inert substance
A substance with very low chemical reactivity.

The combustion of fuel inside the engine is a chemical process that combines the carbon and hydrogen in the fuel with oxygen to release energy. Slightly less than 20% of air is made up of oxygen. Complete combustion produces carbon dioxide (CO_2) and water (H_2O). Neither of these is directly harmful. Both are naturally occurring substances in the atmosphere (but note the comments in the previous section).

Incomplete combustion leaves some of the carbon and oxygen not fully combined. The product of this is carbon monoxide (CO), which is toxic. Small quantities of carbon monoxide molecules are dangerous because they attach themselves to red blood cells. This reduces the oxygen that the cells normally carry around the body, resulting in oxygen deprivation, brain damage and fatality.

Another product of incomplete combustion is particles of fuel that have not been burnt. These are carried, with the exhaust gases, into the atmosphere and are called unburnt hydrocarbons. Very small amounts of hydrocarbons in the atmosphere can cause respiratory problems.

Engine oil drawn into the combustion chamber, either from the inlet valve stem or by bypassing the pistons, can also be a source of hydrocarbon pollution. Oil vapours form in the engine crankcase and can escape into the atmosphere. A positive crankcase ventilation system is now used to draw the vapours into the engine so that they are burnt to form water and carbon dioxide.

On old vehicles, vapour in the fuel tank was directly vented to the atmosphere. This is no longer the case, but the fuel tank must still be vented in some way to allow air to flow into the tank as fuel is used. A charcoal filter is now used to prevent the loss of fuel vapour and for the expansion of the fuel when the weather is hot. The fuel vapour in the charcoal canister is drawn into the engine and burnt.

Good fuel economy is obtained with a lean air-to-fuel mixture. However, this mixture produces higher combustion temperatures and greater risks of NO_x being formed. In order to prevent, or reduce to a minimum, the formation of NO_x, the combustion temperature has to be kept as cool as possible and the amount of oxygen limited to match the quantity of fuel delivered. To reduce the amount of oxygen in the air charge, a gas that is low in oxygen can be introduced. This maintains the total air-charge mass to give good compression pressures and efficient operation of the engine. The available gas is the exhaust gas that has already used up its oxygen content during combustion. The addition of a regulated charge of exhaust gas reduces the oxygen content of the new charge to suit the amount of fuel delivered. This, in turn, reduces the combustion temperature and limits the formation of NO_x. Catalytic conversion of any remaining harmful gases can result in a much cleaner exhaust gas.

Key fact

Good fuel economy is obtained with a lean air-to-fuel mixture.

2.4.2 Reducing pollution

Vehicle engine and component manufacturers have put a great deal of effort into reducing pollution. For example, lead is no longer needed in petrol (gasoline)

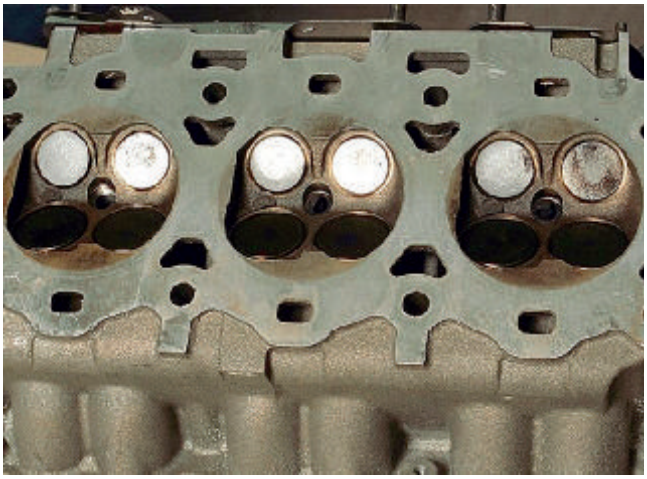


Figure 2.178 Valves

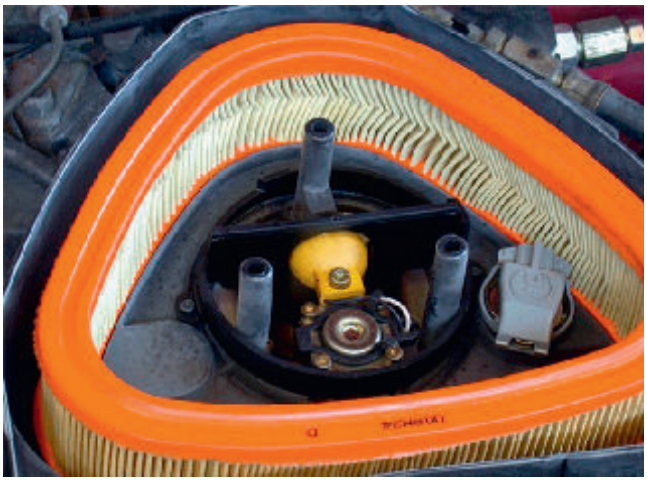


Figure 2.179 Air filter

because other less damaging substitutes have been found. The changes in the fuel have necessitated the use of hardened valves and valve seats and changes to the ignition timing and fuel delivery systems (Fig. 2.178).

Air-intake systems have been developed from a simple ducting to a complex air-flow design adapting to the changing speed and load conditions of the engine. Filtration is also an important aspect (Fig. 2.179).

Electronic control of the combustion process has been the key development, and has achieved reductions in CO, NO_x and hydrocarbon emissions. Exhaust gases are monitored by the electronic engine control module by signals sent from a lambda, or oxygen, sensor in the exhaust (Fig. 2.180). This monitoring allows fuel and air supplies to be accurately controlled for optimum combustion.

The remaining pollutants in the exhaust gases, which cannot be eliminated or reduced by the electronic systems, are converted into less harmful substances. This is achieved by using a catalytic converter (Fig. 2.181).

Developments to improve the atomization and the mixing of the fuel in the incoming air stream include heating the inlet manifold, or heating the air as it enters the inlet manifold. This is achieved by preheating the air by ducting the air supply over the exhaust manifold (Fig. 2.182).

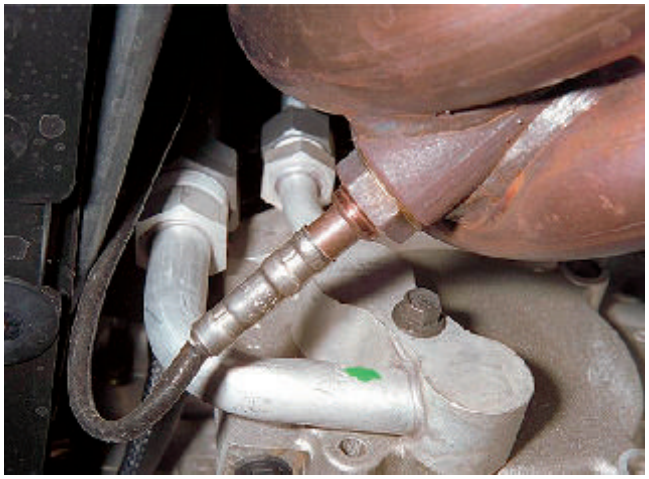


Figure 2.180 Lambda sensor in the exhaust

Figure 2.181 Catalytic converter

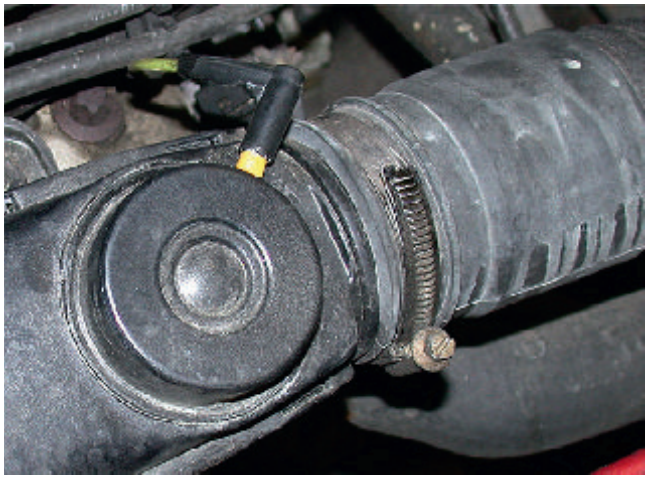


Figure 2.182 Air temperature control valve

Oil and fuel vapours are trapped and routed through the engine to be burnt. Positive crankcase ventilation and a charcoal filter in an evaporative canister are used for this purpose (Fig. 2.183). Nitrogen oxide formation is reduced with EGR.

Figure 2.183 Evaporative emission control system (EVAP) canister

Figure 2.184 Turbocharger with electronic control. (Source: Bosch Media)

Engine performance has been increased, without an increase in weight, by the use of supercharging and turbocharging (Fig. 2.184). Other emission-control devices that correct the ignition timing and fuel delivery are covered in the appropriate sections. These devices improve the performance of those systems, as well as reducing harmful exhaust emissions.

2.4.3 Air supply system

Key fact

Creating a swirl in the air flow as it enters the cylinders improves efficiency.

The air supply system has to provide clean air in sufficient quantity to the engine (Fig. 2.185) and supply equal quantities of air to each cylinder. This will assist fuel vaporization and an even mixture distribution. Creating a swirl in the air flow as it enters the cylinders is also desirable. A system of warm air for cold starts, followed by temperature-controlled air for normal running, is essential. Finally, the system must silence the air flow and provide a flame trap in the event of fire in the inlet manifold.

The air supply systems for most vehicles are similar. They consist of an air-intake duct, an air-temperature control mechanism, an air-cleaner housing and filter, an inlet manifold and inlet ports. A position for an EGR system may also be

Figure 2.185 Air supply components

Figure 2.186 Throttle body

included. For fuel injection engines, the system will also include a throttle-body housing and an air-flow meter (Figs 2.186–2.188).

Clean air is required in the engine to prevent particles of dust and grit from damaging, or blocking, engine and fuel-supply components. Air is filtered through an element in the air cleaner. Most air-cleaner elements are made from microporous paper, which allows a good flow of air but traps airborne dust. Other elements have included oiled wire gauze and foam rubber. The air-cleaner housing and the filter elements are cleaned, or replaced, at scheduled service intervals.

Key fact

Most air-cleaner elements are made from microporous paper, which allows a good flow of air but traps airborne dust.

Paper elements are folded to provide a large surface area and long service life. The element can be wrapped to form a circular element if required. The outside edges are sealed with an integral, or separate, rubber sealing ring. Air-cleaner housings have internal ducting to distribute the air over the full surface of the filter (Fig. 2.189). The air flow in some filter housings is made to swirl so that airborne dirt is thrown out and falls into a dust trap in the base of the filter. The air flow into flat filters is from the underside so that dirt falls out from below, rather than into the top of, the filter.

The inlet manifolds on modern engines are usually of the same length and diameter to enable all cylinders to be supplied with the same volume of air and

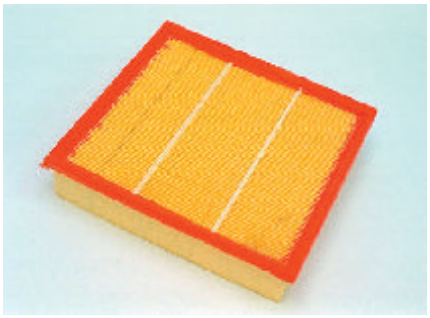


Figure 2.187 Air filter

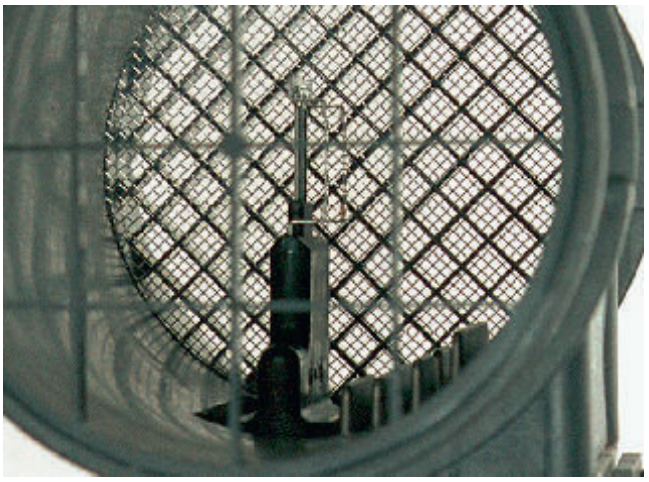


Figure 2.188 Air flow meter

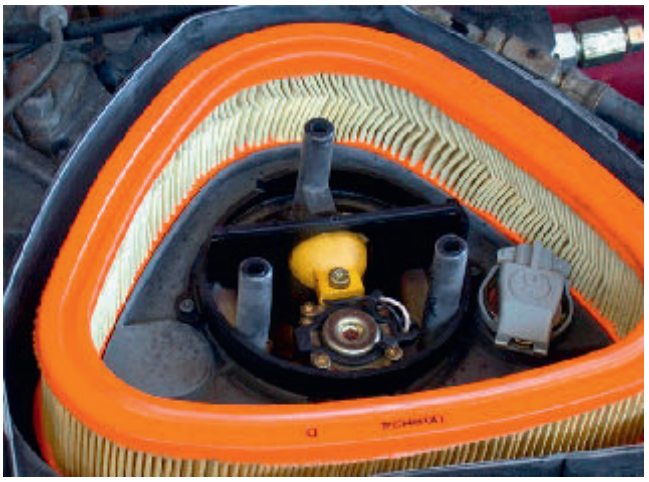


Figure 2.189 Filter in its housing

to provide the same air flow characteristics (Fig. 2.190). Early engines, with manifolds using pipes of differing lengths, often produced slightly different combustion patterns in each of the cylinders.

At the entrance to the inlet manifold is the throttle body controlling the flow and quantity of air entering the engine.

On most engines, the temperature of the incoming air supply is controlled. Heating the air entering the inlet duct assists in atomization and fuel distribution

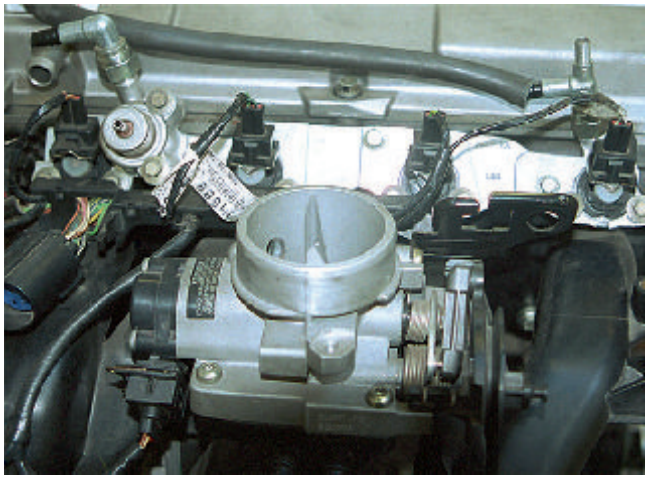


Figure 2.190 Plastic inlet manifold

Figure 2.191 Pick-up for hot air on an exhaust manifold

in the air charge. To warm the air, it is passed over the exhaust manifold before being drawn into the air duct (Fig. 2.191). This is only necessary when the air is cold. When the engine temperature increases, the air density, and therefore mass, would be reduced if heating of the air were continued. At an engine temperature of about 50°C, the full air supply is drawn from a cold position in the engine compartment, or from the front of the vehicle. Between a cold engine and 50°C, progressive mixing occurs.

Key fact

Heating the air entering the inlet duct assists in atomization and fuel distribution in the air charge.

The ducting of warm, or cool, air is controlled by a flap in the air-cleaner intake. This provides either a normal air flow, or one from over the exhaust manifold. Several designs of thermostatically controlled air-cleaner operation are used. One type uses a vacuum motor and bimetallic vacuum valve, while another uses a wax-pellet actuator. On some vehicles an electrical actuator is used under the control of the engine management system.

The layout of the vacuum system is shown in Fig. 2.192. The bimetallic valve responds to the temperature of the incoming air stream and opens or closes the vacuum supply from the inlet manifold to the vacuum motor. The motor reacts to the vacuum supply to move the flap and mix warm and cool air.

Figure 2.192 Warm-air control (vacuum type)

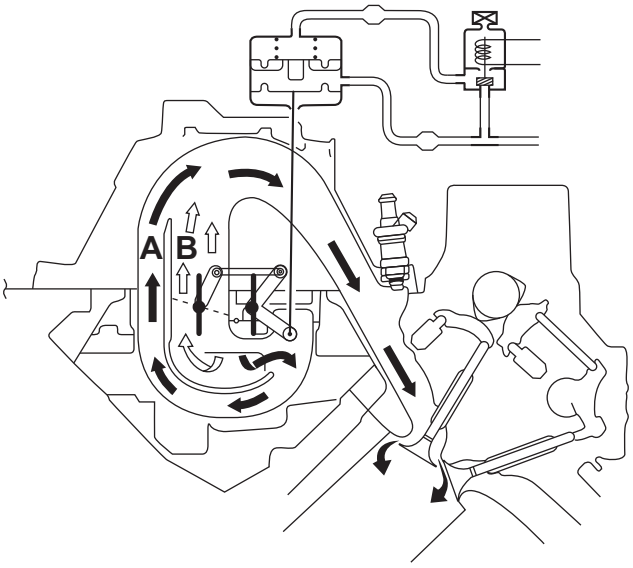


Figure 2.193 Inlet tracts change at different speeds: A: long tract, B: short tract

The air supply to each cylinder passes through equal length and diameter tubes of the inlet manifolds. Feeding the manifold tubes is a plenum chamber, which holds a large volume of air so that each intake tube receives an equal air supply. The air flow is made to swirl in the intake tubes, and careful design of the shape and direction of the tubes is required to make this happen. Another factor affecting the swirl is the volume and speed of the air flow.

Some engines have a dual-intake system that responds to low and high engine speeds (Fig. 2.193). These systems have valves that open at higher engine speeds to balance the pressure in the two intake manifolds, or open to enable a secondary air supply to provide an adequate air flow for the higher engine speed. These systems have been developed to meet the changing air flow and swirl characteristics occurring with increases in air mass and speed.

2.4.4 Exhaust systems

The exhaust system has to carry the exhaust gases out of the engine to a safe position on the vehicle, silence the exhaust sound and cool the exhaust gases.

Figure 2.194 Exhaust system

It also has to match the engine gas flow, resist internal corrosion from the exhaust gas, and resist external corrosion from water and road salt.

The exhaust system consists of the exhaust manifold, silencers, mufflers, expansion boxes and resonators (Fig. 2.194). It also has down or front pipes, intermediate and tail pipes, heat shields and mountings. Also included are one or more catalytic converters, one or two lambda sensors and a connection for the EGR system.

The exhaust gases are at a very high temperature when they leave the combustion chambers and pass through the exhaust ports. The exhaust manifold is made from cast iron to cope with the high temperatures. The remainder of the exhaust system is made from steel, which is alloyed and treated to resist corrosion. The downpipe, or front pipe, is attached to the manifold with a flat, or ball, flange. This joint is subject to bending stresses with the movement of the engine in the vehicle. To accommodate the movement and reduce stress fractures, some flange connections have a flexible coupling made from a ball flange joint and compression springs on the mounting studs.

Safety first

The exhaust gases are at a very high temperature when they leave the combustion chambers and pass through the exhaust ports.

Another system to accommodate movement is a flexible pipe constructed from interlocking stainless-steel coils or rings. Where a flexible joint is not required, the front pipe may be supported by a bracket welded to the pipe, which is bolted to a convenient position on the engine or gearbox. Where a catalytic converter is used, it is fitted to the front pipe so that the exhaust heat is used to aid the chemical reactions taking place within the catalytic converter. The pipe continues and then connects to an expansion box or silencer (muffler). The exhaust gases are allowed to expand into this box and begin to cool. They contract on cooling and slow down.

Silencers or mufflers are constructed as single- or twin-skin boxes, and there are two main types: the absorption type, which uses glass fibre or steel wool to absorb the sound, and the baffle type, which uses a series of baffles to create chambers (Figs 2.195 and 2.196). In the baffle type, the exhaust gases are transferred from a perforated inlet pipe to a similarly perforated outlet pipe. These silencers have a large external surface area so that heat is radiated to the atmosphere. Additional pipes and silencers carry the exhaust gas to the rear.

Pipes are joined together by a flange, or clamp, fitting. Flange connections have a heat-resistant gasket and through-bolts to hold the flange together (Fig. 2.197).

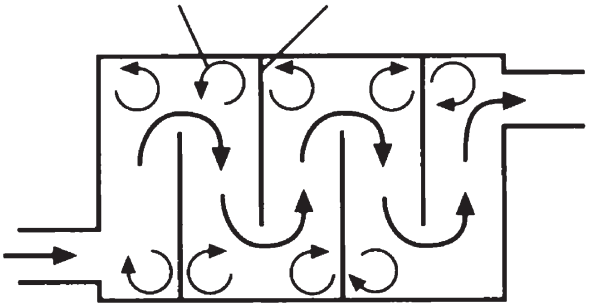


Figure 2.195 Baffle silencer

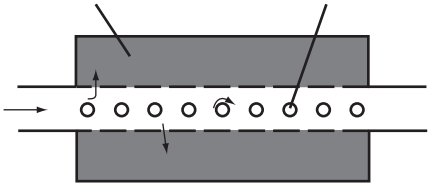


Figure 2.196 Absorption silencer

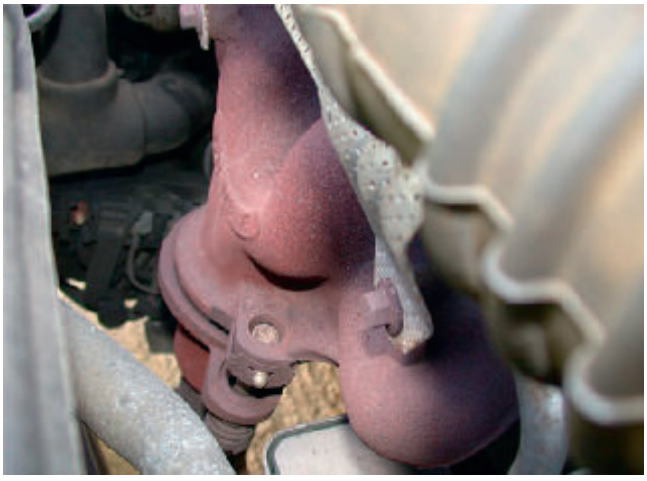


Figure 2.197 Flange connections

Clamp fittings are used where pipes fit into each other (Fig. 2.198). The larger pipe is toward the front and the smaller pipe fits inside. A ring clamp, or 'U' bolt and saddle, are tightened around the pipes to give a gas-tight seal. An exhaust paste is usually applied to improve the seal of the joint. The exhaust system must be sealed to prevent toxic exhaust gases from entering the passenger compartment.

The exhaust is held underneath the vehicle body on flexible mountings (Fig. 2.199). These are usually made from a rubber compound and many are formed as a large ring that fits on hooks on the vehicle and the exhaust-pipe brackets. Other mountings are bonded-rubber blocks on two steel plates (Fig. 2.200).

Heat shields are fitted to the exhaust, or to the vehicle floor, to prevent the ignition of sound-deadening and anti-corrosion materials. Catalytic converters become very hot during operation. It is important, therefore, that all heat shields are correctly fitted and positioned to insulate the vehicle from the high temperature of the catalytic converter (Fig. 2.201).

Key fact

Heat shields are fitted to the exhaust, or to the vehicle floor, to prevent the ignition of sound-deadening and anti-corrosion materials.

Figure 2.198 Pipe connections

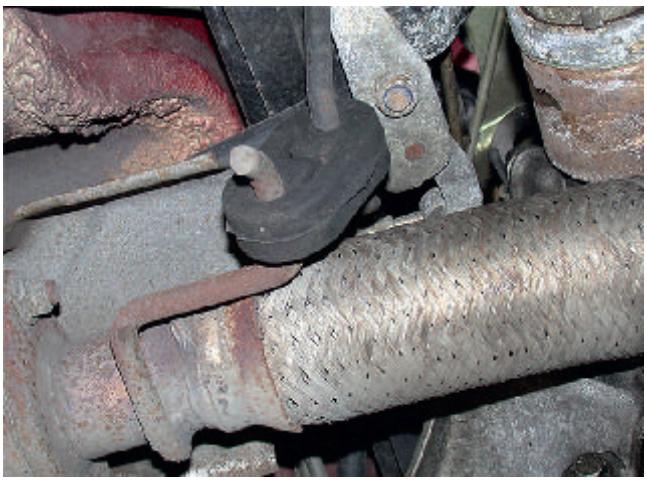


Figure 2.199 Flexible mountings (sometimes called pig noses)

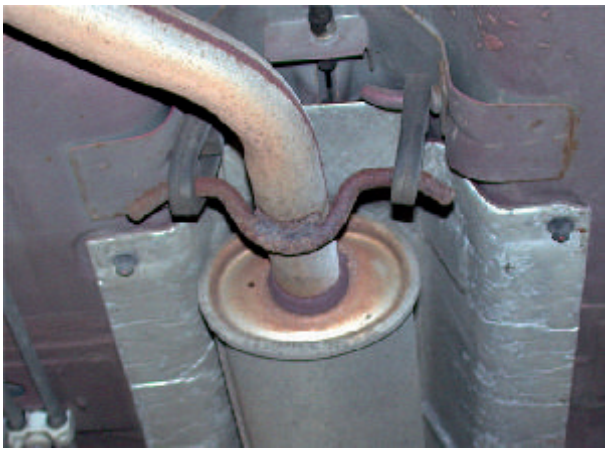


Figure 2.200 Rubber mountings

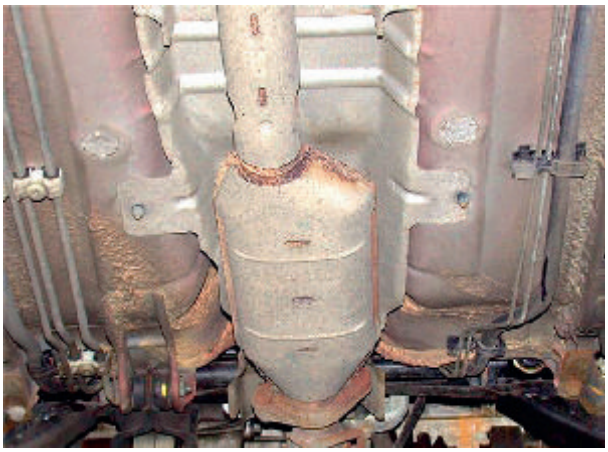


Figure 2.201 Catalytic converter in position with a heat shield above

2.4.5 Catalyst systems

A catalyst is a substance that will accelerate (or, in some cases, slow down) chemical changes in other substances without itself changing. The purpose of the catalytic converter on a vehicle is to convert potentially harmful chemicals

Definition

Catalyst
A substance that will accelerate chemical changes in other substances without itself changing.

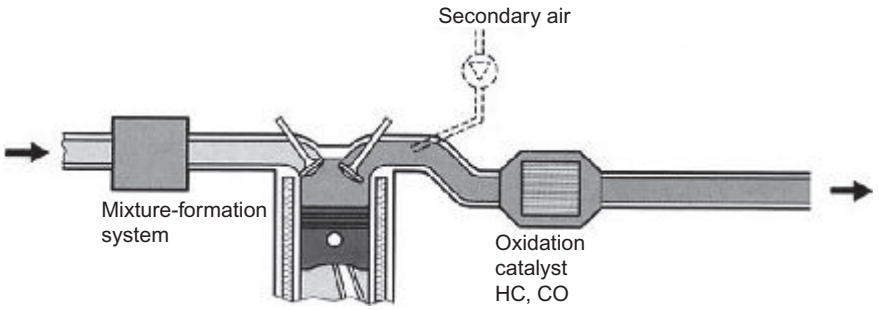


Figure 2.202 Early catalytic system with additional air injection

Figure 2.203 Honeycomb substrate. (Source: Denso Media)

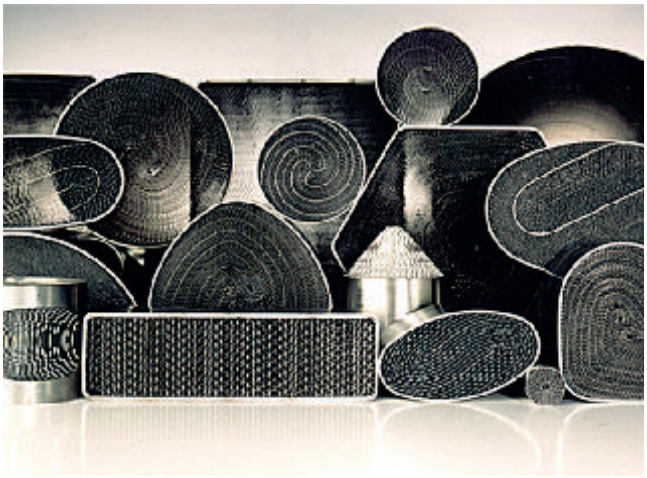


Figure 2.204 Steel substrate

in the exhaust gas into harmless water vapour, carbon dioxide, nitrogen and oxygen.

Several types of catalytic converters have been used on motor vehicles. However, almost all petrol (gasoline) vehicles now use a three-way catalyst. The main catalytic materials used consist of a mixture of platinum, palladium and rhodium, but less expensive materials are being investigated and developed. The catalytic material is applied as a thin coat to ceramic or stainless-steel 'honeycomb' or pellets (Figs 2.203 and 2.204). The exhaust gases flow freely through the honeycomb, or pellets, where the catalytic chemical reactions take place. The operating temperature of the catalyst is high, and the catalyst must be heated before it becomes effective. Exhaust heat is used for this.

Some catalysts require surplus oxygen in the exhaust gases for use in the conversion of hydrocarbons and carbon monoxide (CO) to water (H_2O) and carbon dioxide (CO_2). Oxidation catalysts are suitable for engines that run with a surplus of oxygen, such as diesel engines, and where additional air and, therefore, oxygen can be supplied.

Three-way oxidizing catalysts convert the hydrocarbon and CO to H_2O and CO_2 and additionally reduce the nitrogen oxides (NO_x). In these catalytic converters, the NO_x reacts with carbon monoxide to give nitrogen (N_2) and CO_2. The nitrogen oxides also react with hydrogen to give nitrogen and water vapour. The performance of catalytic converters relies on the correct exhaust gas constituents being produced. Modern engines do this by using electronic closed-loop control with an oxygen sensor in the exhaust manifold or downpipe.

Key fact

Three-way oxidizing catalysts convert the hydrocarbon and CO to H_2O and CO_2, and reduce the nitrogen oxides (NO_x).

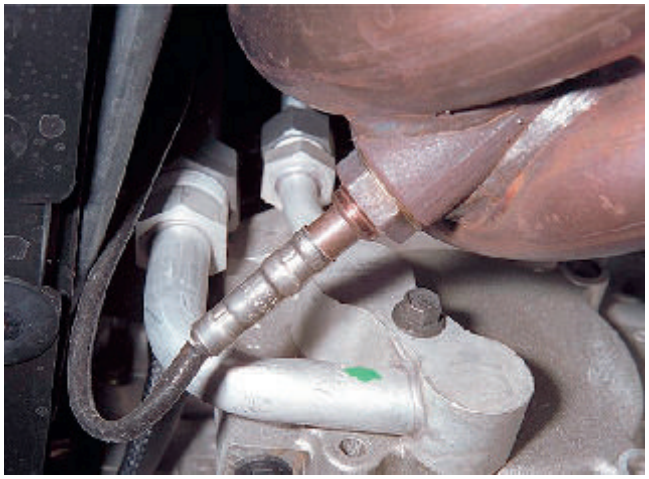


Figure 2.205 Heated exhaust gas oxygen sensor in the inlet manifold

The oxygen or lambda sensor is named after the Greek letter lambda, which is used as the symbol for a chemically correct air-to-fuel ratio, or stoichiometric ratio of 14.7 parts of air to 1 part of fuel. This sensor is known as an exhaust gas oxygen (EGO) sensor, or a heated exhaust gas oxygen (HEGO) sensor when it is preheated (Fig. 2.205). The sensor measures the presence of oxygen in the exhaust gas and sends a voltage signal to the engine electronic control module (ECM).

More fuel is delivered when an oxygen content is detected and less fuel when it is not. In this way, an accurate fuel mixture close to the stoichiometric ratio, or lambda, is maintained. This produces the correct exhaust gas constituents for chemical reactions in the catalytic converter.

2.4.6 Emission control systems

2.4.6.1 Crankcase ventilation

Oil vapour occurs in the engine crankcase because of heat, spray and the churning action of engine components as the engine is running. A fine mist of oil vapour is always present in a running engine. The engine crankcase pressure is never constant. Slight leakages into and from the combustion chambers, and the movement of the pistons, are responsible for most of the pressure variations.

A vent to atmosphere system was once used for ventilating pressure variations in the engine. This simple vent allowed a large quantity of oil vapour to escape. By fitting an oil separator the quantity of oil was reduced but still unacceptable quantities of oil vapour were emitted. Developments since that time have seen the introduction of a positive crankcase ventilation (PCV) system. This takes any escaping oil vapour into the engine for combustion.

The PCV system shown in Figs 2.206 and 2.207 consists of a valve mounted in the crankcase vent oil separator (attached to the cylinder block) and two hoses. One PCV hose connects the PCV valve to the intake manifold; the other connects the valve cover to the air cleaner. Under idle and part throttle conditions, the crankcase vapour flows through the intake manifold into the combustion chambers where the vapour is burnt during combustion. Under full throttle conditions, the crankcase vapour flows from the valve cover into the air cleaner through the PCV hose.

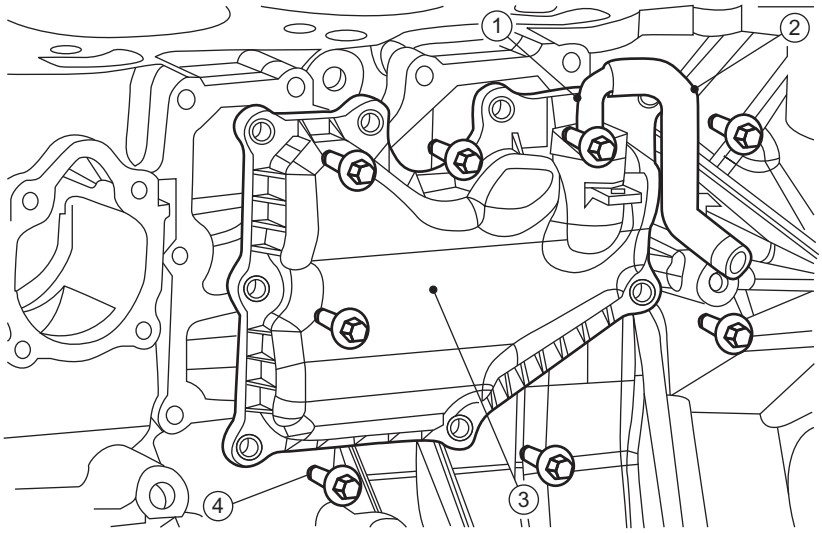


Figure 2.206 Positive crankcase ventilation (PCV) system oil separator on the side of a block: 1, PCV valve; 2, PCV hose; 3, crankcase vent oil separator; 4, crankcase vent oil separator retaining bolt. (Source: Ford Motor Company)

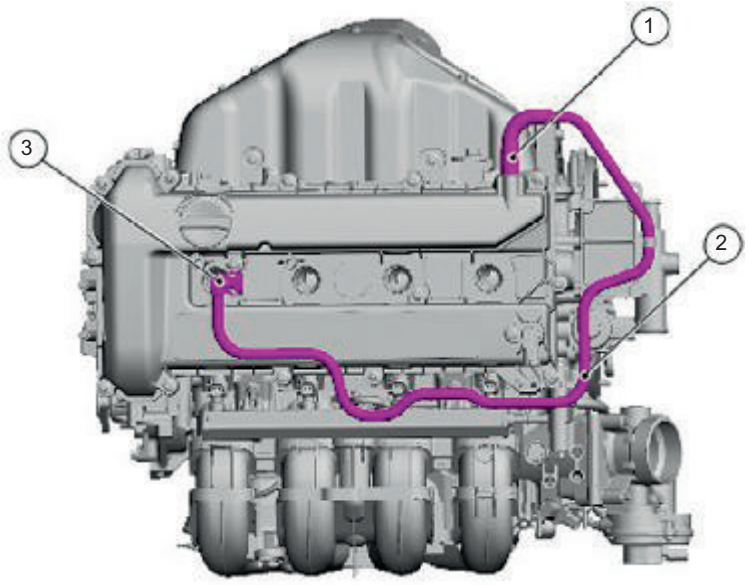


Figure 2.207 Positive crankcase ventilation (PCV) connection from rocker cover to the air cleaner box: 1, PCV hose to valve cover connector; 2, PCV hose; 3, PCV hose to air cleaner connector. (Source: Ford Motor Company)

Safety first

Fuel vapour, particularly petrol (gasoline) vapour, is harmful.

2.4.6.2 Evaporative emission control

Fuel vapour and particularly petrol vapour is harmful. It is given off from petrol at quite low ambient temperatures. Fuel is stored in underground tanks to reduce vapour formation. However, during filling up and when fuel is in the tank, vapour can escape into the atmosphere. Modern vehicles are fitted with fuel systems that prevent vapour loss from the vehicle (Fig. 2.208).

An evaporative emission control system (EVAP) has a sealed tank and fuel lines (Fig. 2.209). It allows for expansion and reuse of the fuel through a charcoal canister (Fig. 2.210). Air can pass through but the fuel vapour is trapped. To prevent the filter becoming saturated it is cleaned, or purged, by drawing air

Figure 2.208 Fuel tank cap

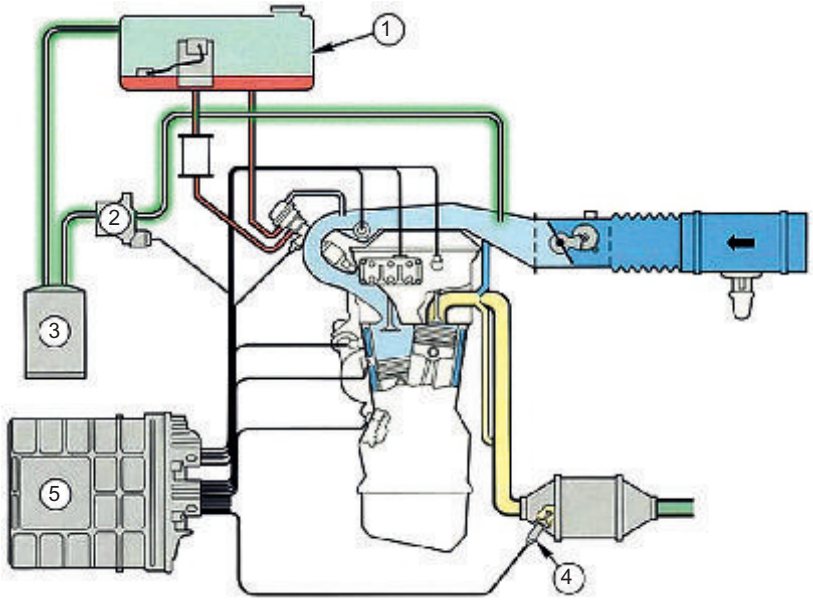


Figure 2.209 Evaporative emission control system (EVAP) components: 1, fuel tank; 2, control valve; 3, charcoal canister; 4, lambda sensor; 5, ECU; 6, electronic control module (ECM)

Figure 2.210 Charcoal canister

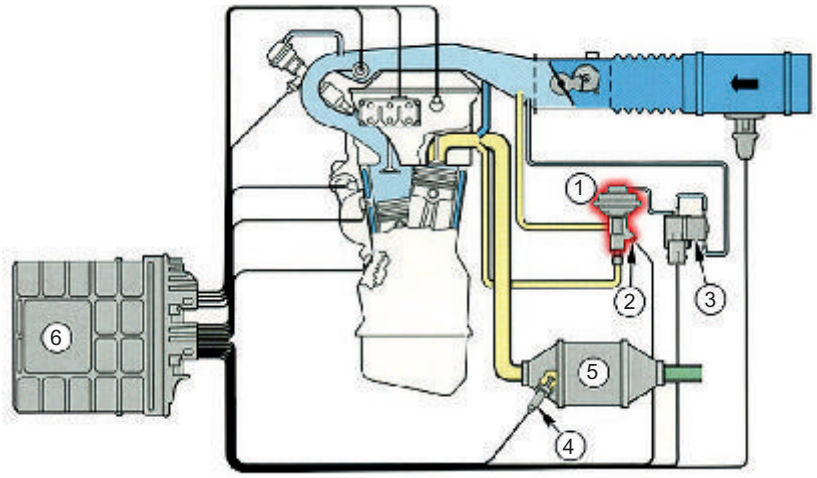


Figure 2.211 Exhaust gas recirculation (EGR) system: 1, vacuum actuator; 2, sensor; 3, vacuum control valve; 4, lambda sensor; 5, catalytic converter; 6, electronic control module (ECM)

through the filter in the opposite direction. The air collects the deposited fuel vapour and carries it through pipes into the inlet manifold and engine, where it is burnt. To prevent vapour loss through this route when the engine is not running, a canister purge control valve is fitted into the fuel vapour line. The valve is closed when the engine is stationary and during warm-up. When the engine is at normal running temperature the valve opens and the inlet manifold vacuum is able to cause air flow through the canister. This draws vapour out of the filter and into the inlet manifold.

The evaporative canister can be fitted almost anywhere on the vehicle. It may be near to the fuel tank, in the engine compartment or under a body panel. Fuel traps, to prevent fuel loss if the vehicle turns over in an accident, are also fitted.

2.4.6.3 Exhaust gas recirculation

Exhaust gas recirculation (EGR) has become a common feature on petrol and diesel engines (Fig. 2.211). The addition of exhaust gas to a fresh air and fuel charge lowers the combustion temperature and reduces the formation of NOx. EGR operates during normal engine temperature and high vacuum conditions. Exhaust gases are piped from the exhaust manifold to the inlet manifold through a vacuum or electrically operated valve.

Key fact

The addition of exhaust gas to a fuel/air charge lowers the combustion temperature and reduces the formation of nitrogen oxides.

The amount of exhaust gas introduced into the air supply is usually less than 15% of the total charge. However, where closed-loop control is used, up to 50% can be used under some conditions on diesel engine systems. Some systems use a one-piece electrical solenoid valve, in place of the separate electronic vacuum regulator and valve. Some valves have a sensor fitted above the valve so that the ECM can monitor the opening performance.

Key fact

Superchargers are driven from the engine crankshaft.

2.4.7 Turbocharging and supercharging

Supercharging is a method of increasing the performance of internal combustion engines by boosting the air charge with an air pump. The most popular method is turbocharging, as this uses some of the lost energy in the exhaust gas flow

(Fig. 2.212). Superchargers are driven from the engine crankshaft. Turbocharging (supercharging) of an engine is not strictly an emission control device but a method by which an increase in power and fuel efficiency can be obtained from a smaller engine. At the same time, there are improvements in exhaust emissions. Forced air induction has advantages over natural aspiration, because cylinder charging is more consistent over the full engine speed range. This helps to give high torque and power over a wider speed range, improved overall performance and improved fuel consumption.

Exhaust turbochargers use waste energy in the exhaust gas flow for power. This method of air boost charging is suitable for all types of engine. However, applications on small petrol engines are usually found only on high-performance vehicles.

Key fact

Exhaust turbochargers use waste energy in the exhaust gas flow for power.

Turbocharging of small high-speed diesel engines, used in cars and light vans, is now very popular. Diesel engine cylinder charging can be increased from about 60% for naturally aspirated engines to about 90% with exhaust turbocharging. The increased volume of air means that a corresponding increase in fuel can be delivered and more torque and power can be obtained per litre of engine capacity. Turbochargers use the energy in the exhaust gas to drive a turbine. The turbine is connected by means of a shaft to a compressor wheel in the engine air intake tract. The greater the flow of exhaust gas, the greater the speed of the turbine and compressor wheel and therefore the amount of additional charging.

The boosted air pressure is from 0.2 to 0.9 bar, depending on compressor speed. The maximum boost pressure is regulated by splitting the exhaust gas stream so that the excess gas flow and energy bypasses the turbine through a waste gate. The waste gate is a pressure-operated poppet or plate valve, which normally remains closed (Fig. 2.213).

When the boost pressure in the inlet air stream rises, it is applied to the waste gate valve. The pressure acts on a diaphragm connected to the waste gate valve, and when it reaches the maximum operational pressure the valve opens. This allows exhaust gases to bypass the turbine. With the reduced gas flow, the turbine and compressor slow down, the pressure reduces and the waste gate closes. This opening and closing cycle maintains the boost pressure within operational limits. An intercooler cools the air and therefore it becomes denser, further increasing efficiency (Figs 2.214 and 2.215).

Key fact

An intercooler cools the air and therefore it becomes denser, further increasing efficiency.

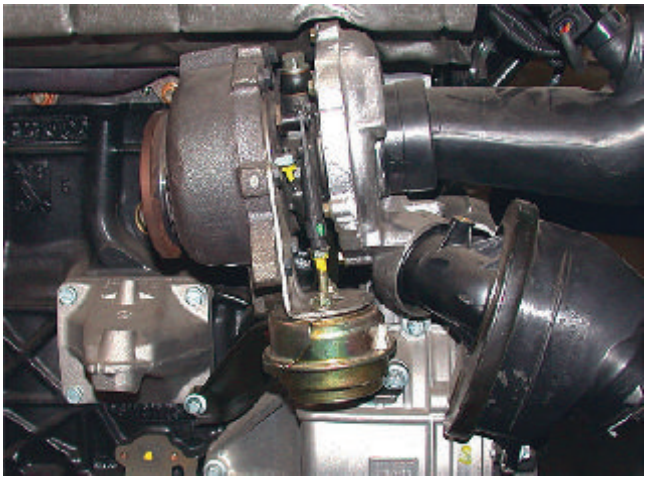


Figure 2.212 Turbocharger

Figure 2.213 Waste gate actuator under electronic control. (Source: Bosch Media)

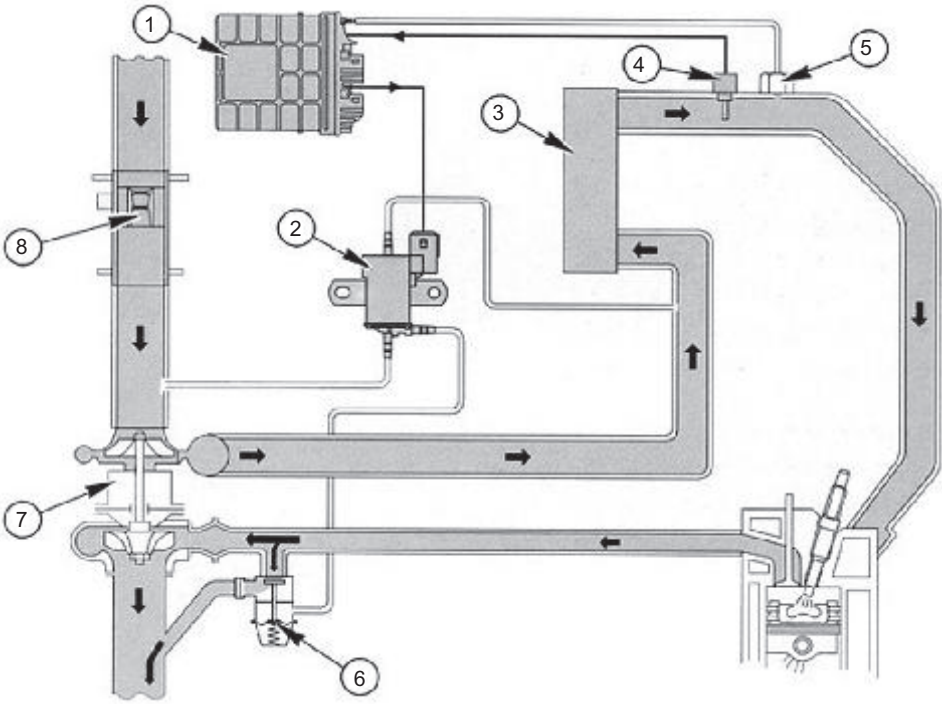


Figure 2.214 Boost control system: 1, electronic control unit (ECU); 2, boost control pressure solenoid; 3, intercooler; 4, temperature sensor; 5, boost pressure sensor; 6, boost pressure control valve; 7, turbocharger; 8, mass air flow (MAF) sensor

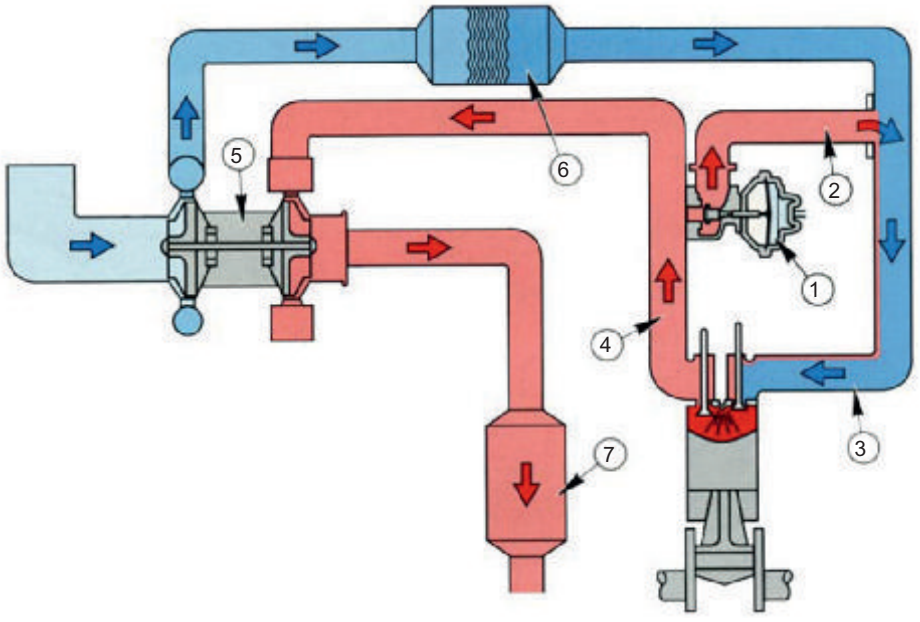


Figure 2.215 Air and exhaust flow on a turbocharged system with exhaust gas recirculation (EGR): 1, EGR valve; 2, tube; 3, inlet manifold; 4, exhaust manifold; 5, turbocharger; 6, intercooler; 7, catalytic converter

The turbine and compressor fan wheels are radial flow types (Fig. 2.216). The exhaust flows towards the centre and then out. The inlet air flows in at the centre and outwards to the engine air intake duct. The air is forced out by the rotary centrifugal action of the compressor wheel. Air and gas flow is directed

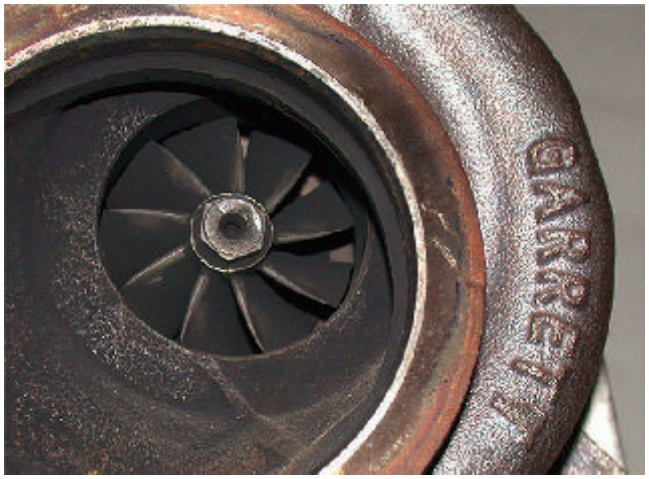


Figure 2.216 Turbine blades

by spiral ducting in the turbocharger body. The spindle carrying the turbine and compressor wheel is mounted on special bearings with forced feed oil lubrication, which allows rotation with a minimum of metal-to-metal contact.

The oil feed is made from the engine main oil gallery and returns to the oil sump/pan. The lubricating oil is also used for cooling in the turbocharger. Turbochargers must be allowed to slow down and to cool down before the engine is switched off. Usually about 30–60 seconds is required for this. The charged air increases in temperature through the turbocharger and becomes less dense and of lower mass. To overcome this loss, an intercooler is often fitted between the turbocharger and the inlet manifold. The intercooler is similar in construction to a coolant radiator but is an air-to-air heat exchanger.

Key fact

Lubrication is used for cooling in the turbocharger.

Some vehicles have a variable vane turbocharger instead of a waste gate. The turbocharger is designed to improve engine induction and engine performance.

A standard turbocharger has two key weaknesses (although these are much reduced on many systems):

- High engine speed produces excessive turbine speed and therefore creates excessive turbocharger boost pressure.
- Low engine speed does not produce sufficient turbine speed and therefore not enough turbocharger boost pressure is achieved.

The variable vane turbocharger does not have a waste-gate control valve. Instead, it has variable turbocharger vanes which are located in the turbocharger turbine housing and can overcome the previous weaknesses. The turbocharger vanes act as the control for the turbocharger boost pressure.

The variable vane turbocharger produces its full turbocharger boost pressure over the entire engine speed range, not just at high engine speed. This is achieved through the adjustment of the vanes and the resulting change in the velocity of the exhaust gas. The speed of flow of the stream of exhaust gas is increased independently of engine speed by varying the intake cross-section in front of the turbocharger turbine. The variable vanes are controlled by the powertrain control module (PCM). A duty cycle signal from the PCM controls a vacuum supply to the turbocharger vacuum diaphragm unit using a solenoid valve (Fig. 2.217).

Superchargers (Figs 2.218 and 2.219) are mainly of the Roots blower or radial flow types. The radial flow types are similar to the compressor on the exhaust

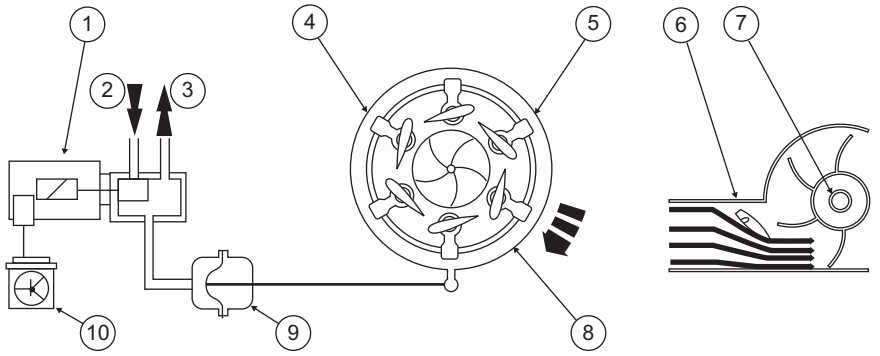


Figure 2.217 1, Vane adjustment solenoid valve; 2, atmospheric pressure; 3, vacuum; 4, adjusting ring; 5, vanes; 6, vanes; 7, turbine; 8, turbine; 9, vacuum diaphragm unit; 10, electronic control module (ECM). (Source: Ford Motor Company)

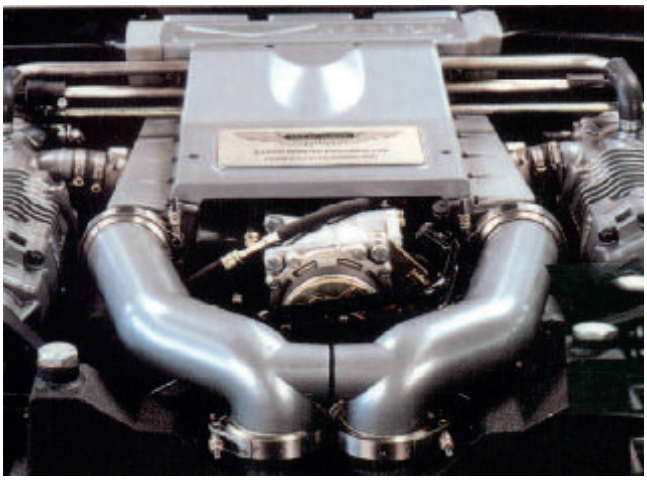


Figure 2.218 Twin Roots blowers

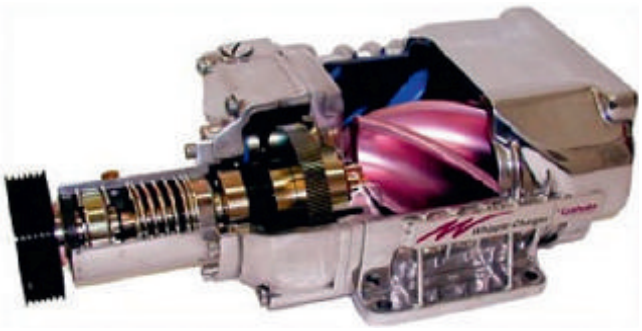


Figure 2.219 Cutaway supercharger

turbocharger. However, they are driven by belts and gears from the engine crankshaft. Vane radial superchargers have been used but are less popular.

The Roots blower uses two or three lobe intermeshed rotors to pump air. The rotors have helical rotor vanes to reduce noise and improve efficiency. The rotor vanes are driven and matched together with a pair of gears, so that they rotate in mesh with each other. They run on ball or needle roller bearings at each end of the rotor spindles. They must be lubricated with high-performance grease or synthetic oil in the bearing cases.

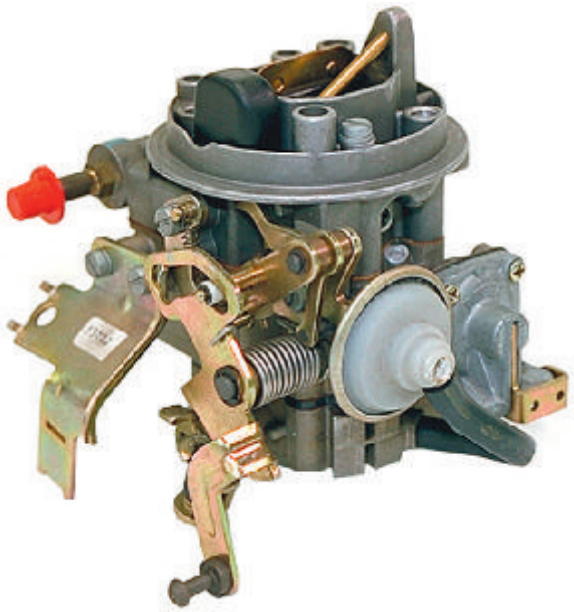


Figure 2.220 Carburettor

Figure 2.221 New petrol/gasoline injection system

2.5 Fuel systems

2.5.1 Introduction

Fuel systems have been extensively developed during the past fifty years. There were many developments in the traditional petrol supply and air mixing methods used in carburettors (Fig. 2.220). However, the introduction of fuel injection systems has made carburettors almost obsolete. Fuel injection is now fitted to all petrol engine vehicles to meet the latest requirements for performance and the reduction of harmful exhaust gas emissions (Fig. 2.221). Diesel fuel pumps and injectors have seen similar developments with the introduction of electronic control and common rail systems (Fig. 2.222).

All fuel delivery systems have to supply a quantity of fuel that matches the amount of oxygen that is in the air entering the engine. For petrol engine

Key fact

The introduction of fuel injection systems has made carburettors almost obsolete.

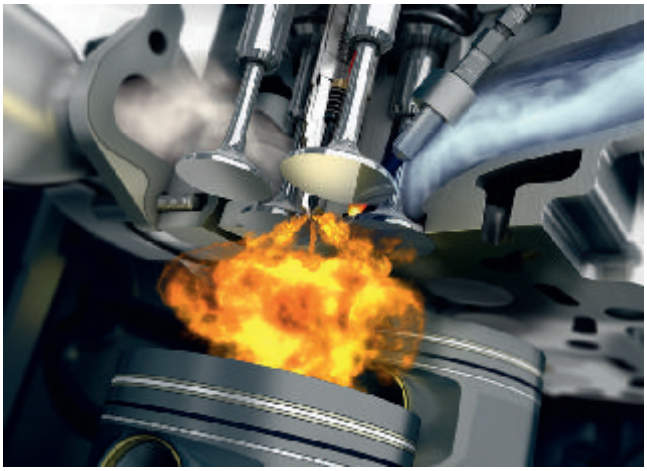


Figure 2.222 New diesel injection system

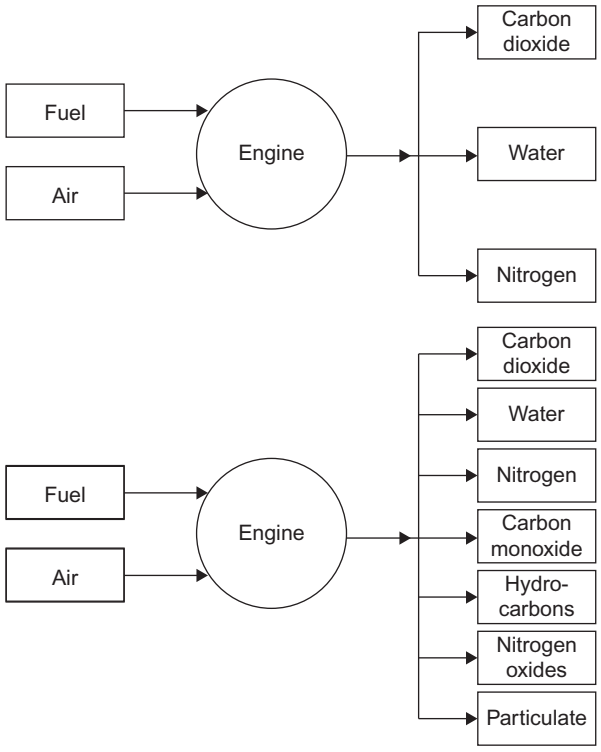


Figure 2.223 Ideal (upper) and incomplete (lower) combustion

Key fact

All fuel delivery systems have to supply a quantity of fuel that matches the amount of oxygen that is in the air entering the engine.

vehicles, the quantities of hydrogen and carbon in the fuel and the oxygen content of the air should be chemically correct to allow a complete chemical change during combustion. The chemical formula for clean combustion is $CH_4 + 2O_2 = CO_2 + 2H_2O$, or hydrocarbon plus oxygen results in carbon dioxide and water.

For complete and clean combustion (Fig. 2.223), the ratio of air to fuel should be as close as possible to the stoichiometric value. This is where λ (lambda) equals one. This is a ratio of 14.7:1 by mass of air to fuel. In petrol engines, the optimum for clean combustion is for these quantities to be delivered accurately to each cylinder in the engine.

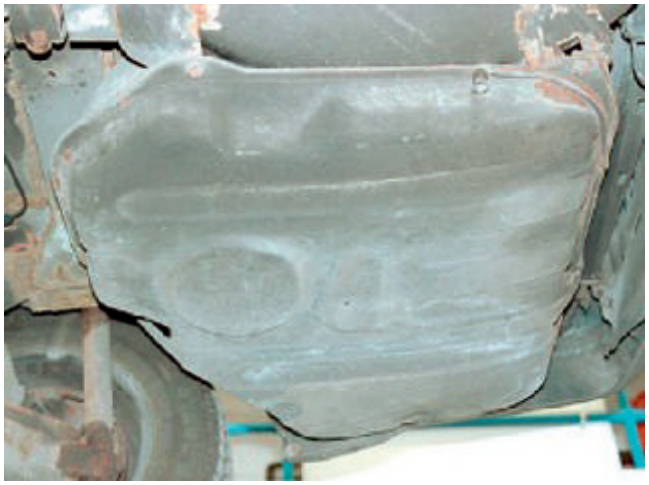


Figure 2.224 Steel fuel tank in position

Definition

Lambda (λ) value
A λ value of 1 is a ratio of 14.7:1 by mass of air to fuel.

Petrol is ignited in the combustion chamber by a spark arcing across the electrode gap of a spark plug. Diesel fuel ignites following injection into the high-temperature air charge. The high temperature is obtained by compression of the air charge. The air charge on petrol engines is matched to the amount of fuel delivered. In diesel engines, a full air or gas charge is required to raise the temperature by compression.

The fuel on the vehicle is held in a tank fitted in a safe position (Fig. 2.224). Recent construction legislation requires that the tank is unlikely to be ruptured in a vehicle collision. The positioning and protection of the tank are considered at the design stage of the vehicle and tested during development. The tank is fitted with a filler neck and pipework from the filler cap to the tank. Also fitted are the outlets to the atmospheric vent or evaporative canister and the fuel feed and return pipes to the engine. The fuel gauge is located in the fuel tank. Fuel supply and return lines are made from steel pipes, plastic pipes and flexible rubber joining hoses, depending on application and the type of fuel used.

A pump to supply fuel to the engine is fitted into or near the tank on petrol injection vehicles. On carburettor vehicles, a mechanical lift pump (Fig. 2.225) is fitted to the engine and is operated by a cam on the camshaft or crankshaft, or an electric pump is fitted in the engine compartment. Diesel-engined vehicles using a rotary fuel injection pump may use the injection pump to lift fuel from the tank. Alternatively, they may have a separate lift pump similar to the ones used on carburettor engines. A separate priming pump fitted in the fuel line may also be used.

The carburettor was the traditional method of mixing petrol with air as it enters the engine (Fig. 2.226). However, a simple carburettor is only capable of providing a correct air and fuel mixture ratio within a very small engine speed range. For road vehicles a wide engine speed range and a wide engine load are required. To respond to the speed and load variations, complex carburettors are used (Fig. 2.226).

There are two basic carburettor designs, the fixed venturi and the variable venturi types (Fig. 2.227). The term choke is often used to describe the venturi and this gives the alternative carburettor definitions of fixed choke and variable choke types. The usual meaning of the term choke is to describe the engine cold-start device fitted to the carburettor.

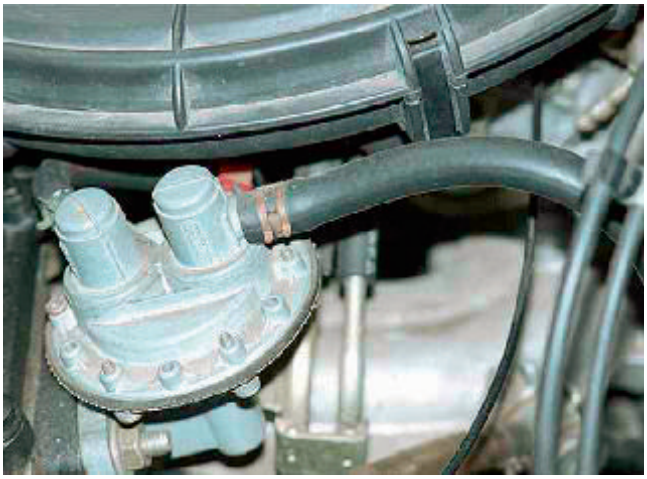


Figure 2.225 Mechanical fuel pump

Figure 2.226 Single-choke (left) and twin-choke (middle and right) carburettors

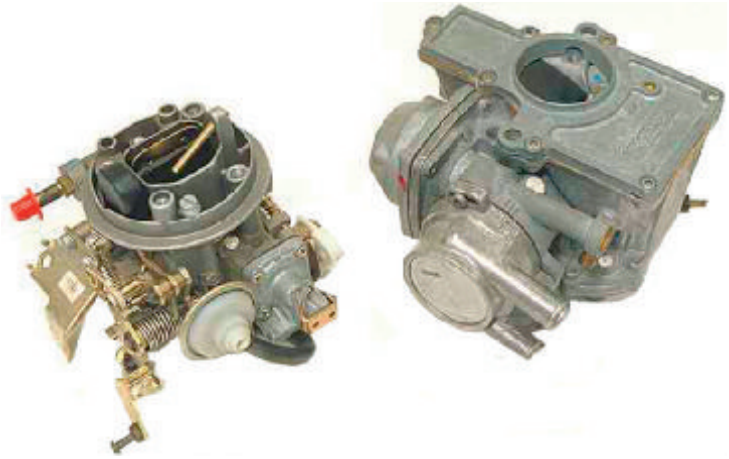


Figure 2.227 Fixed-choke (left) and variable-choke (right) carburettors

Key fact

The function of the carburettor is to meter a quantity of petrol into the air stream entering the engine cylinders.

The function of the carburettor is to meter a quantity of petrol into the air stream entering the engine cylinders. As the pistons move down in the cylinders on the induction stroke the pressure in the space above the cylinders falls. On naturally aspirated engines, that is, those that are not fitted with pressure chargers, atmospheric pressure provides the force for the air flow into the cylinders.

The greater the difference in pressure, the greater will be the volume of air that enters the engine and the speed of the air flow through the carburettor and inlet

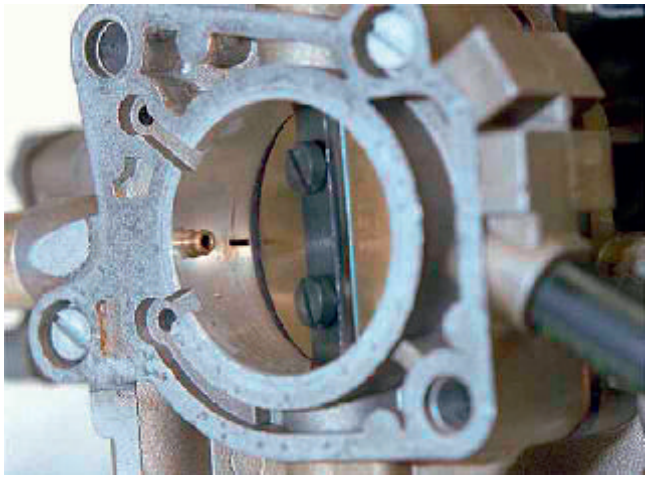


Figure 2.228 Throttle butterfly

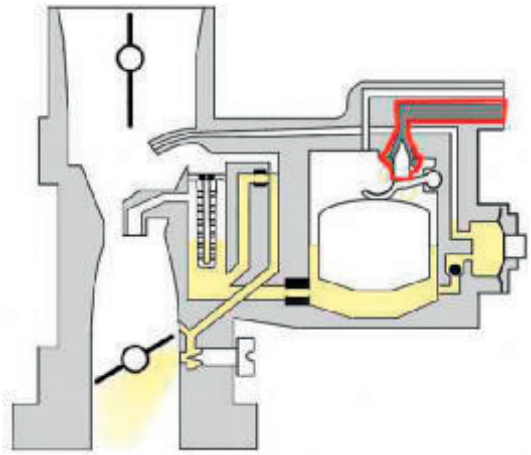


Figure 2.229 Fuel level is control by a float and needle valve

manifold. A valve to meter the air flow is fitted at the base of the carburettor just in front of the inlet manifold. This valve is called the throttle and it consists of a round plate on a spindle (Fig. 2.228). The spindle has a lever attached to one end and this is connected directly to the throttle pedal with a cable or rods. The throttle restricts the air flow in all positions except when wide open, and this gives a range of variable pressures in the carburettor and the inlet manifold.

The basic carburettor consists of the venturi, through which the air flows, and the float chamber, which holds a supply of petrol at a constant level in relation to the supply beak in the venturi (Fig. 2.229). The level of petrol in the float chamber is maintained by a needle valve that is lifted onto its seat by the float so that it stops the flow when the chamber is full. As petrol is used the level drops, the needle valve opens and the flow of petrol into the chamber resumes. In this way, a constant petrol level is maintained. The float level should be checked and adjusted if necessary, if problems occur or if the carburettor is stripped for cleaning.

The main jet in the fuel feed to the venturi forms a restriction in the petrol flow and by virtue of its size acts as a metering device (Fig. 2.230). The venturi is a tube with an inward curving restriction. Air flow through the venturi speeds up as it passes through the restriction. The effect of this is to reduce the air pressure at

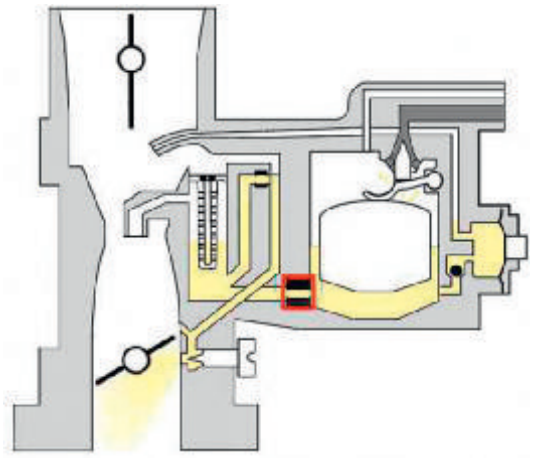


Figure 2.230 Main jet in the fuel feed to the venturi

that point. Inside the float chamber, atmospheric pressure is applied to the top of the petrol held there. A vent in the top of the float chamber allows a free passage of air and atmospheric pressure.

A pressure differential exists at each end of the fuel supply tube between the float chamber and the venturi supply beak, when there is sufficient air flow to create a vacuum in the venturi. It is this pressure differential that is used to lift petrol up to the beak. From here, it passes into the air stream through the venturi and into the engine cylinders.

Although there is an increase in fuel delivery with an increase in air flow, these do not match sufficiently to maintain the correct air and fuel ratio over the full operating range. Other devices are needed to adjust the metering of petrol to the correct ratios. These are explained later in this section. The venturi can be positioned vertically with the air flow being downward or upward, or it can be positioned horizontally. This gives the expressions downdraft, updraft and sidedraft for descriptions of carburettors.

Key fact

There are six clearly identifiable engine and vehicle use conditions, known as the stages of carburation.

There are six clearly identifiable engine and vehicle use conditions, known as the stages of carburation. These are outlined in Table 2.1.

The development of twin-choke progressive carburettors was a way by which designers tackled the problems of maintaining correct mixture strengths, over the full range of engine operating conditions. The primary venturi works at the low throttle positions and a secondary venturi is added at the higher throttle positions. However, carburettors have had their chance, so fuel injection it is from now on!

2.5.2 Petrol fuel injection systems

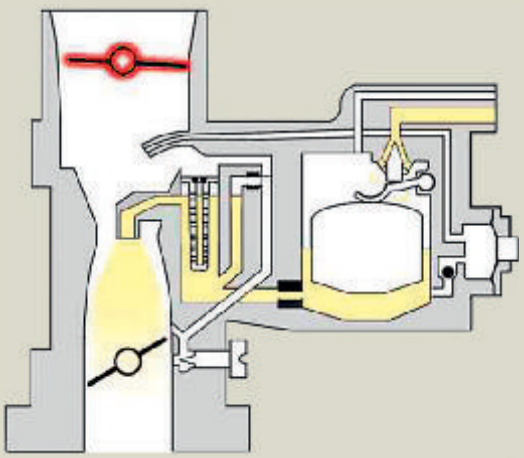
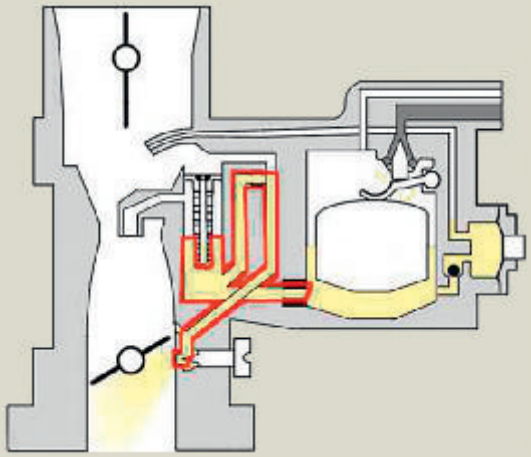
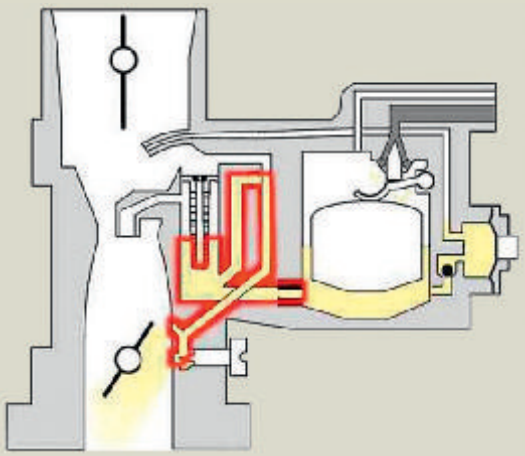
Key fact

The tougher standards of exhaust emission regulations have made the use of microelectronic control systems for fuel delivery a virtual necessity.

Electronic fuel injection (EFi) systems (Fig. 2.237) have been in use now for many years, first on expensive and sports vehicles and now as standard equipment on petrol (gasoline)-engined vehicles. The tougher standards of exhaust emission regulations have made the use of microelectronic control systems for fuel delivery a virtual necessity. There are many different manufacturers of electronic fuel, so this section concentrates on fundamentals as well as looking at one of the key OEMs, Bosch.

EFi systems are named by the position and operation of the fuel injectors. There is a range of throttle body injection (TBI) systems. They are also known as single

Table 2.1 Stages of carburation

Stage	Description	Diagram
Cold starting	Cold start and warm-up conditions require a rich mixture. This is to keep the engine running smoothly and allow a smooth acceleration response. The mixture ratio for starting a very cold engine can be as low as 4:1. This ratio increases as the engine temperature increases, so that by the time the engine is at normal operating temperature, a correct ratio can be used. Cold start enrichment devices on fixed venturi carburettors use a choke plate at the top of the venturi. This lifts the engine vacuum higher into the carburettor. A manual choke plate is a flap fitted to an offset spindle, which is rotated to the on position by a spring when the choke is applied. The choke is held in the partial and off positions by a cam connected to the choke cable. There is usually a linkage between the choke plate lever and the throttle, to increase the engine speed. This increase in speed is called fast idle	 **Figure 2.231** Choke operation
Idle	On this carburettor, the devices for engine idle or tickover can be seen. The air flow through the venturi restriction is insufficient at idle speeds to give the pressure differential requirement for petrol flow into the venturi at the supply beak. The idle device is required to supply the low quantity of fuel needed at engine idle speeds. The vacuum in the inlet manifold is high when the throttle plate is closed. This vacuum is used in the idle device to create a flow of petrol and air through jets and drillings in the carburettor body. The petrol and air mixture enters the air intake through the idle port just below the throttle plate. The size of the pilot petrol jet and adjustment of the air flow provides a suitable air to fuel ratio for engine idle operation	 **Figure 2.232** Idle circuit
Progression	Progression is used to describe the increase in engine speed, from idle, up to the point where the venturi and main jet come into operation. At idle speeds, the air flow through the venturi is not enough to provide a suitable pressure differential. Normal venturi mixing of petrol in the air stream flowing into the engine is therefore not possible. Additional drillings in the lower part of the venturi, just above the throttle plate, connect to the float chamber. This allows an extra fuel supply during this phase. There are some variations in the number and routing of these drillings, but they all provide for a smooth response to initial acceleration from idle	 **Figure 2.233** Progression air and fuel paths

(*Continued*)

Table 2.1 (Continued)

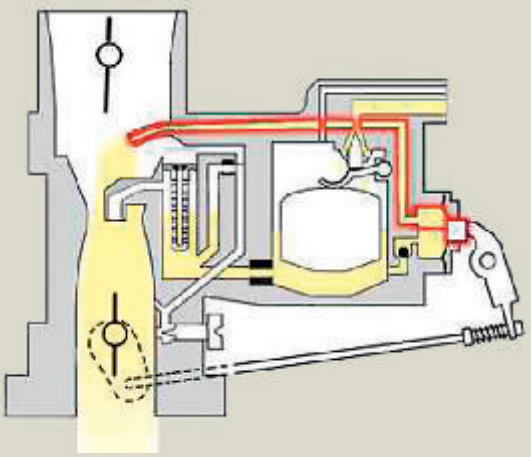
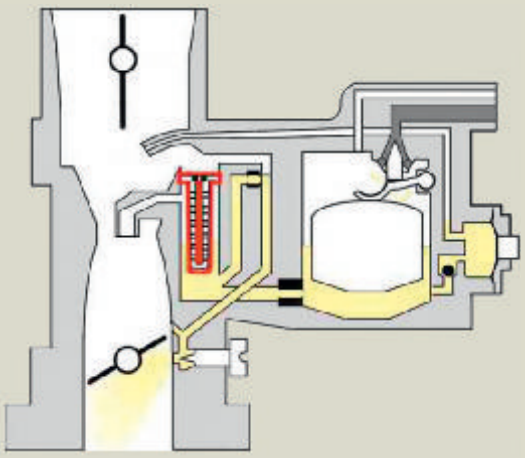
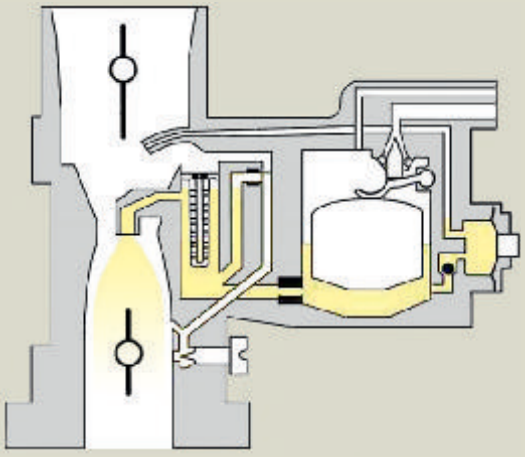
Stage	Description	Diagram
Acceleration	If rapid acceleration is demanded, the vacuum in the venturi is lost for an instant when the throttle is opened quickly. The petrol flow through the supply beak from the float chamber cuts off and without a supplementary supply a 'flat spot' would be experienced. To prevent flat spots on acceleration, an accelerator pump and petrol discharge nozzle are fitted. The pump consists of a piston or diaphragm, a one-way valve and drillings for a petrol supply from the float chamber. The pump is connected by a rod or cam linkage to the throttle plate lever. This causes a pulse of petrol to be sprayed into the venturi when rapid opening of the throttle occurs	 **Figure 2.234** Accelerator pump and jet
Cruising	The cruising speed range is wide and covers most operating conditions from light cruising up to a position just below full throttle. Petrol is drawn from the float chamber into the air stream passing into the engine. The supply beak design and position give good atomization and distribution of the fuel in the air flow. The air fuel ratio in a simple venturi becomes richer with an increase in engine speed. Correction devices are used to maintain the correct ratio mixture. It is also desirable for the engine to run on a lean mixture when the vehicle is cruising	 **Figure 2.235** Emulsion tube in use at cruise
Full load	Carburettors were designed to meet full throttle conditions without additional devices being fitted. However, these designs were unable to meet tougher environmental regulations, which required accurate control of exhaust emissions	 **Figure 2.236** Emulsion tube and 'beak' at full load

Figure 2.237 Electronic fuel injection system components. (Source: Bosch Media)

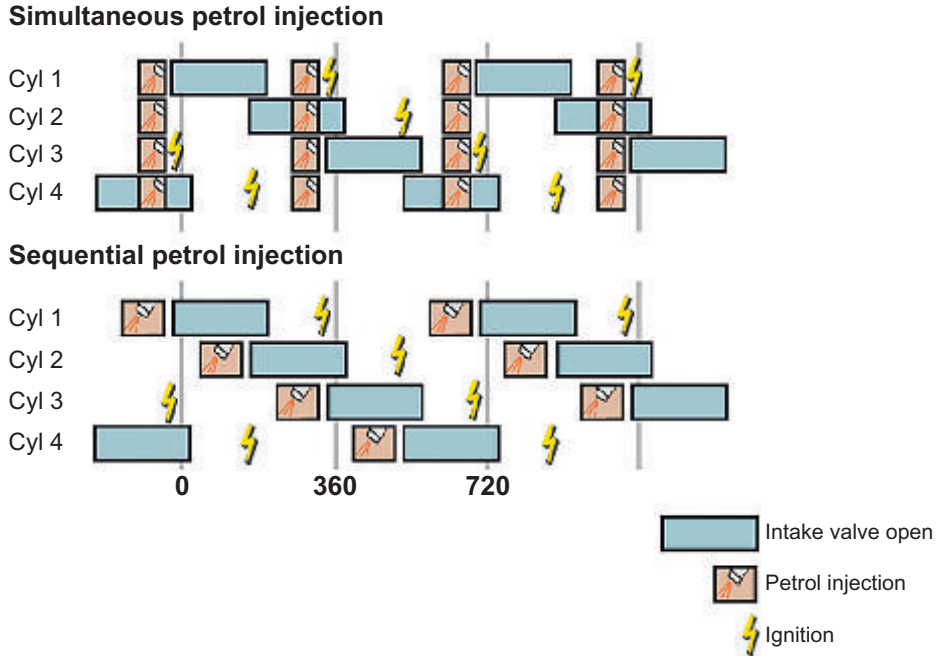


Figure 2.238 Types of fuel injection systems. (Source: Bosch Media)

point (SPI) or central point (CPI) systems. However they are named, the injector is positioned in a housing positioned on the inlet manifold in much the same position as the carburettor was traditionally fitted.

The port fuel injection (PFi) or multipoint (MFi) systems have individual injectors for each cylinder. The injectors are fitted so that fuel is sprayed into the inlet ports. These systems are either simultaneous, where all injectors operate at the same time, or sequential, where each injector operates on the induction stroke of each cylinder in turn (Fig. 2.238). Multipoint systems are now by far the most common, even on smaller vehicles.

A more recent development has been the introduction of a gasoline direct injection (GDi) system, where the fuel is injected into the combustion chamber (Fig. 2.239).

Figure 2.239 Bosch gasoline direct injection (GDi). (Source: Bosch Media)

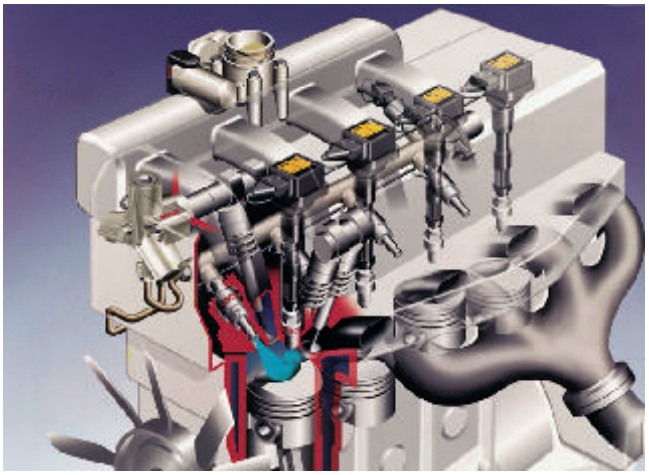


Figure 2.240 Ignition and fuel systems are now always combined

Modern petrol injection systems are linked to the ignition systems and are controlled by an engine control module (ECM) (Fig. 2.240). All modern fuel injection systems have closed loop electronic control using an EGO sensor.

The components for any electronic fuel injection system can be divided into three groups (Fig. 2.241):

- electronic control system (ECU, sensors and actuators)
- air supply components
- fuel supply components.

2.5.2.1 Electronic control system

At the heart of EFi systems is the fuel control or ECU with a stored map of operating conditions (also referred to as the electronic control module or ECM) (Fig. 2.242). Electronic sensors provide data to the microprocessor in the ECM, which calculates and sends the output signals to the system actuators, which are the fuel pump, fuel injectors and idle air control units. The ECM will also switch some of the exhaust emission and auxiliary system components. ECU and ECM tend to be used interchangeably.

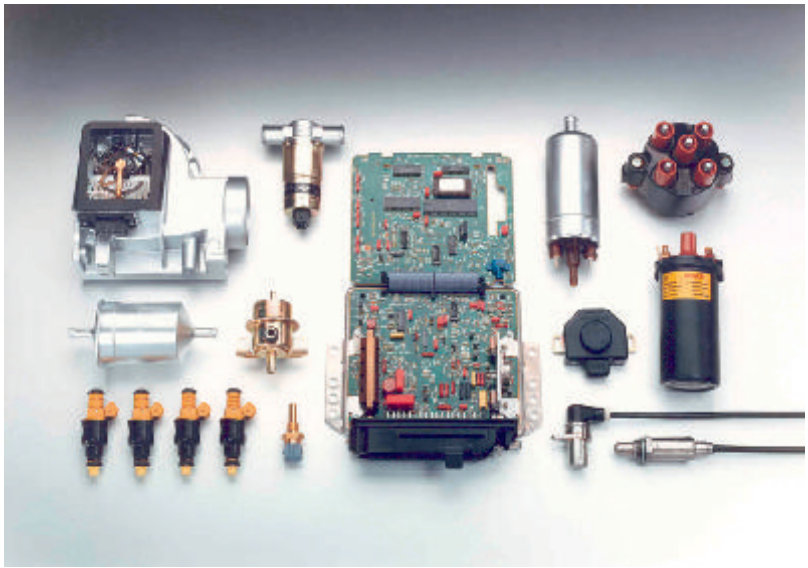


Figure 2.241 Fuel injection and ignition components from an earlier Motronic system. (Source: Bosch Media)

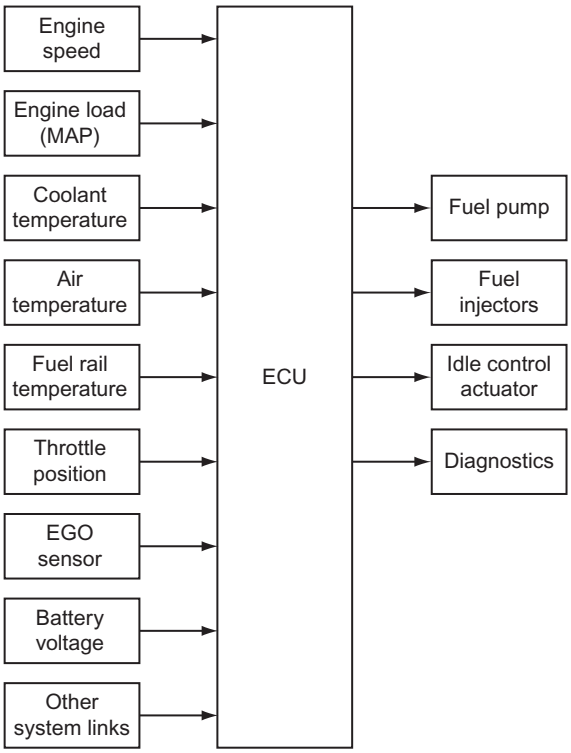


Figure 2.242 Fuel control electronic control unit (ECU) with some typical inputs and outputs

The ECU is an electronic microcomputer with a central processing unit (CPU) or microprocessor (Fig. 2.243). Inside the CPU are software programs that compare all sensor input data with a fixed map of operating conditions. It then calculates the required output signal values for the injection valves and other actuators.

The fixed map of operating conditions specific for each engine is held in a fixed value memory or read only memory (ROM) (Figs 2.244–2.246). The operating data store of input values from the sensors is held in a random access memory (RAM). A 'keep

WWW

A computer program that demonstrates the operation of an engine management ECU and system is available from www.automotive-technology.co.uk

Figure 2.243 Inside an electronic control unit (ECU)

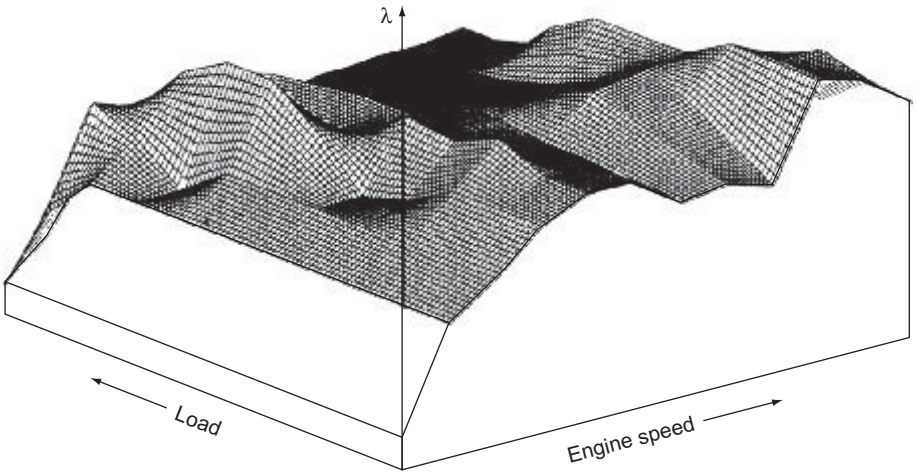


Figure 2.244 Fuel map

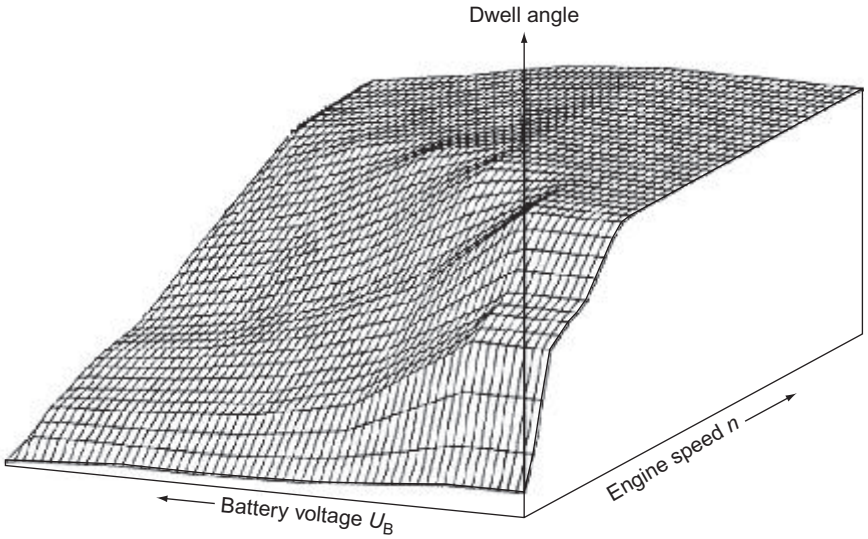


Figure 2.245 Dwell map

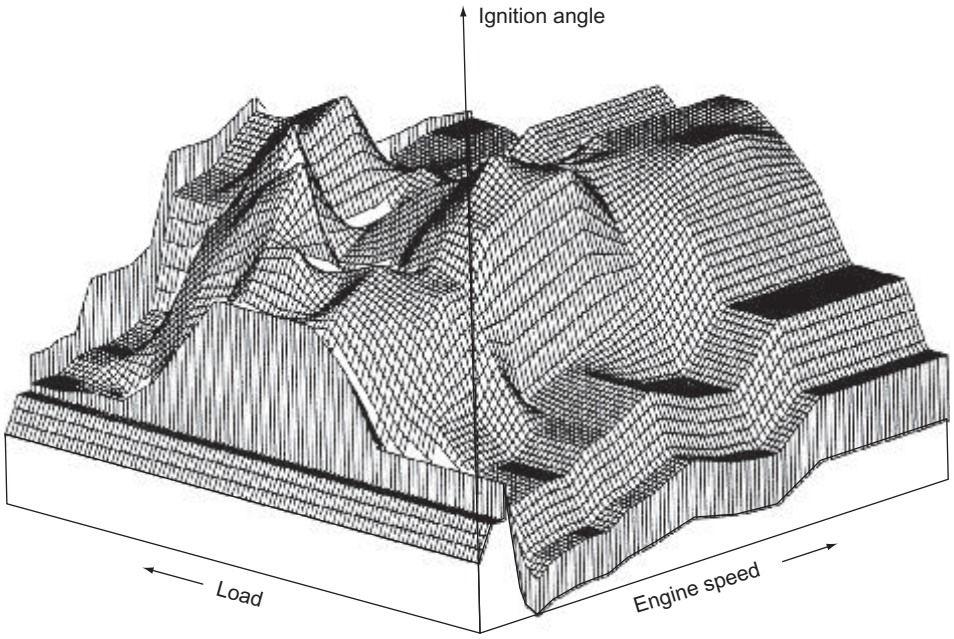


Figure 2.246 Ignition map

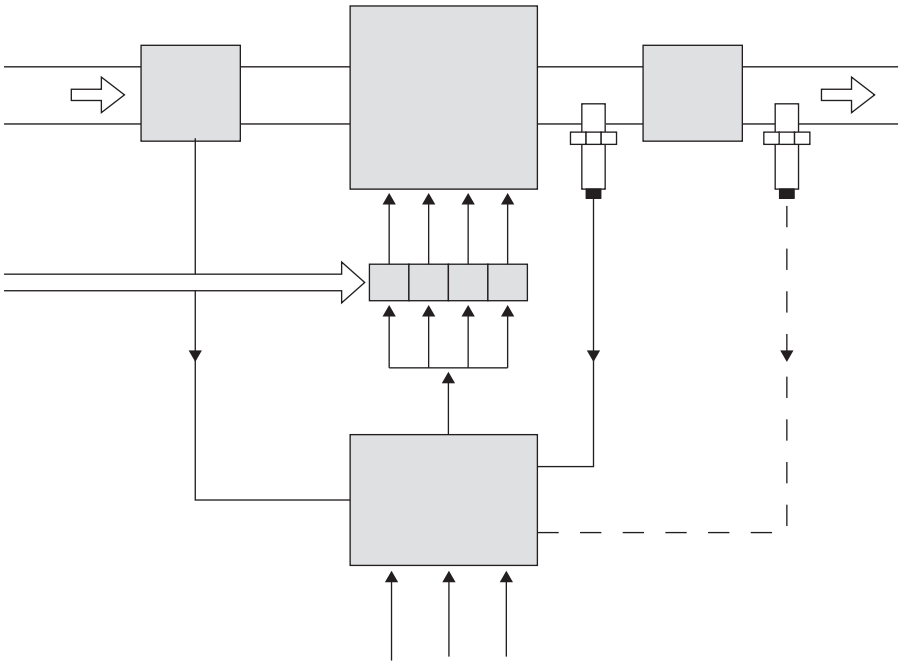


Figure 2.247 Closed loop control with lambda sensor (with a second sensor after the catalytic converter)

alive' memory (KAM) of specific data such as adjustments, faults and deviations in component performance may also be used. The RAM data is erased when the ignition is switched off. The KAM data is erased when the battery is disconnected. New data is replaced in the RAM and KAM during engine start-up and operation.

During the cold-start and warm-up phases of engine operation the computer operates in an open loop mode based on the sensor data. Once the engine reaches a certain temperature and the signals from the EGO (or lambda) sensor are logical, the computer operates in a closed loop mode based on the data from this sensor (Fig. 2.247).

Key fact

The fixed map of operating conditions specific for each engine is held in a fixed value memory or read only memory (ROM).

Figure 2.248 Injection wiring harness

Figure 2.249 An inductive speed sensor produces a sine-wave signal, the frequency being proportional to engine speed. (Source: Denso Media)

Other programs in the CPU monitor the system and sensor data. They provide fault diagnosis and limp-home or a limited operation strategy in the event of any defects being detected. Other components in the ECU provide signal amplification and pulse shaping. This includes analogue to digital (A/D) converters for direct current (d.c.) voltages, and pulse formers for alternating current (a.c.) voltages. The CPU requires digital signals for all processing functions. On the output side, power transistors are used for switching the actuator supply voltages either to the components or to an earth or ground point.

The ECU also operates the emission control components at appropriate times depending on the engine operating conditions. Typical emission control actuators are the canister purge solenoid valve, the EGR valve and the secondary air solenoid valve.

The electrical harness for the engine management system is a complex set of cables and sockets (Fig. 2.248). Cables have colour and/or numerical coding and the sockets are keyed so that they can be connected in one way only. Special low-resistance connectors are used for low-current sensor wiring. Follow manufacturer's data sheets for further technical detail.

Sensors provide data to the ECU. The engine speed and load conditions are used to calculate the base time value (in milliseconds) for the injector pulse width. A range of correction factors is added to or subtracted from the base time value to suit the engine operating conditions occurring at all instances of time.

In early electronic fuel injection systems, the engine speed was provided from signals obtained from the ignition low-tension primary circuit. In engine management systems, the engine speed and position are required for the ignition and fuel systems (Fig. 2.249).

There are two methods of engine speed and position sensing. The older system is a conventionally geared distributor with an inductive or Hall effect generator (Fig. 2.250). This provides an alternating signal current that is used by the ignition system. It is also used for engine speed sensing in the fuel ECM.

All of the latest systems have inductive pulse generators mounted close to, and responding to, a toothed wheel attached to the crankshaft pulley or flywheel. There is an air gap between the toothed wheel and the inductive generator and as the teeth pass the inductive generator, an alternating electric current is produced. The waves of the alternating current are used to measure engine speed. For position sensing, a missing or different size of tooth or mask opening

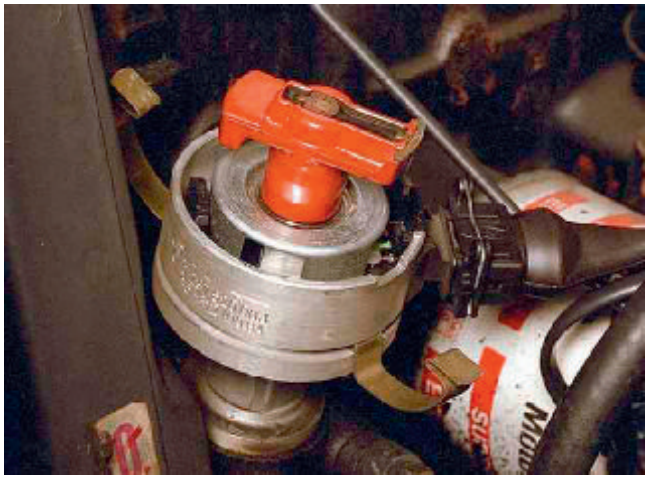


Figure 2.250 Distributor for engine speed sensing on early systems

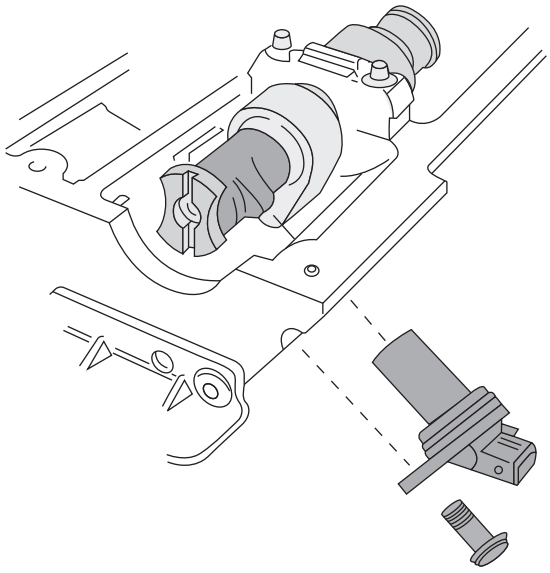


Figure 2.251 Camshaft position sensor. (Source: Ford Motor Company)

on the sensor ring is used. A distributor can also provide a reference for number one cylinder at TDC. When a sensor is fitted to determine the crankshaft position, this is suitable for continuous injection systems.

For sequential injection, a camshaft position sensor is used to recognize the position of number one cylinder (Fig. 2.251). The ECU is then able to follow the engine firing order.

Inductive sensors produce an output pulse each time a lobe or tooth passes the inductive coil. The frequency and pattern of the pulses are used by the ECU to determine the engine speed and position.

The fuel requirement is calculated in the ECU from the engine speed and load conditions. An air flow meter is one method of measuring the engine load conditions. A variable voltage, corresponding to the measured value at the air flow meter, is used by the ECU to calculate the amount of fuel needed to give a correct air/fuel ratio. Often now, engine load is determined from the inlet manifold absolute pressure (MAP). In these systems, an air flow meter is not used.

Key fact

For sequential injection, a camshaft position sensor is used to recognize the position of number one cylinder.

Key fact

Inductive sensors produce an output pulse each time a lobe or tooth passes the inductive coil.

Figure 2.252 Vane type air flow meter

Figure 2.253 Hot wire/film air flow meter

There are two main types of air flow meter. These are vane air flow (VAF) (Fig. 2.252) and the mass air flow (MAF). The vane type air flow meter consists of an air passage and damping chamber into which is fitted a fixed pair of flaps (or vanes), which rotate on a spring-loaded spindle. The spindle connects to and operates a potentiometer and switches.

Definition

MAP
Manifold absolute pressure

Air flowing through the meter acts on the intake air flap and moves it in opposition to a spring force. The integral damper flap moves into the sealed damper chamber to smooth out the intake pulses. The degree of flap movement and spindle rotation is measurable at the potentiometer as a variable voltage dependent on position. The voltage signal, together with other signals, is used in the ECU to calculate the fuel requirement.

A bypass air duct is built into the housing. This provides for starting without opening the throttle, a smooth air flow during engine idle and a means to adjust the idle mixture.

Mass air flow meters are fitted with two similar resistors inside an air tube. A measurement resistor is heated and often referred to as a hot wire (Fig. 2.253). The other resistor is not heated. It provides a reference value for use in the calculation of the air mass. The control circuit maintains the temperature differential between the two resistors. The signal sent to the ECU is proportional to the current required to heat the measurement resistor and maintain the temperature differential. The output signal from some mass air flow meters is similar to that of the air vane types. However, some produce a digital output signal.

On many systems MAP sensor signals are used by the ECU to calculate the fuel requirements (Fig. 2.254). These systems do not have an air flow meter. The signals from manifold absolute pressure, engine speed, air charge temperature and throttle position sensors are compared in the ECU to calculate the injector pulse width.

The MAP sensor is a pressure-sensitive component consisting of a diaphragm and piezoelectric circuit. It can be a component fitted in the engine compartment or be integral with the ECU. It is connected by a rubber hose to the inlet manifold.

Two types of throttle position sensor are used (Fig. 2.255): a throttle switch assembly and a throttle potentiometer. Both are fitted to the throttle body

Figure 2.254 Manifold absolute pressure (MAP) sensor. (Source: Denso Media)

Figure 2.255 Throttle controller and position sensor. (Source: Bosch Media)

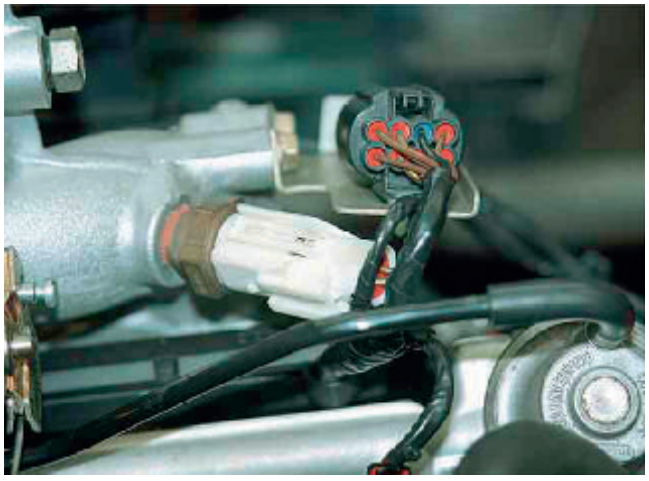


Figure 2.256 Air temperature sensor

and operated by the throttle plate spindle. A throttle switch assembly has two switches, one to indicate the closed throttle or idle position and the other for the wide open throttle position. A throttle potentiometer is a variable resistor with a rotary sliding contact. The sliding contact is moved along the rotary resistance track to provide changes in voltage proportional to the position of the throttle.

The throttle potentiometer signals are used in the ECU for a number of functions. At the closed throttle position, idle speed and deceleration fuel cut-off are controlled. In the part open throttle position (about 5–70% open), there is normal operation with close control of fuel delivery and exhaust emissions. In the wide open throttle position (70–100%), full load enrichment and starting of a flooded engine are provided. During rapid movement of the throttle plate there is acceleration enrichment, depending on the rate of change of the throttle plate and signal voltages from the sensor.

In order for the ECU to correctly calculate the required fuel for a correct mixture ratio, an accurate figure for air mass is necessary. However, air volume and density are affected by changes in temperature. As the temperature rises, the air density falls. The air flow, or MAP measurement, therefore, must be corrected for temperature. The sensor is a temperature-dependent resistor with a negative temperature coefficient (NTC) (Fig. 2.256).

Key fact

In order for the ECU to correctly calculate the required fuel for a correct mixture ratio, an accurate figure for air mass is necessary.

Figure 2.257 Coolant thermistor

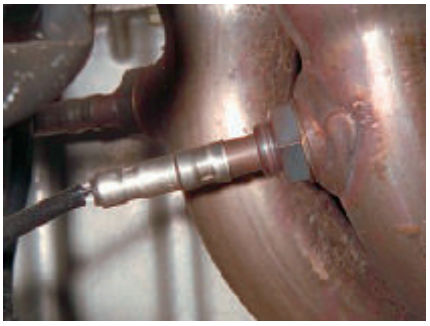


Figure 2.258 Exhaust gas oxygen (lambda) sensor

Key fact

The engine coolant temperature sensor is a negative temperature coefficient (NTC) thermistor.

Key fact

The lambda sensor is often known as an exhaust gas oxygen sensor.

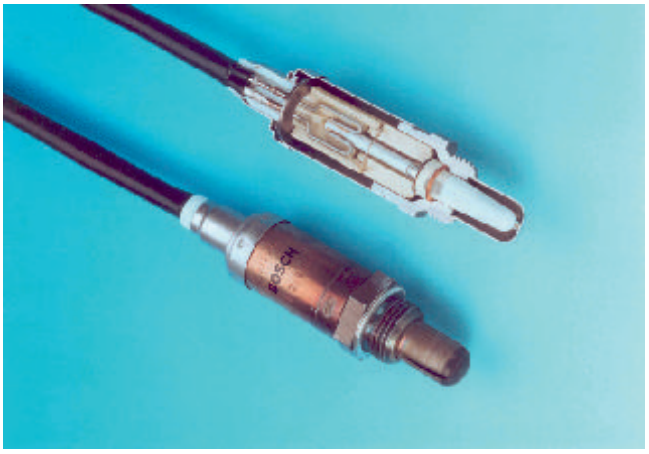


Figure 2.259 Construction of a zirconia type lambda sensor

The engine coolant temperature sensor is an NTC thermistor (Fig. 2.257). It is of a similar type to the air temperature sensor. It is fitted into the water jacket close to the thermostat or bypass coolant circuit passages. The sensor measures the engine coolant temperature and provides a signal voltage to the ECU. This is used for cold-start and warm-up enrichment as well as fast idle speed control through the idle speed control valve.

The Greek letter (λ) lambda is used as the symbol for a chemically correct air to fuel ratio; hence the use of this letter for naming the sensor that is used to control the amount of fuel delivered, so that a very close tolerance to the stoichiometric ratio is maintained. The lambda sensor is often known as an EGO sensor (Figs 2.258 and 2.259). Some of these sensors are electrically heated. Preheating allows the sensor to be fitted lower down in the exhaust stream and prolongs the life of the active element. The sensor measures the presence of oxygen in the exhaust gas and sends a voltage signal to the engine ECU.

More fuel is delivered when oxygen content is detected and less fuel when it is not. In this way, an accurate fuel mixture close to the stoichiometric ratio is maintained. This produces the correct exhaust gas constituents for chemical reactions in the catalytic converter. Exhaust gases pass over the active element and when the oxygen concentration on each side is different an electric voltage is produced. Voltages of about 0.8 V for little or no exhaust oxygen and 0.2 V for higher content are typical outputs.

The sensors for power steering and air conditioning are pressure or mechanically operated switches. They provide a voltage signal when the system is in operation. The ECU uses these signals to increase the engine idle speed to accept the increased engine load.

Switches are used in automatic transmission. They include the neutral drive switch, which is used for idle speed control, the kick-down switch for acceleration control, and the brake on/off switch, which is used to ensure that the torque converter lock-up clutch is released. This is to prevent the engine stalling as the vehicle comes to rest.

A sensor can be used to measure exhaust gas pressure (Fig. 2.260). It uses a ceramic resistance transducer, which responds to the exhaust gas pressure applied through a pipe connection to the exhaust system. The signal voltage from the electronic pressure transducer is used to regulate the EGR valve. The valve may be operated directly from the ECU if electromechanical or by vacuum through a solenoid vacuum switch.

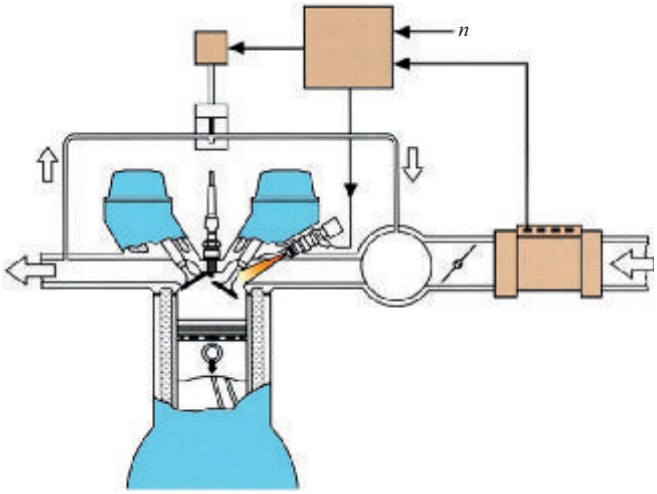


Figure 2.260 Exhaust gas recirculation (EGR) system

Figure 2.261 Throttle body assembly

Service and on-board diagnostic (OBD) plugs are used for diagnostic and corrective actions with scan tools, dedicated test equipment and other test equipment. If faults are detected the system malfunction indicator lamp (MIL) will come on. Alternatively, it will fail to go out after the preset time duration after switching on the engine. All faults should be investigated as soon as possible. Many electronic systems have a limp-home or limited operation strategy (LOS) program, which allows the vehicle to be driven to a workshop for repair.

Key fact

Service and on-board diagnostic (OBD) plugs are used for diagnostic and corrective actions with scan tools, dedicated test equipment and other test equipment.

2.5.2.2 Air supply

The air supply components consist of ducting and silencing components between the air intake and the inlet manifolds. This will also include an air filter, a throttle body, throttle plate assembly and idle control components. The air supply components must provide sufficient clean air for all operating conditions. The air flow into the engine would be noisy and unbalanced between cylinders without the use of resonators and plenum chambers. A plenum chamber is a large volume air chamber that can be fitted either in front of or behind the throttle plate housing.

Air filters on most modern petrol (gasoline)-engined vehicles consist of a plastic casing with a paper filter element. Air flow into the filter is upwards so that dust and dirt particles drop into the dust chamber, or rotary so that dust and dirt are thrown out before the air enters the engine. Crankcase ventilation and the air supply or pulse air exhaust emission systems are also connected to the filter assembly.

The throttle is a conventional circular plate in an air tube (Fig. 2.261). For fast idle and warm up, an auxiliary air valve is fitted to bypass the throttle plate, or an electromechanical link is made to the throttle plate spindle. An auxiliary air valve, idle air control (IAC) or idle speed control (ISC) valve is operated from signals from the ECM.

The auxiliary air valve is often a rotary air valve. This has a special electric motor to move and hold the valve in position. The position is based on the electrical signals supplied by the ECU. Two electric windings in the motor work in opposition to each other so that the motor is variable over a 90° arc. Other designs have graduated opening values based on the signal supplied from the ECU. This type consists of a solenoid valve with a spring-loaded armature

Figure 2.262 Solenoid air valve

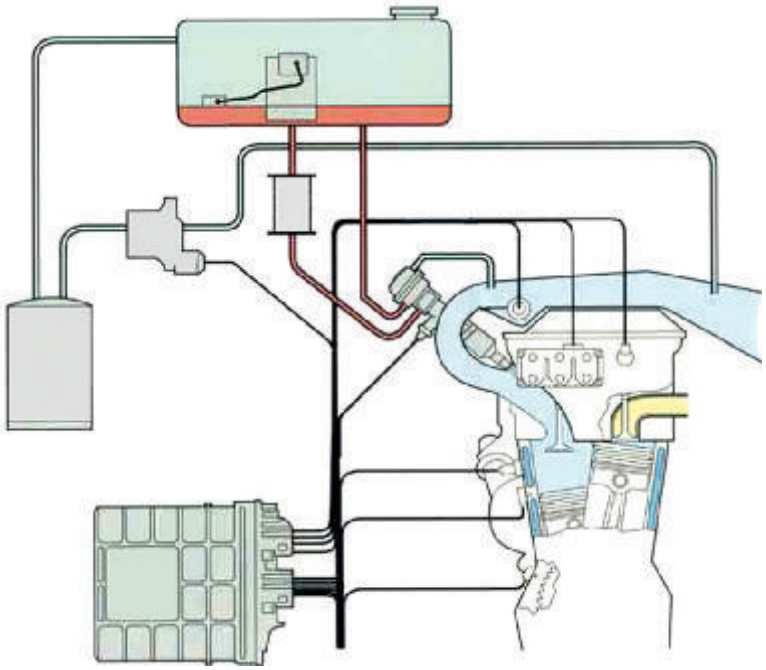


Figure 2.263 Fuel supply components shown in red

connected to the valve in the air channel (Fig. 2.262). All idle control valves operate to hold the engine speed to the stored data specification for engine temperature and load conditions.

Stepper motors are also used to control idle speed and give graduated positions depending on the supply current to a number of electric windings. Sensors in the idle control mechanisms provide feedback signals to the ECU to provide data on operation and position.

2.5.2.3 Fuel supply

The fuel supply, from the fuel tank to the injector valves, for most systems except GDi, follows the same basic layout. A basic layout of fuel supply components is shown in Fig. 2.263. A fuel pump is fitted either in or close to the fuel tank. A fuel filter is fitted in the delivery fuel lines from the tank to a fuel rail. A fuel pressure regulator is located on either the housing for throttle body injector systems or the fuel rail for port fuel injection systems. Return fuel lines run from the pressure regulator to the fuel tank.

The fuel pumps on injection systems are usually roller cell types (Fig. 2.264), driven by a permanent magnet electric motor. Fuel flows through the pump and motor, but there is no risk of fire as there is never an ignitable mixture in the motor. The pump delivery pressure is set by a pressure relief valve, which allows fuel to return to the inlet side of the pump when the operating pressure is reached. There is also a non-return valve in the pump outlet. Typical delivery pressures are between 300 and 400 kPa (3–4 bar).

The rollers in the roller cell pump are thrown out by centrifugal force when the motor armature and pump rotor spindle rotate. The rotor is fitted eccentrically to the pump body and as the rollers seal against the outer circumference, they create chambers that increase in volume to draw fuel in (Fig. 2.265). They then carry the fuel around and finally discharge it as the chamber volume decreases (Fig. 2.266).

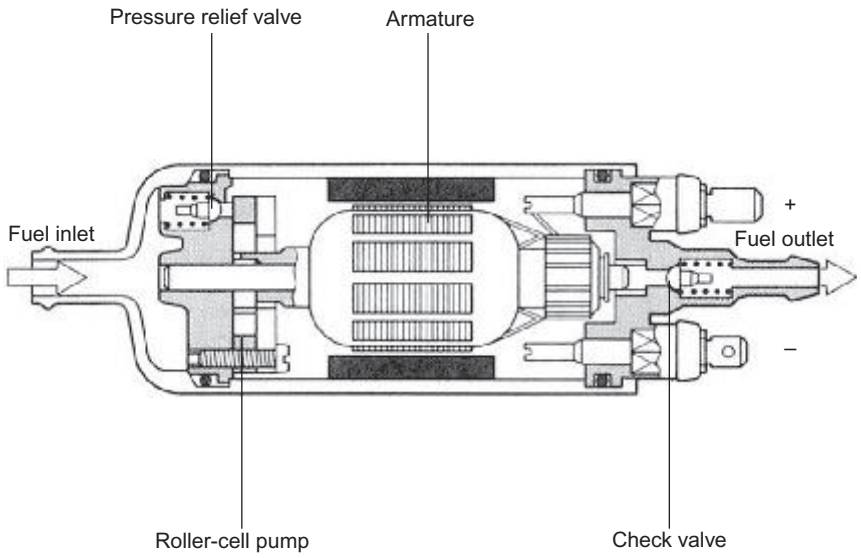


Figure 2.264 Roller cell pump

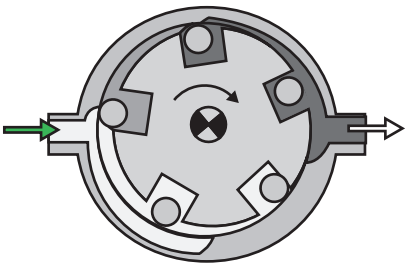


Figure 2.265 Roller cell pump: fuel intake

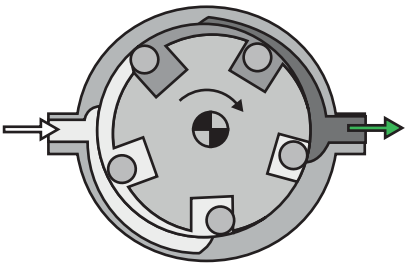


Figure 2.266 Roller cell pump: fuel discharge

Figure 2.267 Fuel filters have been developed to match specific needs of system manufacturers

The fuel pump electrical supply is live only when the engine is being cranked for starting or is running. The fuel pump electric feed is from a relay that is switched on with the ignition. Safety features are built into the electric control feed to the relay so that it operates only to initially prime the system or when the engine is running. The control functions of the fuel pump relay are usually provided by the fuel control module. A further safety feature is the use of an inertia switch in the feed from the relay to the fuel pump. This operates, in the event of an accident, to cut the electric feed to the fuel pump and to stop the fuel supply. It is an impact-operated switch with a weight that is thrown aside to break the switch contacts. Once the switch has been operated it has to be manually reset.

The fuel filter is an in-line paper element type that is replaced at scheduled service intervals. The filter uses microporous paper that is directional for filtration. Filters are marked for fuel flow with an arrow on the casing and correct fitting is essential. They are often matched specifically to a vehicle and fuel type, so, as always, refer to manufacturers' specifications (Fig. 2.267).

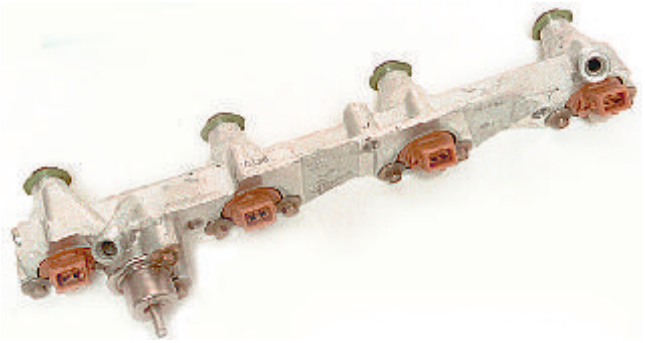


Figure 2.268 Fuel pressure regulator on rail

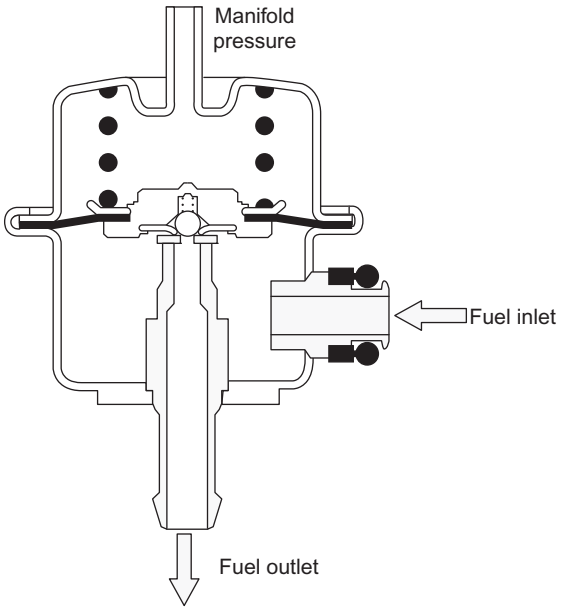


Figure 2.269 Fuel pressure regulator valve closed

Key fact

A fuel pressure regulator is fitted to maintain a precise pressure at the fuel injector valve nozzles.

A fuel pressure regulator is fitted to maintain a precise pressure at the fuel injector valve nozzles. On port fuel injection systems, a fuel rail is used to hold the pressure regulator and the fuel feed to the injector valves (Fig. 2.268). The injector valves usually fit directly onto or into the fuel rail. The fuel rail holds sufficient fuel to dampen fuel pressure fluctuations and keep the pressure applied at all injector nozzles at a similar level.

Fuel regulators are sealed units with a spring-loaded diaphragm and valve on the return outlet to the fuel tank (Figs 2.269 and 2.270). Fuel is pumped into the regulator and when the pressure is high enough, it acts against the diaphragm and compression spring to open the valve. Surplus pressure and fuel is allowed to return to the fuel tank. Once the pressure in the fuel regulator is reduced, the valve closes and the pressure builds up again. Throttle body injection systems operate in the region of 1 bar, and port fuel injection systems in the region of 2.5 bar.

Key fact

Throttle body injection systems operate in the region of 1 bar, and port fuel injection systems in the region of 2.5 bar.

In port fuel injection systems, the inlet manifold vacuum acts against the compression spring in the fuel pressure regulator. This is required to maintain a constant pressure differential between the fuel rail and the inlet manifold. With a constant pressure differential, the amount of fuel delivered during a set time will be the same irrespective of inlet manifold pressure.

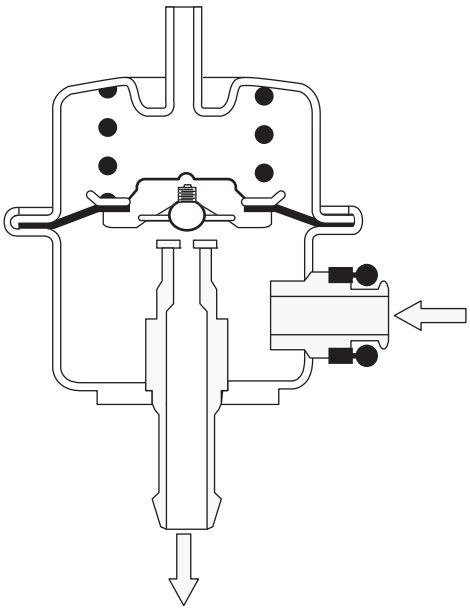


Figure 2.270 Fuel pressure regulator valve open

Figure 2.271 Injector operating

For vehicles fitted with a turbocharger or supercharger, inlet manifold pressure is applied to the diaphragm and regulator valve. When the inlet manifold pressure rises above a certain value, the regulator valve is closed so that the full pump delivery pressure is applied to the injector valve nozzles. This raises the amount of fuel delivered to match the boosted air charge.

The injector valves spray finely atomized fuel (Fig. 2.271) into the throttle body or inlet ports, depending on the system. The electromagnetic injection valves are actuated by signals from the ECU. The signals are of a precise duration depending on operating conditions but within the range of about 1.5–10. milliseconds. This open phase of the injector valve is known as the 'injector pulse width'.

Key fact

Injector signals are of a precise duration depending on operating conditions but usually within the range of about 1.5–10 milliseconds.

There is a range of individual injector valve designs but all have the same common features (Fig. 2.272). These are an electromagnetic solenoid, with a spring-loaded plunger, connected to a jet needle in the injector valve nozzle. The electrical supply to the solenoid is made from the system relay or ECU. Grounding the other connection energizes the solenoid. This lifts the plunger and jet needle so that fuel is injected for the duration that the electric current remains live. As soon as the electrical supply is switched off in the ECU, a compression spring in the injector valve acts on the solenoid plunger to close the nozzle.

A top-feed fuel injector valve for port fuel injection systems is shown on the left of Fig. 2.272. One problem experienced with this fuel feed arrangement is fuel vaporization and bubbles forming in the fuel rail. The bubbles can cause starting and running problems. To overcome this problem lateral or side or bottom-feed injectors are used (shown on the right). When fitted in the fuel rail it can be seen that any bubbles that may form will be at the top of the rail. They will therefore be flushed out through the regulator as soon as the fuel pump is actuated.

The multipoint fuel injection system outlined above is now very common as it works well to meet stringent economy and emission requirements. However, as these requirements increase further, new ways of meeting them are being sought. One of these is direct injection, which is discussed in the next section.

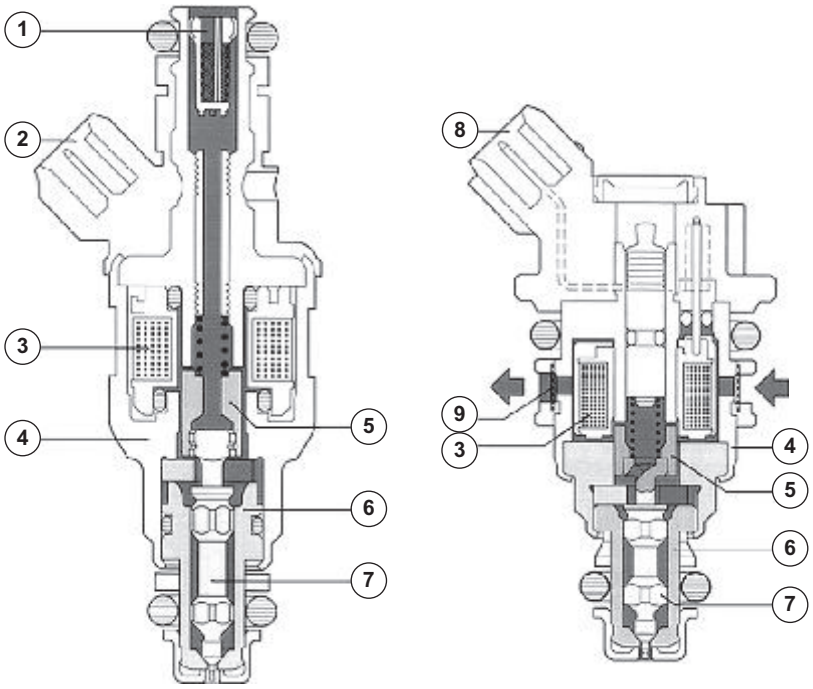


Figure 2.272 Injector features; top-feed (left), bottom-feed (right): 1, fuel supply and filter; 2, electrical connection; 3, solenoid (winding); 4, injector body; 5, armature (moving part); 6, valve body; 7, needle; 8, electrical connection; 9, filter

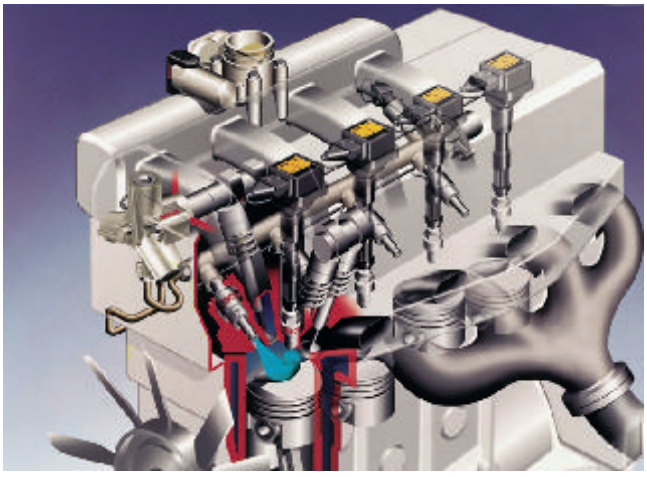


Figure 2.273 Gasoline direct injection on an engine. (Source: Bosch Media)

2.5.2.4 Gasoline direct injection

Bosch's high-pressure injection system for petrol engines is based on a pressure reservoir and a fuel rail, which a high-pressure pump charges to a regulated pressure of up to 120 bar. The fuel can therefore be injected directly into the combustion chamber via electromagnetic injectors (Figs 2.273–2.276).

Key fact

This sensor on the Bosch GDi system can measure a range between lambda = 0.8 and infinity.

The air mass drawn in is adjusted through an electronically controlled throttle valve and is measured with the help of an air mass meter. For mixture control, a wide-band oxygen sensor is used in the exhaust, before the catalytic converters. This sensor can measure a range between $\lambda = 0.8$ and infinity. The electronic

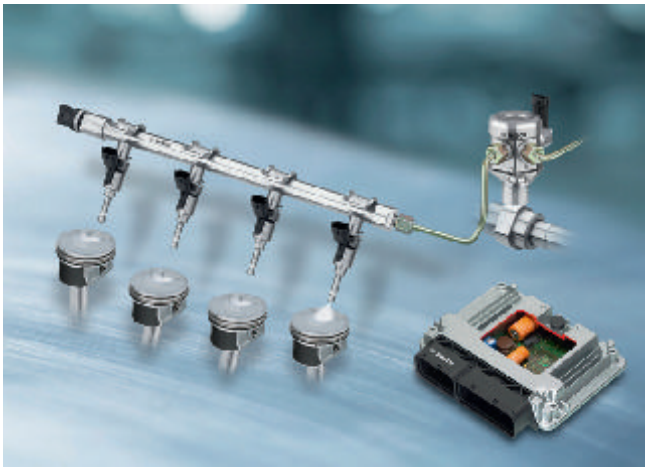


Figure 2.274 Components of gasoline direct injection. (Source: Bosch Media)

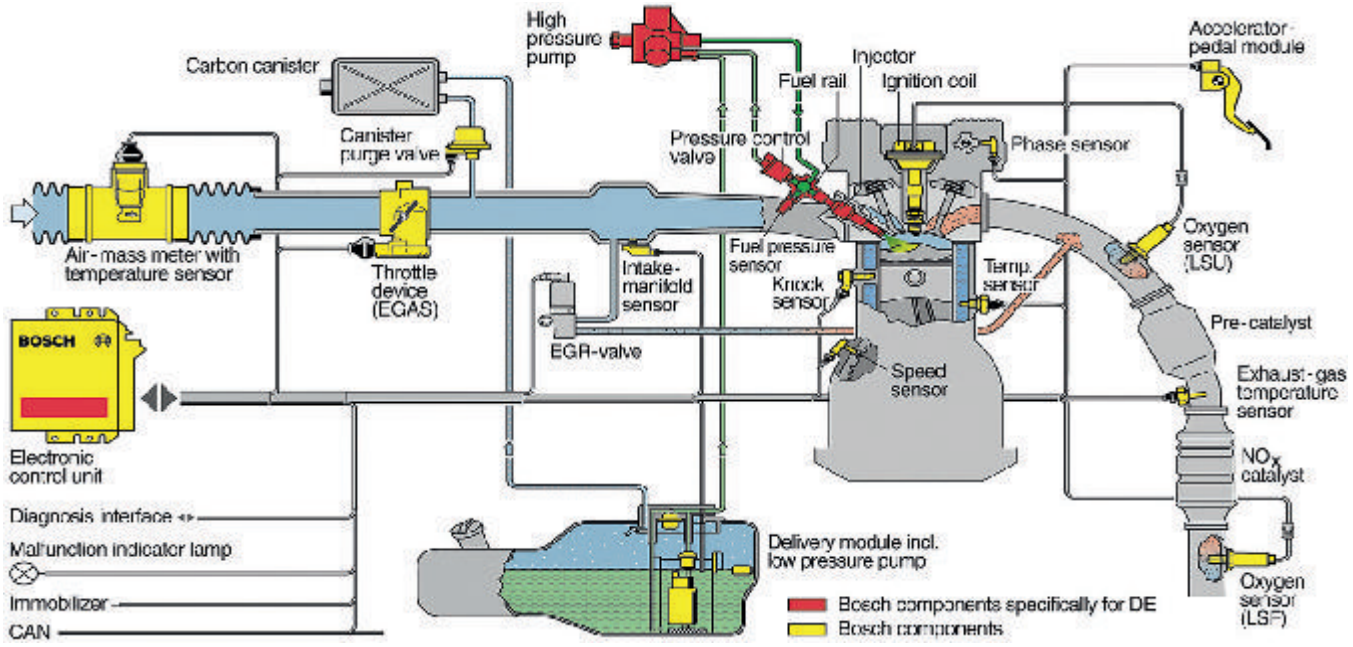


Figure 2.275 Bosch DI-Motronic. (Source: Bosch Media)

Figure 2.276 Injector for direct injection under test. (Source: Bosch Media)

Figure 2.277 Fuel droplet size is important. (Source: Bosch Media)

engine control unit regulates the operating modes of the engine with gasoline direct injection in three ways:

- stratified charge operation – with λ values greater than 1
- homogeneous operation – at $\lambda = 1$
- rich homogeneous operation – with $\lambda = 0.8$.

Definition

Micrometre (μm)
One micrometre (1 μm) is a millionth of a metre.

Compared to the traditional manifold injection system, the entire fuel amount must be injected in full-load operation in a quarter of the time. The available time is significantly shorter during stratified charge operation in part-load. Especially at idle, injection times of less than 0.5 milliseconds are required owing to the lower fuel consumption. This is only one-fifth of the available time for manifold injection.

The fuel must be atomized very finely to create an optimal mixture in the brief moment between injection and ignition (Fig. 2.277). The fuel droplets for direct injection are on average smaller than 20 μm (micrometres, i.e. a millionth of a metre). This is one-fifth of the droplet size reached with the traditional manifold injection and one-third of the diameter of a single human hair. It improves efficiency considerably. However, even more important than fine atomization is even fuel distribution in the injection beam. This is done to achieve fast and uniform combustion.

Key fact

The fuel droplets for direct injection are on average smaller than 20 μm.

Conventional spark ignition engines have a homogeneous (well mixed up!) air/fuel mixture at a 14.7:1 ratio, corresponding to a value of $\lambda = 1$. Direct injection engines, however, operate according to the stratified charge concept in the part-load range and function with high excess air. In return, very low fuel consumption is achieved.

Definition

Stratified
Arranged in approximately horizontal layers.

Fuel injection just before the ignition point and injection directly into the combustion chamber is to create a stratified (layered) mode (Fig. 2.278). The result is a combustible air/fuel mixture cloud on the spark plug, cushioned in a thermally insulated layer, composed of air and residual gas. This raises the efficiency level because heat loss is avoided on the combustion chamber walls. The engine operates with an almost completely opened throttle valve, which avoids additional charge losses.

With stratified charge operation, the lambda value in the combustion chamber is between about 1.5 and 3. In the part-load range, gasoline direct injection achieves the greatest fuel savings, with up to 40% at idle compared to conventional petrol injection processes.

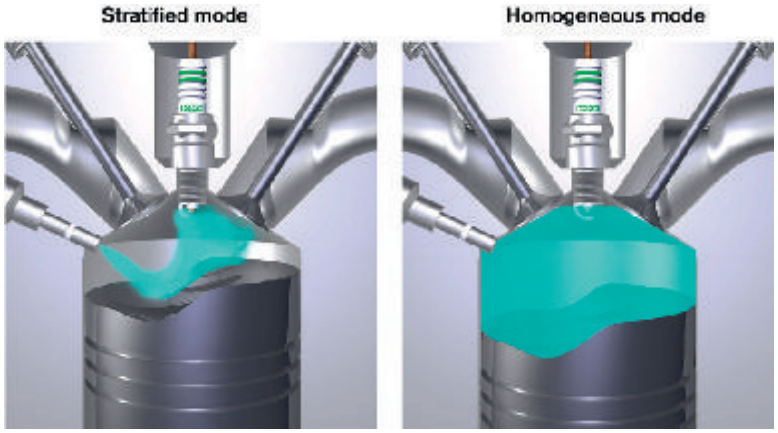


Figure 2.278 Operating modes. (Source: Bosch Media)

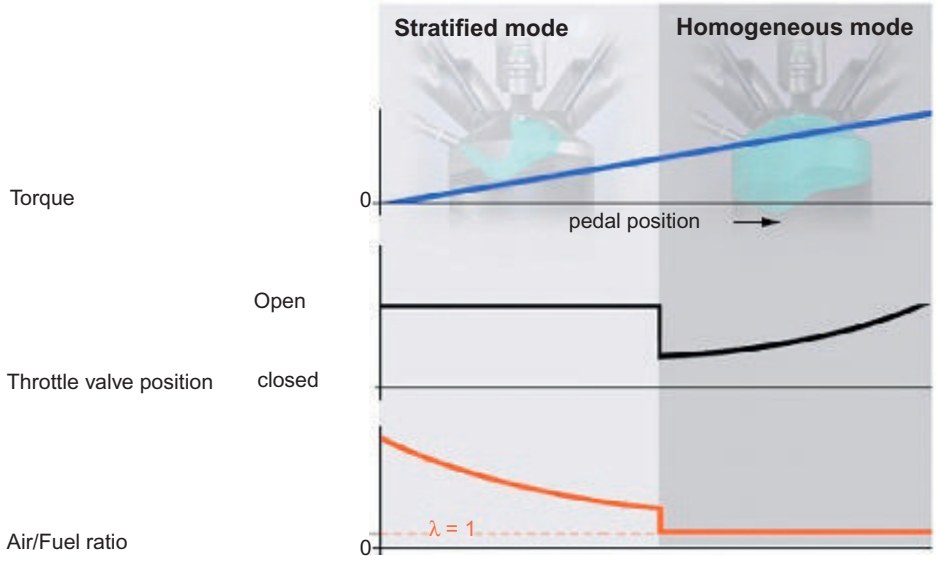


Figure 2.279 Switching between operating modes depending on engine load. (Source: Bosch Media)

With increasing engine load, and therefore increasing injection quantities, the stratified charge cloud becomes even richer and emission characteristics become worse. As in diesel engine combustion, soot may form. In order to prevent this, the DI-Motronic engine control converts to a homogeneous cylinder charge at a predefined engine load (Fig. 2.279). The system injects very early during the intake process to achieve a good mixture of fuel and air at a ratio of $\lambda = 1$.

As is the case for conventional manifold injection systems, the amount of air drawn in for all operating modes is adjusted through the throttle valve according to the desired torque specified by the driver. The Motronic ECU calculates the amount of fuel to be injected from the drawn-in air mass and performs an additional correction via lambda control. In this mode of operation, a torque increase of up to 5% is possible. Both the thermodynamic cooling effect of the fuel vaporizing directly in the combustion chamber and the higher compression of the engine with gasoline direct injection play a role in this (Fig. 2.280).

Definition

Homogeneous
Of uniform composition throughout.

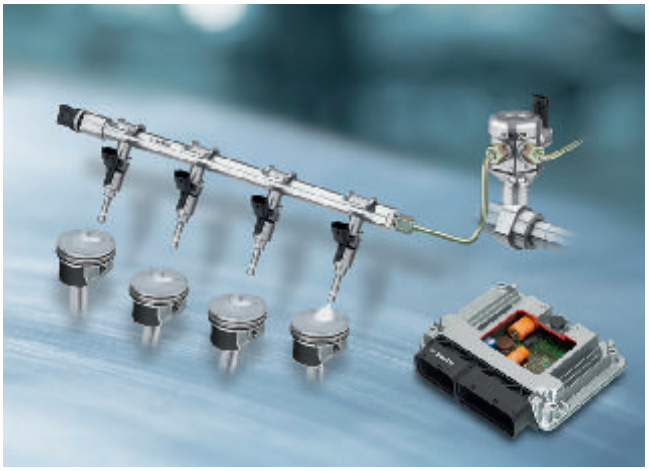


Figure 2.280 Electronic control unit (ECU), rail and injectors. (Source: Bosch Media)

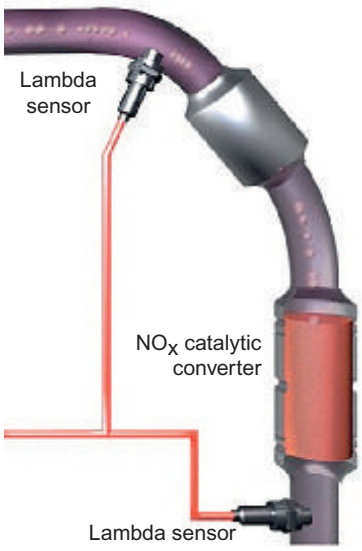


Figure 2.281 NO_x catalytic converter. (Source: Bosch Media)

For these different operating modes, two central demands are raised for engine control:

- The injection point must be adjustable between 'late' (during the compression phase) and 'early' (during the intake phase) depending on the operating point.
- The adjustment for the drawn-in air mass must be detached from the throttle pedal position to permit unthrottled engine operation in the lower load range. However, throttle control in the upper load range must also be permitted.

With optimal use of the advantages, the average fuel saving is up to 15%.

In stratified charge operation the nitrogen oxides (NO_x) segments in the very lean exhaust cannot be reduced by a conventional, three-way catalytic converter. The NO_x can be reduced by approximately 70% through exhaust returns before the catalytic converter. However, this is not enough to fulfil the ambitious emission limits of the future. Therefore, emissions containing NO_x must undergo special treatment. Engine designers are using an additional NO_x accumulator catalytic converter in the exhaust system (Fig. 2.281). The NO_x is deposited in the form of nitrates on the converter surface, with the oxygen still contained in the lean exhaust.

Key fact

In a GDi system, NO_x emissions are reduced by an accumulator catalytic converter in the exhaust system.

Figure 2.282 Diesel fuel injection components. (Source: Bosch Media)

The capacity of the NO_x accumulator catalytic converter is limited. As soon as it is exhausted, the catalytic converter must be regenerated. To remove the deposited nitrates, the DI-Motronic briefly changes over to its third operating mode (rich homogeneous operation with lambda values of about 0.8). The nitrate together with the carbon monoxide is reduced in the exhaust to non-harmful nitrogen and oxygen. When the engine operates in this range, the engine torque is adjusted according to the accelerator pedal position via the throttle valve opening. Engine management has the difficult task of changing between the two different operating modes, in a fraction of a second, in a way not noticeable to the driver.

The continuing challenge, set by legislation, is to reduce vehicle emissions to very low levels. Bosch is a key player in the development of engine management systems. The DI-Motronic system, which is now used by many manufacturers, continues to reflect the good name of the company.

2.5.3 Diesel fuel injection systems

Diesel engines have the fuel injected into the combustion chamber where it is ignited by heat in the air charge. This is known as compression ignition (CI) because no spark is required. The high temperature needed to ignite the fuel is obtained by a high compression of the air charge. Diesel fuel is injected under high pressure from an injector nozzle, into the combustion chambers. The fuel is pressurized in a diesel injection pump. It is supplied and distributed to the injectors through high-pressure fuel pipes or directly from a rail and/or an injector. The high pressure is generated from a direct acting cam or a separate pump.

Key fact

The high temperature needed to ignite fuel in a diesel engine is obtained by high compression of the air charge.

The air flow into a diesel engine is usually unobstructed by a throttle plate so a large air charge is always provided. Throttle plates may be used to provide control for emission devices. Engine speed is controlled by the amount of fuel injected. The engine is stopped by cutting off the fuel delivery. For all engine operating conditions a surplus amount of air is needed for complete combustion of the fuel.

Diesel engines used to be considered as indirect and direct injection. Nowadays, almost all are direct and a number of methods are used, as shown in Figs 2.282 and 2.283. The rotary pumped direct injection and common rail systems will be discussed further in this section.

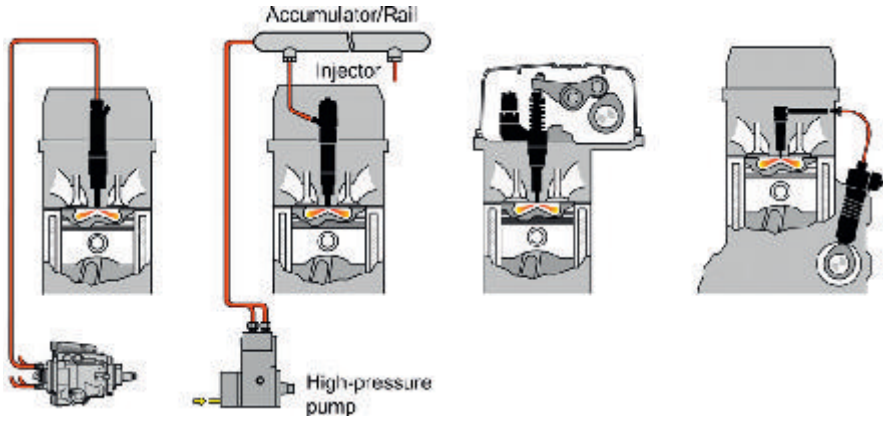


Figure 2.283 Types of diesel injection: direct using a rotary pump, common rail, unit injection and pumped unit injection. (Source: Bosch Media)

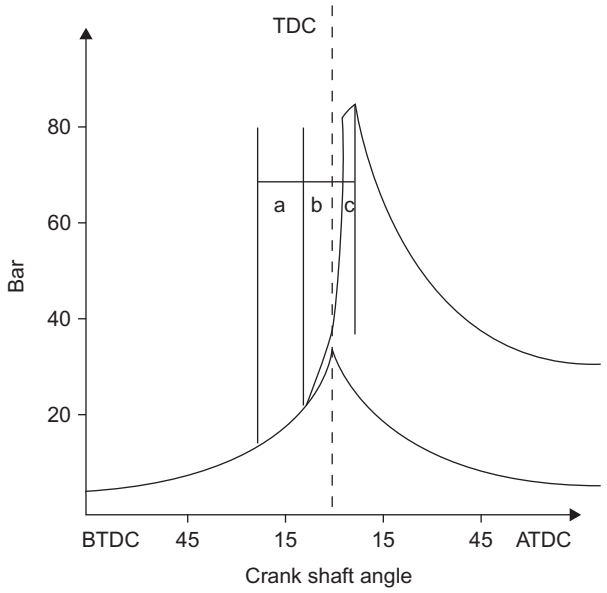


Figure 2.284 Combustion phases: a, delay; b, flame spread (rapid pressure rise); c, controlled combustion (afterburn); BTDC, before top dead centre; ATDC, after top dead centre

Small high-speed diesel engine compression ratios are about 20:1 for direct injection systems. This compression ratio is capable of raising the air charge to temperatures of between 500°C and 800°C. Very rapid combustion of the fuel therefore occurs when it is injected into the hot air charge.

The combustion process in a diesel engine follows three phases: ignition delay, flame spread and controlled combustion (Fig. 2.284). In addition, an injection lag occurs in the high-pressure pipes of earlier systems, as the pressure builds up just before injection.

Figure 2.285 Glow plugs. (Source: Bosch Media)

The most important phase of controlled combustion is when fuel is being injected into a burning mixture. This must be at a rate that maintains an even combustion pressure onto the piston throughout the critical crankshaft rotational angles. This gives maximum torque and efficient fuel usage, because temperatures remain controlled and the heat lost to the exhaust is minimized. The low temperatures also help to keep NO_x emissions to a minimum.

The speed of flame spread in a diesel engine is affected by the air charge temperature and the atomization of the fuel. These characteristics are shared with the delay period. A sufficiently high air charge temperature, of at least 450°C, is a minimum requirement for optimum ignition and combustion.

The delay phase or ignition lag for diesel fuel combustion lasts a few milliseconds. It occurs immediately on injection as the fuel is heated up to the self-ignition temperature. The length of the delay is dependent on the compressed air charge temperature and the grade of fuel. The air charge temperature is also affected by the intake air temperature and the engine temperature.

Key fact

The delay phase or ignition lag for diesel fuel combustion lasts a few milliseconds.

A long delay period allows a high volume of fuel to be injected before ignition and flame spread occurs. In this situation diesel knock is at its most severe. When a diesel engine is cold, there may be insufficient heat in the air charge to bring the fuel up to the self-ignition temperature. When ignition is slow, heavy knocking occurs.

To aid starting and to reduce diesel knock, cold-start devices may be used (Fig. 2.285). For indirect injection engines, starting at lower than normal operating temperatures requires additional combustion chamber heating. For direct injection engines, cold-start devices are only required in frosty weather.

An initial delay, known as injection lag, occurs in the high-pressure fuel lines of rotary pumped systems. This occurs between the start of the pressure rise and the point when pressure is sufficient to overcome the compression spring force in the injectors. Diesel fuel pipes and injectors are shown in Fig. 2.286.

Key fact

An initial delay, known as injection lag, occurs in the high-pressure fuel lines of rotary pumped systems.

Ignition of the fuel occurs in the combustion chamber at the time of injection into the heated air charge. The injection point and the ignition timing are therefore

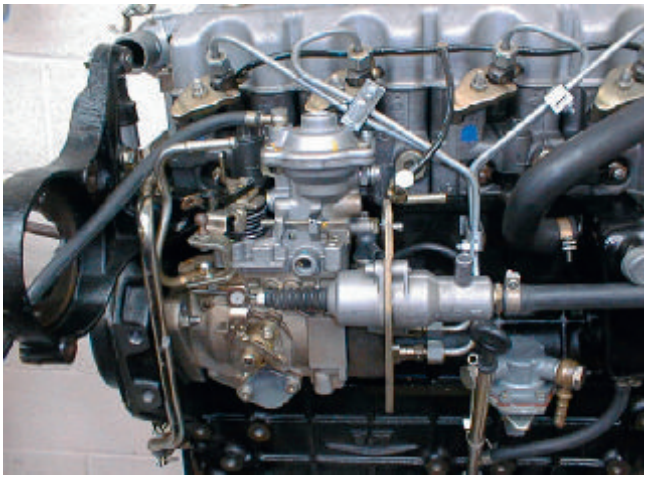


Figure 2.286 Pipes and injectors

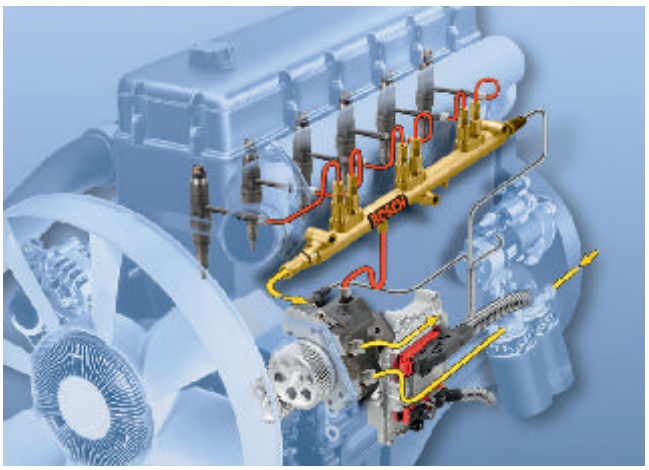


Figure 2.287 Common rail injection. (Source: Bosch Media)

effectively the same thing. Diesel engine injection timing is equivalent to the ignition timing for petrol engines. Injection timing must fall within a narrow angle of crankshaft rotation. It is advanced and retarded for engine speed and load conditions. Injection timing is set by accurate positioning of the fuel injection pump. Incorrect timing leads to power loss. An increase in the production of NO_x when too far advanced, or an increase in the hydrocarbon emissions when too far retarded, can occur.

Particulate emissions result from incomplete combustion of fuel. Particulates are seen as black carbon smoke in the exhaust under heavy load or when fuel delivery and/or timing is incorrect. White smoke may also be visible at other times, such as when the injection pump timing is incorrect. It also occurs when compression pressures are low or when coolant has leaked into the combustion chambers.

Key fact

Diesel engines are particularly suitable for turbocharging.

Recent developments in electronic diesel fuel injection control have made it possible to produce small direct injection engines (Fig. 2.287). Diesel engines are built to withstand the internal stresses, which are greater than in other engines. Diesel engines are particularly suitable for turbocharging, which improves power and torque outputs.

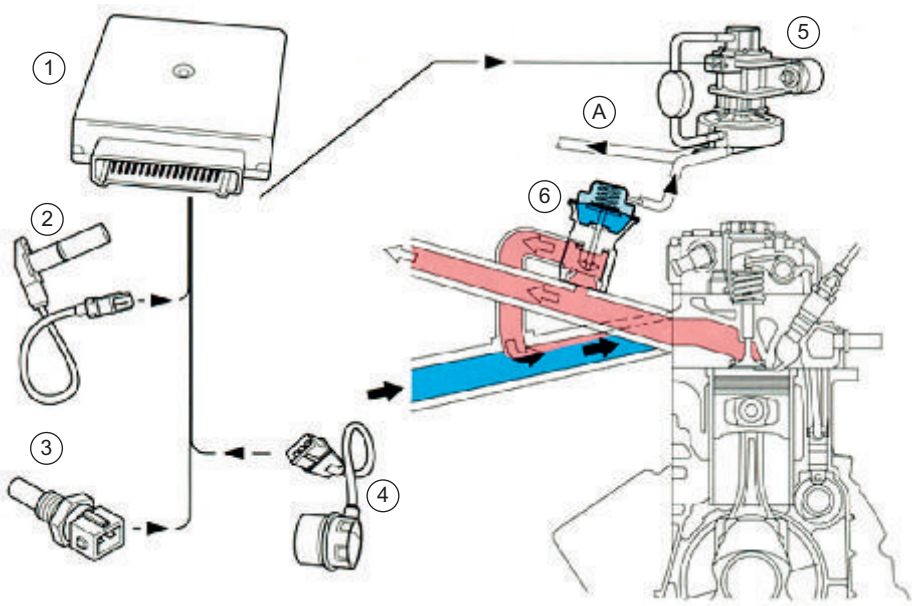


Figure 2.288 Diesel exhaust gas recirculation (EGR): 1, electronic control unit (ECU) and sensors; 2, EGR actuator and control valve; 3, coolant temperature sensor; 4, intake air temperature sensor; 5, ECU controlled valve; 6, vacuum actuator; A, connection to vacuum source

Figure 2.289 Bosch rotary injection pump. (Source: Bosch Media)

Exhaust gas recirculation is used to reduce NO_x emissions from petrol engines; this is also true for diesel engines (Fig. 2.288). In addition, a small quantity of hot exhaust gas in the air charge of a cold engine helps to reduce the delay period and the incidence of cold engine diesel knock.

Many diesel-engined vehicles are now fitted with oxidation catalytic converters that work in conjunction with other emission components to reduce hydrocarbon and particulate emissions.

The fuel systems for traditional direct and indirect injection are similar and vary only in injection pressures and injector types (Fig. 2.289). Until more recently, all light high-speed diesel engines used rotary diesel fuel injection pumps, producing injection pressures of over 100 bar for indirect engines. However, these can rise up to 1000 bar at the pump outlet for turbocharged direct injection engines.

Safety first

Caution: pressure can be up to 1000 bar at the outlet of a rotary pump.

Figure 2.290 Fuel filter

Key fact

Injectors operate with a pulsing action at high pressure to break the fuel down into finely atomized parts.

Injectors operate with a pulsing action at high pressure to break the fuel down into finely atomized parts. Atomization is critical to good fuel distribution in the compressed air charge. The air charge pressure may be in excess of 60 bar. The pressure differential between the fuel injection pressure and air charge pressure must be sufficient to overcome the resistance during injection. This will also give good fuel atomization and a shorter injection time.

The main components of a diesel fuel system provide for either the low-pressure or the high-pressure functions. The low-pressure components are the fuel tank, the fuel feed and return pipes and hoses, a renewable fuel filter with a water trap and drain tap, and a priming or lift pump.

The high-pressure components are the fuel injector pump, the high-pressure pipes and the injectors. Other components provide for cold engine starting. Electronically controlled systems include sensors, an electronic diesel control (EDC) module and actuators in the injection pump.

Key fact

The internal components of the pump and injectors are manufactured to very fine tolerances.

All diesel fuel entering the injection pump and injectors must be fully filtered (Fig. 2.290). The internal components of the pump and injectors are manufactured to very fine tolerances. Even very small particles of dirt could be damaging to these components.

The most common rotary injection pumps are axial-piston designs having a roller ring and cam plate attached to an axial piston or plunger in the distributor head to generate the high pressure. The latest versions have full electronic control. The details are examined further in the next section.

The high-pressure pipes are of double-thickness steel construction and are all of the same length. This is so that the internal pressure rise characteristics are identical for all cylinders. The high-pressure connections are made by rolled flanges on the pipe ends and threaded unions securing the rolled flanges to convex, or occasionally concave, seats in the delivery valves and injectors.

The fuel injectors are fitted into the cylinder head with the nozzle tip projecting into the precombustion (indirect injection) or combustion chamber (direct injection). The injectors for indirect combustion are of a pintle or ‘pintaux’ design (similar to petrol injectors in many ways) and produce a conical spray pattern on injection. The injectors for direct injection (DI) are of a pencil-type multihole design that produces a broad distribution of fuel on injection (Fig. 2.291).

Fuel injectors are held closed by a compression spring. They are opened by hydraulic pressure when it is sufficient to overcome the spring force on the

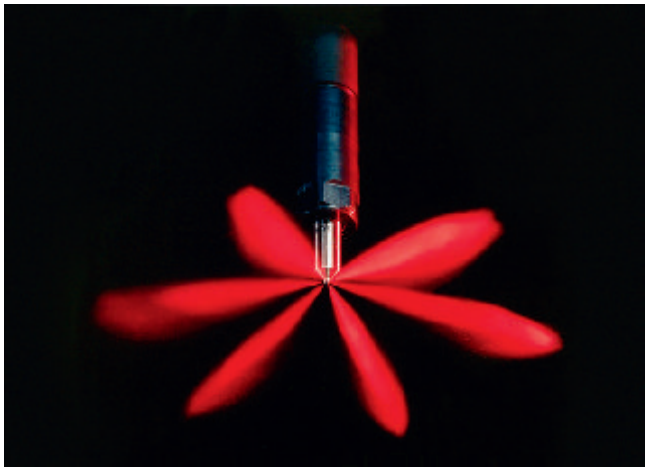


Figure 2.291 Direct injection (DI) injector

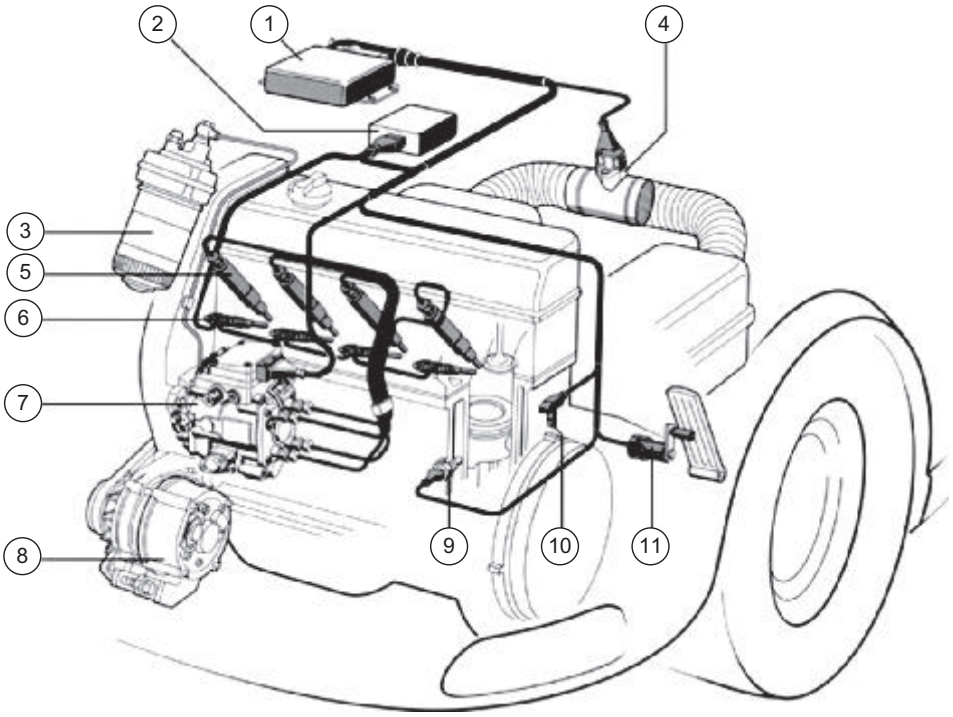


Figure 2.292 Electronic diesel control (EDC) rotary pump system: 1, engine ECU; 2, glow control unit; 3, filter; 4, air-mass meter; 5, injectors; 6, glow plugs; 7, rotary distributor pump with ECU; 8, alternator; 9, coolant temperature sensor; 10, crankshaft sensor; 11, throttle pedal sensor

injector needle. The hydraulic pressure is applied to a face on the needle where it sits in a pressure chamber. The fuel pressure needed is in excess of 100 bar (1500 psi). This pressure lifts the needle and opens the nozzle, so that fuel is injected in a fine spray pattern into the combustion chamber.

The next section examines the Bosch rotary pump electronic diesel control system, while the section after that looks at the system now in use on most modern cars: common rail direct injection.

Key fact

The fuel pressure needed to open the fuel injector is in excess of 100 bar (1500 psi).

2.5.3.1 Rotary pump system

Bosch rotary VR pumps are used on high-speed direct injection diesel engines for cars and light commercial vehicles (Fig. 2.292). They are radial-piston distributor injection pumps having opposing plungers that are forced inwards by

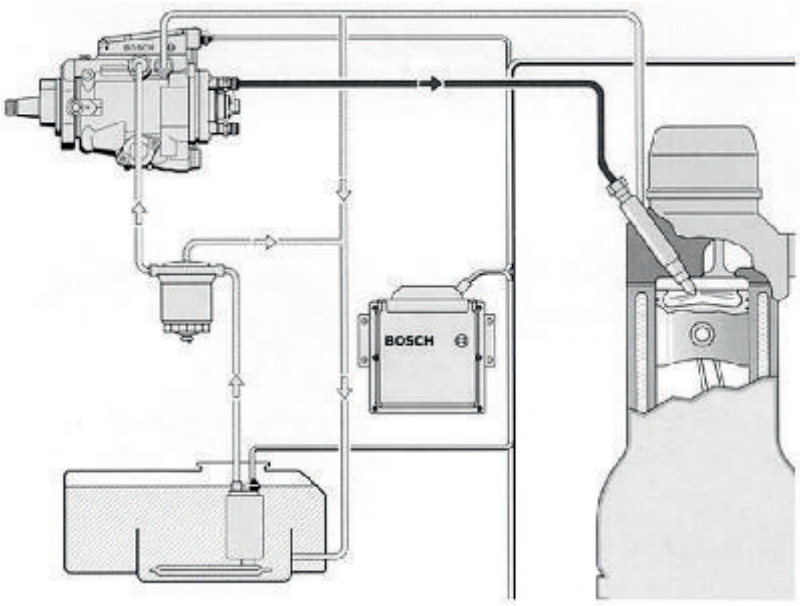


Figure 2.293 Low-pressure (white and grey) and high-pressure (in black) pressure fuel system

cam lobes on the inside of a cam ring to produce high pressure, which can be up to 1400 bar in some applications. The cam is located in the pump body and the plungers are in the rotor driven by the pump spindle. Four-cylinder engines have two plungers and four cam lobes. Six-cylinder engines have three plungers and six cam lobes. The pump is driven from the engine at half crankshaft speed.

A low-pressure feed to the injection pump is provided by a submerged electrical pump in the fuel tank (Fig. 2.293). This provides for priming and positive pressure in the injection pump. In common with all diesel fuel systems, a fuel filter and water trap is used to ensure that only very clean fuel is delivered to the pump. Return pipes are used for excess fuel leakage, for purging the pump and for lubrication of the injectors.

Inside the distributor pump is a vane type pump, which is used to produce the pump body pressure. Pump body pressure is used for charging the high-pressure chamber between the plungers and for injection advance. A pressure control valve is used to prevent excessive pressure. It is a spring-loaded plunger that is lifted by hydraulic pressure to expose ports in the valve bore. This will then allow fuel to flow back to the inlet side of the vane-type pump.

An overflow throttle valve, in the pump housing, is used to allow a defined quantity of fuel to flow back to the fuel tank at all times. This provides some cooling in the pump and venting of air during pump priming. A second, larger overflow bore in the valve opens at a given pressure to allow a flow of fuel from the distributor head.

The Bosch pump shown in Fig. 2.294 has full electronic control for fuel metering and for injection advance. The electronic diesel control unit consists of two ECMs to perform the control functions (Fig. 2.295). These two modules are the engine control ECU and the injection pump ECU. The pump ECU is fitted on top of the pump.

Key fact

Fuel metering is controlled by the ECU, which operates a high-pressure solenoid valve.

Fuel metering is controlled by the high-pressure solenoid valve. This is an electrically actuated valve set centrally inside the distributor rotor. There are connecting bores in the distributor rotor for filling of the high-pressure circuit, through the inlet port at pump body pressure, and for delivery at high pressure to the fuel injectors. These are either connected or separated by the position of the valve.

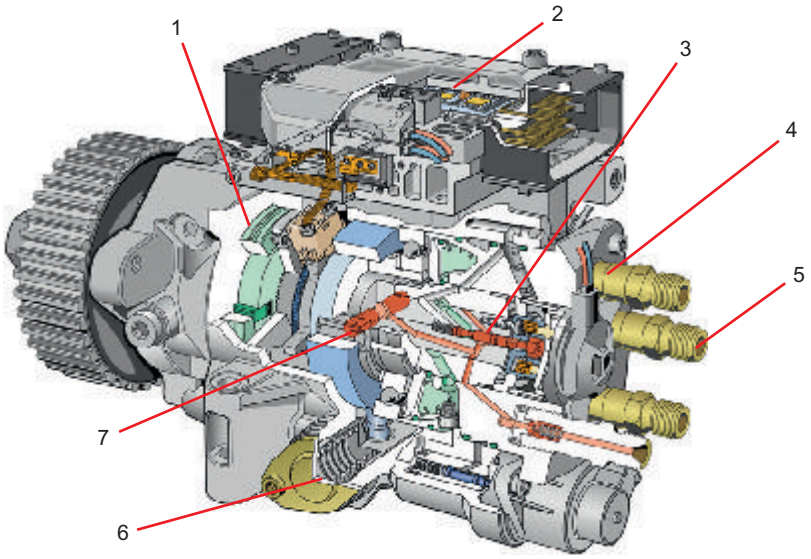


Figure 2.294 Solenoid valve-controlled radial-piston distributor pump: 1, Sensor (position/timing); 2, ECU; 3, high-pressure solenoid valve needle; 4, solenoid; 5, outlets to injectors; 6, timing device (ignition advance mechanism); 7, radial-piston high-pressure pump. (Source: Bosch Media)

Figure 2.295 Electronic diesel control (EDC) unit

A high-pressure solenoid valve is closed by an electrical signal from the pump ECU. When the valve is closed, fuel under high pressure passes from the high-pressure pump chamber, through the bores in the rotor and distributor head, through the return-flow throw throttle valve (delivery valve) and out to the injectors. It is then injected into the engine combustion chambers. The few microseconds of time during which the valve remains closed is referred to as the delivery or injection period.

The quantity of fuel that is metered for injection at any time is computed by the engine ECU (Fig. 2.296), which sends signals to the injection pump ECU for control of the high-pressure solenoid valve. The electrical current for operating this valve is high, and the two ECUs are separated to avoid high current interference in the electronically more vulnerable engine ECU.

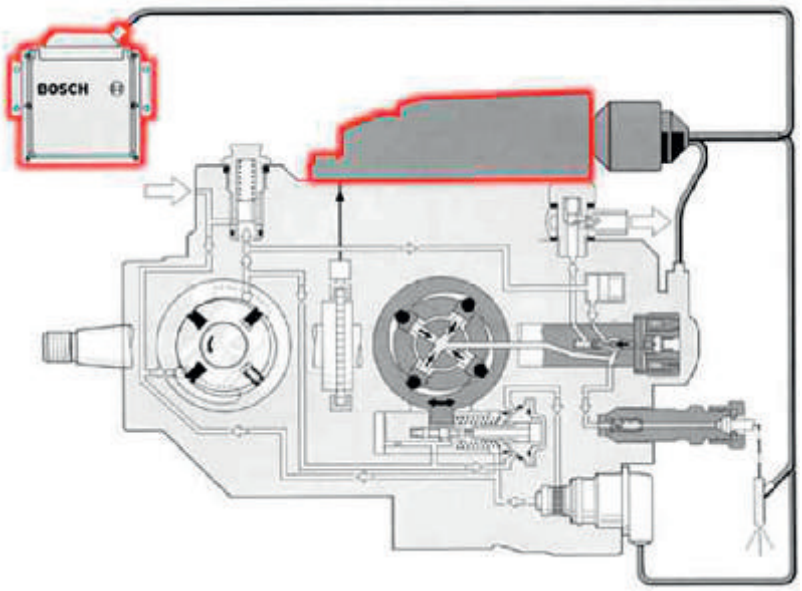


Figure 2.296 Electronic control units

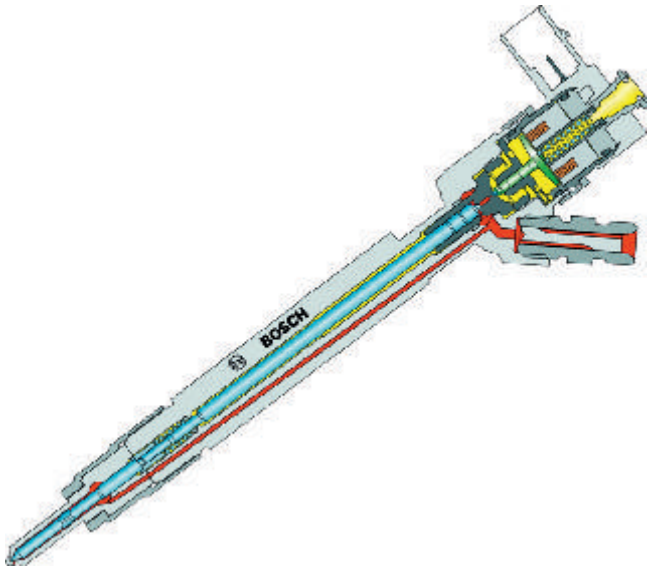


Figure 2.297 Injector. (Source: Bosch Media)

The electronic diesel control units are provided with data signals from sensors and switches attached to the engine, the pump and other vehicle systems. The sensors are used for comparisons to programmed operating parameters and for calculations for metering the amount of fuel delivered and for controlling the injection advance.

Injection advance is obtained by rotation of the cam ring by pump body pressure in the injection advance mechanism. The injection advance mechanism consists of a transverse timing device piston and control components and an electrical solenoid valve. Maximum advance is 40° of crankshaft rotation.

A needle motion sensor in the injector sends a signal to the engine ECU at the instant of opening of the injector (Fig. 2.297). This point, relative to the crankshaft rotational angle before TDC, is used for load and speed injection timing calculations and for control of the EGR valve.

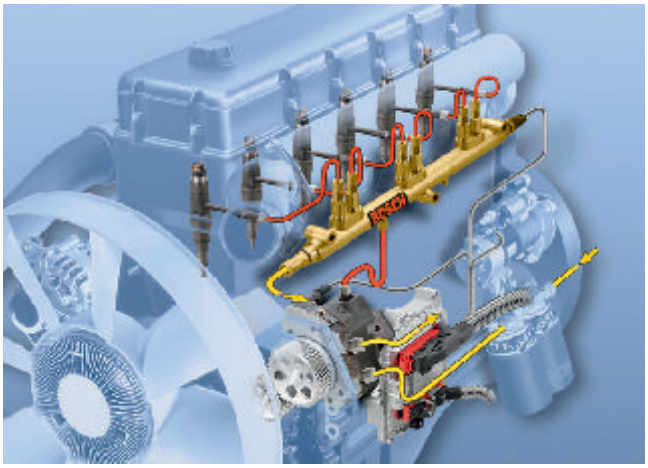


Figure 2.298 Common rail system. (Source: Bosch Media)

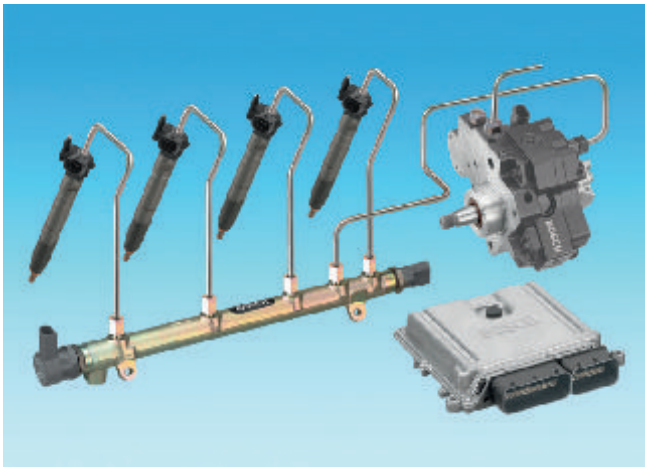


Figure 2.299 Four-cylinder system. (Source: Bosch Media)

The Bosch VR electronic diesel control system uses a number of sensors and control actuators. This allows it to achieve optimum performance. However, even this sophisticated system has virtually been superseded, so read on to discover more about the common rail system!

2.5.3.2 Common rail system

The development of diesel fuel systems is continuing, with many new electronic changes to the control and injection processes. One of the latest developments is the common rail (CR) system, which operates at very high injection pressures (Fig. 2.298). It also has piloted and phased injection to reduce noise and vibration.

The common rail system has made it easier for small high-speed diesel engines to have all the advantages of direct injection (Fig. 2.299). These developments have resulted in significant improvements in fuel consumption and performance.

The combustion process, with common rail injection, is improved by a pilot injection of a very small quantity of fuel, at between 40° and 90° before top dead centre (BTDC). This pilot fuel ignites in the compressing air charge so that the cylinder temperature and pressure are higher than in a conventional diesel

Key fact

The combustion process, with common rail injection, is improved by a pilot injection of a very small quantity of fuel, at between 40° and 90° BTDC.

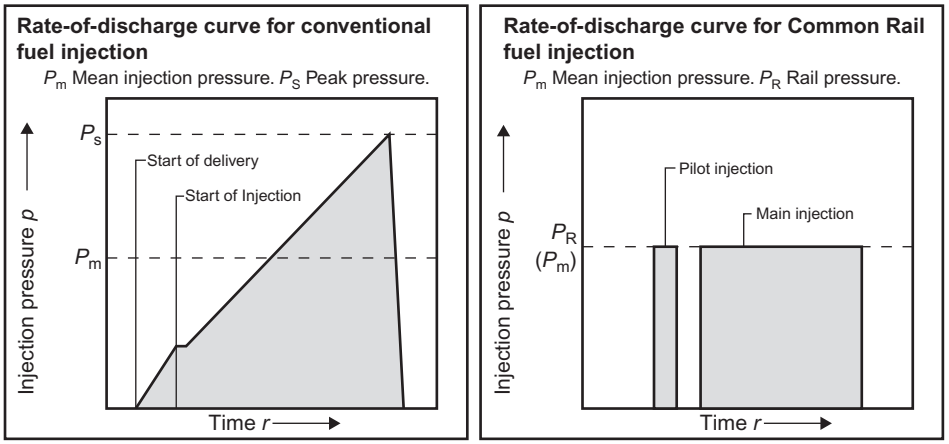


Figure 2.300 Conventional system and common rail system

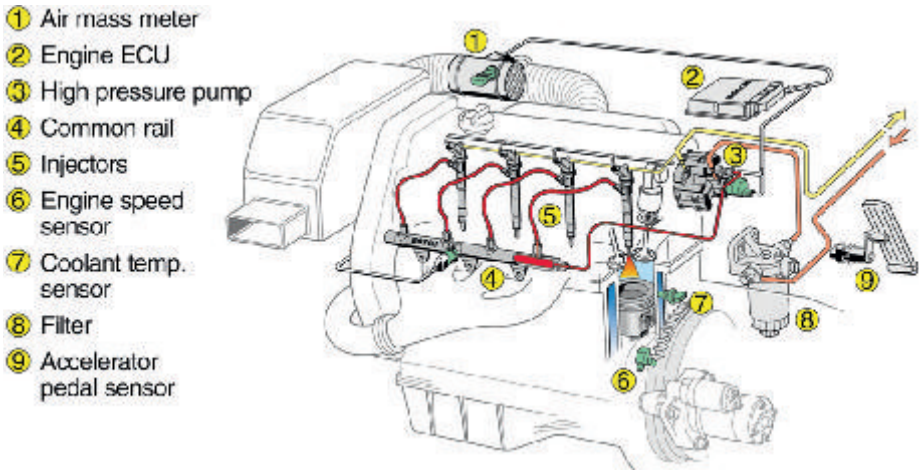


Figure 2.301 Main components of the common rail system

injection engine at the start of injection. The higher temperature and pressure reduce ignition lag to a minimum, so that the controlled combustion phase during the main injection period is softer and more efficient (Fig. 2.300).

Fuel injection pressures are varied throughout the engine speed and load range to suit the instantaneous conditions of driver demand and engine speed and load conditions. Data input from other vehicle system ECUs is used to further adapt the engine output, to suit changing conditions elsewhere on the vehicle. Examples are traction control, cruise control and automatic transmission gearshifts. The EDC module carries out calculations to determine the quantity of fuel delivered. It also determines the injection timing based on engine speed and load conditions. The actuation of the injectors, at a specific crankshaft angle (injection advance) and for a specific duration (fuel quantity), is made by signal currents from the EDC module. A further function of the EDC module is to control the accumulator (rail) pressure.

The Bosch CR common rail diesel fuel injection system, for light vehicles, consists of four main component areas: the low-pressure delivery components, high-pressure delivery with a high-pressure pump and accumulator (rail), the electronically controlled injectors, and the ECU and associated sensors and switches (Fig. 2.301).

Key fact

CR fuel injection pressures can be varied, throughout the engine speed and load range.

Definition

Accumulator
Apparatus by means of which energy can be stored (the rail on a common rail system).

Figure 2.302 High-pressure pump. (Source: Bosch Media)

The low-pressure delivery components are the fuel tank, a prefilter, presupply (low-pressure) pump, a fuel filter and the low-pressure delivery pipes to the high-pressure pump and for excess fuel return. The low-pressure pump, depending on application, can be of the roller cell type and be fitted either in the fuel tank or in-line where it is mounted to the vehicle body close to the fuel tank. Where the pump is fitted in the fuel tank, it includes a prefilter and has the fuel gauge sender unit attached to the same attachment flange on the side or top of the fuel tank.

The electrical supply to the fuel pump is made either directly or through a relay from the EDC module. An inertia switch is generally used to cut the electrical current to the pump motor in an accident. On some vehicles, a gear-type pump may be incorporated into the high-pressure pump and be driven from a common drive shaft. It can be a separate pump attached to the engine with a geared drive from the camshaft or crankshaft. The low-pressure delivery pipes connect to a fuel filter and water trap. A continuous flow of fuel runs through the filter and primes the high-pressure pump or returns to the fuel tank.

Key fact

An inertia switch is generally used to cut the electrical current to the pump motor in an accident.

The high-pressure pump is driven from the engine crankshaft through a geared drive at half engine speed and can be fitted where a conventional distributor pump would be. It can also be fitted on the end of the camshaft housing and be driven by the camshaft. It is lubricated by the diesel fuel that flows through it.

The pump has to produce all of the high pressure for fuel injection (Fig. 2.302). It is a triple-piston radial pump, with a central cam for operation of the pressure direction of the pistons and return springs to maintain the piston rubbing shoes in contact with the cam. The pump has a positive displacement with inlet and outlet valves controlling the direction of flow through the pump.

The pump delivery rate is proportional to the speed of rotation of the engine so that it meets most engine speed requirements. To meet the engine load requirements the pump has a high volume. To meet the high-pressure requirements for fine atomization of the fuel on injection, the pump can produce pressures in the region of 1400 bar (scary!). A pressure control valve returns excess fuel to the fuel tank.

Safety first

A CR pump can produce pressures in the region of 1400 bar.

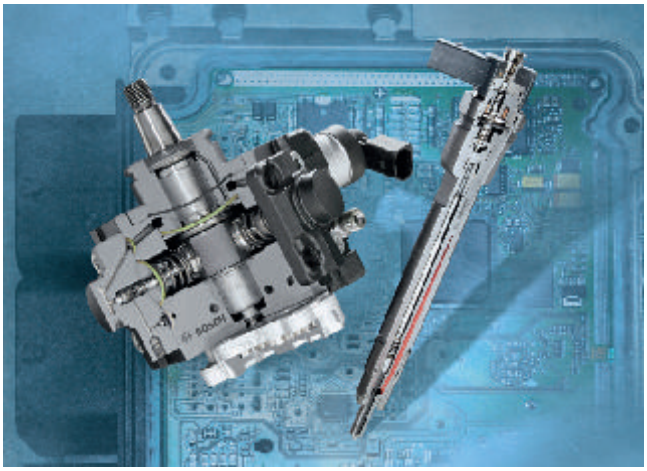


Figure 2.303 Sectioned common rail pump and injector. (Source: Bosch Media)

The pressure control valve is a mechanical and electrical unit. It is fitted on the pump or the high-pressure accumulator (rail). The mechanical part of the valve consists of a compression spring that acts on a plunger and ball valve. The electrical component is a solenoid that puts additional and variable force on the ball valve. The solenoid is actuated on signal currents from the EDC module. When the solenoid is not actuated, the ball valve opens at 100 bar against the resistance of the compression spring. This spring valve damps some of the high-frequency pressure fluctuations produced by the pump.

Key fact

The solenoid in the pressure control valve is used for setting pressure in the rail.

The solenoid in the pressure control valve is used for setting a variable mean pressure in the high-pressure accumulator (rail). The pressure in the rail is measured by a sensor and compared with a stored map in the EDC module for the current engine operating conditions. To increase the fuel rail pressure, an electrical alternating current is applied to the solenoid. The energizing current is varied by the EDC module, so that the additional force on the ball valve produces the required fuel rail pressure.

The high-pressure accumulator (rail) is common to all cylinders and derives its name,'common rail', from this. This term is used in preference to fuel rail, which is used for petrol engines. The rail is an accumulator because it holds a large volume of fuel under pressure (Fig. 2.303). The volume of fuel is sufficient to dampen the pressure pulses from the high-pressure pump.

The injectors on the common rail system have nozzles that are similar to all other diesel injectors for direct injection engines. The nozzle needle seats in the nozzle to obstruct the holes in the tip where the fuel is injected into the combustion chamber. The nozzle needle is held closed by a compression spring and opened by hydraulic pressure.

Key fact

The piezo injector reacts very quickly, thereby improving fuel control.

Opening and closing of the injector is controlled not by high-pressure fuel pulse from an injector pump, as in a conventional rotary distributor pump, but by actuation of an electrical solenoid in the injector body. This is controlled by the electronic diesel control module. A permanent high pressure is maintained in the injector at the same pressure as the rail. Operation of the injector is controllable for very small intervals of time.

The electronic control of the common rail diesel injection system allows for precise control of fuelling (Figs 2.304 and 2.305). This results in excellent economy and very low emissions.

Figure 2.304 Piezo common rail injector

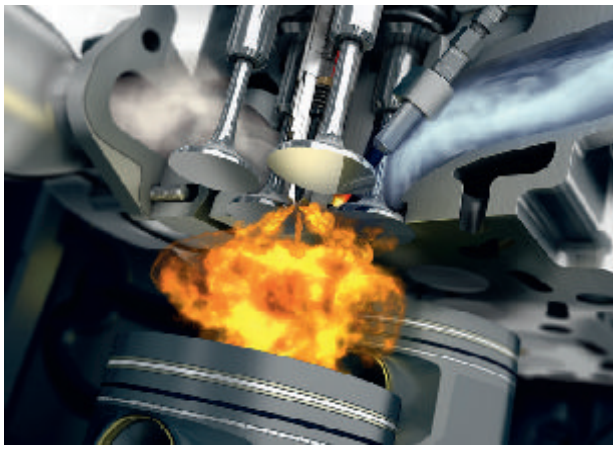


Figure 2.305 Common rail injection combustion

2.5.4 Alternative fuels

The use of an alternative fuel can lessen dependence upon oil and reduce greenhouse gas emissions. There are several alternative fuels and each of these is outlined briefly in this section.

2.5.4.1 Ethanol

Ethanol is an alcohol-based fuel made by fermenting and distilling starch crops, such as corn. It can also be made from plants such as trees and grasses. E10 is a blend of 10% ethanol and 90% petrol (gasoline). Almost all manufacturers approve the use of E10 in their vehicles. E85 is a blend of 85% ethanol and 15% petrol and can be used in flexible fuel vehicles (FFVs) (Fig. 2.306). FFVs are specially designed to run on petrol, E85, or any mixture of the two. These vehicles are offered by several manufacturers.

Key fact

Ethanol is an alcohol-based fuel made by fermenting and distilling starch crops, such as corn.

There is no noticeable difference in vehicle performance when E85 is used. However, FFVs operating on E85 usually experience a 20–30% drop in miles per gallon owing to the lower energy content of ethanol (Fig. 2.307).

There are some advantages and disadvantages of using ethanol:

Advantages:

- lower emissions of air pollutants
- more resistant to engine knock
- added vehicle cost is very small.

Figure 2.306 NASCAR flex-fuel. (Source: Ford Media)

Figure 2.307 E85 vehicle. (Source: Ford Media)

Disadvantages:

- can only be used in flexible fuel vehicles
- lower energy content, resulting in fewer miles per gallon
- limited availability.

2.5.4.2 Biodiesel

Key fact

Biodiesel is a form of diesel fuel manufactured from vegetable oils, animal fats or recycled restaurant oils.

Biodiesel is a form of diesel fuel manufactured from vegetable oils, animal fats or recycled restaurant oils. It is safe and biodegradable, and produces fewer air pollutants than petroleum-based diesel. It can be used in its pure form (B100) or blended with petroleum diesel. Common blends include B2 (2% biodiesel), B5 and B20. B2 and B5 can be used safely in most diesel engines (Fig. 2.308). However, most vehicle manufacturers do not recommend using blends greater than B5, and engine damage caused by higher blends is not covered by some manufacturer warranties.

Advantages:

- can be used in most diesel engines, especially newer ones
- produces fewer air pollutants (other than NO_x) and greenhouse gases
- biodegradable

Figure 2.308 Biodiesel engine

- non-toxic
- safer to handle.

Disadvantages:

- use of blends above B5 may not yet be approved by manufacturers
- lower fuel economy and power (10% lower for B100, 2% for B20)
- more NO_x emissions
- B100 generally not suitable for use in low temperatures
- concerns about B100's impact on engine durability.

2.5.4.3 Natural gas

Natural gas is a fossil fuel made up mostly of methane. It is one of the cleanest burning alternative fuels. It can be used in the form of compressed natural gas (CNG) or liquefied natural gas (LNG) to fuel cars and trucks. Dedicated natural gas vehicles are designed to run on natural gas only, while dual-fuel or bi-fuel vehicles can also run on petrol (gasoline) or diesel (Fig. 2.309). Dual-fuel vehicles take advantage of the widespread availability of conventional fuels but use a cleaner, more economical alternative when natural gas is available. Natural gas is stored in high-pressure fuel tanks so dual-fuel vehicles require two separate fuelling systems, which take up extra space. Natural gas vehicles are not produced commercially in large numbers. However, conventional vehicles can be retrofitted for CNG.

Key fact

Natural gas is a fossil fuel made up mostly of methane.

Advantages:

- 60–90% less smog-producing pollutants
- 30–40% less greenhouse gas emissions
- less expensive than petroleum fuels.

Disadvantages:

- limited vehicle availability
- less readily available
- fewer miles on a tank of fuel.

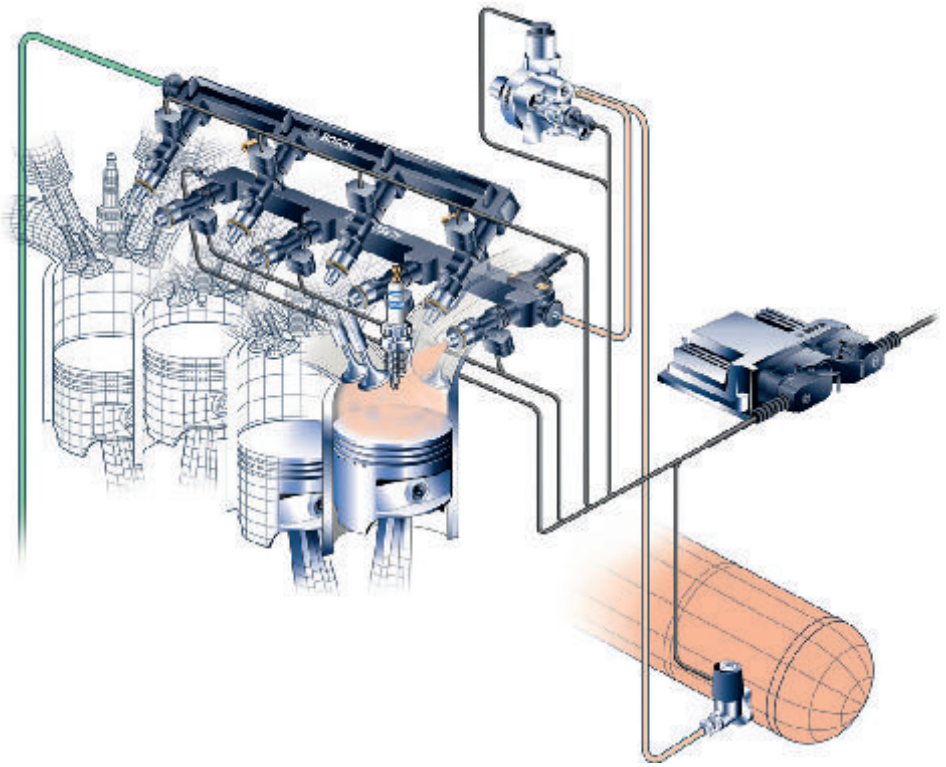


Figure 2.309 Natural gas and gasoline direct injection (GDi) system. (Source: Bosch Media)

Figure 2.310 Propane tank. (Source: http://www.rasoenterprises.com)

Key fact

Propane or liquefied petroleum gas (LPG) is a clean-burning fossil fuel.

2.5.4.4 Liquefied petroleum gas

Propane or liquefied petroleum gas (LPG) is a clean-burning fossil fuel that can be used to power internal combustion engines. LPG-fuelled vehicles produce fewer toxic and smog-forming air pollutants. Petrol (gasoline) and diesel vehicles can be retrofitted to run on LPG in addition to conventional fuel. The LPG is stored in high-pressure fuel tanks (Fig. 2.310), so separate fuel systems are needed in vehicles powered by both LPG and a conventional fuel.

Advantages:

- fewer toxic and smog-forming air pollutants
- less expensive than petrol.

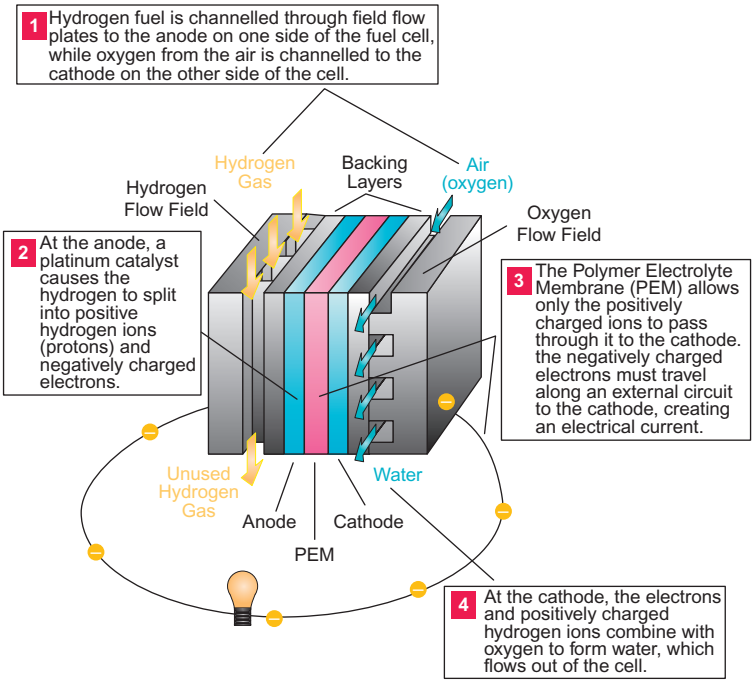


Figure 2.311 Fuel cell operation

Disadvantages:

- no new passenger cars or trucks commercially available, but vehicles can be retrofitted for LPG
- less readily available than conventional fuels
- fewer miles on a tank of fuel.

2.5.4.5 Hydrogen

Hydrogen (H_2) can be produced from fossil fuels (such as coal), nuclear power or renewable resources, such as hydropower. Fuel cell vehicles powered by pure hydrogen emit no harmful air pollutants. Hydrogen is being aggressively explored as a fuel for passenger vehicles. It can be used in fuel cells (Fig. 2.311) to power electric motors or burned in internal combustion engines. Hydrogen is an environmentally friendly fuel that has the potential to dramatically reduce dependence on oil, but several significant challenges must be overcome before it can be widely used.

Key fact

Hydrogen (H_2) can be produced from fossil fuels (such as coal), nuclear power or renewable resources, such as hydropower.

Advantages:

- can be produced from several sources, reducing dependence on petroleum
- no air pollutants or greenhouse gases when used in fuel cells
- it produces only NO_x when burned in internal combustion engines.

Disadvantages:

- expensive to produce and is only available at a few locations
- fuel cell vehicles are currently too expensive for most consumers
- hydrogen has a lower energy density than conventional petroleum fuels, so it is difficult to store enough hydrogen on a vehicle to travel more than 200 miles.

This section has given an overview of some alternative fuels. All of them offer some significant advantages either commercially, environmentally or both. There

Figure 2.312 First ethanol vehicle in the UK. (Source: Ford Media)

Figure 2.313 Escape hybrid E85 produced in the USA. (Source: Ford Media)

are also some disadvantages, not least of which is that the cost of production is high. This is likely to change, however, as their use becomes more widespread (Figs 2.312 and 2.313).

Key fact

The purpose of the ignition system is to supply a spark inside the cylinder, near the end of the compression stroke, to ignite the compressed charge of air/fuel vapour.

2.6 Ignition systems

2.6.1 Ignition overview

2.6.1.1 Introduction

The purpose of the ignition system is to supply a spark inside the cylinder, near the end of the compression stroke, to ignite the compressed charge of air/fuel vapour (Fig. 2.314).

For a spark to jump across an air gap of 1.0 mm under normal atmospheric conditions (1 bar) a voltage of 4–5 kV is required. For a spark to jump across a similar gap in an engine cylinder, having a compression ratio of 8:1, approximately 10 kV is required. For higher compression ratios and weaker mixtures, a voltage up to 20 kV may be necessary. The ignition system has to transform the normal battery voltage of 12 V to approximately 8–20 kV and, in addition, has to deliver this high voltage to the right cylinder, at the right time. Some ignition systems will supply up to 40 kV to the spark plugs.

Figure 2.314 Combustion taking place. (Source: Ford Media)

Table 2.2 Ignition systems

Type	Conventional	Electronic	Programmed	Distributorless
Trigger	Mechanical	Electronic	Electronic	Electronic
Advance	Mechanical	Mechanical	Electronic	Electronic
Voltage source	Inductive	Inductive	Inductive	Inductive
Distribution	Mechanical	Mechanical	Mechanical	Electronic

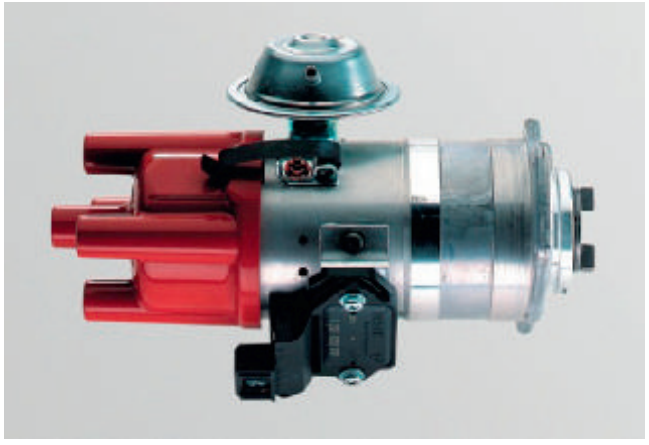


Figure 2.315 Electronic ignition distributor and ignition module

Conventional ignition is the forerunner of the more advanced systems controlled by electronics. It is worth mentioning at this stage, however, that the fundamental operation of most ignition systems is very similar. One winding of a coil is switched on and off, causing a high voltage to be induced in a second winding. The basic types of ignition system can be classified as shown in Table 2.2.

Modern ignition systems now are part of the engine management, which controls fuel delivery, ignition and other vehicle functions (Fig. 2.315). These systems are under continuous development and reference to the manufacturer's workshop

Key fact

Modern ignition systems now are part of the engine management.

manual is essential when working on any vehicle. The main ignition components are the engine speed and load sensors, knock sensor, temperature sensor and ignition coil. The ECU reads from the sensors, interprets and compares the data, and sends output signals to the actuators. The output component for ignition is the coil.

Ignition systems continue to develop and will continue to improve. However, keep in mind that the simple purpose of an ignition system is to ignite the fuel/air mixture every time at the right time. And, no matter how complex the electronics may seem, the high voltage is produced by switching a coil on and off.

Key fact

No matter how complex the electronics may seem, a high-voltage spark is produced by switching a coil on and off.

2.6.1.2 Generation of high voltage

If two coils (known as the primary and secondary) are wound on to the same iron core then any change in magnetism of one coil will induce a voltage in the other (see Chapter 3 for more details). This happens when a current is switched on and off to the primary coil. If the number of turns of wire on the secondary coil is more than on the primary a higher voltage can be produced. This is called transformer action and is the principle of the ignition coil.

The value of this 'mutually induced' voltage depends on:

- the primary current
- the turns ratio between primary and secondary coils
- the speed at which the magnetism changes.

The two windings are wound on a laminated iron core to concentrate the magnetism. This is how all types of ignition coil are constructed.

2.6.1.3 Ignition timing (advance angle)

Key fact

For optimum efficiency the ignition advance angle should be such as to cause the maximum combustion pressure to occur about 10° after TDC.

For optimum efficiency the ignition advance angle should be such as to cause the maximum combustion pressure to occur about 10° after TDC. The ideal ignition timing is dependent on two main factors, engine speed and engine load. An increase in engine speed requires the ignition timing to be advanced.

The cylinder charge of fuel/air mixture requires a certain time to burn (normally about 2 ms). At higher engine speeds the time taken for the piston to travel the same distance reduces. Advancing the time of the spark ensures that full burning is achieved.

A change in timing due to engine load is also required as the weaker mixture used on low load conditions burns at a slower rate. In this situation further ignition advance is necessary. Greater load on the engine requires a richer mixture, which burns more rapidly. In this case some retardation of timing is necessary. Overall, under any condition of engine speed and load an ideal advance angle is required to ensure that maximum pressure is achieved in the cylinder just after TDC. The ideal advance angle may also be determined by engine temperature and any risk of detonation.

Spark advance is achieved in a number of ways. The simplest of these is the mechanical system comprising a centrifugal advance mechanism and a vacuum (load-sensitive) control unit. Manifold depression is almost inversely proportional to the engine load. I prefer to consider manifold pressure; although it is less than atmospheric pressure, the MAP is therefore proportional to engine load. Digital ignition systems adjust the timing in relation to the temperature as well as speed and load. The values of all ignition timing functions are combined either mechanically or electronically to determine the ideal ignition point.

Figure 2.316 First Bosch high-voltage magneto ignition system with spark plug in 1902. (Source: Bosch Media)

Table 2.3 Traditional ignition components

Component	Function
Spark plug	Seals electrodes for the spark to jump across in the cylinder. Must withstand very high voltages, pressures and temperatures
Ignition coil	Stores energy in the form of magnetism and delivers it to the distributor via the high-tension (HT) lead. Consists of primary and secondary windings
Ignition switch	Provides driver control of the ignition system and is usually also used to cause the starter to crank
Contact breakers (breaker points)	Switches the primary ignition circuit on and off to charge and discharge the coil. The contacts are operated by a rotating cam in the distributor
Capacitor (condenser)	Suppresses most of the arcing as the contact breakers open. This allows for a more rapid break of primary current and hence a more rapid collapse of coil magnetism, which produces a higher voltage output
Distributor	Directs the spark from the coil to each cylinder in a preset sequence
Plug leads	Thickly insulated wires to connect the spark from the distributor to the plugs
Centrifugal advance	Changes the ignition timing with engine speed. As speed increases the timing is advanced
Vacuum advance	Changes timing depending on engine load. On conventional systems the vacuum advance is most important during cruise conditions

Energy storage takes place in the ignition coil. The energy is stored in the form of a magnetic field. To ensure the coil is charged before the ignition point, a dwell period is required. Ignition timing is at the end of the dwell period as the coil is switched off.

2.6.1.4 Traditional ignition system

Very early cars used something called a magneto, which is a story for another time, but Fig. 2.316 shows a nice picture of one anyway! For many years ignition systems were mechanically switched and distributed. Table 2.3 gives an overview of the components of this earlier system (see Figs 2.317–2.320).

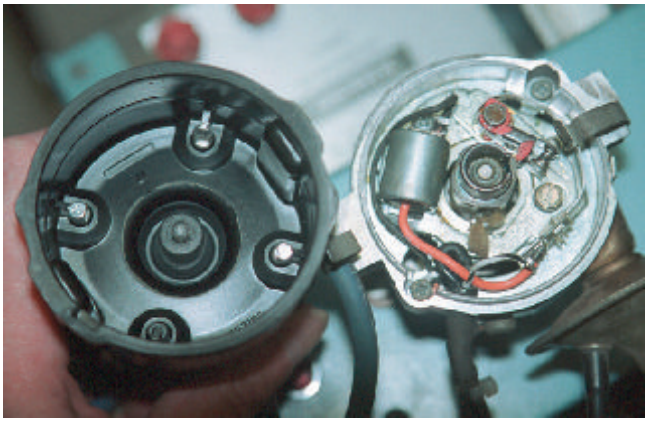


Figure 2.317 Contact breaker system

Figure 2.318 Traditional ignition coil

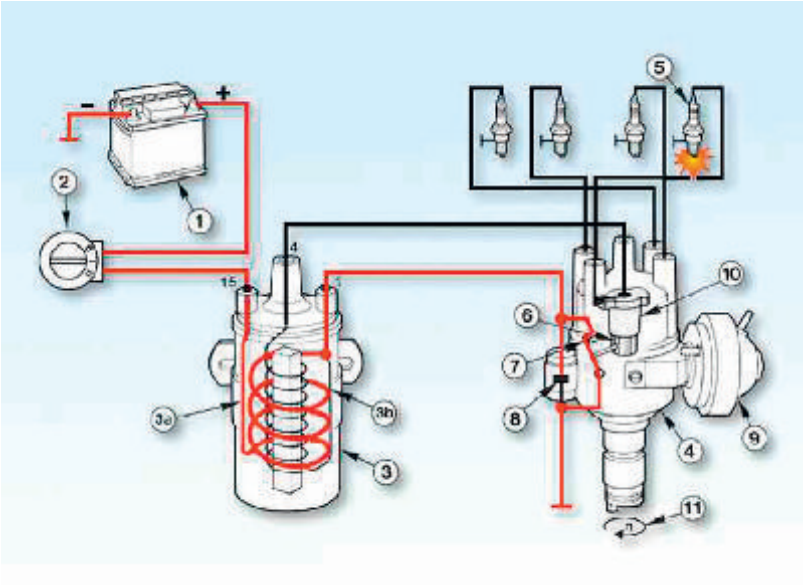


Figure 2.319 Ignition circuit of an early system: 1, battery; 2, ignition key switch; 3, coil; a, primary winding; b, secondary winding; 4, distributor body containing centrifugal (speed) advance/retard mechanism; 5, spark plug; 6, cam (with a lobe for each cylinder); 7, contact breakers (points); 8, condenser (capacitor); 9, vacuum (load) advance/retard mechanism; 10, rotor arm; 11, direction of rotation (at n rpm)

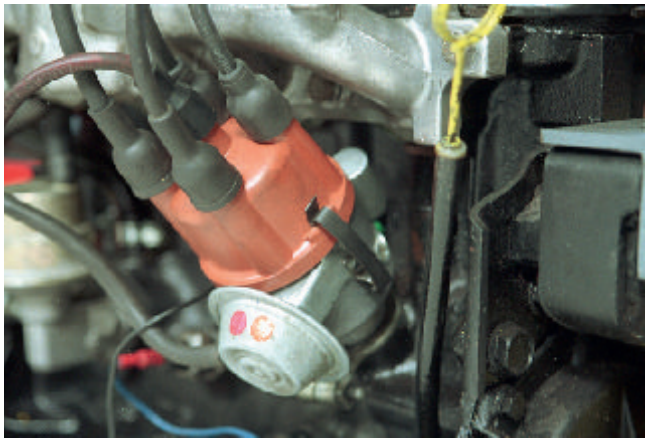


Figure 2.320 Traditional system using a distributor

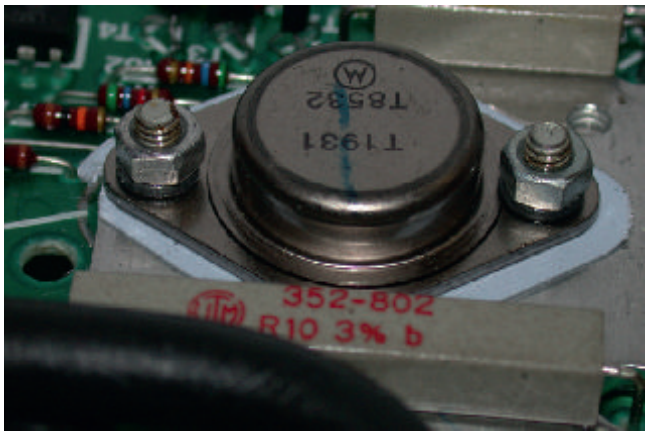


Figure 2.321 Power transistor

All current vehicle ignition systems are electronically switched and most are now digitally controlled as part of the engine management system. However, there are many vehicles out there still using conventional electronic ignition, so the next section will give an overview of these systems.

2.6.2 Electronic ignition

2.6.2.1 Constant dwell

Mechanical ignition systems have some major disadvantages:

- Mechanical problems with the contact breakers occur, not least of which is the limited lifetime.
- Current flow in the primary circuit is limited to about 4 A or damage will occur to the contacts; or at least the lifetime will be seriously reduced.
- Legislation requires stringent emission limits, which means that the ignition timing must stay in tune for a long time.
- Weaker mixtures require more energy from the spark to ensure successful ignition, even at very high engine speed.

These problems were overcome by using a power transistor (Fig. 2.321) to carry out the switching function and a pulse generator to provide the timing signal.

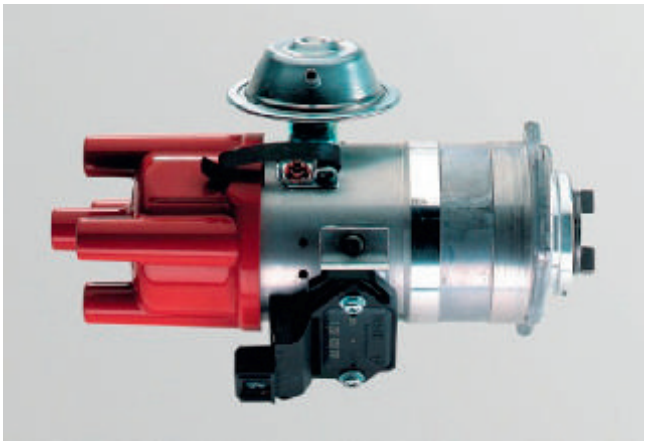


Figure 2.322 Distributor with electronic control unit (ECU) fitted. (Source: Bosch Media)

Definition

Dwell
A measure of the time during which the ignition coil is charging.

The term 'dwell' when applied to ignition is a measure of the time during which the ignition coil is charging, in other words when primary coil current is flowing. The dwell in traditional systems was simply the time during which the contact breakers were closed, and in these early electronic systems it was the time that the transistor was switched on. Although this was a very good system in its time, constant dwell still meant that at very high engine speeds the actual time available to charge the coil would only produce a lower power spark. Note that as engine speed increases, dwell angle or dwell percentage remains the same but the actual time is reduced. All systems nowadays are known as constant energy, ensuring high-performance ignition even at high engine speed.

2.6.2.2 Constant energy

In order for a constant energy electronic ignition system to operate, the dwell must increase with engine speed. This will only be of benefit if the ignition coil can be charged up to its full capacity in a very short time (the time available for maximum dwell at the highest expected engine speed). To this end, constant energy coils are very low resistance, so a high current will flow quickly. Constant energy means that within limits, the energy available to the spark plug remains constant under all operating conditions.

This was achieved by using a pulse generator in the distributor to inform an ignition module of the engine position and speed so that the module could determine the switch-on (start of dwell) and switch-off points (end of dwell and ignition timing spark) (Figs 2.322 and 2.323).

Owing to the high-energy nature of constant energy ignition coils, the coil cannot be allowed to remain switched on for more than a certain time. This is not a problem when the engine is running, as the variable dwell or current-limiting circuit prevents the coil overheating. Some form of protection must be provided however, when the ignition is switched on but the engine is not running. This is known as stationary engine primary current cut-off.

Two types of pulse generator (sensors) were most common:

- Hall effect
- inductive.

As the central shaft of the Hall effect distributor (Fig. 2.324) rotates, the chopper plate attached under the rotor arm alternately covers and uncovers the Hall chip.

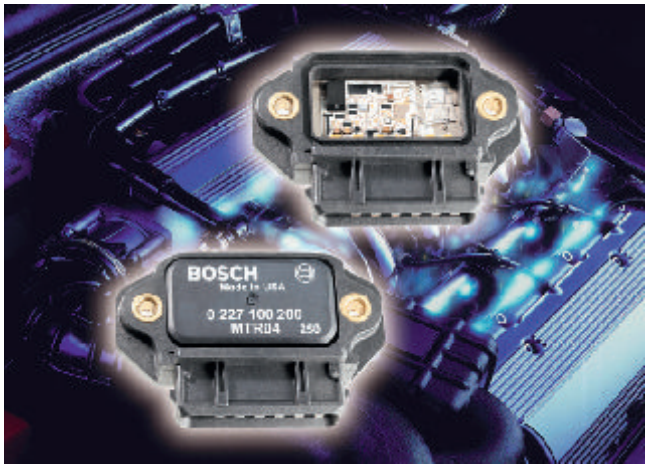


Figure 2.323 Electronic ignition module. (Source: Bosch Media)

Figure 2.324 Hall effect distributor

The number of vanes corresponds with the number of cylinders. In constant dwell systems the dwell is determined by the width of the vanes. The vanes cause the Hall chip to be alternately in and out of a magnetic field. The result of this is that the device will produce almost a square-wave output, which can then easily be used to switch further electronic circuits. The three terminals on the distributor are marked + , 0 and − : terminals + and − are for a voltage supply and terminal 0 is the output signal.

Typically, the output from a Hall effect sensor will switch between 0 V and about 7 V. The supply voltage is taken from the ignition ECU and on some systems is stabilized at about 10 V to prevent changes to the output of the sensor when the engine is being cranked. Hall effect distributors are very common owing to the accurate signal produced and long-term reliability. They produce a kind of square-wave output signal.

Key fact

Typically, the output from a Hall effect sensor will switch between 0 V and about 7 V (but always check specifications).

Inductive pulse generators use the basic principle of induction to produce a signal. Many forms exist, but all are based around a coil of wire and a permanent magnet. The distributor shown in Fig. 2.325 has the coil of wire wound on the pick-up and as the reluctor rotates the magnetic flux varies due to the peaks on the reluctor. The number of peaks or teeth on the reluctor corresponds to the number of engine cylinders. The gap between the reluctor and pick-up can be important and manufacturers have recommended settings. These systems produce a kind of sine-wave output.

Figure 2.325 Inductive distributor

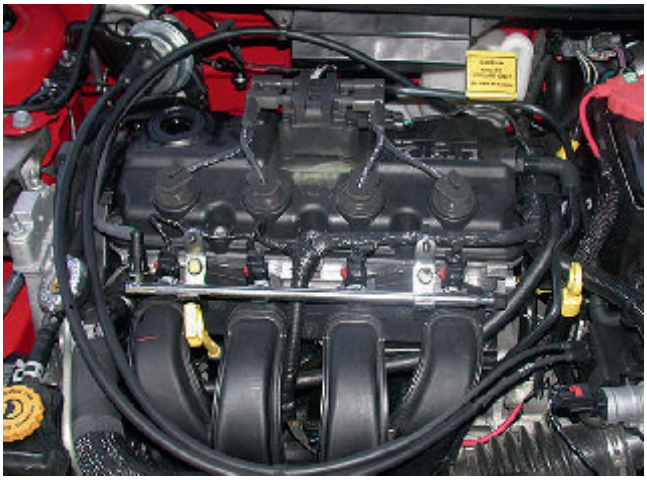


Figure 2.326 Distributorless ignition coil in position

Key fact

Distributorless ignition outputs to the spark plugs without using a distributor.

2.6.3 Distributorless ignition system (DIS)

Distributorless ignition uses a special type of ignition coil, which outputs to the spark plugs without the need for a high-tension distributor (Fig. 2.326).

The basic principle is that of the 'lost spark' (Fig. 2.327). The distribution of the spark is achieved by using two double-ended coils, which are fired alternately by the ECU. The timing is determined from a crankshaft speed and position sensor as well as a load (MAP) sensor and other corrections such as engine temperature. When one of the coils is fired a spark is delivered to two engine cylinders, either 1 and 4 or 2 and 3. The spark delivered to the cylinder on the compression stroke will ignite the mixture as normal. The spark produced in the other cylinder will have no effect, as this cylinder will be just completing its exhaust stroke.

Because of the low compression, and the exhaust gas in the lost spark cylinder, the voltage used for the spark to jump the gap is only about 3 kV. The spark produced in the compression cylinder is therefore not affected. An interesting point here is that the spark on one of the cylinders will jump from the earth electrode to the spark plug centre. Many years ago this would not have been acceptable as the spark quality when jumping this way would not have been as good as when jumping from the hotter-centre electrode. However, the energy available from modern constant energy systems will result in a spark of high quality regardless of its polarity.

The DIS consists of three main components: the ECU, a crankshaft position sensor and the DIS coil. An MAP sensor is integrated in the module or mounted

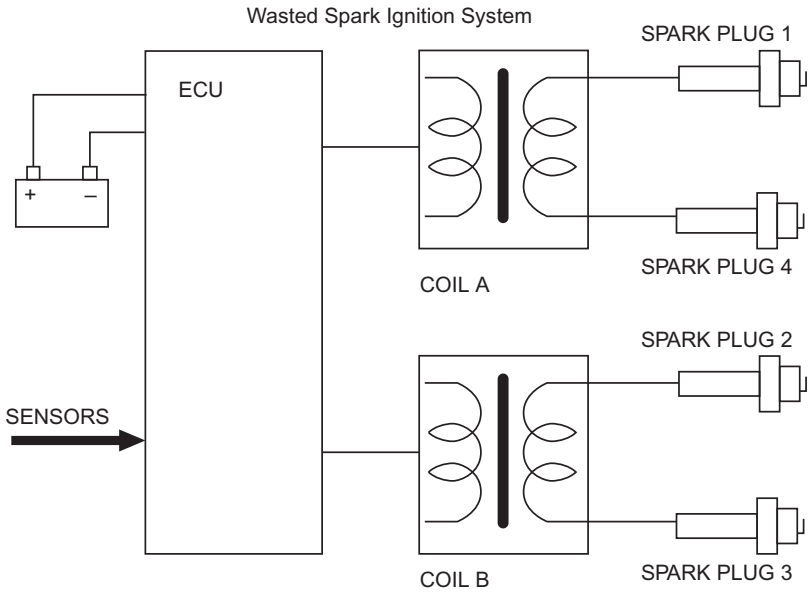


Figure 2.327 Distributorless ignition system (DIS) simplified circuit (wasted spark ignition system)

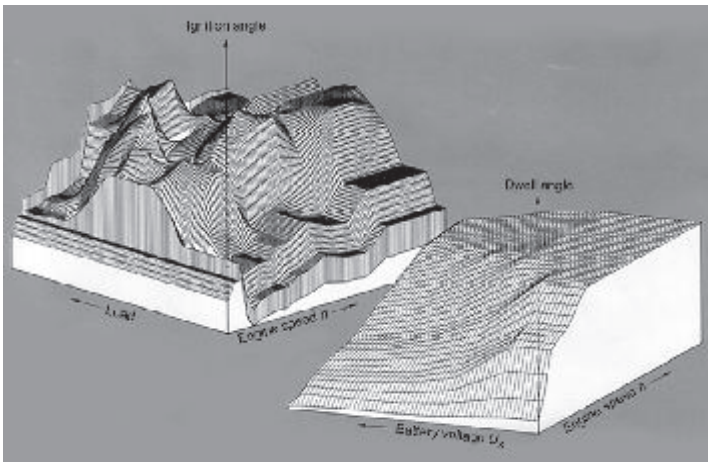


Figure 2.328 Timing and dwell maps

separately. The module uses an electronic spark advance system. Data on ideal dwell and timing is held in memory maps for a wide range of speed, load and voltage conditions (Fig. 2.328). This can be described as an electronic spark advance (ESA) system.

The crankshaft position sensor is similar in operation to the one described in the fuel section. It is an inductive sensor (Fig. 2.329) and is positioned against the front of the flywheel or against a reluctor wheel just behind the front crankshaft pulley. The tooth pattern usually consists of 35 teeth. These are spaced at 10° intervals with a gap where the 36th tooth would be. The missing tooth is positioned at 90° BTDC for numbers 1 and 4 cylinders. This reference position is placed a fixed number of degrees BTDC, to allow the timing or ignition point to be calculated as a fixed angle after the reference mark.

The primary winding is supplied with battery voltage to a centre terminal. The appropriate half of the winding is then switched to earth in the module. The high-tension windings are separate and are specific to cylinders 1 and 4 or 2 and 3 (or as appropriate if a six-cylinder engine) (Fig. 2.330).

Key fact

The crankshaft position sensor (CPS) is similar in operation to the one described in the fuel section – and in most cases the same one is used.

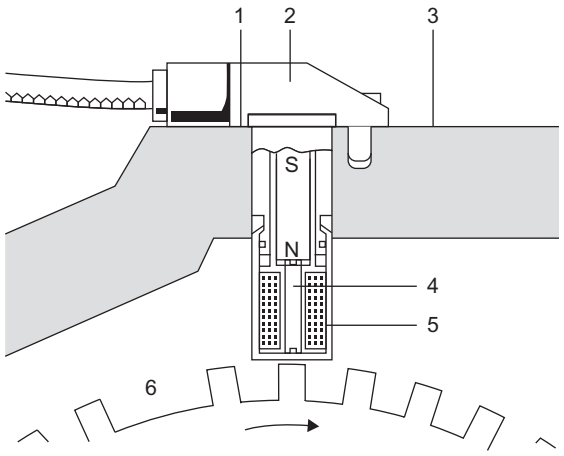


Figure 2.329 Inductive sensor: 1, magnet; 2, cover; 3, engine; 4, core; 5, winding; 6, missing tooth

Figure 2.330 Distributorless ignition system (DIS) coil and plug leads

On most cars now the ignition system is combined with the fuel system so that even more accurate control of outputs is possible and input data from sensors can be shared.

2.6.4 Coil on plug (COP) direct ignition system

Key fact

Direct ignition has a coil for each spark plug.

Direct ignition is, in a way, a further improvement on distributorless ignition. This system utilizes an inductive coil for each engine cylinder. These coils are mounted directly on the spark plugs (Figs 2.331 and 2.332). The use of an individual coil for each plug ensures that the charge time is very fast (full coil charge in a very small dwell angle). This ensures that a very high-voltage, high-energy spark is produced. This voltage, which can be in excess of 40 kV, provides efficient initiation of the combustion process under cold starting conditions and with weak mixtures.

Definition

ESA
Electronic spark advance.

Ignition timing and dwell are controlled in a manner similarly to the previously described ESA system. The one important addition to this on most systems is a camshaft sensor to provide information as to which cylinder is on the compression stroke. A system that does not require a sensor to determine which cylinder is on compression (engine position is known from a crank sensor)

Figure 2.331 Six direct ignition coils in position

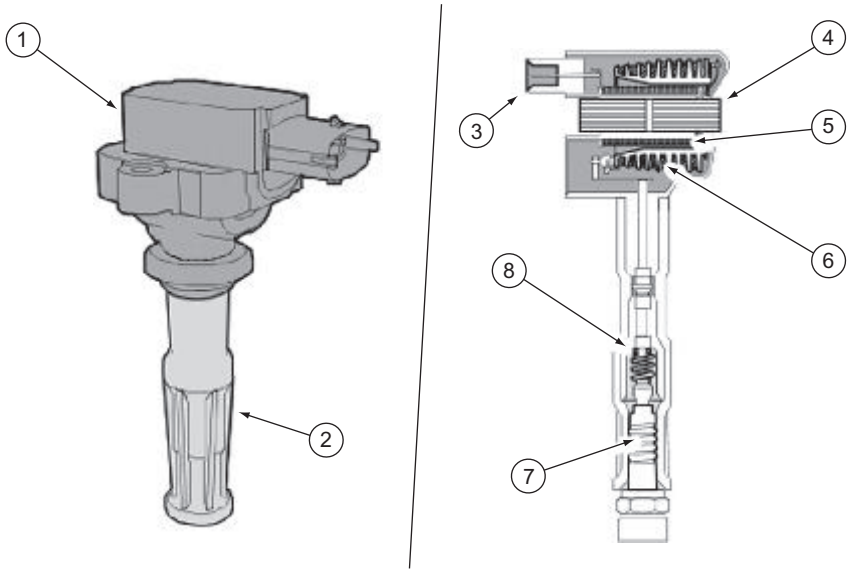


Figure 2.332 Direct ignition coil features: 1, direct ignition coil; 2, spark plug connector; 3, low voltage connection, outer; 4, laminated iron core; 5, primary winding; 6, secondary winding; 7, spark plug; 8, high-voltage connection, inner, via spring contact

determines the information by initially firing all of the coils. The voltage across the plugs allows measurement of the current for each spark and will indicate which cylinder is on its combustion stroke. This works because a burning mixture has a lower resistance. The cylinder with the highest current at this point will be the cylinder on the combustion stroke.

A further feature of some systems is the case when the engine is cranked over for an excessive time making flooding likely. The plugs can all be fired with multisparks for a period of time after the ignition is left on to burn away any excess fuel. During difficult starting conditions, multisparking is also used by some systems during 70° of crank rotation BTDC. This assists with starting and then once the engine is running, the timing will return to its normal calculated position.

2.6.5 Spark plugs

The simple requirement of a spark plug is that it must allow a spark to form within the combustion chamber, to initiate combustion (Fig. 2.333). In order to do this

Figure 2.333 Modern high-performance spark plug

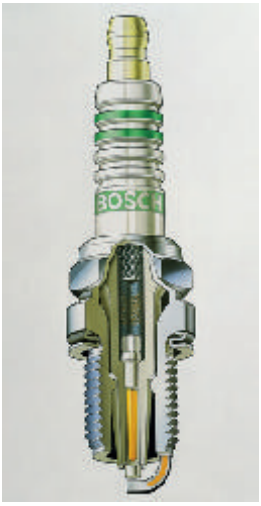


Figure 2.334 Cutaway section of a standard spark plug

the plug has to withstand a number of severe conditions. It must withstand severe vibration and a harsh chemical environment. Finally, but perhaps most importantly, the insulation properties must withstand voltages pressures up to 40 kV.

Figure 2.334 shows a standard spark plug. The centre electrode is connected to the top terminal by a stud. The electrode is constructed of a nickel-based alloy. Silver and platinum are also used for some applications. If a copper core is used in the electrode this improves the thermal conduction properties. The insulating material is ceramic based and of a very high grade. Flash over or tracking down the outside of the plug insulation is prevented by ribs which effectively increase the surface distance from the terminal to the metal fixing bolt, which is earthed to the engine.

Because of the many and varied constructional features involved in the design of an engine, the range of temperatures a spark plug is exposed to can vary significantly. The operating temperature of the centre electrode of a spark plug is critical. If the temperature becomes too high then preignition may occur, where the fuel/air mixture may be ignited owing to the incandescence of the plug electrode. If the electrode temperature is too low, then carbon and oil fouling can occur as deposits are not burnt off. The ideal operating temperature of the plug electrode is between 400 and 900°C.

Key fact

The ideal operating temperature of a spark plug electrode is between 400 and 900°C.

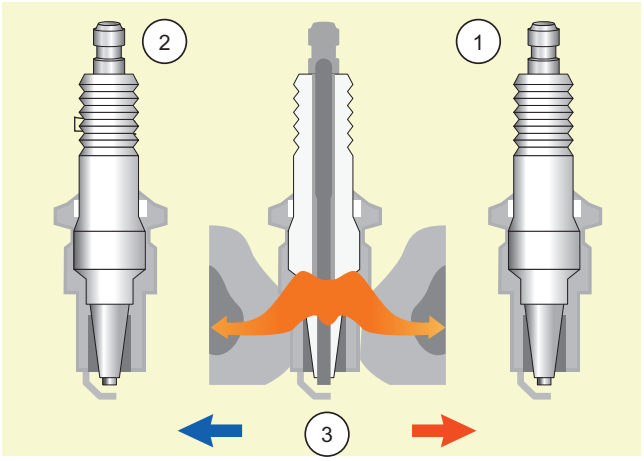


Figure 2.335 Heat-loss paths: 1, cold plug; 2, hot plug; 3, temperature (the cold plug is able to transfer heat more easily so is suitable for a hot engine)

Figure 2.336 A range of spark plugs. (Source: Bosch Media)

The heat range of a spark plug is a measure of its ability to transfer heat away from the centre electrode (Fig. 2.335). A hot running engine will require plugs with a higher thermal ability than a colder running engine. Note that hot and cold running of an engine in this sense refers to the combustion temperature, not to the cooling system.

Spark plug electrode gaps in general have increased as the power of the ignition systems driving the spark has increased. The simple relationship between plug gap and voltage required is that as the gap increases so must the voltage (leaving aside engine operating conditions). Further, the energy available to form a spark at a fixed engine speed is constant, which means that a larger gap using higher voltage will result in a shorter duration spark. A smaller gap will allow a longer duration spark. For cold starting an engine and for igniting weak mixtures the duration of the spark is critical. Likewise, the plug gap must be as large as possible to allow easy access for the mixture to prevent quenching of the flame. The final choice is therefore a compromise reached through testing and development of a particular application. Plug gaps in the region of 0.6–1.2 mm seem to be the norm at present (Fig. 2.336).

Key fact

Plug gaps of 0.6–1.2 mm are in common use.

2.7 Hybrid cars

2.7.1 Safety

Integrated motor assist (IMA) hybrid vehicles use high-voltage batteries so that energy can be delivered to a drive motor or returned to a battery pack in a very short time. The Honda Insight system, for example, uses a 144 V battery module to store regenerated energy. This energy is then used to drive the IMA motor. This decreases the load on the fuel engine, resulting in reduced emissions and increased efficiency.

The Toyota Prius (Fig. 2.337) originally used a 273.6 V battery pack but this was changed in 2004 to a 201.6 V pack, which reduced weight by 26%. Clearly, there are safety issues when working with hybrid vehicles.

Hybrid vehicle batteries and motors have high electrical and magnetic potential that can severely injure or kill if not handled correctly. Any person with a heart pacemaker or any other electronic medical device should not work on an IMA system since the magnetic effects could be dangerous. It is essential that you take note of all the warnings and recommended safety measures outlined by manufacturers and in this resource.

Most of the hybrid components are combined in the power unit (or integrated power unit, IPU). This is located behind the rear seats or under the luggage compartment floor (Fig. 2.338). The unit is a metal box that is completely closed with bolts. A battery module switch is usually located under a small secure cover on the power unit. The electric motor is located between the engine and the transmission or as part of the transmission (Fig. 2.338).

Safety first

Whenever high-voltage (orange) wires have to be disconnected SWITCH OFF the battery module switch.

All high-voltage components (except the motor) are located in the power unit (Figs 2.339 and 2.340). The electrical energy is conducted to or from the motor via three thick orange wires. Whenever these wires have to be disconnected SWITCH OFF the battery module switch. This will prevent the risk of electric shock or short-circuit of the high-voltage system. High-voltage wires are always orange.

Figure 2.337 At the time of writing, the world land speed record for a Prius hybrid was 130.794 mph! (Source: Toyota Media)

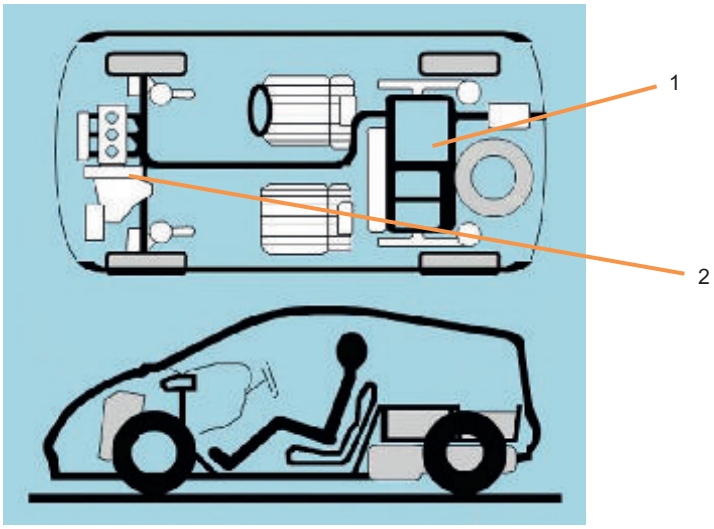


Figure 2.338 Motor and power pack locations: 1, power pack; 2, integrated motor assist (IMA) (motor)

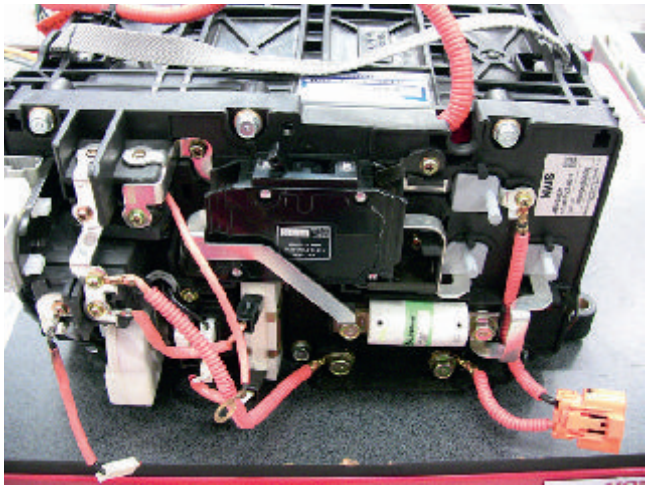


Figure 2.339 Honda battery pack (integrated power unit)

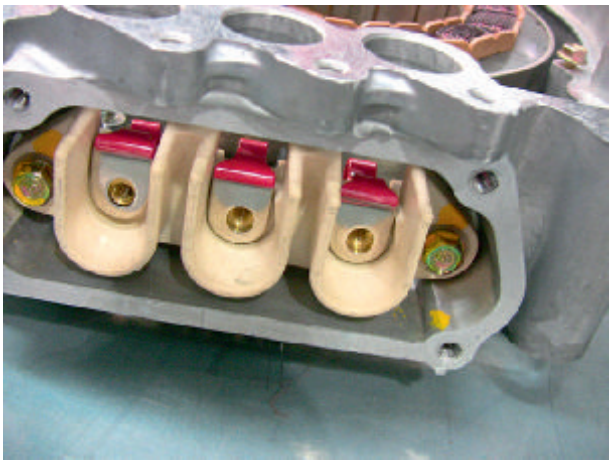


Figure 2.340 Motor power connections

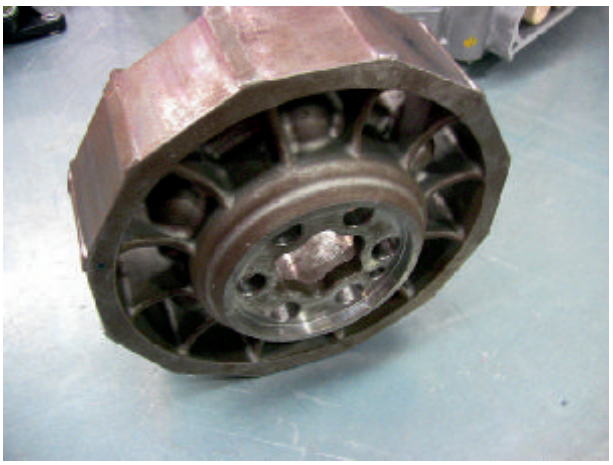


Figure 2.341 The core or rotor is made of very strong rare earth metal permanent magnets

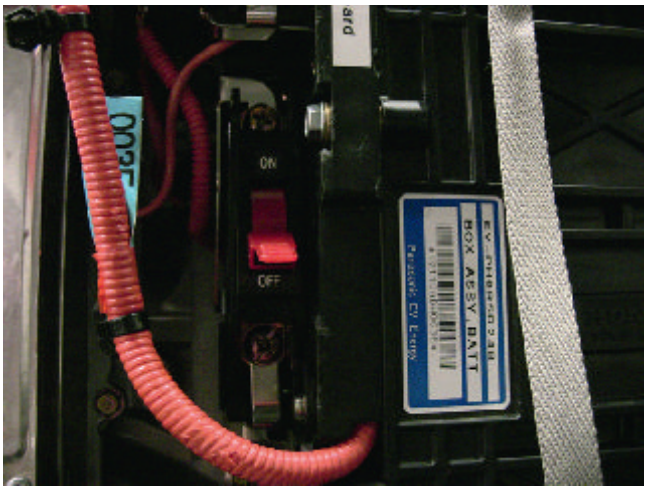


Figure 2.342 High-voltage battery power switch

Safety first

Any person with a heart pacemaker or any other electronic medical device should not work on the IMA system because of the high-strength magnetic fields.

As already mentioned, any person with a heart pacemaker or any other electronic medical device should not work on the IMA system. The magnetic fields present (Fig. 2.341) can affect these devices and therefore present a very significant danger. The use of any magnetic storage media near the IMA system should be avoided. In the presence of the system's strong magnetic field, data could be partially or totally erased. A mechanical or electronic wristwatch would also be damaged.

Before maintenance:

- Turn OFF the ignition switch and remove the key.
- Switch OFF the battery module switch (Fig. 2.342).
- Wait for 5 minutes before performing any maintenance procedures on the system. This allows the large storage capacitors to be discharged.
- Make sure that the junction board terminal voltage is nearly 0 V.

Safety first

Electrical safety gloves are NOT the same as general working gloves.

During maintenance:

- Always wear insulating gloves (Fig. 2.343).
- Always use insulated tools when performing service procedures to the high-voltage system. This precaution will prevent accidental short-circuits.

Figure 2.343 Electrical warning sign and insulated gloves

Figure 2.344 Hybrid cars still use a normal 12V battery

When maintenance procedures have to be interrupted while some high-voltage components are uncovered or disassembled, make sure that:

- the ignition is turned off and the key is removed
- the battery module switch is switched off
- no untrained persons have access to that area, and any unintended touching of the components is prevented (Fig. 2.344).

Before switching on the battery module after repairs have been completed, make sure that:

- all terminals have been tightened to the specified torque
- no high-voltage wires or terminals have been damaged or shorted to the body (Fig. 2.345)
- the insulation resistance between each high-voltage terminal of the part you disassembled and the vehicle's body has been checked.

Working on hybrid vehicles is not dangerous IF the previous guidelines and manufacturers' procedures are followed. Before starting work, check the latest information – DON'T take chances. Dying from an electrical shock is not funny.

2.7.2 Hybrids overview

A hybrid power system for an automobile can have a series, parallel or power split configuration (Fig. 2.346). With a series system, an engine drives a generator,

Figure 2.345 High-voltage cables are always orange

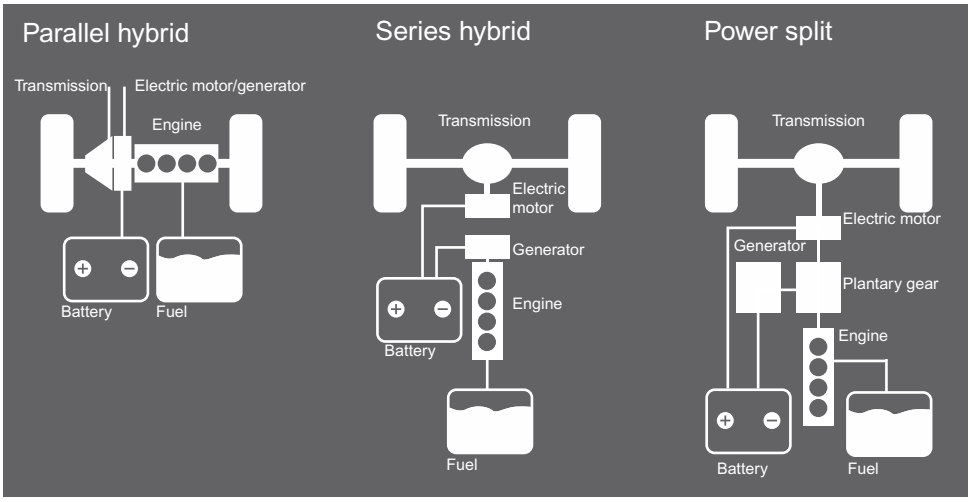


Figure 2.346 Three types of hybrid vehicle

Key fact

The IMA system is a parallel hybrid system.

which in turn powers a motor. The motor propels the vehicle. With a parallel system, the engine and motor can both be used to propel the vehicle. Most hybrids in current use employ a parallel system known as integrated motor assist (IMA). The power split has additional advantages but is also more complex.

The IMA method is a technologically advanced parallel hybrid power system. By using techniques such as brake-energy regeneration to maximize the efficiency with which energy is used, it combines low-pollution, low-cost operation with high levels of safety and running performance. The main components of the system are:

- IMA motor
- battery module
- power drive unit (PDU)
- motor control module (MCM)
- d.c. – d.c. converter.

There are five main IMA operating modes. Figures 2.347 and 2.348 give an overview of each mode and Table 2.4 explains these modes in more detail.

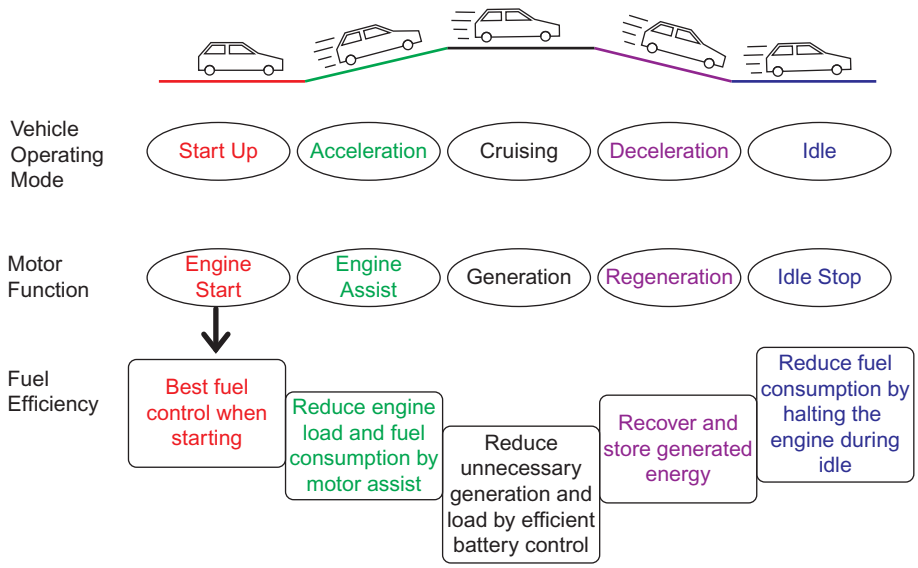


Figure 2.347 Operating conditions

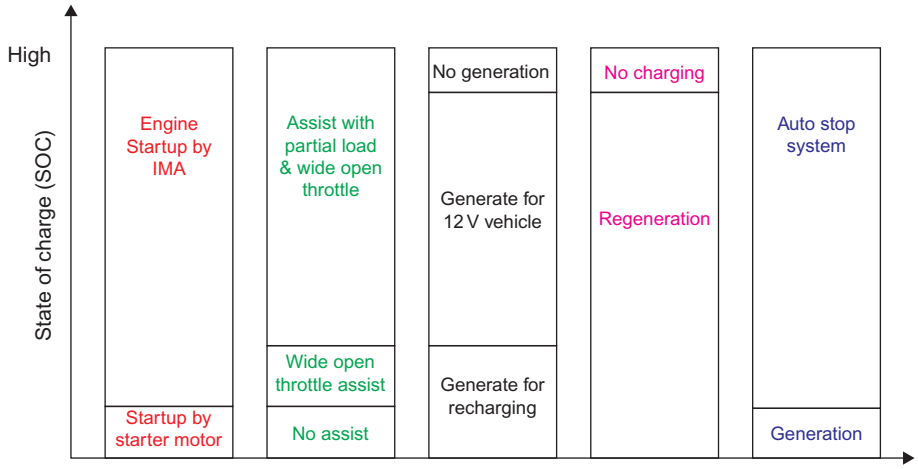


Figure 2.348 Integrated motor assist (IMA) operating details

The IMA technique used by most hybrid cars can be thought of as a kinetic energy recovery system (KERS). This is because instead of heat energy from the brakes being wasted as the vehicle is slowed down, some is converted to electrical energy and stored in the battery as chemical energy. This is then used to drive the wheels, so saving chemical energy from the fuel. However, hybrid vehicles still need exhaust extraction (Fig. 2.349).

Key fact

The IMA system is a kinetic energy recovery system (KERS).

2.8 Formula 1 engine technology

2.8.1 Engines overview

Formula 1 currently uses four-stroke V8, 2400 cc, naturally aspirated engines (Fig. 2.350). These produce in the region of 224 kW (300 bhp, 304 PS [metric hp]) per litre of displacement. This is much greater than most road car engines. This huge power output is partly due to being able to operate at a very high rpm. Engines of a similar size in road vehicles typically operate at less than 7000 rpm. The torque

Key fact

Formula 1 currently uses four-stroke V8, 2400 cc, naturally aspirated engines.

Table 2.4 Integrated motor assist (IMA) operating modes

Mode	Details
Start-up	Under normal conditions, the IMA motor will immediately start the engine at a speed of 1000 rpm. When the state of charge (SOC) of the high-voltage battery module is too low, when the temperature is too low, or if there is a failure of the IMA system, the engine will be cranked by the normal 12 V starter motor
Acceleration	During acceleration, current from the battery module is converted to a.c. by the power drive unit (PDU) and supplied to the IMA motor, which functions as a motor. The IMA motor output is used to supplement the engine output so that power available for acceleration is maximized. Current from the battery module is also converted to 12 V d.c. for supply to the vehicle electrical system. This reduces the load that would have been caused by a normal alternator and so improves acceleration. When the remaining battery module state of charge is too low, but not at the minimum level, assist will only be available during wide open throttle (WOT) acceleration. When the remaining state of charge is reduced to the minimum level, no assist will be provided. The IMA system will generate energy only to supply the vehicle's 12 V system
Cruising	When the vehicle is cruising and the battery module requires charging, the engine drives the IMA motor, which now acts as a generator. The resulting output current is used to charge the battery module and is converted to 12 V d.c. to supply the vehicle electrical system. When the vehicle is cruising and the high-voltage battery is sufficiently charged, the engine drives the IMA motor. The generated current is converted to 12 V d.c. and only used to supply the vehicle electrical system
Deceleration	During deceleration (during fuel cut), the IMA motor is driven by the wheels such that regeneration takes place. The generated a.c. is converted by the power drive unit (PDU) into d.c. and used to charge the battery module. The d.c. output of the PDU is also applied to the d.c. – d.c. converter which reduces the voltage to 12 V, which is supplied to the vehicle electrical system. It is further used to charge the 12 V battery as necessary. During braking (brake switch on), a higher amount of regeneration will be allowed. This will increase the deceleration force so the driver will automatically adjust the force on the brake pedal. In this mode, more charge is sent to the battery module. If the ABS system is controlling the locking of the wheels, an 'ABS-busy' signal is sent to the motor control module. This will immediately stop generation to prevent interference with the ABS system. When the high-voltage battery is fully charged, there will only be generation for the vehicle's 12 V system
Idling	During idling, the flow of energy is similar to that for cruising. If the state of charge of the battery module is very low, the motor control module (MCM) will signal the engine control module (ECM) to raise the idle speed to approximately 1100 rpm

of an F1 engine is not much higher than that of a conventional petrol engine in a top-end BMW, for example. However, much more power is produced because of the higher rpm.

The speed required to operate the engine valves at a higher rpm is much greater than metal valve springs can achieve. F1 engine manufacturers therefore use pneumatic valve springs with the pressurized air allowing engines to reach speeds of nearly 20 000 rpm. At the time of writing, engine speed is limited to 18 000 rpm. A shorter stroke (BDC to TDC) enables the engine to produce a higher rotating speed at a constant mean piston speed, but also increases the speed at which the piston must travel in each revolution. Shortening the stroke requires enlarging the bore to produce an F1 engine's 2400 cc displacement.

The stroke of an F1 engine is approximately 40 mm, less than half as long as the bore, which is about 98.0 mm. This is described as an 'over-square' engine.

In addition to the use of pneumatic valve springs, an F1 engine's high rpm output has been made possible because of significant advances in metallurgy and component design. These have resulted in lighter pistons and connecting rods, which can withstand the high acceleration forces at such high speeds. Further, narrower connecting rod little ends and main bearings are used. This allows

Figure 2.349 Exhaust extraction from hybrid vehicles

Figure 2.350 Cosworth Formula 1 engine used by Lotus in 2010. (Source: John O'Nolan, Flickr)

Key fact

F1 Engine rules (possible changes for 2013)

1. 1.6 litre, four-cylinder turbos with energy recovery and fuel restrictions
2. Fuel efficiency to increase by a target of 50%
3. Overall power to remain same at approx 750bhp
4. Plan for advanced 'compound' turbos to be introduced in subsequent years
5. Kinetic energy recovery system (KERS) to increase from 60kw in 2011 to 120kw in 2013

higher rpm because heat build-up in the bearings is reduced. During each engine revolution, the piston goes from a zero speed to almost 40 m/s then back to zero. Maximum piston acceleration occurs at TDC and is in the region of 95 000 m/s^2, or about 10 000 times Earth's gravity!

The fuel/air mixture is carefully controlled, just like in a standard engine, but in the case of F1, torque and power are far more important than consumption and emissions. Inlet and exhaust manifolds and ports are very carefully designed to achieve optimum gas flow, as is the exhaust system, where noise reduction is not considered.

Overall, the principles of operation are no different to a standard road car engine's, except that, keeping within the regulations, the F1 engine is designed and tuned as near to perfection as possible.

2.8.2 FIA technical regulations

This section gives a simplified overview of the technical regulations as at 2011, which relate to the F1 engine (Source: www.fia.com). Please note that before you design and build your own F1 engine, you should refer to the official FIA technical regulations!

2.8.2.1 Specification

- Only four-stroke engines with reciprocating pistons are permitted.
- Engine capacity must not exceed 2400 cc.
- Crankshaft rotational speed must not exceed 18 000 rpm.
- Supercharging is forbidden.
- All engines must have eight cylinders arranged in a 90° V configuration and the normal section of each cylinder must be circular.
- Engines must have two inlet and two exhaust valves per cylinder.
- Only reciprocating poppet valves are permitted.
- The sealing interface between the moving valve component and the stationary engine component must be circular.

2.8.2.2 Dimensions, weight and centre of gravity

- Cylinder bore diameter may not exceed 98 mm.
- Cylinder spacing must be fixed at 106.5 mm (±0.2 mm).
- The crankshaft centreline must not be less than 58 mm above the reference plane.
- The overall weight of the engine must be a minimum of 95 kg.
- The centre of gravity of the engine may not lie less than 165 mm above the reference plane.
- The longitudinal and lateral position of the centre of gravity of the engine must fall within a region that is the geometric centre of the engine, ±50 mm. The geometric centre of the engine in a lateral sense will be considered to lie on the centre of the crankshaft and at the mid-point between the centres of the forward and rear-most cylinder bores longitudinally.
- Variable geometry systems are not permitted.

2.8.2.3 Materials

- Magnesium-based alloys, metal matrix composites (MMCs) and intermetallic materials may not be used anywhere in an engine.
- Coatings are free provided the total coating thickness does not exceed 25% of the section thickness of the underlying base material in all axes. In all cases the relevant coating must not exceed 0.8 mm.
- Pistons must be manufactured from an aluminium alloy which is Al–Si, Al–Cu, Al–Mg or Al–Zn based.
- Piston pins, crankshafts and camshafts must be manufactured from an iron-based alloy and must be machined from a single piece of material.
- A supplementary device temporarily connected to the car may be used to start the engine both on the grid and in the pits.

CHAPTER 3

Electrical systems

3.1 Electrical and electronic principles

3.1.1 Electrical fundamentals

To understand electricity properly we must start by finding out what it really is. This means we must think very small. The molecule is the smallest part of matter that can be recognized as that particular matter. Subdivision of the molecule results in atoms. The atom is a basic unit of matter and consists of a central nucleus made up of protons and neutrons. Around this nucleus electrons are in orbit, like planets around the sun (Fig. 3.1). The neutron is a very small part of the nucleus. It has an equal positive and negative charge. It is therefore neutral and has no polarity. The proton is another small part of the nucleus. It is positively charged. As the neutron is neutral and the proton is positively charged, this means the nucleus of the atom is positively charged.

The electron is an even smaller part of the atom, and is negatively charged. It is held in orbit around the nucleus by the attraction of a positively charged proton. When atoms are in a balanced state the number of electrons orbiting the nucleus equals the number of protons. The atoms of some materials have electrons which are easily detached from the parent atom and join an adjacent atom. In so doing they move an electron (like polarities repel) from this atom to a third atom and so on through the material. These are called free electrons.

Materials are called conductors if the electrons can move easily. However, in some materials it is difficult to move the electrons. These materials are called insulators (Fig. 3.2).

If an electrical pressure (voltage) is applied to a conductor, a directional movement of electrons will take place. There are two conditions for electrons to flow: a pressure source, e.g. from a battery or generator, and a complete conducting path for the electrons to move, e.g. wires.

An electron flow is termed an electric current. The battery positive terminal is connected, through a switch and lamp, to the battery negative terminal. With the switch open, the chemical energy of the battery will remove electrons from the positive terminal to the negative terminal via the battery. This leaves the positive terminal with fewer electrons and the negative terminal with a surplus of electrons. An electrical pressure exists between the battery terminals. With the switch closed, the surplus electrons on the negative terminal will flow through the lamp back to the electron-deficient positive terminal. The lamp will therefore light until the battery runs down.

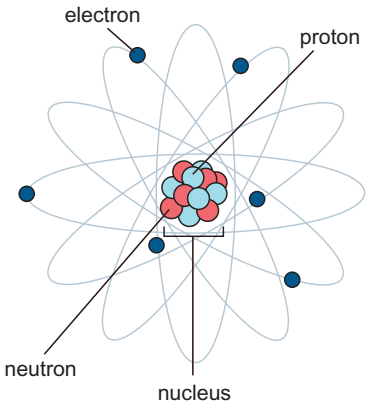


Figure 3.1 Basic representation of an atom

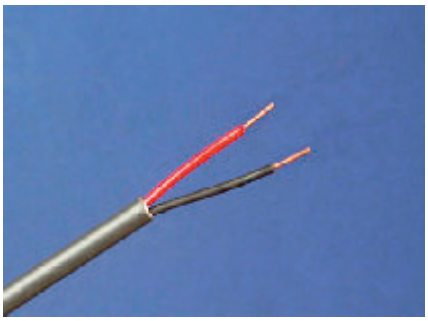


Figure 3.2 Insulated conductors

Definition

Electron

A subatomic particle that carries a negative electric charge. It has a mass that is approximately 1/1836 that of the proton (not very big then!).

Automobile Mechanical and Electrical Systems.
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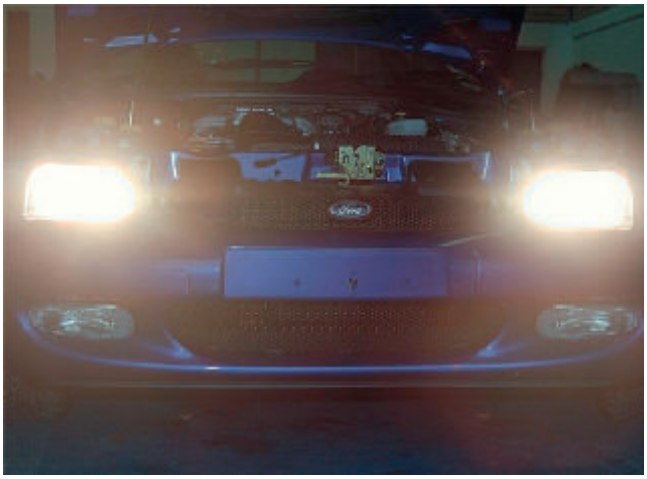

Figure 3.3 Heating effect

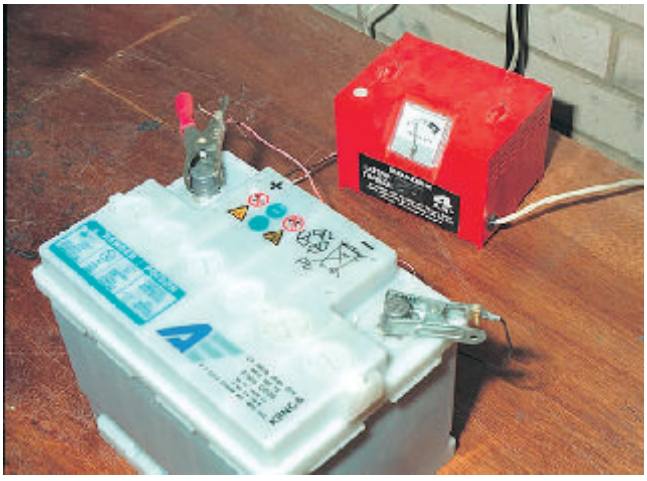

Figure 3.4 Chemical effect

Definition

Current flow
Conventional current flow is from positive to negative.

The movement from negative to positive is called the electron flow. However, it was once thought that current flowed from positive to negative. This convention is still followed for practical purposes. Therefore, even though it is not correct, the most important point is that we all follow the same convention. We say that current flows from positive to negative.

When a current flows in a circuit, it can produce only three effects: heat, chemical and magnetic (Figs 3.3–3.6). The heating effect is the basis of electrical components such as lights and heater plugs. The chemical effect is the basis for electroplating and battery charging. The magnetic effect is the basis of relays, motors and generators. The three effects are reversible. For example, electricity can make magnetism, and magnetism can be used to make electricity.

Definition

Rate of flow
The number of electrons passing through a circuit in 1 second.

The number of electrons through a circuit (Fig. 3.7) in every second is the rate of flow. The cause of electron flow is the electrical pressure. A lamp, for example, produces an opposition to the rate of flow set up by the electrical pressure. Power is the rate of doing work or changing energy from one form to another. If the voltage applied to the circuit was increased but the lamp resistance stayed the same, then current would increase. If the voltage was kept constant but the lamp was changed for one with a higher resistance, then current would decrease.

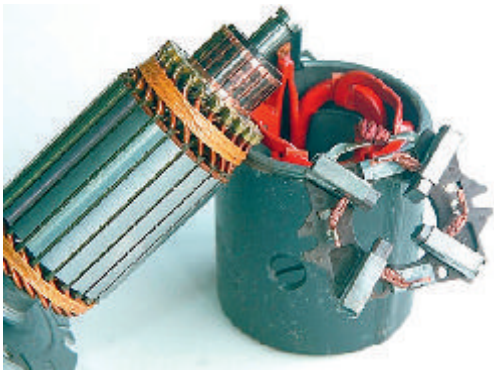

Figure 3.5 Magnetic effect

Figure 3.6 Reversibility: motor and generator

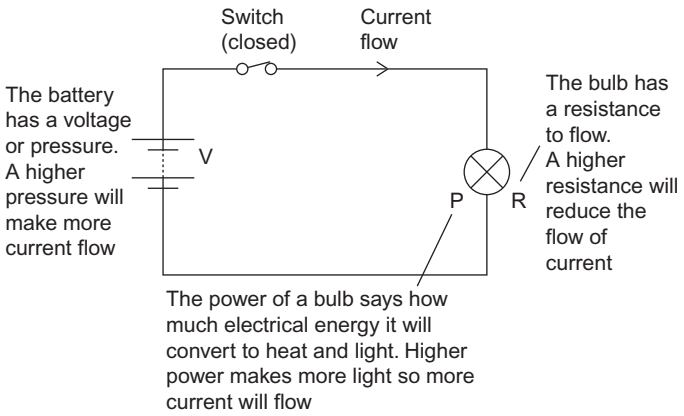

Figure 3.7 Basic circuit

Any one value can be calculated if the other two are known. This relationship is stated in a law called Ohm's law.

Ohm's law states that in a closed circuit the current is proportional to the voltage and inversely proportional to the resistance. This means:

$$\text{Voltage} = \text{Current} \times \text{Resistance}$$

$$(V = IR) \text{ or } (R = V/I) \text{ or } (I = V/R)$$

When voltage causes current to flow, energy is converted. This is described as power. The unit of power is the watt. As with Ohm's law, any one value can be calculated if the other two are known.

$$\text{Power} = \text{Voltage} \times \text{Current}$$

$$(P = VI) \text{ or } (I = P/V) \text{ or } (V = P/I)$$

Check the book website for the Ohm's law and power 'magic' triangles

Electrical units are summarized in Table 3.1.

All metals are conductors. Silver, copper and aluminium are among the best and are frequently used. Liquids that will conduct an electric current are called electrolytes. Insulators are generally non-metallic and include rubber, porcelain, glass, plastic, cotton, silk, wax, paper and some liquids. Some materials can act as either insulators or conductors depending on conditions. These are called semiconductors. They are used to make transistors and diodes (Fig. 3.8).

Table 3.1 Electrical units summary

Name	Definition	Name	Symbol	Abbreviation
Electrical flow or current	The number of electrons past a fixed point in one second	Ampere	I	A
Electrical pressure	A pressure of 1 volt applied to a circuit will produce a current flow of 1 amp if the circuit resistance is 1 ohm	Volt	V	V
Electrical resistance	The opposition to current flow in a material or circuit when a voltage is applied across it	Ohm	R	Ω
Electrical power	When a voltage of 1 volt causes a current of 1 amp to flow the power developed is 1 watt	Watt	P	W

Figure 3.8 Semiconductor transistors

The amount of resistance offered by a conductor is determined by four factors (Fig. 3.9):

- **Length** – The greater the length the greater the resistance.
- **Cross-sectional area** – The larger the area the smaller the resistance.
- **The material** – The resistance offered by a conductor will vary according to the material from which it is made.
- **Temperature** – Most metals increase in resistance as temperature increases.

When resistors are connected so that there is only one path for the same current to flow through each resistor they are connected in series. In a series circuit (Fig. 3.10):

- Current is the same in all parts of the circuit.
- Applied voltage equals the sum of the volt drops around the circuit.
- The total resistance of the circuit equals the sum of the individual resistance values.

When resistors are connected such that they provide more than one path for the current to flow in, and have the same voltage across each component, they are connected in parallel. In a parallel circuit (Fig. 3.11):

- Voltage across all components of a parallel circuit is the same.
- Total current from the source is the sum of the current flowing in each branch. The current splits up depending on each component's resistance.
- The total resistance of the circuit is the sum of the reciprocal (one divided by the resistance) values.

Magnetism can be created by a permanent magnet or by an electromagnet (Fig. 3.12). The space around a magnet in which the magnetic effect can be detected is called the magnetic field. Flux lines or lines of force represent the

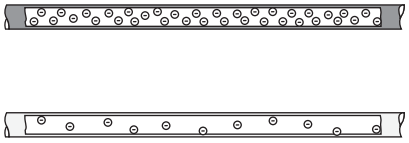

Figure 3.9 Conductor resistance

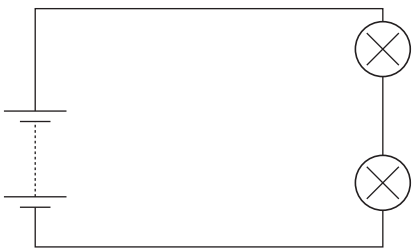

Figure 3.10 A simple series circuit

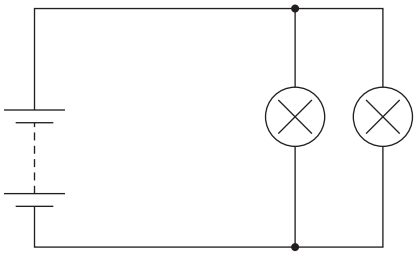

Figure 3.11 A simple parallel circuit

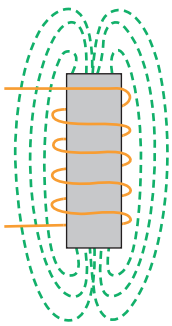

Figure 3.12 Electromagnet showing the field or lines of flux

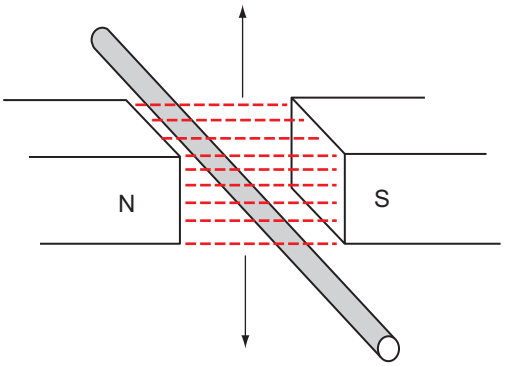

Figure 3.13 Induction

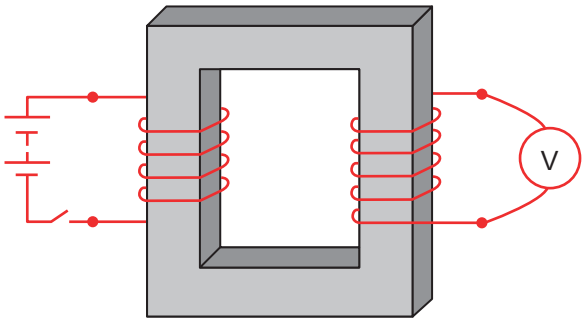

Figure 3.14 Transformer: as the switch is turned on and off the voltmeter needle will move

Key fact

Magnetism can be created by a permanent magnet or by an electromagnet.

shape of magnetic fields in diagrams. Electromagnets are used in motors, relays and fuel injectors, to name just a few. Force on a current carrying conductor in a magnetic field results from two magnetic fields interacting. This is the basic principle of how a motor works.

When a conductor cuts or is cut by magnetism a voltage is induced in the conductor (Fig. 3.13). The direction of this voltage depends on the direction of the magnetic field and the direction in which the field moves relative to the conductor. The size is proportional to the rate at which the conductor cuts or is cut by the magnetism. This effect of induction, meaning that voltage is made in the wire, is the basic principle of how generators such as the alternator in a car work.
A generator is a machine that converts mechanical energy into electrical energy.

If two coils, primary and secondary, are wound on to the same iron core, any change in magnetism of one coil will induce a voltage in the other. This happens when the primary current is switched on and off (Fig. 3.14). If the number of turns of wire on the secondary coil is more than on the primary, a higher voltage can be produced. This is called transformer action and is the principle of the ignition coil.

3.1.2 Electrical components and circuits

A switch is a simple device used to break a circuit; that is, it prevents the flow of current. A wide range of switches is used. Some switches are simple on/off devices such as an interior light switch on the door pillar. Other types of switch are more complex. They can contain several sets of contacts to control, for

Figure 3.15 Multifunction switch

Figure 3.16 Simple 'cube' relay

Figure 3.17 Blade fuses

example, a vehicle's indicators, headlights and horn. These are described as multifunction switches (Fig. 3.15).

A relay is a very simple device (Fig. 3.16). It can be thought of as a remote-controlled switch. A very small electric current is used to magnetize a small winding. The magnetism then causes some contacts to close, which in turn can control a much heavier current. This allows small, delicate switches to be used, to control large current users, such as the headlights or the heated rear window.

Some form of circuit protection is required to protect the electrical wiring of a vehicle and to protect the electrical and electronic components. It is now common practice to protect almost all electric circuits with a fuse. A fuse is the weak link in a circuit. If an overload of current occurs then the fuse will melt and disconnect the circuit before any serious damage is caused. Automobile fuses are available in three types: glass cartridge, ceramic and blade (Fig. 3.17).

The blade type is now the most popular choice owing to its simple construction and reliability. Fuses are available in a number of rated values (Table 3.2). Only the fuse recommended by the manufacturer should be used.

A fuse is used to protect the device as well as the wiring. A good example of this is a fuse in a wiper motor circuit. If a value were used that was much too high then it would still protect against a severe short-circuit. However, if the wiper

Key fact

A fuse is used to protect the device as well as the wiring.

Table 3.2 Blade type fuse ratings

Continuous current (A)	Colour
3	Violet
4	Pink
5	Clear/beige
7.5	Brown
10	Red
15	Blue
20	Yellow
25	Neutral/white
30	Green

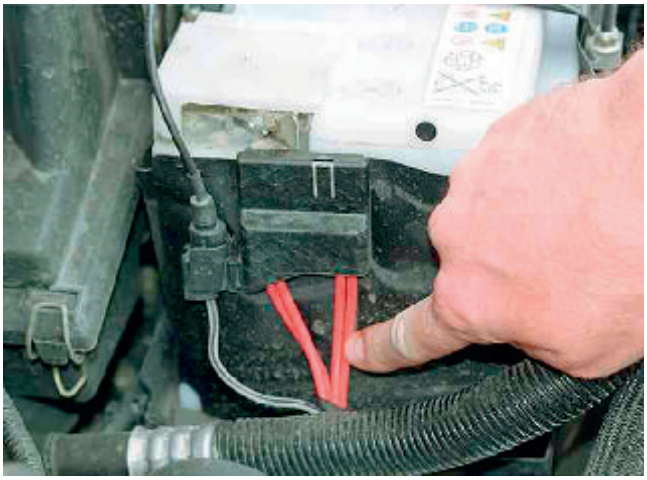

Figure 3.18 Fusible links

blades froze to the screen, a large value fuse might not protect the motor from overheating.

Fusible links in the main output feeds from the battery protect against major short-circuits in the event of an accident or error in wiring connections. These links are simply heavy-duty fuses and are rated in values such as 50, 100 or 150 A (Fig. 3.18).

Many types of terminal are available. These have developed from early bullet-type connectors into the high-quality waterproof systems now in use (Fig. 3.19). A popular choice for many years was the spade terminal. This is still a standard choice for connection to relays, for example, but is now losing ground to the smaller blade terminals. Circular multipin connectors are used in many cases; the pins vary in size from 1 to 5 mm. With any type of multipin connector an offset slot or similar is used to prevent incorrect connection.

Protection against corrosion of the connector is provided in a number of ways. Earlier methods included applying suitable grease to the pins to repel water. It is now more usual to use rubber seals to protect the terminals, although a small

Figure 3.19 Wiring and connectors on a vehicle

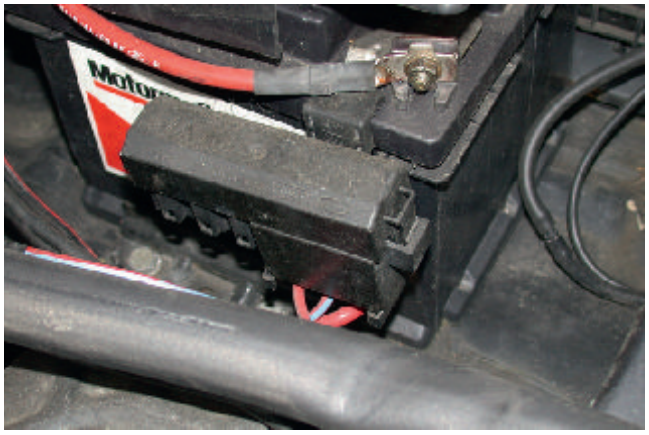

Figure 3.20 Heavy cable from the battery

amount of contact lubricant can still be used. Many multiconnectors use some kind of latch not only to prevent individual pins working loose but also to ensure that the complete plug and socket is held securely.

Cables or wires used for motor vehicle applications are usually copper strands insulated with polyvinyl chloride (PVC). Copper, besides its very low resistance, has ideal properties such as ductility and malleability. This makes it the natural choice for most electrical conductors. For the insulation, PVC is ideal. It not only has very high resistance, but also is very resistant to fuel, oil, water and other contaminants.

Key fact

Cables or wires for automotive applications are copper strands insulated with PVC.

The choice of cable size depends on the current it will have to carry (Figs 3.20 and 3.21). The larger the cable used then the better it will be able to carry the current and supply all of the available voltage. However, it must not be too large or the wiring becomes cumbersome and heavy. In general, the voltage supply to a component must not be less than 90% of the system supply. Cable is available in stock sizes, but a good rule-of-thumb guide is that one strand of 0.3 mm diameter wire will carry 0.5 A safely.

The selection of symbols shown in Fig. 3.22 is intended as a guide to some of those in use on circuit diagrams. Many manufacturers use their own variation.

Figure 3.21 Light cable to a bulb

The idea of a symbol is to represent a component in a very simple but easily recognizable form.

The conventional type of diagram shows the electrical connections of a circuit but does not attempt to show the various parts in any particular order or position (Fig. 3.23).

A layout circuit diagram attempts to show the main electrical components in a position similar to those on the actual vehicle (Fig. 3.24). Owing to the complex circuits and the number of individual wires some manufacturers now use two diagrams, one to show electrical connections, and the other to show the actual layout of the wiring harness and components.

A terminal diagram shows only the connections of the devices and not any of the wiring (Fig. 3.25). The terminal of each device, which can be represented pictorially, is marked with a code. This code indicates the device terminal designation, the destination device code and its terminal designation, and in some cases the wire colour code.

The diagram in Fig. 3.26 is laid out so as to show current flow from the top of the page to the bottom. These diagrams often have two supply lines at the top marked 30 (main battery positive supply) and 15 (ignition controlled supply). At the bottom of the diagram are the earth or chassis connections (marked 31).

Three descriptive terms are useful when discussing electric circuits:

- **Short-circuit** – A fault has caused a wire to touch another conductor and the current uses this as an easier way to complete the circuit (Fig. 3.27).
- **Open circuit** – The circuit is broken and no current can flow (Fig. 3.28).
- **High resistance** – A part of the circuit has developed a high resistance (such as a dirty connection), which will reduce the amount of current that can flow.

The complexity of modern wiring systems (Fig. 3.29) has increased dramatically in recent years. The number of separate wires required on a top of the range vehicle can be in the region of 1500. The wiring loom required to control all functions in or

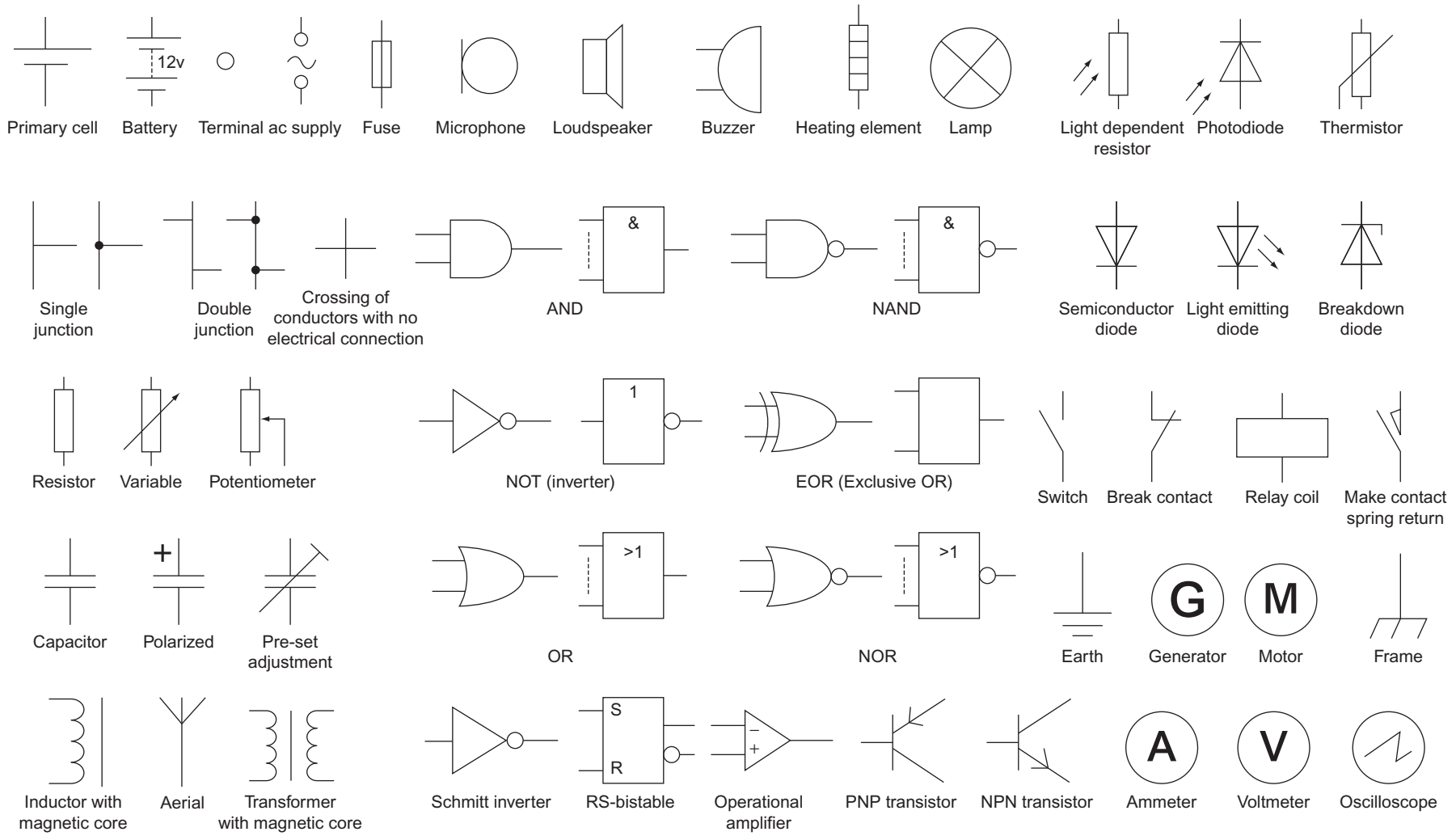

Figure 3.22 Circuit symbols

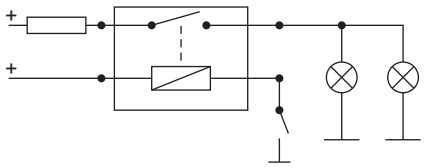

Figure 3.23 Conventional diagram with a resistor, a relay, two bulbs and a switch

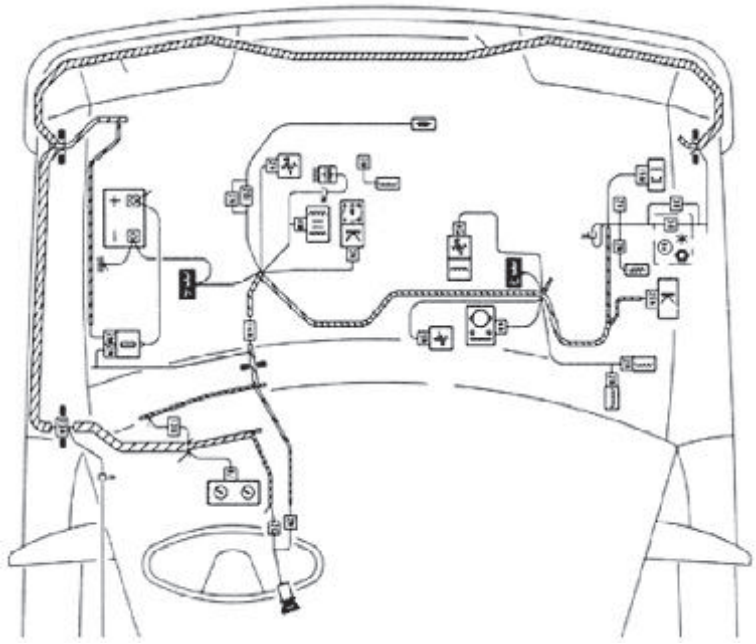

Figure 3.24 Layout circuit

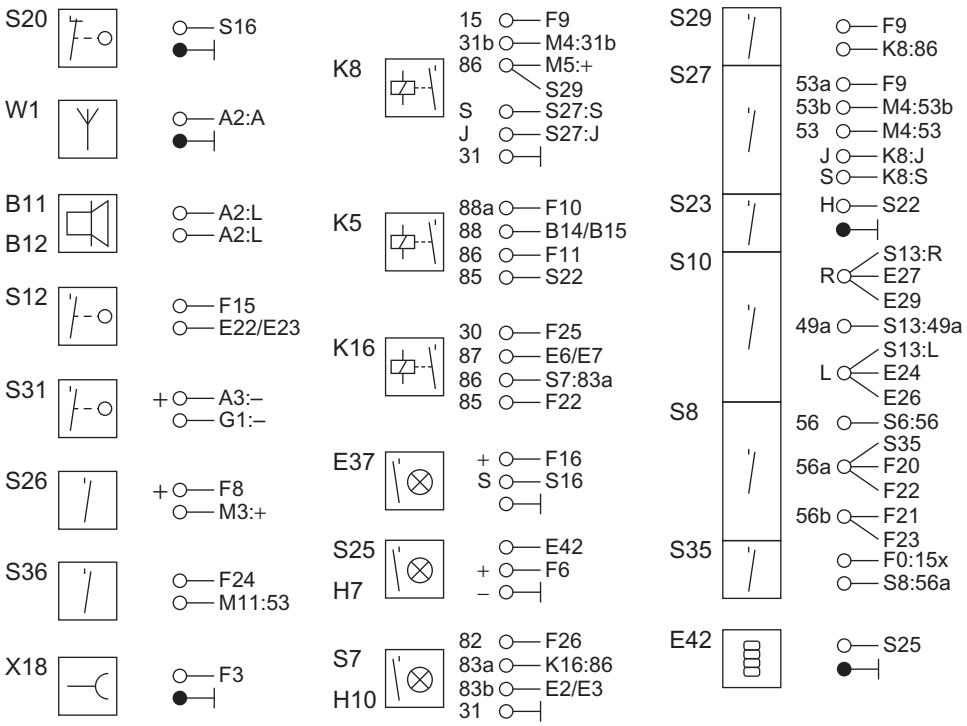

Figure 3.25 Terminal circuit

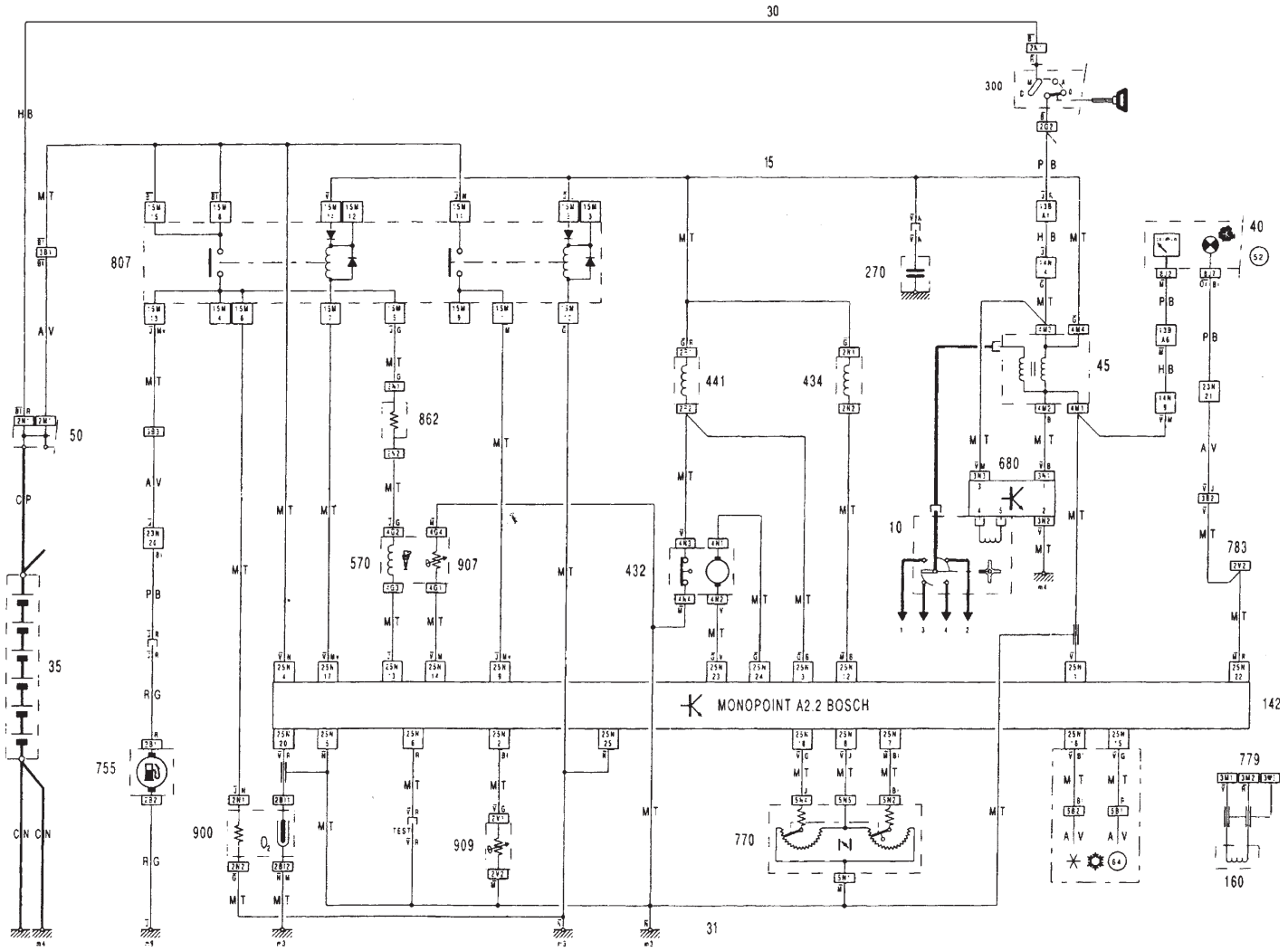

Figure 3.26 Current flow circuit

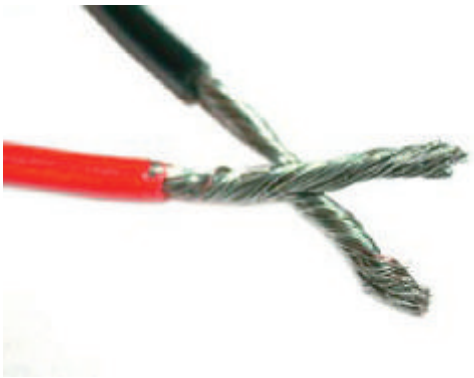

Figure 3.27 Short-circuit

Figure 3.28 Open circuit

from the driver's door alone can require up to fifty wires. This is clearly becoming a problem as, apart from the obvious issue of size and weight, the number of connections and number of wires increase the possibility of faults developing.

A data bus or multiplex system solves many of these problems. The data bus and the power supply cables must 'visit' all areas of the vehicle electrical

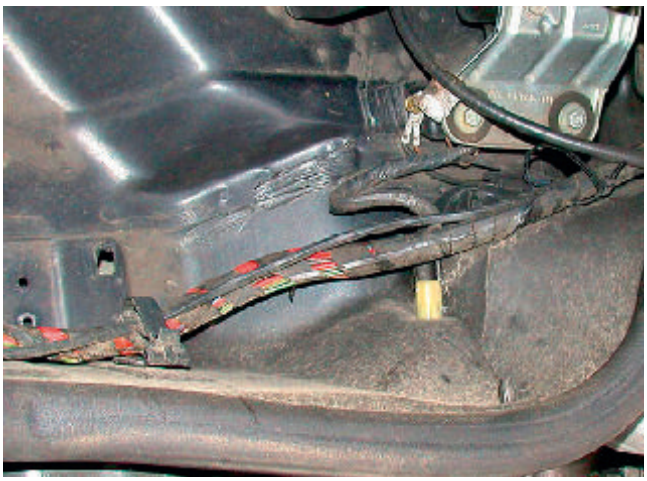

Figure 3.29 Wiring harness

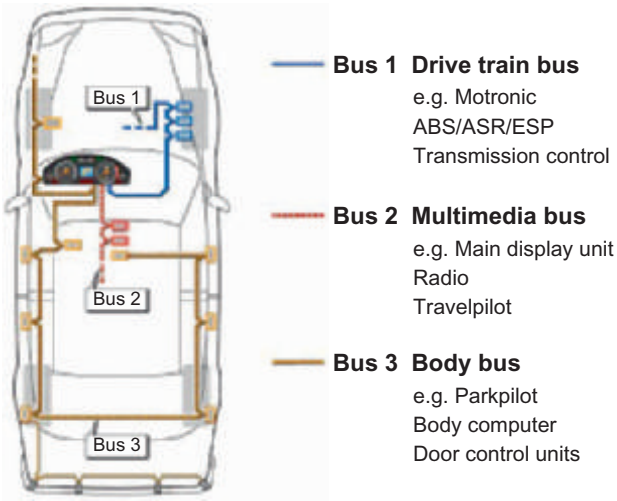

Figure 3.30 Controller area network (CAN) system for instrumentation. (Source: Bosch Media)

Key fact

A data bus can carry information from sensors and allows ECUs to communicate with each other.

system. To illustrate the operation of this system, consider the events involved in switching the sidelights on and off. First, in response to the driver pressing the light switch, a unique signal is placed on the data bus. This signal is only recognized by special receivers built as part of each light unit assembly, which in turn will make a connection between the power supply cable and the lights. The events are similar in turning off the lights, except that the code placed on the data bus will be different and will be recognized only by the appropriate receivers as an off code. A data bus can also carry information from sensors and allows electronic control units (ECUs) to communicate with each other.

Bosch has developed a data bus protocol known the controller area network (CAN) (Fig. 3.30). CAN is suitable for transmitting data in the area of driveline components, chassis components and mobile communications. It is a compact system, which will make it practical for use in many areas. Two variations on the physical layer are available which suit different transmission rates. One variation

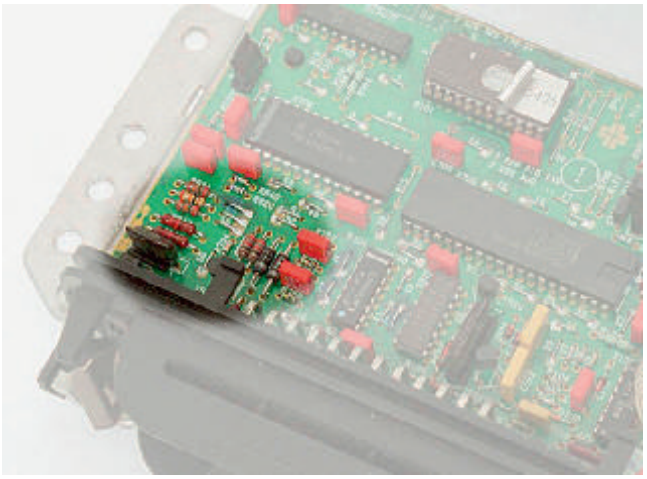

Figure 3.31 Resistors in use

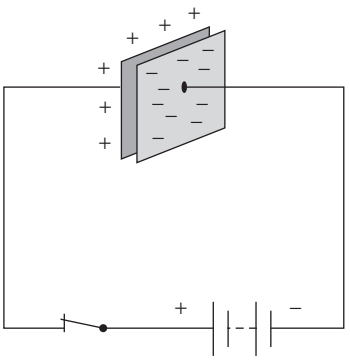

Figure 3.32 Capacitor operation

is for data transmission of between 100 kbits and 1 Mbits per second. It is used for rapid control devices. The other variation transmits data between 10 kbits and 100 kbits per second. It is used for switching and control operations.

3.1.3 Electronic components

Resistors are probably the most widely used component in electronic circuits (Fig. 3.31). Two factors must be considered when choosing a suitable resistor, namely the ohmic value and the power rating. Resistors are used to limit current flow and provide fixed voltage drops. Most resistors used in electronic circuits are made from small carbon rods; the size of the rod determines the resistance. A thermistor is a resistor that changes resistance with temperature.

A capacitor is a device for storing an electrical charge (Fig. 3.32). In its simple form, it consists of two plates separated by an insulating material. One plate can have excess electrons compared to the other. In vehicles, its main uses are for reducing arcing across contacts and for radio interference suppression circuits, as well as in ECUs.

Diodes can be described as one-way valves (Fig. 3.33). For most uses, this is a good description. The diode is made from two types of silicon (N type and P type). Electrons can flow from negative (N-type) to positive (P-type) material, but not the other way. Zener diodes are very similar in operation except that they are designed to conduct in the reverse direction at a preset voltage. They can be thought of as a type of pressure-relief valve.

Definition

Zener diode
A type of electrical pressure-relief valve.

Transistors are the devices that have allowed the development of today's complex and small electronic systems (Fig. 3.34). The transistor is used either as a switch or as an amplifier. Transistors are constructed from the same materials as diodes but with three terminals. A small voltage (about 0.7 V) supplied to the base terminal of a transistor known as an NPN will cause it to fully switch on, joining the collector and emitter. It is sometimes useful to think of a transistor as a type of relay. However, with a transistor, a smaller voltage will partially switch the collector–emitter circuit on and hence the component works as an amplifier.

Inductors are most often used as part of an oscillator or amplifier circuit. In these applications, it is essential for the inductor to be stable and of reasonable size. The basic construction of an inductor is a coil of wire wound on a former.

Figure 3.33 Diodes are one-way valves for electricity

Figure 3.34 Transistor in an electronic control unit

Figure 3.35 Electronic control unit. (Source: Bosch Media)

It is the magnetic effect of the changes in current flow that gives this device the properties of inductance. The inductor is also used as a filter because it tends to prevent changes in signals.

Integrated circuits (ICs) are constructed on a single slice of silicon (Fig. 3.36). Combinations of thousands or even millions of the components mentioned previously can be combined to carry out various tasks. These tasks can range from a simple switching action to the operation of a microprocessor of a computer. The components required for these circuits can be made directly on to one slice of silicon. The advantage of this is not just the size of the ICs (which can be very small) but the speed at which they can be made to work.

Figure 3.36 Integrated circuit (IC) package

3.2 Engine electrical

3.2.1 Batteries

A good supply of electric power is necessary for modern vehicles. The engines require a large current to operate the starter motor and many other systems are electrically powered. All modern cars use a 12 V system. The majority of vehicle batteries are of conventional design, using lead plates in a dilute sulphuric acid electrolyte (Fig. 3.37). This feature leads to the common description of 'lead-acid' batteries. The output from a lead-acid battery is direct current (d.c.).

Definition

Direct current (d.c.)
Current that moves in a single direction in a steady flow.

A rechargeable battery is an electrochemical unit that converts an electric current into a modified chemical compound. This chemical reaction can be reversed to release an electric current. The modified chemical compound in the battery stores energy, which is available as electricity when connected to a circuit.

A few batteries have open cells that require routine maintenance to the electrolyte level. This usually consists of adding distilled water at regular intervals. Most modern lead-acid battery designs have improved plate construction and case design, which with precise alternator charge control allows maintenance-free types to be used.

Definition

Alternating current (a.c.)
This is often used to indicate an alternating potential rather than a current, as in 240V or 110V a.c.

A vehicle 12 V battery is made up from six cells. Each lead-acid cell has a nominal voltage of 2.1 V, which gives a value of 12.6 V for a fully charged battery under no-load conditions. The six cells are connected in series, internally in the battery, with lead bars. The cells are formed in the battery case and are completely separate

Figure 3.37 Vehicle battery. (Source: Bosch Media)

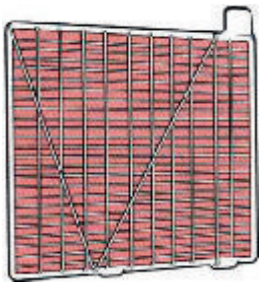

Figure 3.38 Cell plate construction

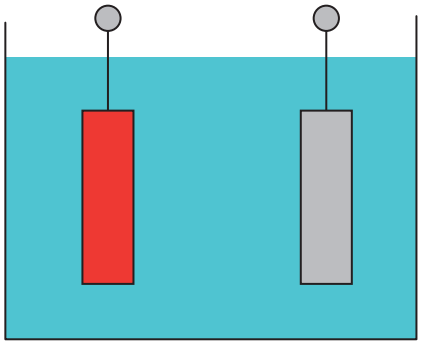

Figure 3.39 Charged state (see text)

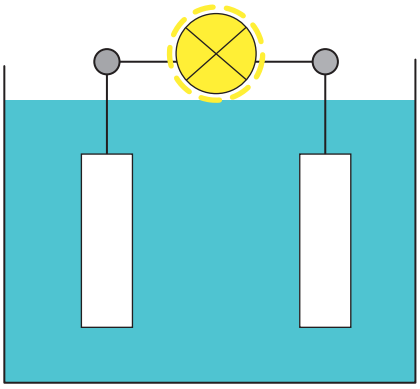

Figure 3.40 Discharged state (see text)

Key fact

A lead-acid cell has a nominal voltage of 2.1 V, which gives a value of 12.6 V for a normal car battery.

from each other. Each cell has a set of interleaved positive and negative plates kept apart by porous separators. The separators prevent contact of the plates, which would give an internal short-circuit and affect the chemical reaction in the battery cell. The cell plates are supported above the bottom of the case. This leaves a sediment trap below the plates so that any loose material that falls to the bottom does not cause a short-circuit between the plates.

The cell plates are formed in a lattice grid of lead–antimony or lead–calcium alloy (Fig. 3.38). The grid carries the active material and acts as the electrical conductor. The active materials are lead peroxide for the positive plate and spongy lead for the negative plate.

When a battery is in a charged state the positive plates of lead peroxide (PbO_2) are reddish brown in colour, and the negative plates of spongy lead (Pb) are grey in colour (Fig. 3.39). When the battery is discharging, a chemical reaction with the electrolyte changes both plates to lead sulphate ($PbSO_4$) (Fig. 3.40).

Applying an electric current to the battery reverses the process (Fig. 3.41). The charged battery stores chemical energy. This can be released as electrical energy when the battery is connected into a circuit.

The electrolyte is dilute sulphuric acid, which reacts with the cell plate material during charging and discharging of the battery. Sulphuric acid (H_2SO_4) consists of hydrogen, sulphur and oxygen. These chemicals separate during the charge and discharge process and attach to the cell plate active material or return to the electrolyte.

During discharge, the sulphate (SO_4) combines with the lead to form lead sulphate ($PbSO_4$). The oxygen in the positive plate is released to the electrolyte and combines with the hydrogen that is left, to form water (H_2O). During charging, the reverse process occurs with the sulphate (SO_4), leaving the cell plates to reform with the hydrogen in the electrolyte to produce sulphuric acid (H_2SO_4). Oxygen in the electrolyte is released to reform with the positive cell plate material as lead peroxide (PbO_2).

Near the fully charged state some hydrogen (H_2) and oxygen (O_2) may be lost as gas from the battery vent (Fig. 3.42). Some water (H_2O) can also be lost by vaporization in hot weather. With older batteries, this meant that the battery electrolyte needed regular inspection and topping up.

Only water is lost from the battery and therefore only water should be used for topping up. Any contaminants will affect the chemical reactions in the battery

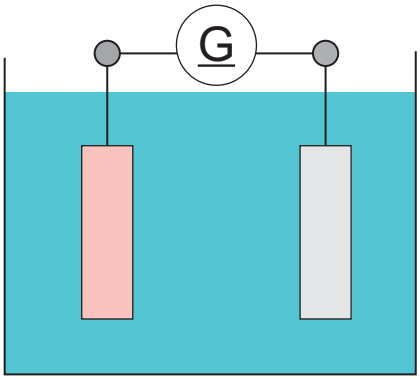

Figure 3.41 Chemical changes reverse when current is applied (see text)

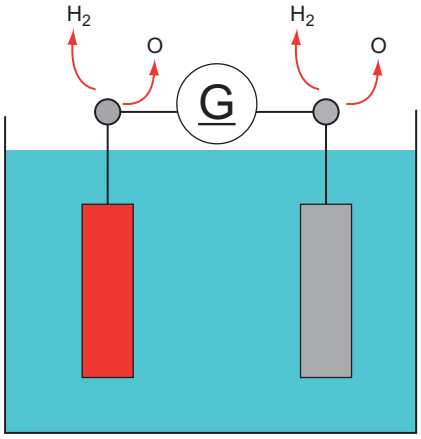

Figure 3.42 Discharge of hydrogen and oxygen (see text)

Figure 3.43 Construction of a hydrometer

and, therefore, the performance. Only distilled or specially produced topping-up water should be used. Tap water is not suitable for topping up a battery. Acid should never be used, as this would strengthen the acid solution and alter the chemical reactions. Most modern batteries, however, include vapour traps and other features to minimize water loss and therefore need little or no attention.

The electrolyte chemical composition changes with the state of charge. It is possible to measure this change using a hydrometer. Sulphuric acid is denser and provides greater buoyancy than water. This property is called specific gravity or relative density. Water, which is used as the base for measurement of all liquids, is given a value of 1 for readings at 15°C (60°F).

The dilute sulphuric acid of the electrolyte of a fully charged battery cell has a reading of 1.280. The reading for a half-charged battery cell is 1.200 and for a fully discharged battery is 1.150. A reading below 1.140 may indicate a cell that can no longer be recharged. It is common to write these values with three decimal places but to just say the significant digits (e.g. twelve eighty).

A hydrometer consists of a calibrated float in a glass cylinder (Fig. 3.43). A bulb on the top of the cylinder is depressed so that it acts as a vacuum pump when it is released. A small rubber tube is attached to the bottom of the cylinder and is inserted into the electrolyte in the battery cell. A sample of the electrolyte can, therefore, be drawn into the cylinder.

Key fact

The relative density reading for a fully charged battery cell is 1.280, for a half-charged cell 1.200 and for a fully discharged cell 1.150.

The sample of electrolyte in the hydrometer lifts the float in proportion to the buoyancy of the liquid. The higher it floats, the greater the relative density. Calibrated marks on the float align with the top of the liquid to give the actual reading (Fig. 3.44). This is compared with standard data and all cells are compared with each other to check the general condition of the battery. There should be very little difference between the cells.

However, as most batteries are sealed the voltage of the battery can be used to indicate battery condition. A fully charged battery will give a reading of 12.6V and a discharged battery 12.0V.

Key fact

A fully charged battery will give a reading of 12.6V and a discharged battery 12.0V (when not under load).

Measurement of battery condition by heavy-duty discharge should only be carried out on a fully charged battery. Heavy-duty discharge is carried out with

Figure 3.44 Reading a hydrometer: fully charged

Figure 3.45 Heavy-duty discharge test equipment

Safety first

A discharge test applies a load similar to that of the starter circuit, which results in a high current and heat.

a specialist item of equipment (Fig. 3.45). The test consists of connecting a low-value resistor in circuit with the battery for a few seconds and measuring the voltage drop. This test applies a load similar to that of the starter circuit. In general, the voltage should not fall below 10 V. Figure 3.45 shows test equipment for this purpose; as always with this type of thing, refer to the manufacturer's instructions before use.

Battery performance can be determined by its ampere-hour (Ah) rating, but this is also affected by the ambient temperature. A cold battery will have a poor performance in comparison to a warm battery. A more useful measure of battery performance is its 'reserve capacity' rating. This refers to the time taken in minutes for a battery to discharge to a cell voltage of 1.75 V, when supplying a constant current of 25 A. This test reflects a typical current draw for a vehicle that would be needed if the charging system failed during night driving. The reserve capacity for a 40 Ah battery will be approximately 60 minutes.

Another measure is the 'cold cranking amps' rating, which is a measure of the maximum current that can be supplied for a period of 30 seconds before the battery voltage falls below 7.2 V. This test is carried out at minus 18°C (0°F) so that it represents the most severe conditions of cold engine starting. The cold-cranking amps (CCA) rating of a battery is an important measure in regions that suffer very cold winter temperatures.

Some maintenance-free batteries incorporate a built-in hydrometer to indicate the state of charge and condition of the battery. The hydrometer is colour coded (Fig. 3.46). A green colour indicates that the battery is charged and serviceable. A green–black or black colour indicates that the battery requires recharging. A yellow colour indicates that the battery is faulty. Where a yellow hydrometer is showing, the battery should not be recharged or tested, and the use of jump leads for starting should not be carried out. A new battery should be fitted and the alternator checked for correct operation.

Battery charging can be described as slow or fast. Slow charging is best but in an emergency a fast charge is acceptable. When recharging, a battery should ideally be disconnected from the vehicle electrical systems.

There are two types of battery charger: the bench charger, which has a current output of up to about 10 A (Fig. 3.47), and the fast charger, which can recharge a battery in about 30 minutes, with a current of up to 50 A (Fig. 3.48).

Figure 3.46 Maintenance-free battery hydrometer colours

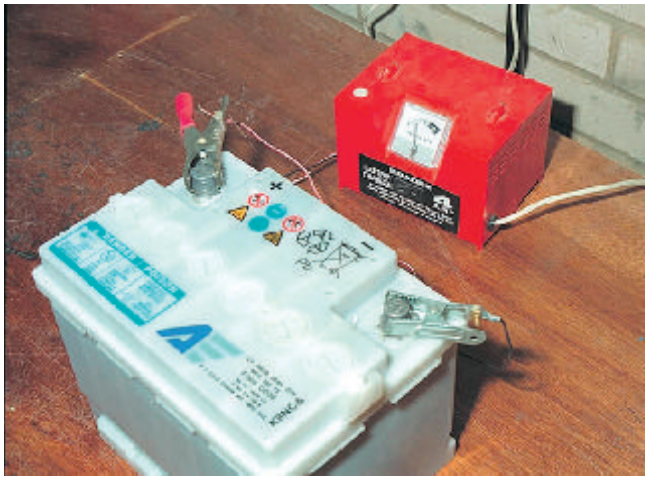

Figure 3.47 Recharging with a small bench charger

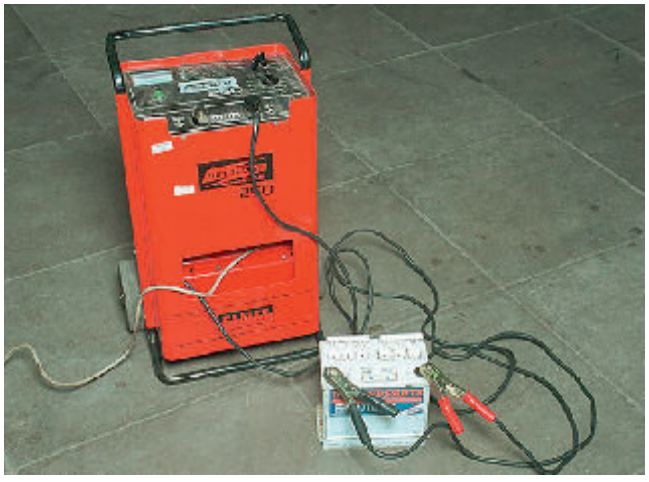

Figure 3.48 Fast chargers

Figure 3.49 Round battery posts

The bench charger should be situated in a well-ventilated area of the workshop. Smoking should also be prohibited, if it is not already. Bench chargers with voltage control have high initial current outputs, which fall as the battery charges. Chargers with current control can be adjusted to suit individual batteries.

Key fact

Ideal charge rates: one-tenth of the ampere-hour rating of the battery, one-sixteenth of the reserve capacity, or one-fortieth of the cold cranking amp rating.

The usual rule for battery charging is that the charge current should be set to about one-tenth of the ampere-hour (Ah) rating of the battery. Alternatively, about one-sixteenth of the reserve capacity, or one-fortieth of the CCA figure gives a good guide. A fully discharged battery will take about 12 hours to fully recharge. When recharging partially charged batteries, it is recommended that they should be checked at regular intervals. Always switch off the charger before disconnecting the leads and carrying out any tests.

Fast chargers are portable items of equipment that will charge a battery in a short space of time at several times the normal rate. They can also be used for engine starting, depending on design. There is a risk of overcharging and overheating a battery with fast chargers, so frequent checks should be made to check for gassing and battery temperature. Charging should be stopped when heavy gassing is evident or if the battery feels more than just warm to the touch.

The external features of a battery are the type and size of the terminal posts, the dimensions of the battery and the method of fixing to the vehicle. The terminal posts are clearly identifiable as positive or negative, by the positive sign (+) and/or red colour, and the negative sign (−) and/or black colour. The positive and negative posts, on tapered round terminals, are different sizes. The larger post is the positive one and the smaller is negative. The difference in the sizes is used to minimize the risk of incorrect fitting. There are two size ranges, with a smaller version used by some manufacturers, generally in the Far Eastern geographical zone, and a larger size used by Western European and American manufacturers. These round post terminals use a clamp-type cable terminal (Fig. 3.49).

Some manufacturers use batteries with a flat, or 'L' terminal on the battery, a flat terminal on the cable, and a nut and bolt to complete the connection (Fig. 3.50). Some US vehicles use a side terminal, which has an internal thread, and the connection is made with a bolt through a flat terminal on the cable.

Key fact

Battery cables must have sufficient cross-sectional area to carry the starter motor and electrical systems current.

Battery cables must have sufficient cross-sectional area to carry the starter motor and electrical systems current. The feed to the starter motor is a heavy-duty insulated cable, and the earth or ground cable is of similar construction.

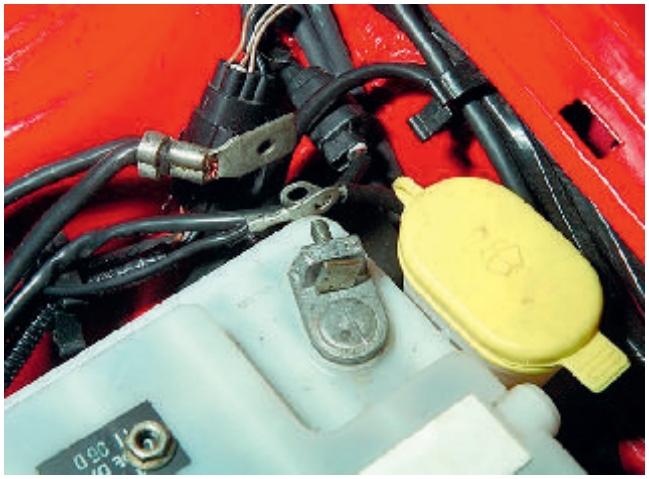

Figure 3.50 Flat posts

Figure 3.51 Correct polarity is important: red cables are used for the positive connection

There are two ways of charging batteries in the workshop; one is a slow or trickle charge and the other a fast charge. These require two different types of charger. Most batteries can be fast charged, but this should only be carried out infrequently. If a high charge is used this can cause some deterioration of the battery's active materials.

A slow charger or bench charger uses mains electricity. Inside is fitted a transformer to reduce the voltage to 6, 12 or 24 V, to suit the battery or batteries on charge. Also fitted is a rectifier to change the a.c. volts of the mains supply to the d.c. volts needed for charging batteries. The charger is connected to the battery terminals with the correct polarity (Fig. 3.51). After setting the control switches, the charger is then turned on at the main switch.

There are several different types of charger and these should be used in accordance with the manufacturers' instructions. The recommended charge rate for a battery is one-tenth of the ampere-hour capacity. A 40 Ah battery should be charged at 4 A. If the ampere-hour capacity is not known, set the rate to one-sixteenth of the reserve capacity. Where the charge current can be adjusted, this facility should be used to set the rate.

Key fact

Smart Charger: A recent 'plug play' development, this device will revive, charge, condition and maintain lead-acid batteries. It determines a battery's charge and then sets the appropriate rate. Intended for unsupervised use they are spark proof and reverse-polarity protected. The clean voltage and current supplied means they are safe to use on a battery, which is still connected to the vehicle. The charger can be left attached to a battery for an indefinite time without risk of damage.

Figure 3.52 Fast charger with time clock

It is important that the charger is switched off before it is disconnected from the battery. For further safety, leave the batteries for about 5 minutes before the charger leads are disconnected. This will allow any flammable gas to dissipate to the atmosphere.

A fast charger can be connected to a battery on a vehicle, to give a quick boost when a battery has a low charge. Some of these chargers have an engine start facility. Always follow the equipment manufacturer's instructions when using this type of charger. Some batteries are not suitable for fast charging; therefore, always refer to the vehicle or battery manufacturer's data for recommendations.

Fast chargers have a time clock for setting the charger for a fixed charge period (Fig. 3.52). Some have a temperature probe included, to switch off the charger if the battery becomes overheated. Keep a close watch on the battery temperature if a fast charger does not have a temperature probe. The maximum setting for a fast charge should not exceed one hour at five times the normal charge rate.

Safety first

The maximum setting for a fast charge should not exceed one hour at five times the normal charge rate.

3.2.2 Starting system

The engine starting system consists of a heavy-duty motor, with a drive pinion that engages with a gear on the engine flywheel, and an electrical control circuit to operate the motor (Figs 3.53 and 3.54).

The starter motor power output has to be able to crank a cold engine at sufficient speed to start it. A 2 litre petrol engine will have a starter motor of about 1 kW, which will spin the engine at about 150 rpm. A similarly sized diesel engine will require double the power and possibly twice the cranking speed to start.

Key fact

The main components of the starter motor are the magnetic fields, armature, drive pinion and solenoid.

The main components of the starter motor are the magnetic fields, armature, drive pinion and solenoid (Fig. 3.55). The circuit consists of a battery supply, earth cables and the starter switch.

The starter motor is a direct current (d.c.) electromagnetic unit that usually has two pairs of magnetic pole shoes arranged at opposite positions inside the motor casing. The casing acts as the yoke for the magnetic poles. The magnetic pole shoes can be strong permanent magnets or electromagnets using a winding.

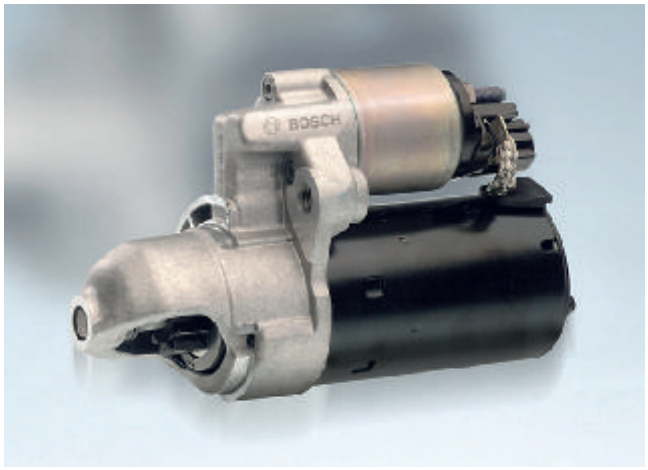

Figure 3.53 Pre-engaged starter

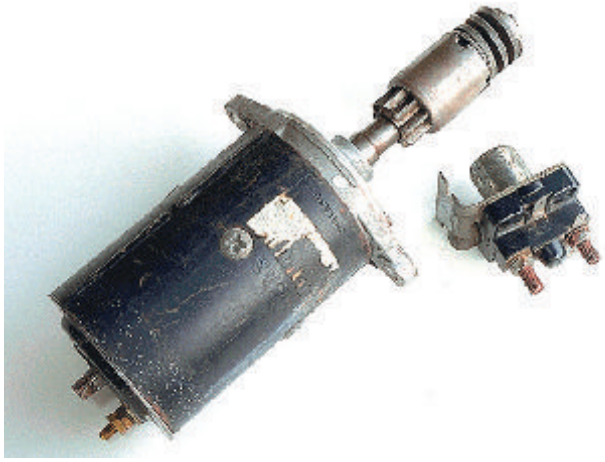

Figure 3.54 Inertia motor and solenoid switch

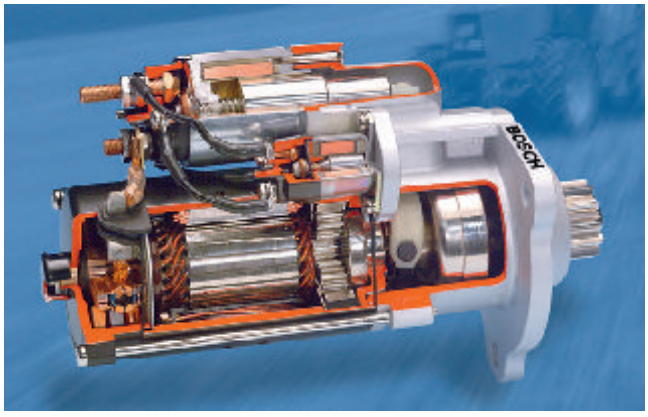

Figure 3.55 Starter internal components

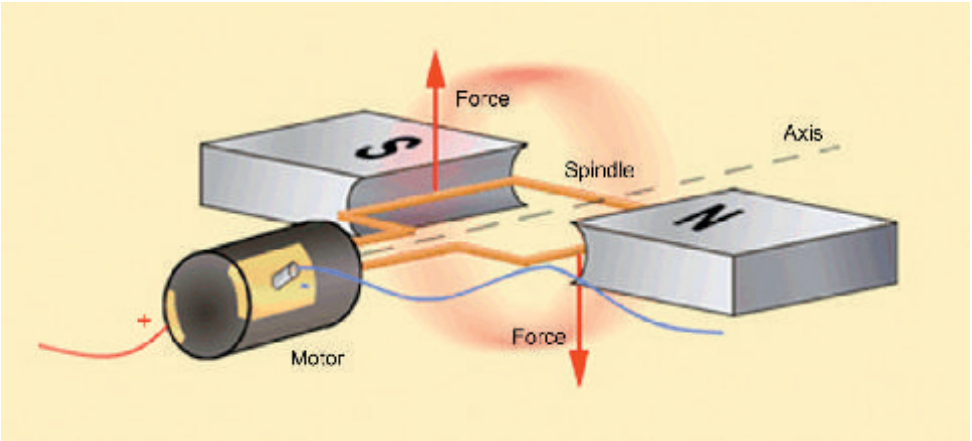

Figure 3.56 Direct current motor operating principle

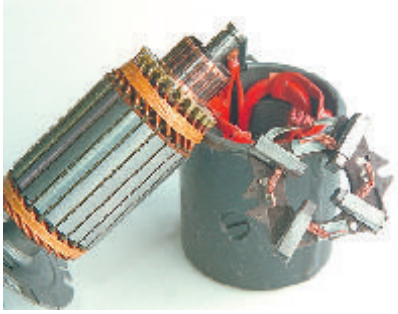

Figure 3.57 A series of windings on the armature gives a continuous rotary motion in conjunction with the windings on the fields, which produce strong magnetism

The armature, which consists of a series of wire conductor loops wound around a laminated iron core, is mounted on the motor spindle. The conductor loops are terminated into segments of a commutator. Carbon or composite brushes conduct the motor electrical supply through the commutator segments to the individual conductor loops. The construction of a simple d.c. motor is shown in Fig. 3.56. The magnetic force between the poles is from north to south. A loop conductor inside the magnetic field is provided with a d.c. electrical supply through a split slip ring, which forms a simple commutator.

When an electrical current is passed through a conductor a magnetic field is formed around that conductor. The magnetic field direction depends on the direction of the current flow. When the conductor is placed inside a fixed magnet, the magnetic field distorts to produce a repelling magnetic force, which pushes on the conductor.

In practice, it requires a large series of loop conductors to provide a motor with continuous rotation and good torque characteristics. In order to supply each loop of the winding, when it is in alignment with the field magnets, and to maintain the current in the proper direction, a commutator is fitted. Current is passed to the commutator segments through spring-loaded brushes held in position by brush holders on the motor end plate (Fig. 3.57).

A starter motor requires strong magnetic forces to produce the speed and torque to crank an engine at sufficient speed for starting. For this, the armature is made with soft iron cores to make strong electromagnets, which are able to change polarity with the direction of current flow in the loop conductors. Laminations of soft iron are used for the cores to reduce magnetization losses. They are insulated from each other and assembled as a single unit on the armature.

The magnetic strength of the field magnetic poles is usually determined by using an electrical winding around the pole shoe. The wire coil is wound around one pole shoe and then the other in the opposite direction, so that the opposing field poles are produced opposite each other in the casing.

Key fact

A pre-engaged starter motor moves the drive pinion into mesh by the action of a solenoid.

The drive from the motor is taken from a pinion gear on the spindle to the large diameter starter ring gear on the engine. The starter ring gear is fitted to the outside of the flywheel on manual transmission vehicles, or the torque converter drive plate on automatic transmission vehicles. The pinion meshes with the ring gear only during starting and is made to slide axially on or with the spindle to engage the drive when operated (Fig. 3.58).

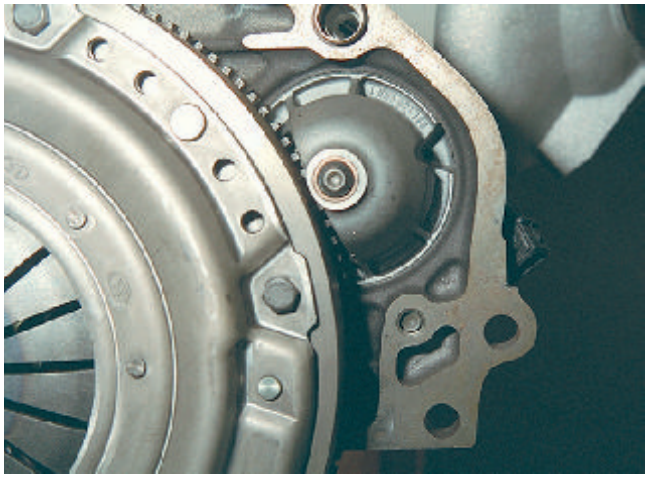

Figure 3.58 Starter in position to mesh with a ring gear on the engine flywheel

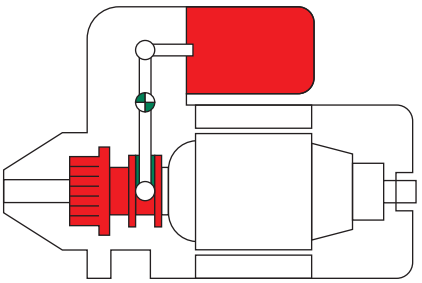

Figure 3.59 Pinion movement

In a pre-engaged starter motor, the drive pinion is brought into mesh by the action of an electromagnetic solenoid mounted on the starter motor casing (Fig. 3.59). The solenoid has a soft iron plunger, which is drawn into the magnetic field that is produced inside the solenoid when an electrical current is passed through the solenoid windings. Connected to the plunger is a lever, which is pivoted so that, as one end is pulled into the solenoid, the opposite end pushes the pinion into mesh with the starter ring gear. The pinion is mounted on a unidirectional clutch, which is fitted to a sleeve with an internal spline to take the drive from the starter spindle. On the outside of the sleeve is a radial groove to take the fork of the engagement lever.

At the other end of the solenoid are the electrical contacts that form the switch to pass the electrical current to the motor. The solenoid on many pre-engaged starter motors has two windings. These are the 'closing' and 'holding' windings.

The closing winding or pull-in coil operates as soon as the solenoid is energized. This winding has an earth, or ground, return through the motor windings. This passes a current into the motor so that it rotates slowly during the engagement phase. Once the switch contacts are fully engaged, the holding winding holds the switch in place. The closing winding does not conduct once the motor current has been switched on.

A holding coil is wound around the solenoid. This creates the magnetic field required to hold the solenoid in the engaged position during starting. When the starter switch is released, a spring returns the solenoid plunger to its 'off' position. If the engine were to start under these conditions, it would drive the motor spindle at an excessive speed. To prevent this occurring in pre-engaged drive starter motors, a unidirectional overrun clutch is fitted on the pinion (Fig. 3.60). This allows the motor to drive the engine but stops the engine driving the motor. A roller-type overrun clutch is a popular method, although a few other types are used. These clutch units are sealed for life and require replacement if they fail in service.

Clutch operation is summarized in Fig. 3.61. On early inertia-type starter motors, a spiral or helical sleeve carried the pinion, which slid into mesh because of the forward drive from the motor spindle, and out of mesh by the engine spinning. A spring inside the pinion barrel held the gears out of mesh when the starter was not in operation (Fig. 3.62).

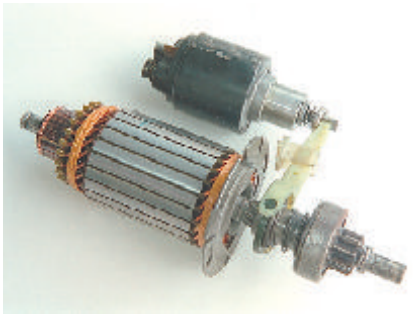

Figure 3.60 One-way clutch behind the drive pinion

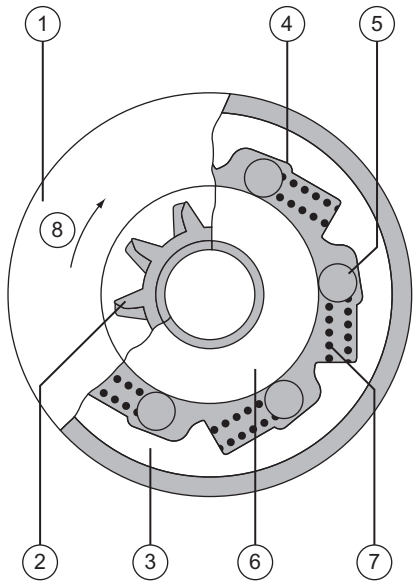

Figure 3.61 Clutch operation: 1, casing; 2, pinion; 3, clutch shell; 4, roller race; 5, roller; 6, pinion shaft; 7, spring; 8, direction of rotation

Figure 3.62 Inertia starter

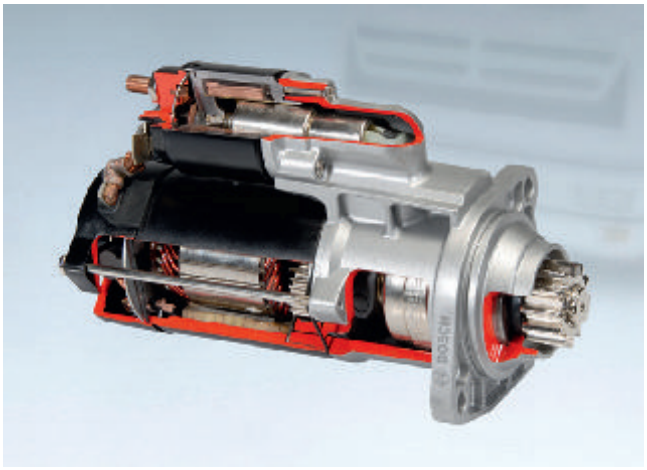

Figure 3.63 Heavy-duty starter motor. (Source: Bosch Media)

Key fact

Small, modern starter motors tend to use permanent magnet field poles.

Most small, modern starter motors use permanent magnets for the field poles. These motors have high speed and low torque characteristics and are suitable, without additional gearing, for engines up to about 2 litres. A heavy-duty starter motor is shown in Fig. 3.63.

On some permanent magnet starter motors, for light diesel engines and petrol/gasoline engines up to 5 litres, an intermediate planetary gear set between the motor and drive pinion may be used (Fig. 3.64). This intermediate gearing modifies the speed and torque characteristics of the motor and makes it possible to construct starter motors that can be 40% lower in weight. The starter electrical current is passed through the armature only. On a planetary gear motor, the spindle is fitted with a sun wheel, and the motor casing with the annulus. The output to the drive pinion is made from the planetary gear carrier.

Key fact

On a planetary gear starter motor, the armature drives the sun wheel, the motor casing holds the annulus and the output to the drive pinion is from the planetary gear carrier.

Starter motor control circuits use a heavy-duty electrical relay, called a solenoid, to switch the large starter current to the motor. The solenoid is an electromagnetic switch and, on modern pre-engaged starter motors, is attached to the top of the motor, where it performs the switching function, and is also used to slide the motor drive pinion into mesh with the starter ring gear on the engine flywheel.

A basic starter circuit is shown in Fig. 3.65. The main components are the battery, starter switch, which is usually part of the ignition switch, the solenoid and motor, connecting cables and the earth, or ground, return circuit. The battery and starter cables are of heavy-duty construction to carry a large current to the motor. The control cables are standard low-current cable sizes. If any of these cables have to be replaced, cables of the same size, or as specified by the vehicle manufacturer, should always be used.

Starter motor circuits may have additional automatic switching to prevent the engine being started in particular situations. Automatic transmission systems incorporate an inhibitor switch on the gear selector, which allows engine starting in the park and neutral positions only. This prevents the engine being started with the transmission in gear, which could result in the vehicle pulling away unexpectedly. The inhibitor switch must be carefully checked and adjusted so that there is no risk of incorrect operation.

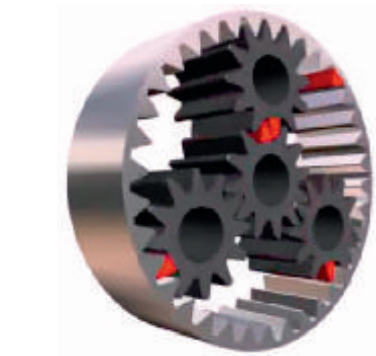

Figure 3.64 Intermediate transmission gears

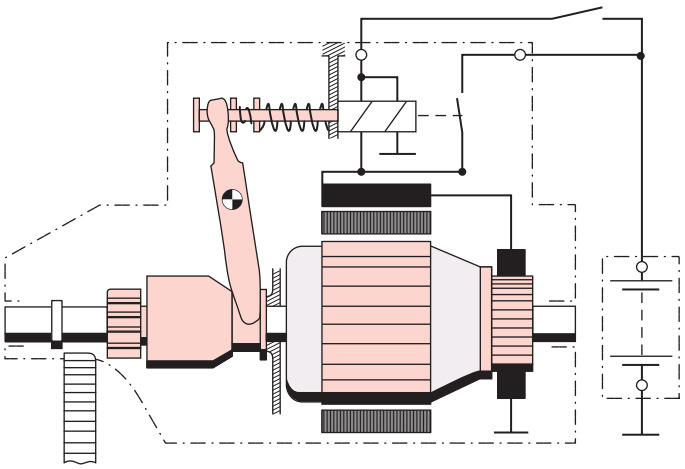

Figure 3.65 Starter circuit

In the Ford diagram shown in Fig. 3.66, the powertrain control module (PCM) allows the engine to start only when the passive anti-theft system (PATS) reads a key which transmits a valid code. In a key-free vehicle, the passive key is recognized by the key-free module and if the key is valid the permission to start is issued directly. In vehicles with a manual transmission it is necessary to depress the clutch pedal; on those with automatic transmission the brake pedal must be pressed. In a key-free system the key-free module switches on the control voltage for the starter relay.

Key fact

In a key-free system the key-free module switches on the control voltage for the starter relay.

The PCM switches the ground in the control circuit of the starter relay, which then connects power through to the starter solenoid. As soon as the speed of the engine has reached 750 rpm or the maximum permitted start time of 30 seconds has been exceeded, the PCM switches off the starter relay and, therefore, the starter motor. This protects the starter. If the engine does not turn or turns only slowly, the starting process is aborted by the PCM.

3.2.3 Charging system

The electrical generator on modern vehicles is an alternator (Fig. 3.67). Older vehicles used a dynamo, which gives a direct current without the need for a rectifier.

Key fact

The main parts of an alternator are the rotor and stator.

There are two main parts of an alternator: the rotor and the stator (Fig. 3.68). Together they produce an a.c. voltage output. An electric current is induced or generated in the stator by the magnetic fields produced in the rotor.

A rectifier changes the a.c. voltage to a d.c. voltage, because that is what is needed for battery charging. Diodes in a bridge formation are used to route the electric current in such a way as to convert the a.c. voltage to a d.c. voltage.

A voltage regulator senses the alternator output voltage. It then controls the rotor magnetic field strength to maintain the voltage at the correct level.

Key fact

A voltage regulator controls the rotor magnetic field strength to maintain the voltage at the correct level.

All the main components of modern alternators are enclosed in a lightweight aluminium casing (Fig. 3.69). The vehicle engine provides power to the alternator, through a drive belt and pulleys to the rotor, which is mounted on bearings in the end covers of the alternator casing.

In a light vehicle, alternator magnetic fields are produced around magnetic poles on the rotor by an electrical current passing through coil windings. The poles are

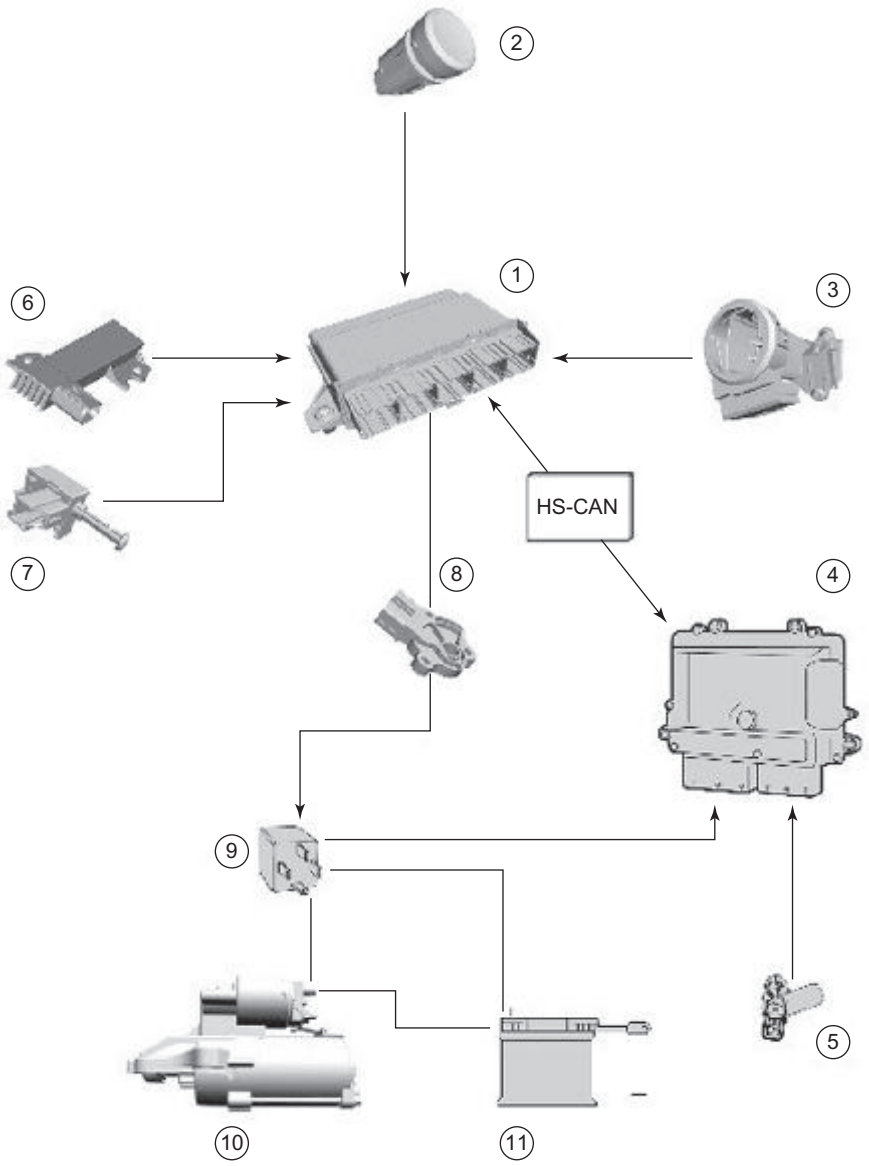

Figure 3.66 Keyless starting system: 1, keyless vehicle module; 2, start/stop button; 3, electronic steering lock; 4, powertrain control module; 5, crank sensor; 6, keyless vehicle antenna; 7, vehicles with manual transmission: clutch pedal position switch/vehicles with automatic transmission: stoplamp switch; 8, transmission range sensor; 9, starter relay; 10, starter motor, 11, battery. (Source: Ford Motor Company)

made from iron and shaped like claws with six fingers. There are two of these, one for each pole, facing each other, and set at each end of the rotor. Wound inside the poles is the rotor winding, which is connected to slip rings at one end of the rotor. Carbon brushes are used to conduct an electrical current to the rotor windings through the slip rings. The rotor rotates inside the stator and induces a current into the stator windings.

When an electrical current is passed through the rotor windings, they become 'excited' and a magnetic field is produced. The strength of the magnetic field is proportional to the voltage in the windings. The voltage in the windings is provided by the alternator during the charging phase and then controlled to regulate the alternator output voltage.

Figure 3.67 Alternator

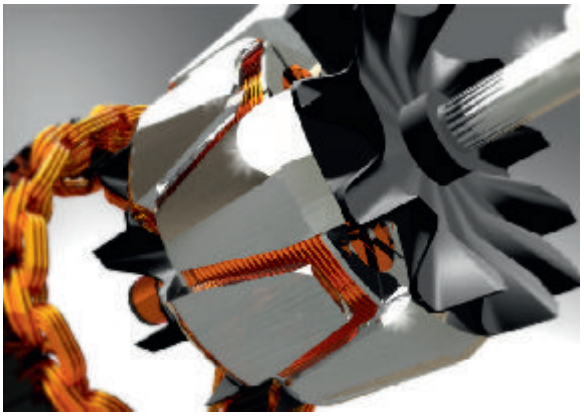

Figure 3.68 Stator and rotor

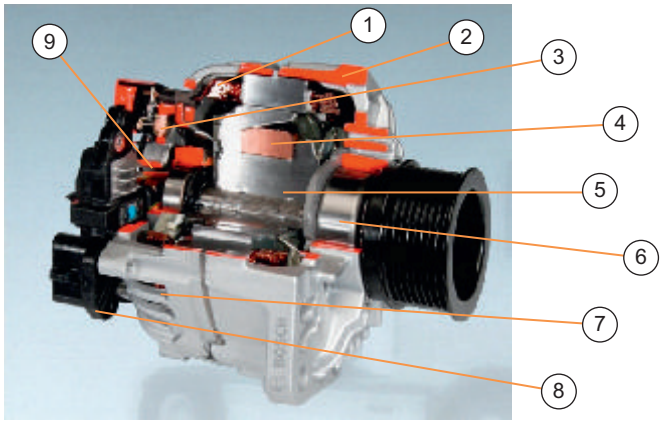

Figure 3.69 Cutaway alternator: 1, stator winding; 2, case; 3, rectifier diodes; 4, rotor (field) winding; 5, claw pole rotor; 6, drive end bearing; 7, ventilation slots; 8, regulator, brush box and slip rings. (Source: Bosch Media)

The initial electrical current to excite the windings can be provided through the ignition or generator warning light circuit. The light acts as an indicator that the generator field is being provided with an initial current to excite the rotor windings, and as a warning when the voltage from the stator is less than battery

Figure 3.70 Stator construction

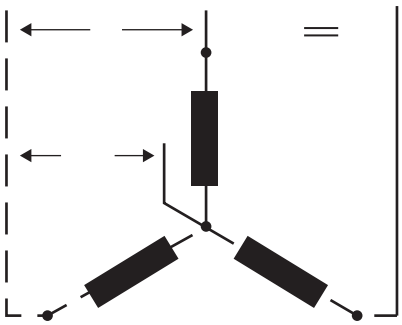

Figure 3.71 Star stator windings showing main output and a tapping from the centre

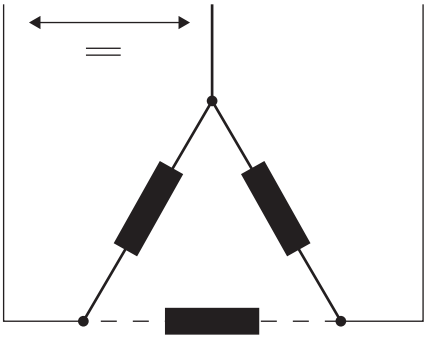

Figure 3.72 Delta stator windings showing main output

voltage. Under normal conditions, the light should go out as soon as the engine is running.

The stator, which is fitted inside the alternator casing, is made from soft iron laminations wound with three sets of windings (Fig. 3.70). The three sets of windings give three separate outputs, or phases, of alternating current. The electrical current induced in the alternator flows in the stator because of the changing magnetic fields produced by rotation of the rotor. The speed of rotation and the magnetic strength of the rotor determine the value of the voltage that is produced.

The three-phase stator windings are enamel-coated copper wire of a heavy gauge and, for light vehicle applications, are usually connected in a 'star' formation (Fig. 3.71). The windings can also be connected in a 'delta' (Greek letter Δ) formation (Fig. 3.72). The voltage and current outputs from the two formations are different for the same magnetic field strength and alternator speed. The voltage is higher and current lower for the star formation, in comparison with the delta formation.

Key fact

Alternator rectifiers use semiconductor diodes in a bridge formation.

Alternator rectifiers use semiconductor diodes, in a bridge formation, to provide rectification of the alternating current to the direct current required to charge the vehicle battery (Fig. 3.73).

Figure 3.73 Rectifier

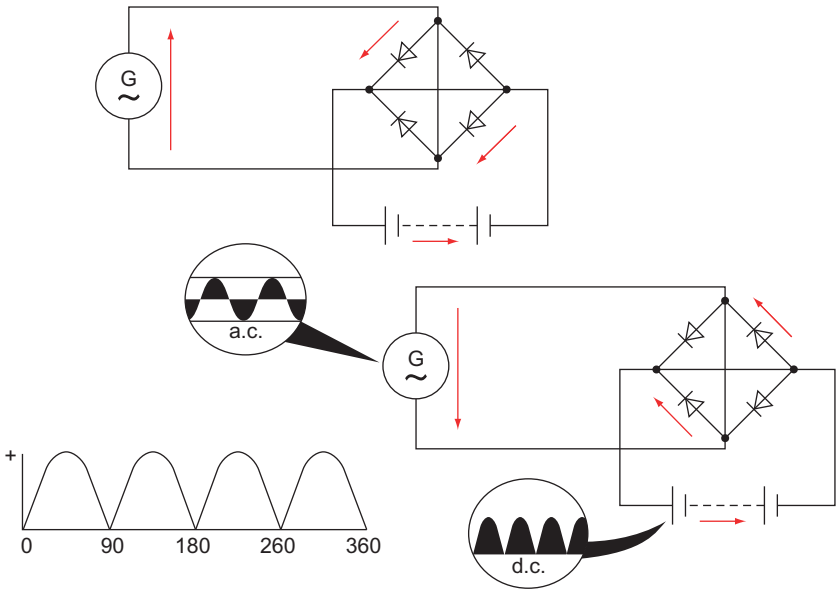

Figure 3.74 Bridge rectifier showing full wave rectification

To achieve full wave rectification, a series of diodes is connected in a 'bridge' arrangement, so that the current flow is routed through open paths created by the bias of the diodes (Fig. 3.74). There are two open paths in the bridge rectifier, one for each direction of current flow. The output current flow is always in the same direction, and this gives a direct current flow.

The three phases of the alternator output require six diodes arranged in the circuit as shown in Fig. 3.75. The arrows of the diode symbols show the current flow for each phase and direction of flow of the alternating current. The output from the rectifier is connected to the vehicle battery and the circuit completed by an earth, or ground return connection through the alternator casing.

Three additional diodes are often fitted in the circuit so that part of the output from the stator can be passed to the rotor. This is to increase the magnetic

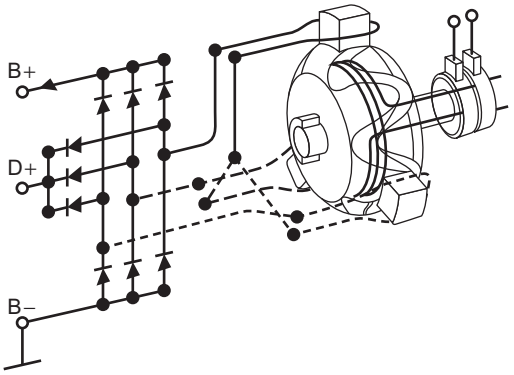

Figure 3.75 Alternator rectifier and current flow paths

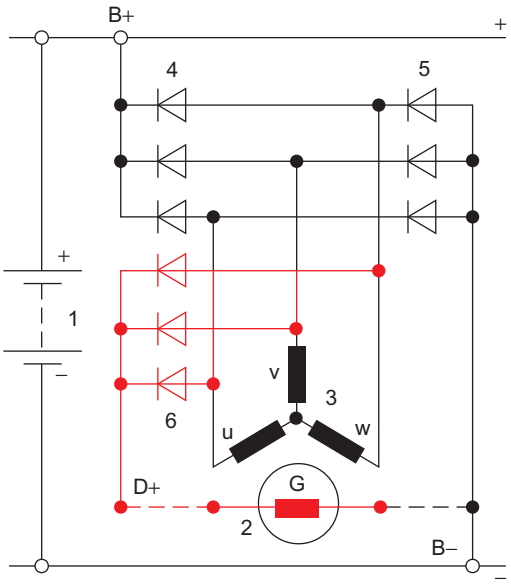

Figure 3.76 Field diodes and current flow to rotor (via a regulator)

Key fact

Voltage from the stator increases as the engine speed increases.

field strength when the stator voltage increases as the engine speed rises (Fig. 3.76). Without a control system, the voltage would rise to high levels and cause extensive damage to the alternator and electrical systems on the vehicle. The regulator is connected into the rotor field circuit to control the rotor winding voltage and therefore the rotor magnetic field strength.

As the alternator output is dependent on speed and rotor magnetic field strength, it is necessary to reduce the magnetic field strength as the speed increases. The regulator does this and therefore maintains a constant alternator output voltage. This is usually at about 14.2 V, which is sufficient to charge the battery without causing excessive gassing and, for maintenance-free batteries, is the optimum voltage level for correct charging.

The regulator consists of a small electronic circuit built around a zener diode. A zener diode conducts an electrical current only when its rated voltage is exceeded. This is used to control transistors that in turn switch the rotor field current on and off. As the voltage in the rotor windings is switched off, the

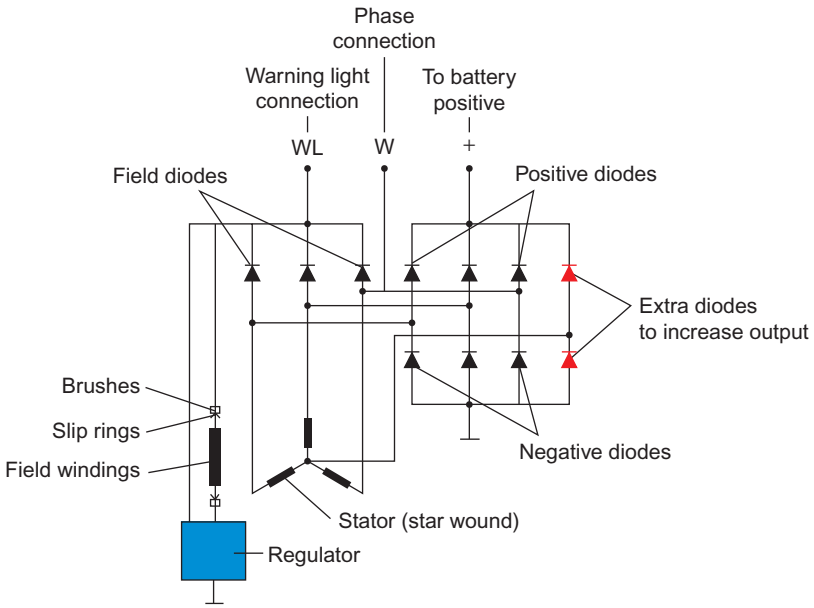

Figure 3.77 Modern alternator circuit

voltage induced in the stator reduces until it falls below the rated voltage of the zener diode. The zener becomes non-conductive and allows the current to return once again to the rotor windings. This cycle occurs very quickly in the regulator to maintain a constant voltage output.

A typical circuit for a modern alternator is shown in Fig. 3.77. The extra diodes from the centre of the stator help to improve the overall efficiency.

3.3 Lighting and indicators

3.3.1 Lighting systems

Safety first

Lights are to see with AND to be seen by.

Vehicle lighting systems are very important, particularly where road safety is concerned. If headlights were suddenly to fail at night and at high speed, the result could be serious. Remember that lights are to see with and to be seen by. Lights are arranged on a vehicle to meet legal requirements and to look good. Headlights, sidelights and indicators are often combined on the front (Fig. 3.78). Taillights, stoplights, reverse lights and indicators are often combined at the rear (Fig. 3.79).

The number, shape and size of bulbs used on vehicles are increasing all the time. A common selection is shown in Fig. 3.80. Most bulbs used for vehicle lighting are generally either conventional tungsten filament bulbs or tungsten halogen.

In the conventional bulb, the tungsten filament is heated to incandescence by an electric current. The temperature reaches about 2300°C. Tungsten, or an alloy of tungsten, is ideal for use as filaments for electric light bulbs. The filament is normally wound into a ‘spiralled spiral’ to allow a suitable length of thin wire in a small space, and to provide some mechanical strength.

Almost all vehicles now use tungsten halogen bulbs for the headlights (Fig. 3.81). The bulb will not blacken and, therefore, has a long life. In normal gas bulbs, about 10% of the filament metal evaporates. This is deposited on the bulb wall. Design features of the tungsten halogen bulb prevent this deposition. The gas in

Figure 3.78 Front lights

Figure 3.79 Rear lights

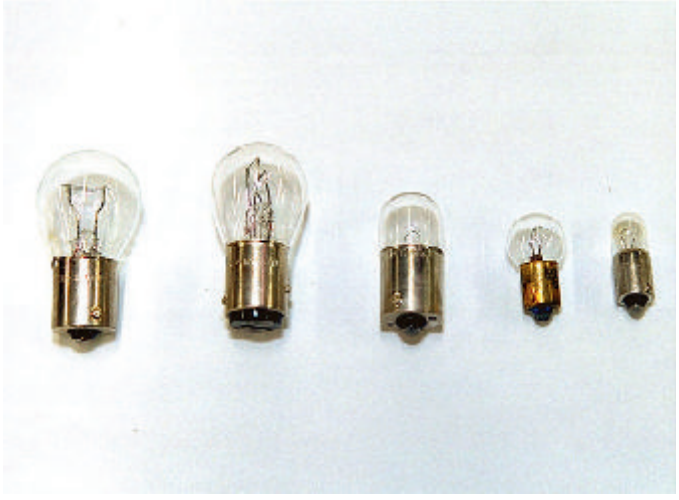

Figure 3.80 Selection of bulbs

Figure 3.81 Headlight bulbs

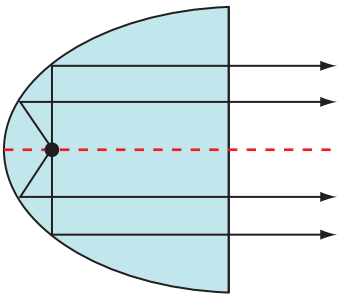

Figure 3.82 Concave reflector (light source at the focal point)

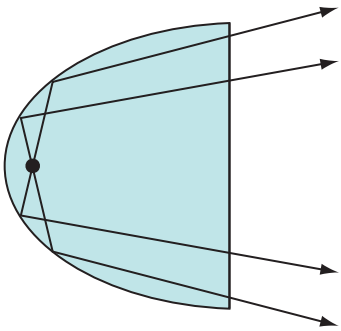

Figure 3.83 Light source behind the focal point

halogen bulbs is mostly iodine and the glass envelope is made from fused silicon or quartz. This allows higher temperatures and the shape of the envelope causes the metal to condense back on the filament.

The object of the headlight reflector is to direct the random light rays produced by the bulb into a beam of concentrated light, by applying the laws of reflection. Bulb filament position relative to the reflector is important if the desired beam direction and shape are to be obtained. A reflector is a layer of silver, chrome or aluminium deposited on a smooth and polished surface such as brass or glass. Consider a mirror reflector that 'caves in': this is called a concave reflector (Fig. 3.82). The centre point on the reflector is called the pole, and a line drawn perpendicular to the surface from the pole is known as the principal axis.

If a light source is moved along the principal axis, a point will be found where the radiating light produces a reflected beam parallel to the axis. This point is known as the focal point, and its distance from the pole is known as the focal length. If the filament is between the focal point and the reflector, the reflected beam will diverge; that is, spread outwards along the principal axis (Fig. 3.83).

Key fact

A headlight reflector directs the random light rays produced by the bulb into a beam.

If the filament is positioned in front of the focal point, the reflected beam will converge towards the principal axis (Fig. 3.84).

A common type of bulb arrangement is shown in Fig. 3.85, where the dip filament is shielded. This gives a nice sharp cut-off line when positioned in a reflector like that of Fig. 3.84 on dip beam (the other filament is at the focal point to give a main beam).

A good headlight should have a powerful, far-reaching central beam, around which the light is distributed both horizontally and vertically to illuminate as great an area of the road surface as possible. The beam formation can be considerably improved by passing the reflected light rays through a transparent block of lenses. It is the function of the lenses to partially redistribute the reflected light beam and any stray light rays. This gives better overall road illumination.

Key fact

A headlight lens redistributes the reflected light beam.

Many headlights are now made with clear lenses, such that all the redirection of the light is achieved by the reflector (Fig. 3.86). A clear lens does not restrict

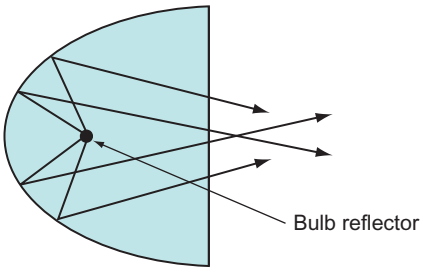

Figure 3.84 Light source in front of the focal point

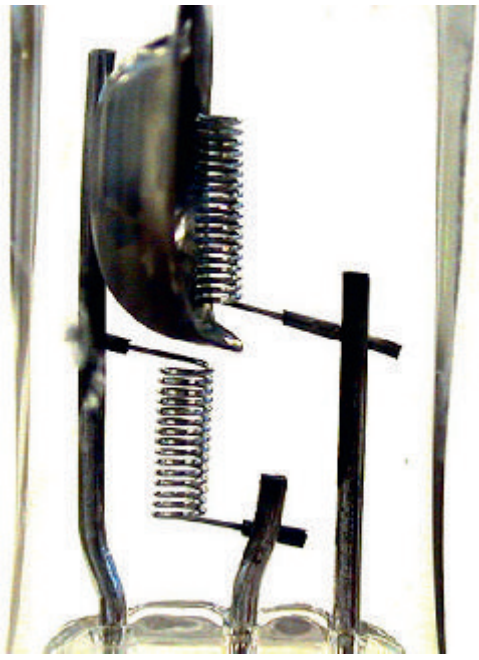

Figure 3.85 Shielded dip filament (top) and main beam filaments in a tungsten halogen bulb

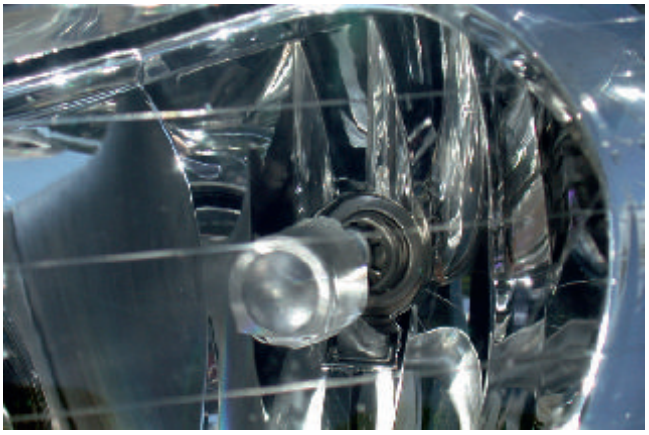

Figure 3.86 Headlights with a clear lens and complex reflector

the light in any way. This makes the headlights more efficient as well as attractive.

Sidelights, taillights, brake lights and others are relatively straightforward. Headlights present the most problems. This is because on dipped beam they must provide adequate light for the driver, but not dazzle other road users (Fig. 3.87). The conflict between seeing and dazzling is very difficult to overcome. The main requirement is that headlight alignment must be set correctly. Some cars have a headlight adjuster that the driver can control. The adjuster is connected to levelling actuators. The function of levelling actuators is to adjust the dipped or low beam in accordance with the load carried by the car. This will avoid dazzling oncoming traffic.

3.3.2 Stoplights and reverse lights

Stoplights, or brake lights, are used to warn drivers behind that you are slowing down or stopping. Reverse lights warn other drivers or pedestrians that you are reversing, or intend to reverse (Fig. 3.88). The circuits are quite simple; one switch in each case operates two or three bulbs via a relay.

Figure 3.87 Beam setter in use

Figure 3.88 Stop and reverse lights form part of the rear light cluster

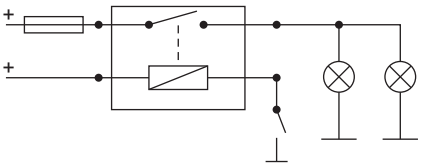

Figure 3.89 Stoplight or reverse light circuit

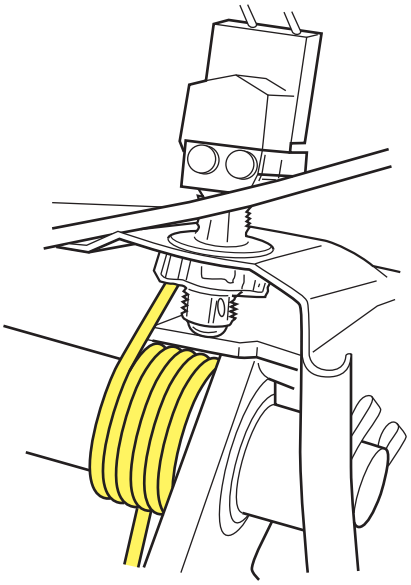

Figure 3.90 Stoplight switch

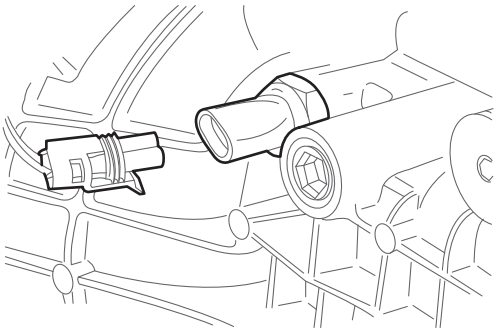

Figure 3.91 Reverse light switch

The circuits for these two systems are similar. Figure 3.89 shows a typical stoplight or reverse light circuit. Most incorporate a relay to switch on the lights, which in turn is operated by a spring-loaded switch on the brake pedal or gearbox. Links from the stoplight circuit to the cruise control system may be found. This is to cause the cruise control to switch off as the brakes are operated. A link may also be made to the antilock brake system.

The circuits are operated by the appropriate switch. The stoplight switch (Fig. 3.90) is usually fitted so that it acts on the brake pedal. The reverse switch (Fig. 3.91) is part of the gearbox or gear change linkage.

Light emitting diodes (LEDs) are more expensive than bulbs. However, the potential savings in design costs due to long life, sealed units being used and greater freedom of design could outweigh the extra expense. LEDs are ideal for stoplights because they illuminate more quickly than ordinary bulbs. This time is approximately the difference between 130 ms for the LEDs and 200 ms for bulbs. If this is related to a vehicle brake light at motorway speeds, then the increased reaction time equates to about a car length. This is potentially a major contribution to road safety.

Safety first

LEDs are ideal for stoplights because they illuminate more quickly than ordinary bulbs.

Figure 3.92 Switch positioned in the door pillar

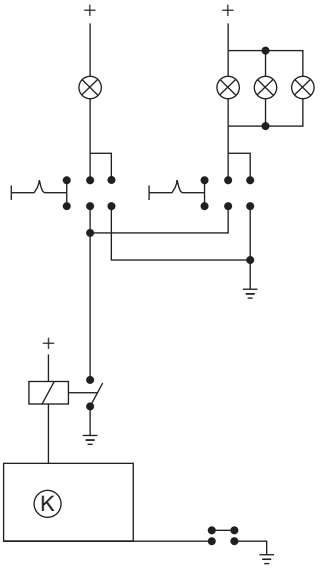

Figure 3.93 Circuit for interior lights

3.3.3 Interior lighting

Interior lighting consists of several systems, the main ones being courtesy lights, map lights and panel illumination lights. Features such as delay and fade-out are now common. This requires some electronic control. Map lights are an extra feature to assist with reading a map in the dark. Many types are available: some are small spotlights, which form part of the interior light assembly, while others are positioned on the centre console of the vehicle.

Lights are designed to illuminate the vehicle interior when the doors are opened. Most cars have one central interior light above the rear-view mirror, or two lights, on the sides above the driver's and passenger's shoulders. Door switches are simple spring-loaded contacts that are made as the door opens (Fig. 3.92). The contacts are broken again as the door closes. Rubber seals are sometimes used to keep water out. The same switches may also be used for the alarm system.

The circuit shown in Fig. 3.93 is typical of many in common use. The sliding switches have three positions: 'off', 'on' and 'door operated'. The control module is to allow delay operation. In this case, it is also used for the central locking system.

Panel and instrument lights are illuminated when the vehicle sidelights are switched on. Most cars also incorporate a dimmer switch so the level of illumination can be set.

Interior lights are important for passenger comfort. Most now operate via some type of electronic control. One enhancement is a switching-off delay, after the doors are closed. Some manufacturers are linking functions such as interior lights with other systems, by a central control module.

3.3.4 Lighting circuits

Lighting circuits can appear complex at first view. However, if you concentrate on just one part of the circuit at a time you will find it easier to understand. Relays are often used because they take load off the control switches. They are still simple switches, so don't panic! Take your time and you will find electrical circuits an interesting challenge.

The diagram shown in Fig. 3.94 is the complete lighting circuit of a vehicle. Operation of the switch allows the supply on the N or N/S wire to pass to fuses

Key fact

Relays take the load off control switches.

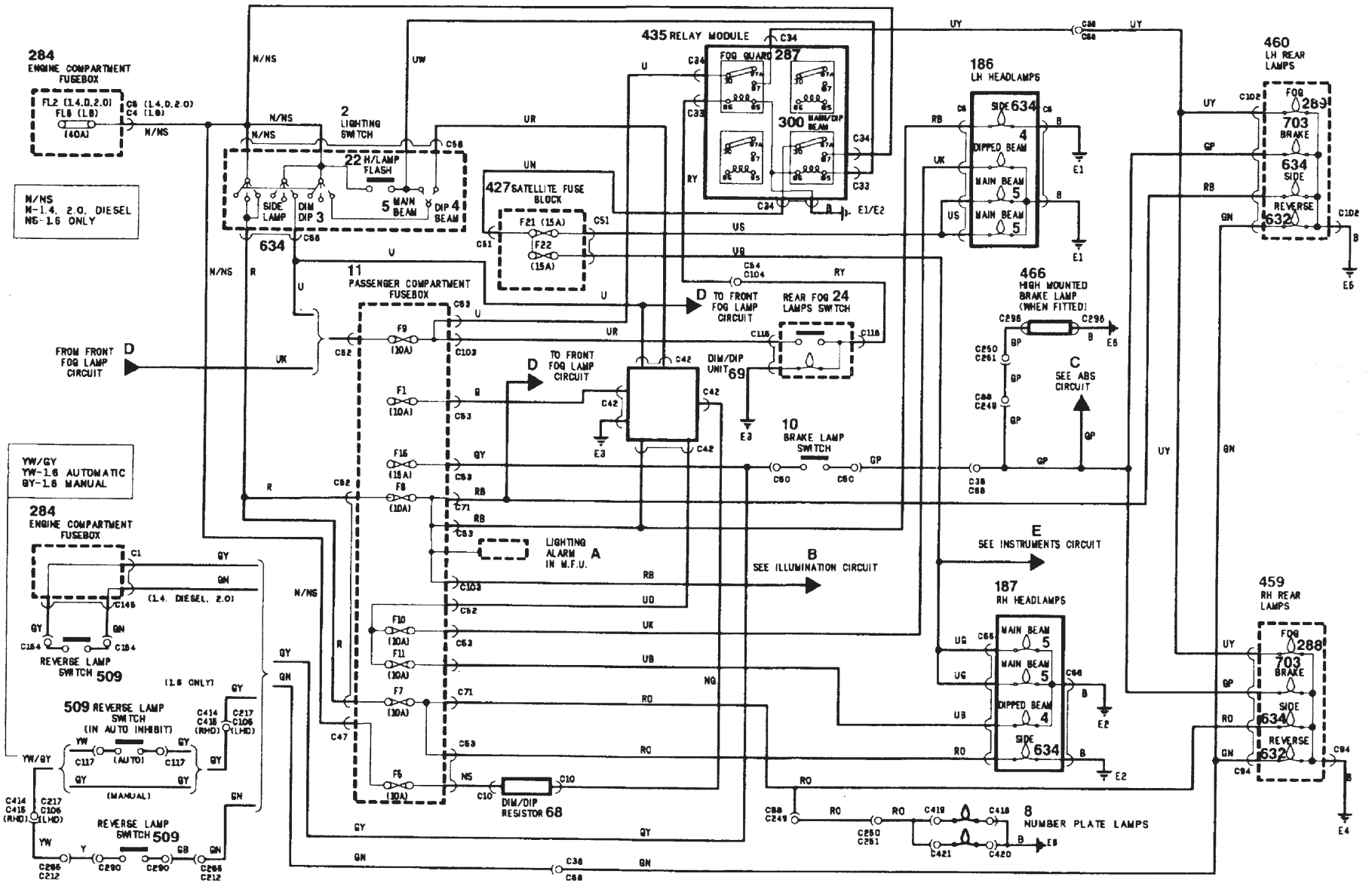

Figure 3.94 Lighting circuit

7 and 8 on the R wire. The two fuses then supply left lights on an RB wire, and right lights on an RO wire. The number plate lights are also supplied from here. When the dip beam is selected, a supply is passed, on a U and UR wire, to the dim dip unit, which is de-energized. This then allows a supply to fuses 10 and 11 on the OU wire. This supply is then passed to the left light on a UK wire and the right light on a UB wire. Selecting main beam allows a supply on the UW wire to the main/dip relay, thus energizing it. A supply is therefore placed on fuses 21 and 22 and hence to each of the headlight main beam bulbs.

When sidelights are on, there is a supply to the dim dip unit on the RB wire. If the ignition supplies a second feed on the G wire from fuse 1, the unit will allow a supply from fuse 5 to the dim dip resistor on the NS wire. This continues on to the dim dip unit on an NG wire. The dim dip unit links this supply to fuses 10 and 11. These are the dip beam fuses. The supply is therefore passed to the left light on a UK wire and the right light on a UB wire. When the headlights are switched on, a supply is made from the light switch to fuse 9 on a U wire. From this fuse, a supply is sent to the fog light relay contacts on a U wire, and the rear fog lamp switch on a UR wire. When the fog switch is operated, it sends a supply on the RY wire to close the relay. The main supply is now fed from the relay on a UY wire to both rear fog lamps.

Following a circuit diagram is easy after a bit of practice. Think of it as a railway map that is used to get from A to B. Electricity will only complete the ‘journey’ if the path is a circuit, i.e. it has a return ticket!

3.3.5 Indicators and hazard lights

Direction indicators (turn signals) have a number of statutory requirements. The light produced must be amber (or red on the rear of some American cars), but they may be grouped with other lamps. The flashing rate must be between one and two per second with a relative ‘on’ time of between 30% and 57%. If a fault develops this must be apparent to the driver by the operation of a warning light on the dash. The fault can be indicated by a distinct change in frequency of operation or by the warning light remaining on. If one of the main bulbs fails then the remaining lights should continue to flash perceptibly.

Legislation exists as to the mounting position of the exterior lamps. The rear indicator lights must be within a set distance of the rear lights and within a set height. The wattage (power) of indicator bulbs is normally 21 W (Fig. 3.95). These lights often come under the heading of auxiliaries or signalling. A circuit is

Figure 3.95 Indicator bulb

Figure 3.96 Light cluster that uses LEDs

Figure 3.97 Stoplight and rear light twin filament bulb

examined later in this section. The bulbs are often combined with the rear lights (Figs 3.96 and 3.97).

The operation of the flasher unit is usually based around an integrated circuit. The electronic type shown in Fig. 3.98 can operate at least four 21 W bulbs (front and rear) and two 5 W side repeaters when operating in hazard mode. This will continue for several hours if required. Flasher units are rated by the number of bulbs they are capable of operating. When towing a trailer the unit must be able to operate at a higher wattage. Most units use a relay for the actual switching as this provides an audible signal. Thermal-type flasher units are still used on older vehicles. LEDs are now also being used in place of indicator bulbs. An indicator warning appears on the dash (Fig. 3.99).

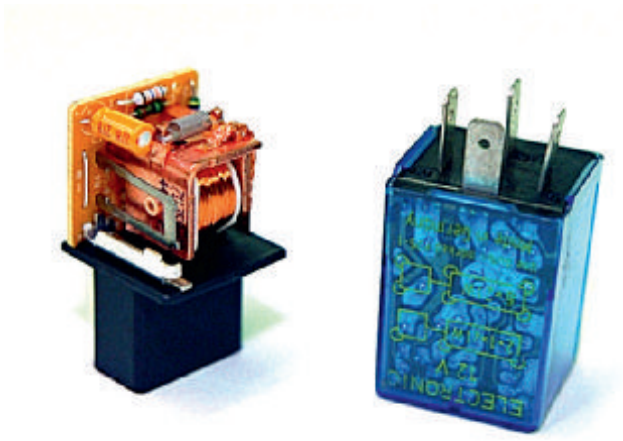

Figure 3.98 Electronic flasher unit

Figure 3.99 Indicator warning light

The diagram shown in Fig. 3.100 is the complete indicator circuit of a vehicle. You can follow the circuit by looking for the labels on the wires. 'G', for example, means 'Green', but this has no effect on how it works.

Note how the hazard switch, when operated, disconnects the ignition supply from the flasher unit and replaces it with a constant supply. The hazard system will therefore operate at any time, but the indicators will only work when the ignition is switched on. When the indicator switch is operated left or right, the front, rear and repeater bulbs are connected to the output terminal of the flasher unit. This is what makes it operate and causes the bulbs to flash.

When the hazard switch is operated, five pairs of contacts are made to open or close. Two sets connect left and right circuits to the output of the flasher unit. One set disconnects the ignition supply and another set connects the battery supply to the unit. The final set of contacts causes a hazard warning light to be operated. On this and most vehicles, the hazard switch is illuminated when the sidelights are switched on.

With the ignition switched on, fuse 1 provides a feed to the hazard warning switch on the G wire. Provided the hazard warning switch is in the off position, the feed crosses the switch and supplies the flasher unit on the LGK wire. When the switch control is moved for a right turn, the switch makes contact with the LGN wire from the flasher unit, which is connected to the GW wire. This allows a supply to pass to the right-hand front and rear indicator lights, and then to earth on the B wire.

When the switch control is moved for a left turn, the switch makes contact with the GR wire, which allows the supply to pass to the left-hand front and rear indicator lights, and then to earth on the B wire. The action of the flasher unit causes the circuit to make and break.

When the hazard warning switch is switched, a battery supply on the N0 wire from fuse 3 or 4 crosses the switch and supplies the flasher unit on the LGK wire. At the same time, contacts are closed to connect the hazard warning light and the flasher unit to both the GW and GR wires. These are the right-hand and left-hand indicators. The warning light and the main lights flash alternately.

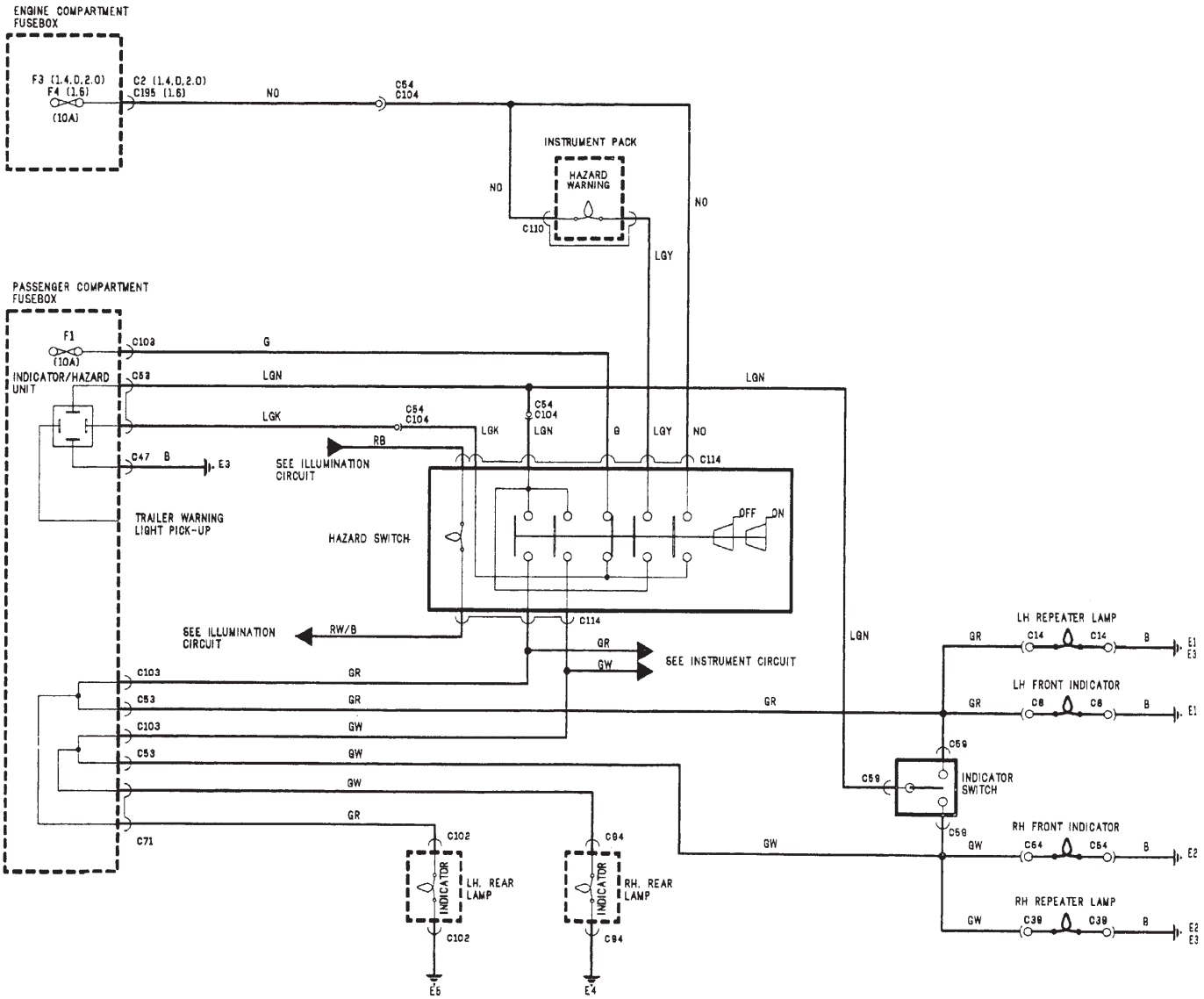

Figure 3.100 Complete indicator and hazard lights circuit

Indicators and hazard lights are interesting circuits. Hazard lights are intended to show a hazard such as a broken-down car. They also seem to be used to prevent parking tickets when in a restricted area; my experience is that this does not work!

3.4 Body electrical and electronic systems

3.4.1 Washers and wipers

The requirements of the wiper system are simple. The windscreen must be clean enough to provide suitable visibility at all times. To do this, it must:

- achieve efficient removal of water and snow
- achieve efficient removal of dirt
- operate at temperatures from −30 to 80°C
- pass the stall and snow load test
- have a service life in the region of 1.5 million wipe cycles
- be resistant to corrosion from acid, alkali and ozone.

Key fact

The aerodynamic property of the wiper blades has become increasingly important.

Wiper blades are made of a rubber compound (Fig. 3.101) and are held on to the screen by a spring in the wiper arm. The aerodynamic property of the wiper blades has become increasingly important. The strip on top of the rubber element is often perforated to reduce air drag. A good quality blade will have a contact width of about 0.1 mm. The lip wipes the surface of the screen at an angle of about 45°. The pressure of the blade on the screen is also important.

Most wiper linkages consist of a series or parallel mechanism (Fig. 3.102). Some older types use a flexible rack and wheel boxes similar to the operating mechanism of many sunroofs. One of the main considerations for the design of a wiper linkage is the point at which the blades must reverse. This is because of the high forces on the motor and linkage at this time. If the reverse point is set so that the linkage is at its maximum force transmission angle, then the reverse action of the blades puts less strain on the system. This also ensures smoother operation.

All modern wiper motors are permanent magnet types. The drive is taken via a worm gear to increase torque and reduce speed. Three brushes may be used,

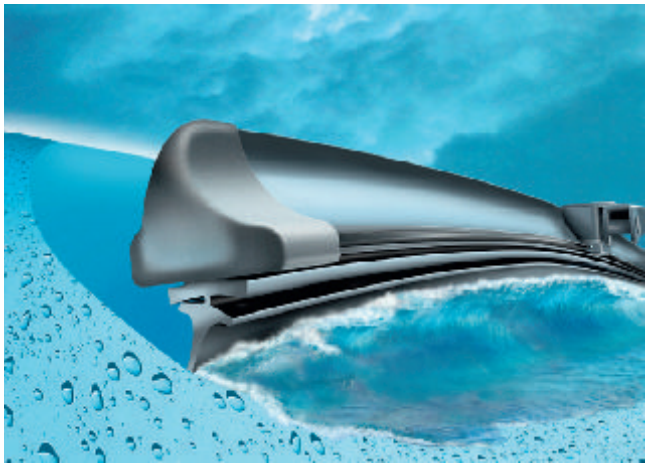

Figure 3.101 Details of a wiper blade

Figure 3.102 Wiper motor and linkage

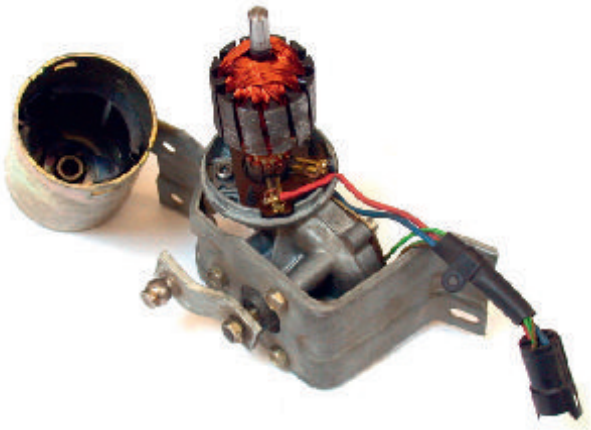

Figure 3.103 Motor brushes and armature

or some form of electronic control, to allow two-speed operation. In three-brush motors, the normal speed operates through two brushes placed in the usual positions opposite to each other. For a fast speed, the third brush is placed closer to the earth brush. This reduces the number of armature windings between them, which reduces resistance, hence increasing current and therefore speed (Fig. 3.103).

Key fact

Wiper motors or the circuit must have short-circuit protection to protect the motor in the event of stalling.

Wiper motors or the associated circuit must have some kind of short-circuit protection. This is to protect the motor in the event of stalling, if the wiper blade is frozen to the screen for example. A thermal trip of some type is often used, or a current sensing circuit in the wiper ECU if fitted.

A windscreen washer system consists of a simple d.c. permanent magnet motor (Fig. 3.104), which drives a centrifugal water pump. The water, preferably with a cleaning additive, is directed onto an appropriate part of the screen by two or more jets. A non-return valve is often fitted in the line to the jets to prevent water siphoning back to the tank. This also allows 'instant' operation when the washer button is pressed. The washer circuit is normally linked in to the wiper circuit,

Figure 3.104 Washer motors. (Source: MadeInChina.com)

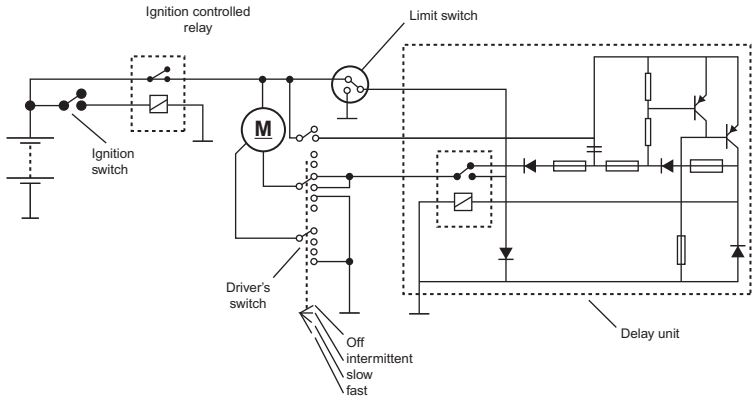

Figure 3.105 Wiper circuit

such that when the washers are operated, the wipers start automatically and will continue, for several more sweeps, after the washers have stopped.

Figure 3.105 shows a circuit for fast, slow and intermittent wiper control. The switches are shown in the off position and the motor is stopped and in its park position. Note that the two main brushes of the motor are connected together via the limit switch, delay unit contacts and the wiper switch. This causes regenerative braking because of the current, generated by the motor due to

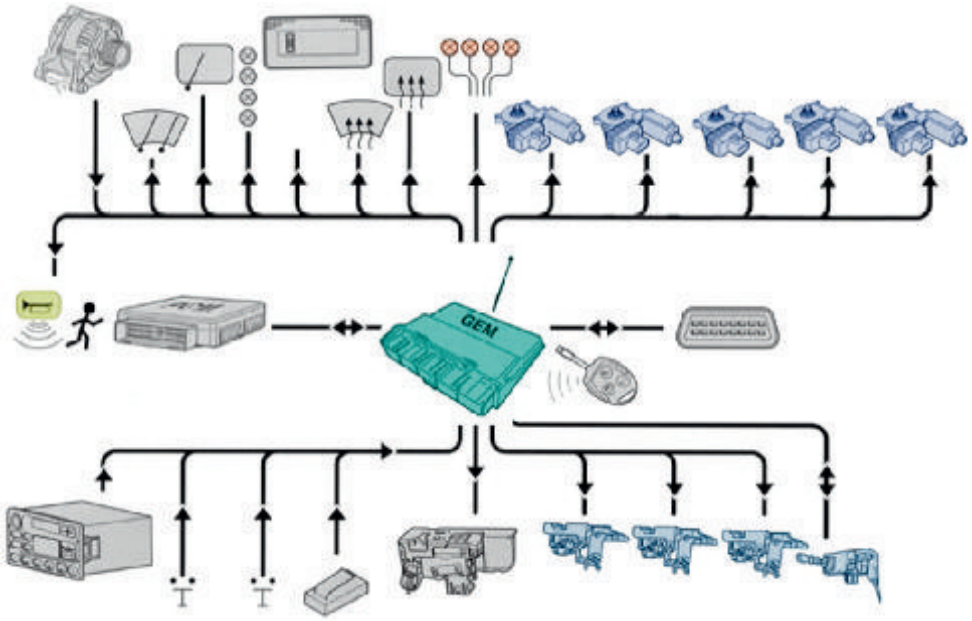

Figure 3.106 General electronic module (GEM) and components. (Source: Ford Motor Company)

its momentum, after the power is switched off. Being connected to a very low resistance loads up the 'motor/generator' and, when the park limit switch closes, it stops instantly.

When either the delay contacts or the main switch contacts are operated, the motor will run at slow speed. When fast speed is selected, the third brush on the motor is used. On switching off, the motor will continue to run until the park limit switch changes over to the position shown in Fig. 3.105. This switch is only in the position shown when the blades are in the parked position.

Many vehicles use a system with more enhanced facilities. This is regulated by what may be known as a central control unit (CCU), a multifunction unit (MFU) or a general electronic module (GEM) (Fig. 3.106). These units often control other systems as well as the wipers, thus allowing reduced wiring bulk under the dash area. Electric windows, headlights and heated rear window, to name just a few, are now often controlled by a central unit.

Using electronic control, a CCU allows the following facilities for the wipers:

- front and rear wash/wipe
- intermittent wipe
- time delay set by the driver
- reverse gear selection rear wipe operation
- rear wash/wipe with 'dribble wipe' (an extra wipe several seconds after washing)
- stall protection.

3.4.2 Horns

Regulations in most countries state that the horn (or audible warning device) (Fig. 3.107) should produce a uniform sound. This makes sirens and melody-type

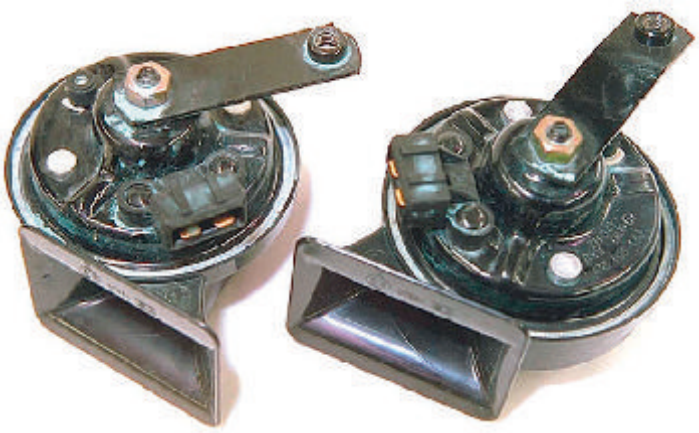

Figure 3.107 Vehicle horns

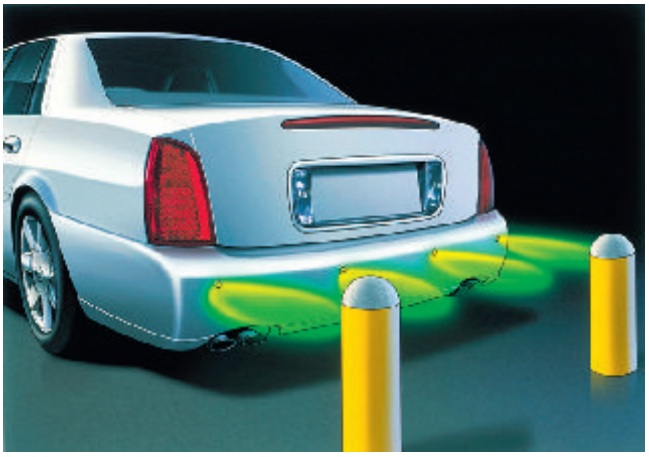

Figure 3.108 Ultrasonic reversing aid

fanfare horns illegal. Most horns draw a large current so are switched by a relay.

The standard horn operates by simple electromagnetic switching. Current flow causes an armature, which is attached to a tone disc, to be attracted to a stop. A set of contacts is then opened. This disconnects the current, allowing the armature and disc to return under spring tension. The whole process keeps repeating when the horn switch is on. The frequency of movement, and hence the tone, is arranged to lie between 1.8 and 3.5 kHz. This note gives good penetration through traffic noise.

Twin horn systems, which have a high and low tone horn, are often used. This produces a more pleasing sound, but is still very audible in both town and higher speed conditions.

Definition

Hertz
One hertz (1 Hz) is one cycle or oscillation per second.

3.4.3 Obstacle avoidance

The principle of radar as a reversing aid is illustrated in Fig. 3.108. This technique is in effect a range-finding system. The output can be audible and/or visual, the former being perhaps more appropriate, as the driver is likely to be looking backwards. The audible signal is a 'pip pip pip' type sound, the repetition

frequency of which increases as the car comes nearer to the obstruction, becoming almost continuous as impact is imminent. Some cars have 'all-round' obstacle avoidance and also use the car speakers in a way such that the sound comes from the direction of the obstacle.

The units fitted in the rear bumper as shown in Fig. 3.108 transmit a radio signal and also receive the reply if the signal bounces off a nearby object. The time it takes to receive the signal tells the system the distance.

3.4.4 Cruise control

Cruise control is the ideal example of a closed loop control system. The purpose of cruise control is to allow the driver to set the vehicle speed and let the system maintain it automatically. The system reacts to the measured speed of the vehicle and adjusts the throttle accordingly. The reaction time is important so that the vehicle's speed does not feel to be surging up and down. Other facilities are included such as allowing the speed to be gradually increased or decreased at the touch of a button (Fig. 3.109). Most systems also remember the last set speed. They will resume this speed at the touch of a button. The main switch switches on the cruise control and this, in turn, is ignition controlled. Most systems do not retain the speed setting in memory when the main switch has been turned off. Operating the 'set' switch programs the memory, but this normally will only work if conditions similar to the following are met:

- Vehicle speed is greater than 40 km/h.
- Vehicle speed is less than 120 km/h.
- Change of speed is less than 8 km/h/s.
- Automatics must be in 'drive'.
- Brakes or clutch are not being operated.
- Engine speed is stable.

Once the system is set, the speed is maintained to within 1–2 mph until it is deactivated by pressing the brake or clutch pedal, pressing the resume switch or turning off the main control switch. The last set speed is retained in memory except when the main switch is turned off. If the cruise control system is required again, then either the set button will hold the vehicle at its current speed or the resume button will accelerate the vehicle to the previous set speed. When

Definition

Closed loop control system
A system in which the output of the system has a direct effect on the input because of a feedback loop.

Figure 3.109 Cruise control switch

cruising at a set speed, the driver can press and hold a button to accelerate the vehicle until the desired speed is reached. If the driver accelerates from the set speed to overtake, for example, then when the throttle is released, the vehicle will slow down again.

Several methods are used to control the throttle position. Vehicles fitted with drive-by-wire systems allow the cruise control to operate the same throttle actuator. A motor can be used to control the throttle cable or, in some cases (Fig. 3.110), a vacuum-operated diaphragm is used.

Key fact

Vehicles fitted with drive-by-wire systems allow the cruise control to operate the throttle actuator.

The brake switch is very important, as braking would be dangerous if the cruise control system was still trying to maintain the vehicle speed. This switch is normally of superior quality and is fitted in place or as a supplement to the brake light switch activated by the brake pedal. Adjustment of this switch is important. The clutch switch is fitted in a similar manner to the brake switch. It deactivates the cruise system to prevent the engine speed increasing, if the clutch is pressed. The automatic gearbox switch will only allow the cruise to be engaged when it is in the 'drive' position. This is to prevent the engine overspeeding if the cruise tried to accelerate to a high road speed with the gear selector in position '1' or '2'.

The speed sensor will often be the same sensor that is used for the speedometer (Fig. 3.111). If not, several types are available, the most common producing a pulsed signal, the frequency of which is proportional to the vehicle speed.

Conventional cruise control has now developed to a high degree of quality. It is, however, not always very practical on many roads as the speed of the general traffic is constantly varying and often very heavy. The driver has to take over from the cruise control system on many occasions to speed up or slow down. Adaptive cruise control can automatically adjust the vehicle speed to the current traffic situation. The system has three main aims:

- to maintain a speed as set by the driver
- to adapt this speed and maintain a safe distance from the vehicles in front
- to provide a warning if there is a risk of collision.

The operation of an adaptive cruise system is similar to a conventional system. However, when a signal from the headway sensor (Fig. 3.112) detects an obstruction, the vehicle speed is decreased. If the optimum stopping distance

Figure 3.110 Throttle motor connected to cable

Figure 3.111 Road speed sensor in position

Figure 3.112 Headway sensor. (Source: Bosch Media)

Key fact

The operation of an adaptive cruise system is similar to a conventional system except that when a headway sensor detects an obstruction, the vehicle speed is decreased.

cannot be achieved by just backing off the throttle, a warning is supplied to the driver. The more complex system can take control of the vehicle transmission and brakes. It is important to note that adaptive cruise control is designed to relieve the burden on the driver, not take full control of the vehicle!

3.4.5 Seats, mirrors, sunroofs, locking and windows

3.4.5.1 Seat adjustment

Electrical movement of seats, mirrors (Fig. 3.113) and the sunroof is included in one area as the operation of each system is quite similar. The operation of electric windows and central door locking is also much the same. Fundamentally, all the systems discussed in this topic operate using one or several permanent magnet motors, together with a supply reversing circuit.

A typical motor reverse circuit is shown in Fig. 3.114. When the switch is moved, one of the relays operates and changes the polarity to one side of the motor. If

Figure 3.113 Mirrors

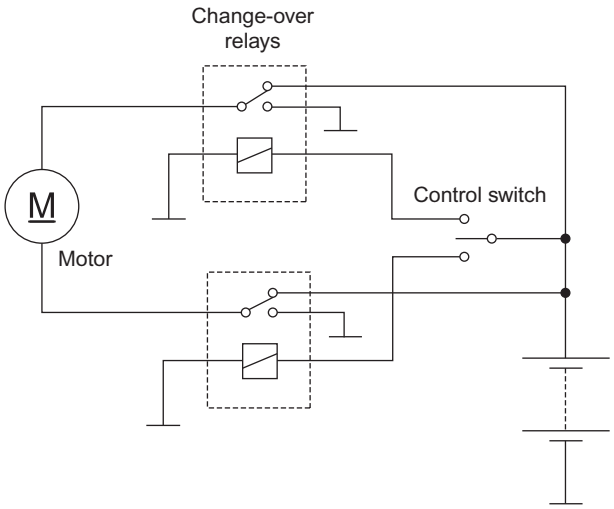

Figure 3.114 Motor reverse circuit

the switch is moved the other way then the polarity of the other side of the motor is changed. When at rest, both sides of the motor are at the same potential. This has the effect of regenerative braking, so that when the motor stops it will do so instantly. Further refinements are used to enhance the operation of these systems. Limit switching, position memory and force limitation are the most common.

Adjustment of a seat is achieved by using a number of motors to allow positioning of different parts of the seat. Movement is possible in the following ways:

- front to rear
- cushion height rear
- cushion height front
- backrest tilt
- headrest height
- lumbar support.

Figure 3.115 Seat motors

Three seat operation motors are shown in Fig. 3.115. Each motor is operated by a simple rocker type switch that controls two relays as described previously. When seat position is set, some vehicles have memories, to allow automatic repositioning if the seat has been moved. This is often combined with electric mirror adjustment.

3.4.5.2 Mirrors

Many vehicles have electrical adjustment of mirrors (Fig. 3.116). The system used is much the same as has been discussed previously in relation to seat movement. Two small motors are used to move the mirror vertically or horizontally (Fig. 3.117). Many mirrors also contain a small heating element on the rear of the glass. This is operated for a few minutes when the ignition is first switched on. The circuit may include feedback resistors for position memory.

3.4.5.3 Sunroof

The operation of an electric sunroof is once again based on a motor reverse circuit (Fig. 3.118). However, further components and circuitry may be needed to allow the roof to slide, tilt and stop in the closed position. The extra components used in many cases are a microswitch and a latching relay. A latching relay works in much the same way as a normal relay except that it locks into position each time it is energized. The mechanism used to achieve this is much like that used in ballpoint pens that have a button on top.

A microswitch is mechanically positioned such as to operate when the roof is in its closed position. A rocker switch allows the driver to adjust the roof. The switch provides a supply to the motor to run it in the chosen direction. The roof will open or tilt. When the switch is operated, to close the roof, the motor is run in the appropriate direction until the microswitch closes (when the roof is in its closed position). This causes the latching relay to change over, which stops the motor. The control switch now has to be released. If the switch is pressed again, the latching relay will once more change over and the motor will be allowed to run (Fig. 3.119).

Figure 3.116 Mirror switch

Figure 3.117 Mirror motors

Figure 3.118 Sunroof

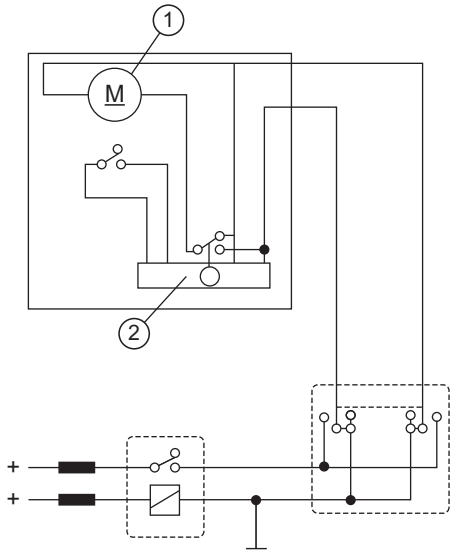

Figure 3.119 Sunroof circuit: 1, motor; 2, micro-switch

Figure 3.120 Remote door locking

3.4.5.4 Locking

When the key is turned in the driver's door lock (or the remote button is pressed), all the other doors on the vehicle should also lock (Fig. 3.120). Motors or solenoids in each door achieve this. If the system can only be operated from the driver's door key, then an actuator is not required in this door. If the system can be operated from either front door or by remote control then all the doors need an actuator. Vehicles with built-in alarm systems lock all the doors as the alarm is set.

A simplified door locking circuit is shown in Fig. 3.121. The main control unit contains two change-over relays (reverse circuit), which are actuated by either the door lock switch or, if fitted, the remote key. The motors for each door lock are wired in parallel and all operate at the same time. Most door actuators are small motors or solenoids.

Remote-control central door locking is controlled by a small hand-held transmitter and a sensor receiver unit. When the key is operated, by pressing a small switch, a complex code is transmitted. Trillions of different code combinations are used in modern systems. The sensor in the car picks up this

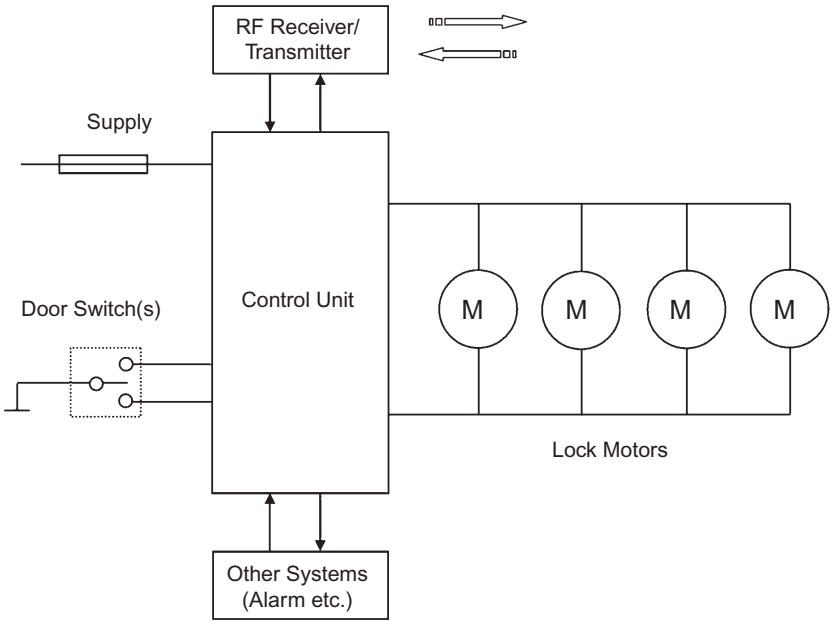

Figure 3.121 Circuit to operate door locks

code and sends it in an electrical form to the main control unit. If the received code is correct, the relays are triggered and the door locks are either locked or unlocked. If an incorrect code is received on three consecutive occasions when attempting to unlock the doors, then some systems will switch off until the door is opened by the key. This technique prevents a scanning-type transmitter unit from being used to open the doors.

Key fact

Trillions of different code combinations are used in modern locking systems.

3.4.5.5 Windows

The basic form of electric window operation is similar to many of the systems discussed so far in this module; that is, a motor reversing system either using relays or directly by a switch. More sophisticated systems are now popular for reasons of safety as well as improved comfort. The following features are now available from many manufacturers:

- one touch up or down
- inch up or down
- lazy lock
- back off or bounce back.

The complete system consists of an electronic control unit containing the window motor relays, switch packs and a link to the door lock and sunroof circuits. This is represented in the form of a block diagram in Fig. 3.122.

When a window is operated in 'one-touch' mode, the window is driven in the chosen direction until the switch position is reversed, the motor stalls or the ECU receives a signal from the door lock circuit. The problem with one-touch operation is that if a child, for example, should become trapped in the window there is a serious risk of injury. To prevent this, a bounce-back feature is used. An extra commutator is fitted to the motor armature. This produces a signal, via two brushes, proportional to the motor speed. Hall sensors are used on some systems. If the rate of change of speed of the motor is detected as being below a certain threshold, the ECU reverses the motor until the window is fully open.

Key fact

A bounce-back feature is used to prevent people and things being trapped in windows.

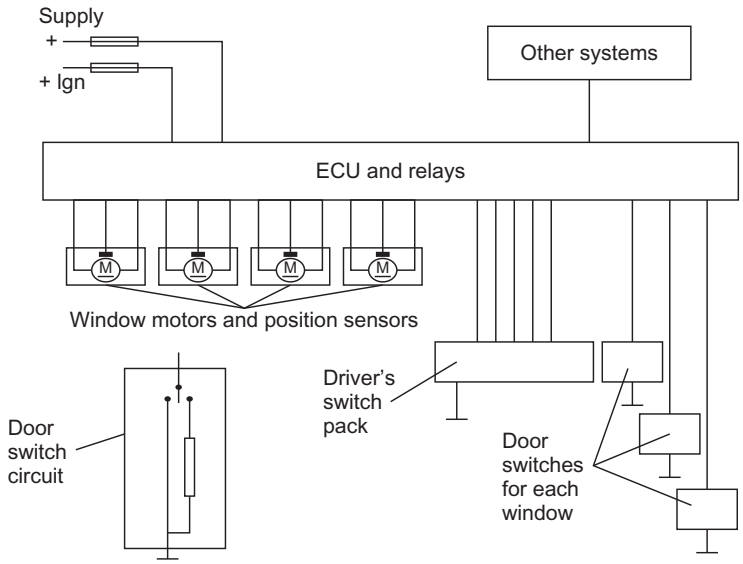

Figure 3.122 Electric window system block diagram

By counting the number of pulses received, the ECU can also determine the window position. This is important, as the window must not reverse when it stalls in the closed position. In order for the ECU to know the window position, it must be initialized. This is often done simply by operating the motor to drive the window first fully open, and then fully closed. If this is not done then the one-touch feature and bounce-back will not operate.

A 'lazy-lock' feature allows the car to be fully secured by one operation of a remote key. This is done by linking the door lock ECU and the window and sunroof ECUs. A signal is supplied and causes all the windows to close in turn, and then the sunroof, and finally locks the doors. The alarm will also be set if required. The windows close in turn to prevent the excessive current demand that would occur if they all tried to operate at the same time.

A circuit for electric windows is shown in Fig. 3.123. Note the rear window isolation switch. This is commonly fitted to allow the driver to prevent rear window operation, for child safety for example.

Most window lift motors (Fig. 3.124) are permanent magnet types and drive through a worm gear. This reduces speed and greatly increases the torque.

All of the systems examined in this section are based on motor reverse circuits. Door locks, windows, sunroofs, mirrors and seats all operate in this way. Most of the systems are designed to improve driver and passenger comfort.

3.4.6 Screen heating

Electrical heating is used for screens, windows, seats and mirrors. Some heavy vehicles also incorporate cab heaters, which use fuel from the tank. As far back as the 1920s, when vehicle heaters were not fitted, electrically heated gloves were available. Beware of short-circuits!

Heating of the rear screen involves a circuit with a relay and usually a timer. The heating elements are thin metallic strips bonded to, or built inside, the glass

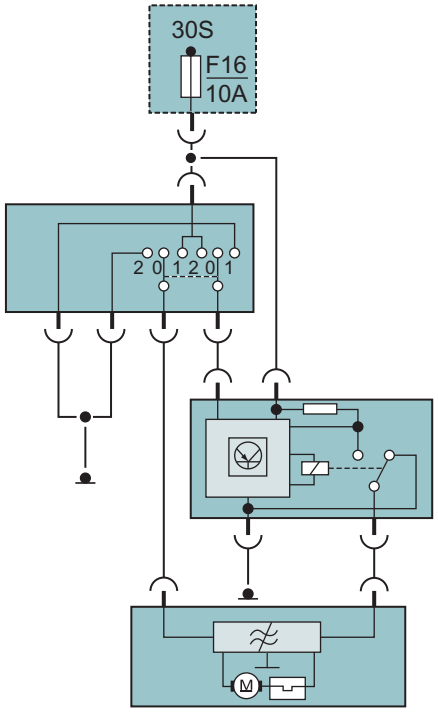

Figure 3.123 Circuit for electric windows

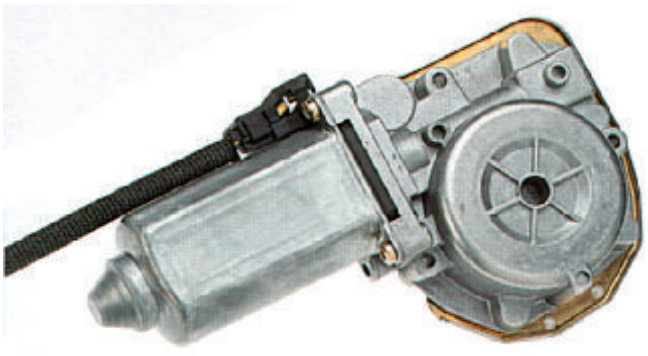

Figure 3.124 Electric window lift motor

(Fig. 3.125). When a current is passed through the elements, heat is generated and the window will defrost or demist.

This circuit can draw high current, 10–15 A being typical. Because of this, the circuit often contains a timer relay to prevent the heater being left on too long (Fig. 3.126). The timer will switch off after 10–15 minutes. The rear screen elements are usually shaped to defrost the area of the rear wiper blade resting position, if fitted.

Front windscreen heating is used on some vehicles (Fig. 3.127). This presents more problems than with the rear screen, as vision must not be obscured. The technology used is drawn from the aircraft industry and involves very thin wires cast into the glass. As with the heated rear window, this device can consume a large current and uses a timer relay.

Figure 3.125 Rear screen heater elements

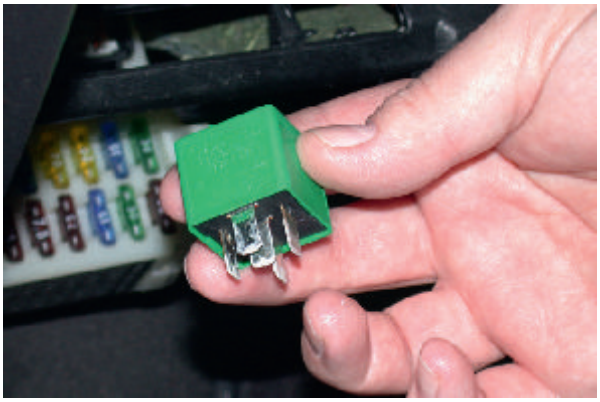

Figure 3.126 Timer relay

Figure 3.127 Front screen heater elements

3.4.7 Security systems

Huge numbers of cars are reported missing each year and many are never recovered; even when returned many are damaged. Most car thieves are opportunists, so even a basic alarm system serves as a deterrent (Fig. 3.128). Car and alarm manufacturers are constantly fighting to improve security.

Figure 3.128 Alarm switch type sensor

Building the alarm system as an integral part of the vehicle electronics has made significant improvements. Even so, retrofit systems can still be very effective. The main types of intruder alarm used are:

- switch operated on all entry points
- trembler operated
- battery voltage sensing
- volumetric sensing.

There are four main ways to disable the vehicle:

- ignition circuit cut-off
- fuel system cut-off
- starter circuit cut-off
- engine ECU code lock (now the most common).

A separate switch or transmitter can be used to set an alarm system. Often, such a device is set automatically when the doors are locked. Some types have electronic sirens and give an audible signal when arming and disarming. They are all triggered when the car door opens and will automatically reset after a period of time, often 1 or 2 minutes. The alarms are triggered instantly when an entry point is breached. Most systems are in two parts, with a separate control unit and siren.

Most systems now come with remote 'keys' (Fig. 3.129) that use small button-type batteries and may have an LED that shows when the signal is being sent; they operate with one vehicle only. When operating with flashing lights most systems draw about 5 A. Without flashing lights (siren only) the current draw is less than 1 A. The sirens produce a sound level of about 95 dB, when measured 2 m in front of the vehicle.

Most factory-fitted alarms are combined with the central door locking system. This allows the facility mentioned in a previous section known as 'lazy lock'. Pressing the button on the remote unit, as well as setting the alarm, closes the windows and sunroof, and locks the doors.

A security code in the engine electronic control unit is a powerful deterrent. This can only be 'unlocked' to allow the engine to start when it receives a coded signal. Many manufacturers use a special ignition key, which is programmed with the required information (Fig. 3.130). Even the correct 'cut' key will not start the engine.

Key fact

When the alarm system is an integral part of the vehicle electronics it is more effective.

Figure 3.129 Inside a remote key

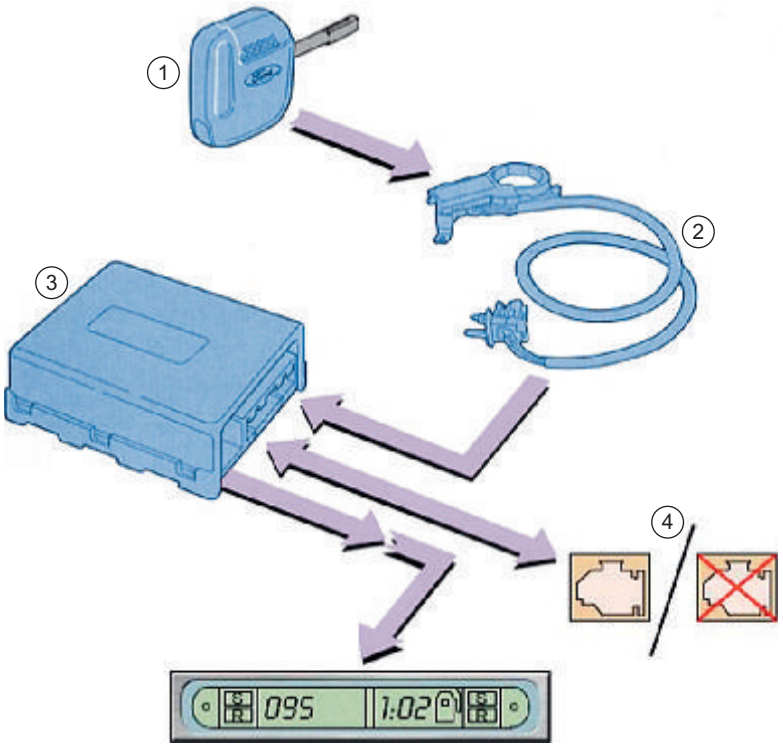

Figure 3.130 Coded key: 1, coded key; 2, harness; 3, ECU; 4, malfunction indicator light (MIL). (Source: Ford Motor Company)

3.4.8 Safety systems

Active safety relates to any development designed to actively avoid accidents. It can be considered under four general headings:

- handling safety
- physiological safety
- perceptual safety
- operational safety.

Passive safety relates to developments that protect the occupants of the vehicle in the event of an accident (Fig. 3.131). Air bags are a good example of this.

A seat belt, seat belt tensioner and an air bag are at present the most effective restraint system in the event of a serious accident. At speeds in excess of

Definition

Passive and active safety features

Passive safety features are used during an unavoidable accident. Active safety features work to avoid the accident in the first place.

Figure 3.131 Passive safety is used only in an emergency. (Source: Saab Media)

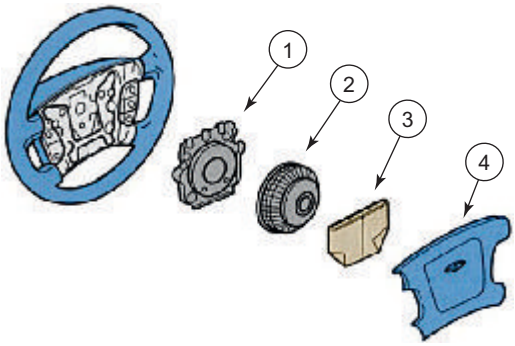

Figure 3.132 Air bag unit: 1, container; 2, gas generator; 3, airbag; 4, cover

40 km/h, the seat belt alone is no longer adequate. Research after a number of accidents has determined that in 68% of cases an air bag provides a significant improvement. It is suggested that if all cars in the world were fitted with an air bag then the number of fatalities annually would be reduced by well over 50 000. Some air bag safety issues have been apparent in the USA, where air bags are larger and more powerful. This is because in many areas the wearing of seat belts is less frequent.

The method becoming most popular for an air bag system is that of building most of the required components into one unit (Fig. 3.132). This reduces the amount of wiring and connections, thus improving reliability. An important aspect is that some form of system monitoring must be built in, as the operation cannot be tested; it only ever works once.

The sequence of events in the case of a frontal impact at about 35 km/h is as follows (Fig. 3.133):

1. Driver in normal seating position prior to impact.
2. About 15 ms after the impact the vehicle is strongly decelerated and the threshold for triggering the air bag is reached. The igniter ignites the fuel tablets in the inflater.
3. After about 30 ms, the air bag unfolds and the driver will have moved forwards as the vehicle's crumple zones collapse. The seat belt will have locked or been tensioned, depending on the system.

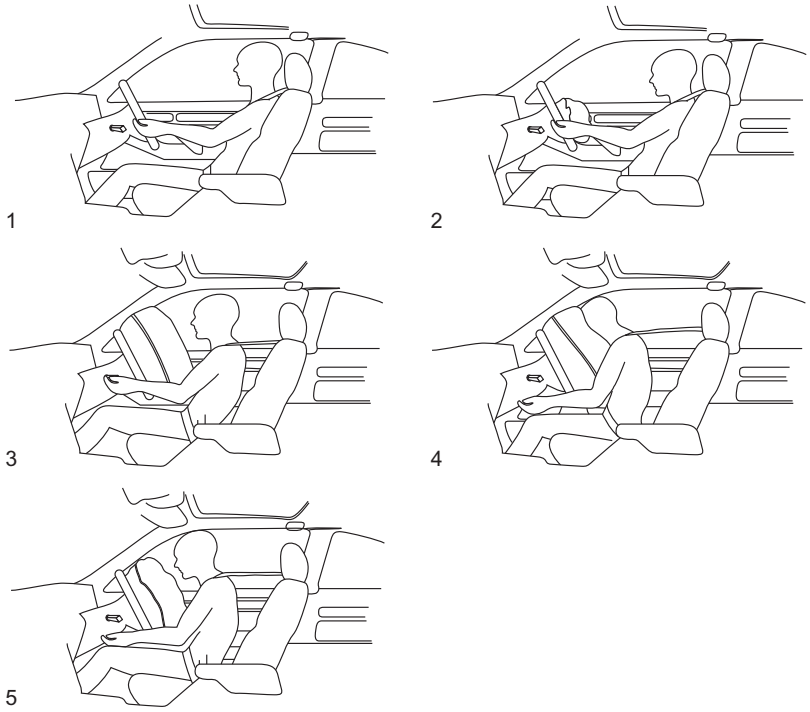

Figure 3.133 Air bag deployment: sequence of events in a frontal impact

4 At 40 ms after impact, the air bag will be fully inflated and the driver's momentum will be absorbed by the air bag.

5 About 120 ms after impact, the driver will be moved back into the seat and the air bag will have almost deflated through the side vents, allowing driver visibility.

Passenger air bag deployment events are similar to the previous description. The position is different but the basic principle of operation is the same. The positions of the side and rear air bags are shown in Figs 3.134 and 3.135, and the ECU in Fig. 3.136.

A block diagram of an air bag circuit is shown in Fig. 3.137. A digitally based system, using electronic sensors, has about 10 ms at a vehicle speed of 50 km/h, to decide whether the restraint systems should be activated. In this time, about 10 000 computing operations are necessary. Data for the development of these algorithms is based on computer simulations, but digital systems can also remember the events during a crash, allowing real data to be collected.

Safety first

Taking the 'slack' out of a seat belt in the event of an impact contributes to passenger safety.

Taking the 'slack' out of a seat belt in the event of an impact is a good contribution to vehicle passenger safety. The decision to take this action is the same as for the air bag. The two main methods are:

- spring tension
- pyrotechnic.

When the explosive charge is fired, the cable pulls a lever on the seat belt reel, which in turn tightens the belt (Fig. 3.138). The unit must be replaced once deployed. This feature is sometimes described as anti-submarining.

Figure 3.134 Side air bag position

Figure 3.135 Rear air bag position

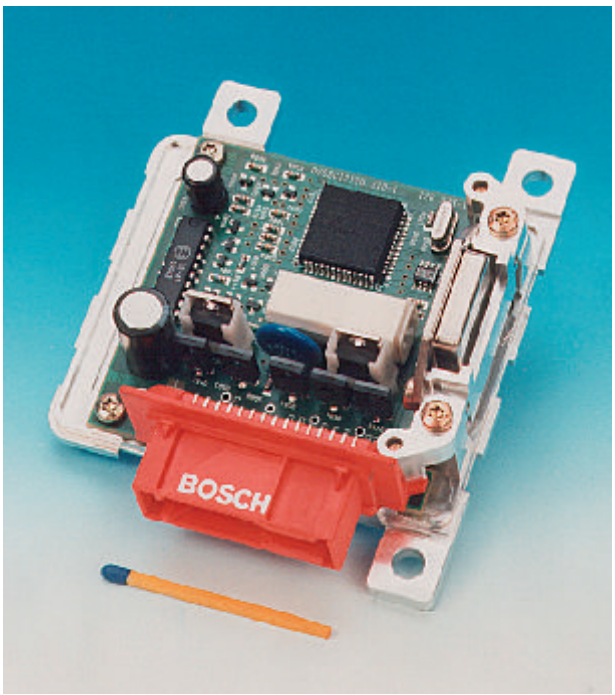

Figure 3.136 Electronic control unit (ECU)

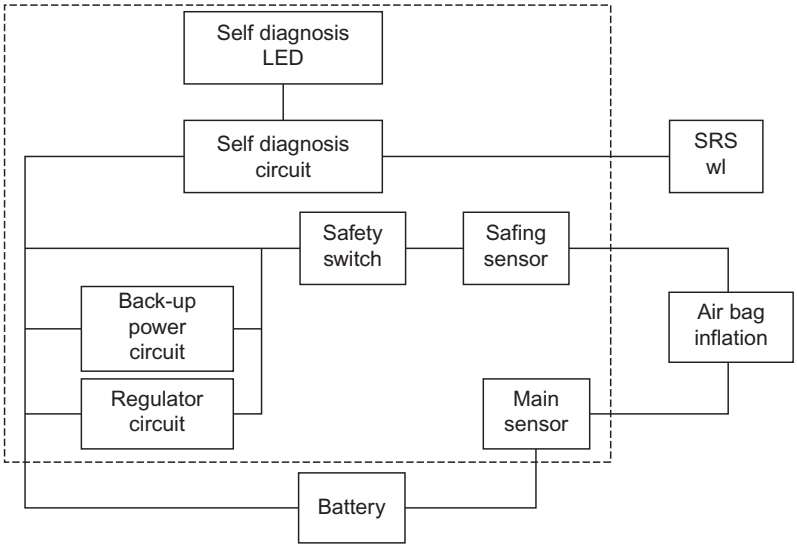

Figure 3.137 Supplementary restraint system (SRS) block diagram

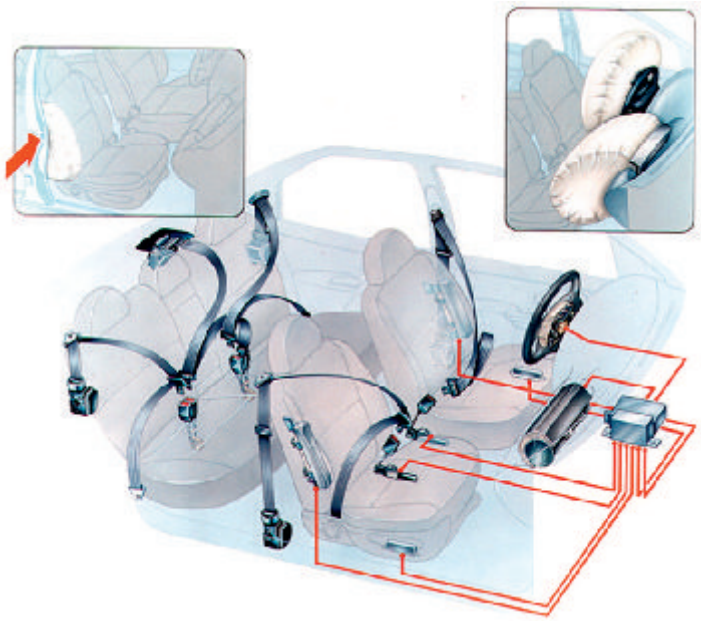

Figure 3.138 Belt tensioners. (Source: Ford Media)

3.5 Monitoring and instrumentation

3.5.1 Sensors

Definition

Sensors
Sensors convert measurable things into electrical signals.

Sensors are used on vehicles for many purposes (Fig. 3.139). For example, the coolant temperature thermistor is used to provide information to the engine management system as well as to the driver. The information to the driver is provided by a display or gauge. Sensors convert what is being measured into an electrical signal. This signal can then be used to operate a display, such as a gauge or warning light, on the instrument panel.

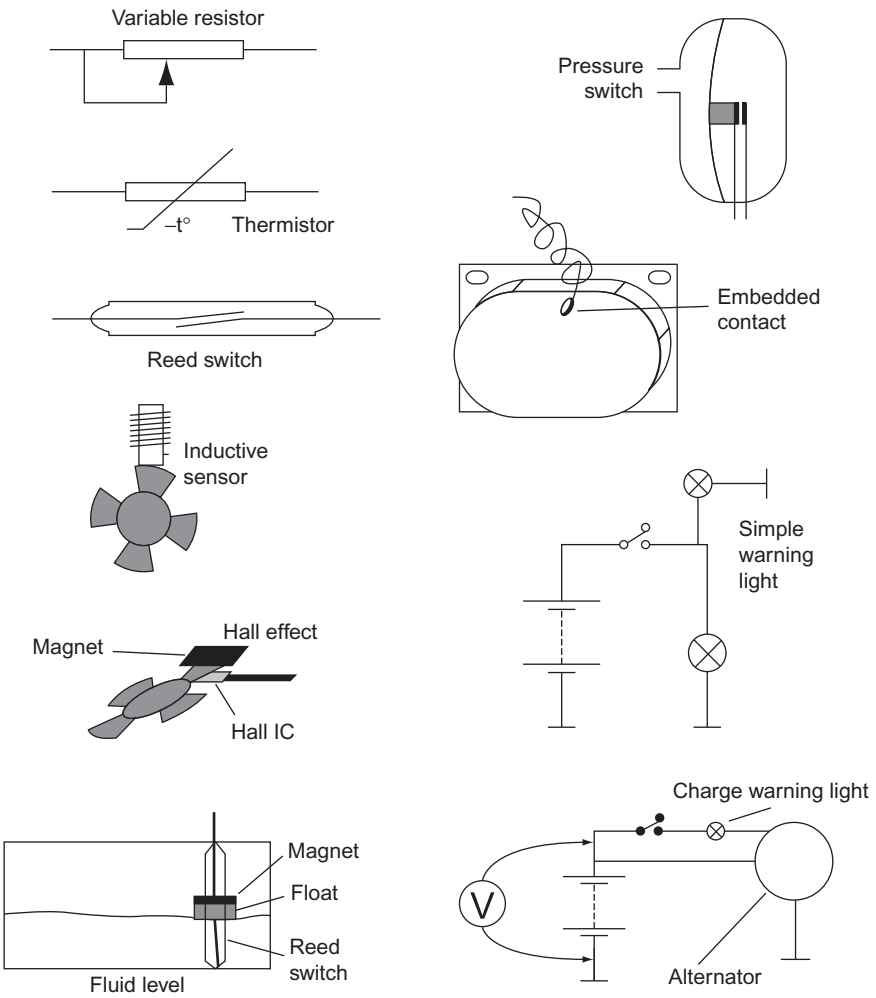

Figure 3.139 Sensors used for instrumentation

Fuel level is measured using a variable resistor that is moved by a float (Fig. 3.140). The position of the float is determined by how much fuel is in the tank. The resistance value is varied by a contact sliding over a resistor.

The most common temperature measurement is that of the engine coolant. However, outside air, cabin, air intake and many other temperatures are measured (Fig. 3.141). Most applications use a thermistor, which is a special material that changes its resistance with temperature. Most types are described as negative temperature coefficient (NTC). This means that, as the temperature increases, their resistance decreases.

Definition

Negative temperature coefficient (NTC)
As temperature increases, resistance decreases.

A reed switch consists of two small strips of steel. When these become magnetized, they join and make a circuit. Bulb failure circuits often use a reed relay to monitor the circuit. In the circuit shown in Fig. 3.139, the contacts of the reed switch will only close when electricity is flowing to the bulb being monitored.

Road speed is often sensed using an inductive pulse generator. This sensor produces an a.c. output with a frequency that is proportional to speed. It is like a small generator that is driven by a gear on the gearbox output shaft. This type of sensor is also used to sense engine speed from the flywheel or crankshaft.

Engine speed can be sensed in a number of ways. An inductive sensor as described in the fuel section is most common. The Hall effect sensor is also

a popular choice, as it is accurate and produces a square-wave output with a frequency proportional to engine speed.

Fluid levels, such as washer fluid or radiator coolant, are often measured or sensed using a float and reed switch assembly. The float has a magnet attached that causes the contacts to join when it is in close proximity. The float moves up or down depending on the fluid level.

Figure 3.140 Tank sender unit

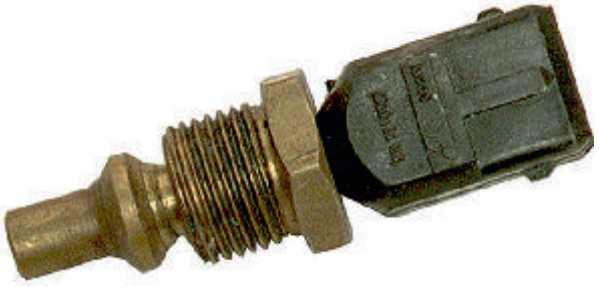

Figure 3.141 Temperature sensor

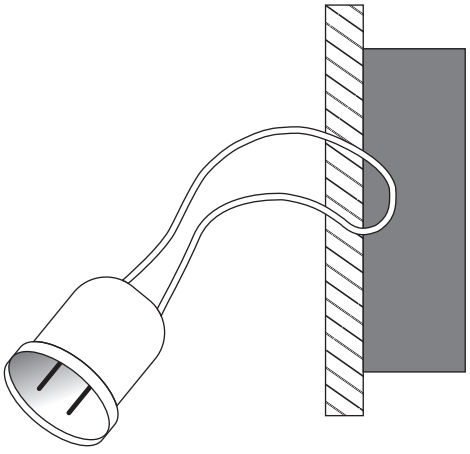

Figure 3.142 Brake pads with sensor wires

Oil pressure may be measured and displayed on a gauge or, as is most common, by using a simple warning light. For this purpose, a diaphragm switch is used. As oil pressure increases, it is made to act on a diaphragm. Once it overcomes spring pressure, the contacts are operated. The contacts can be designed to open or close as the pressure reaches a set level.

Brake pad wear is sensed by using a simple embedded contact wire (Fig. 3.142). When the friction material wears down, the embedded contact makes contact with the disc to complete a circuit. Some systems use a loop of wire that is broken when the pad wears out.

A wide range of sensors is used to operate instrument displays. Sensors convert what is being measured into an electrical signal. This may be by a simple on/off operation, a changing voltage output or a change in resistance.

3.5.2 Gauges

By definition, an instrumentation system can be said to convert a variable into a readable or usable display (Fig. 3.143). For example, a fuel level instrument system will display a representation of the fuel in the tank using an analogue gauge.

Instrumentation is not always associated with a gauge or a read-out type display. In many cases, a system can be used just to operate a warning light. However, it must still work to certain standards. For example, if a low outside temperature warning light did not illuminate at the correct time, a dangerous situation could develop.

Thermal gauges, which are ideal for fuel and engine temperature indication, have been in use for many years (Fig. 3.144). This will continue because of their simple design and inherent ‘thermal’ damping. The gauge works by utilizing the heating effect of electricity and the widely adopted benefit of the bimetal strip. As a current flows through a simple heating coil wound on a bimetal strip, heat causes the strip to bend. The bimetal strip is connected to a pointer on a suitable scale. The amount of bending is proportional to the heat, which in turn is proportional to the current flowing. Provided the sensor can vary its resistance in proportion to the fuel level or temperature, the gauge will indicate a suitable representation (Fig. 3.145).

Figure 3.143 Instrument panel

Figure 3.144 Fuel gauge display

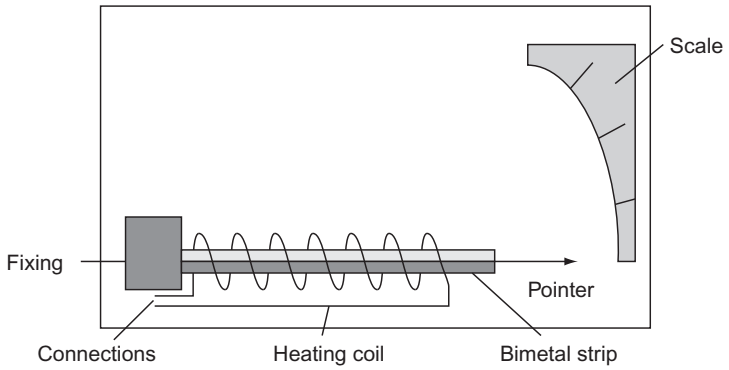

Figure 3.145 Thermal gauge operation

The inherent damping is due to the slow thermal effect on the bimetal strip. This causes the needle to move very slowly to its final position. This is a particular advantage for displaying fuel level, as the variable resistor in the tank will move as the fuel moves, owing to vehicle movement. If the gauge reacted quickly, it would be constantly moving. The movement of the fuel, however, is in effect averaged out and an accurate display can be obtained. Thermal gauges are used with a variable resistor. This is either a float in the fuel tank or a thermistor in the engine water jacket. The sender resistance is usually at a maximum when the tank is empty or the engine is cold.

A constant voltage supply is required to prevent changes in the system voltage affecting the reading. This is because if system voltage increased, the current flowing would increase and the gauges would read higher. Most voltage stabilizers are simple zener diode circuits as shown in Fig. 3.146.

Air-cored gauges work on the same principle as a compass needle lining up with a magnetic field (Fig. 3.147). The needle of the display is attached to a very small permanent magnet. Three or more coils of wire are used and each produces a magnetic field. The magnet, and therefore the needle, will line up with the

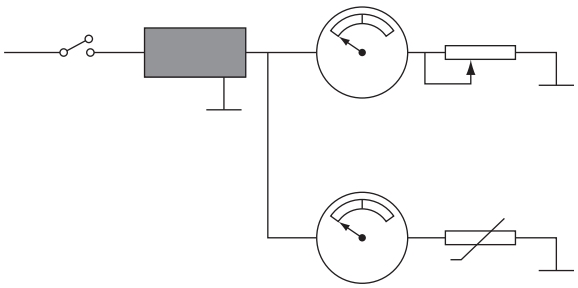

Figure 3.146 Fuel and temperature gauge circuit with a voltage stabilizer

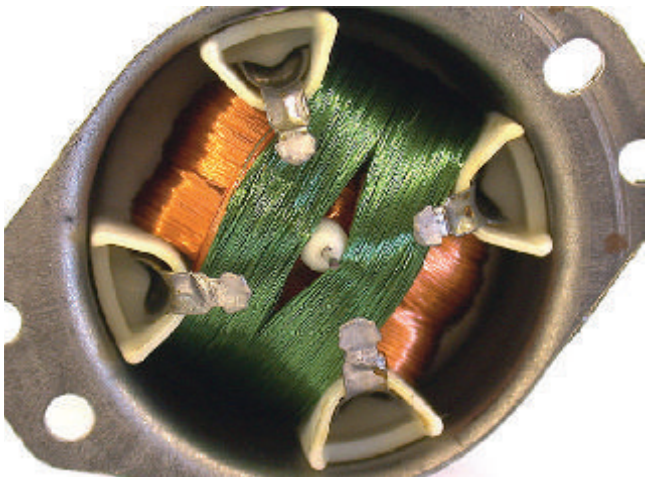

Figure 3.147 Air-cored gauge details

resultant of the three fields. The current flowing through each coil is, therefore, the key to moving the needle position.

When an air-core gauge is used as a temperature gauge and the thermistor resistance changes, the current in all three coils is made to change. This moves the needle from cold to hot, or the other way, as needed.

The air-cored gauge has a number of advantages. It has almost instant response and as the needle is held in a magnetic field, it will not move as the vehicle changes position. The gauge can be arranged to continue to register the last position even when switched off. If a small 'pull-off' magnet is used, it will return to its zero position. A change in system voltage would affect the current flowing in all three coils. Variations are therefore cancelled out so that a voltage stabilizer is not needed.

A variation of any of the above types of gauge can be used to display other required outputs such as voltage or oil pressure. Gauges to display road or engine speed, however, need to react very quickly to changes. Many systems now use a stepper motor or another type of electrical gauge for this purpose.

A few cars still use conventional cable-driven speedometers. The head units usually work by either friction or magnetism. The frictional or magnetic drag increases as speed increases and this is used to move a needle. The flexible

Key fact

Many systems now use a stepper motor to drive speedometers and tachometers.

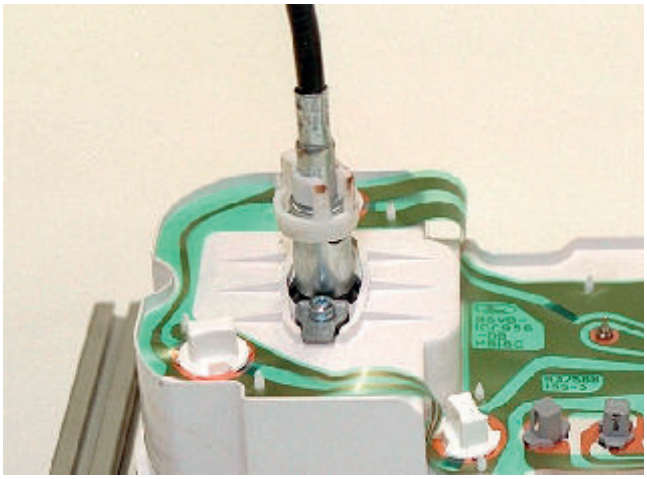

Figure 3.148 Speedometer cable and head

Figure 3.149 Tachometer and speedometer display

cable is driven from the gearbox output. It has square ends to transfer the rotation (Fig. 3.148).

The system for driving most rev-counters (or tachometers) is similar to the electronic speedometer system. Pulses from the ignition primary circuit are often used to drive the gauge. The rev-counter needle response is damped to give a steady reading (Fig. 3.149).

Various gauges are used for instrumentation displays. The most common for fuel and temperature display are thermal and air-cored. Speedometers and tachometers use stepper motors (Fig. 3.150), electrical gauges or mechanical systems.

3.5.3 Global Positioning System (GPS)

From 1974 to 1979, a trial using six satellites allowed navigation in North America for just four hours per day. This trial was extended worldwide by using eleven satellites until 1982, at which time it was decided that the system would be

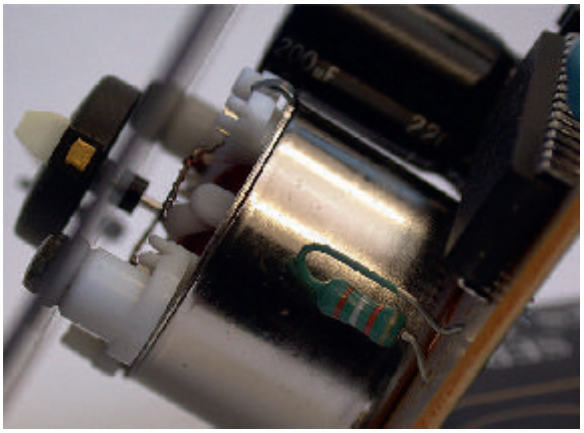

Figure 3.150 Stepper motor tachometer

Figure 3.151 GPS display in a Jaguar

extended to twenty-four satellites, in six orbits, with four operating in each. There are now over thirty satellites in use. They are set at a height of about 21 000 km (13 000 miles), inclined 55° to the equator, and take approximately twelve hours to orbit the Earth. The orbits are designed so that there are always six satellites in view from most places on the Earth (Fig. 3.152).

The system was developed by the American Department of Defense. Using an encrypted code allows a ground location to be positioned to within a few centimetres. The signal employed for civilian use is artificially reduced in quality so that positioning accuracy is in the region of 50 m. Some systems, however, now improve on this and can work down to about 15 m.

GPS satellites send out synchronized information fifty times a second. Orbit position, time and identification signals are transmitted. A modern GPS receiver will typically track all of the available satellites, but only a selection of them will be used to calculate position. The times taken for the signals to reach the vehicle are calculated and from this information the computer can determine the distance from each satellite. The current vehicle position can then be worked out using three coordinates. Imagine the three satellites forming a triangle (represented in Figs 3.153–3.155 as A, B and C). The position of a vehicle within

Key fact

Position can be worked out using three coordinates; this is known as triangulation.

Figure 3.152 If you look really hard you can see the satellites, honest …

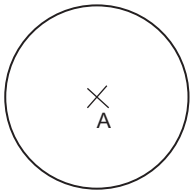

Figure 3.153 At a known distance from a fixed point A you could be anywhere on a circle

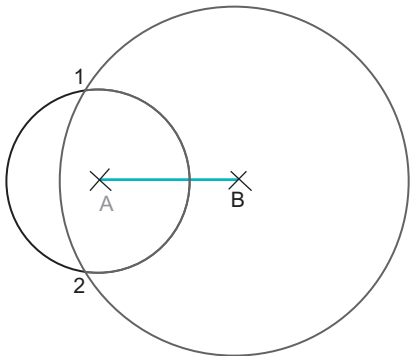

Figure 3.154 At a known distance from two fixed points A and B you must be at position 1 or 2

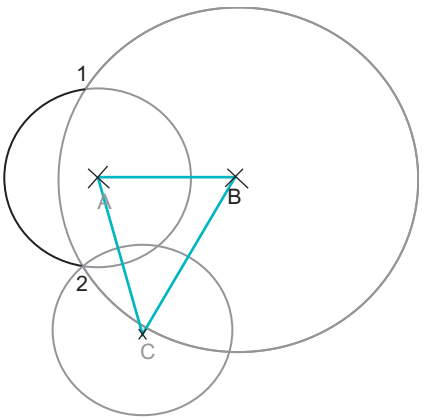

Figure 3.155 At a known distance from three fixed points A, B and C you must, in this case, be at position 2

that triangle can be determined if the distance from each fixed point (satellite) is known. This is called triangulation.

The GPS receiver receives a signal from each GPS satellite. The satellites transmit the exact time at which the signals are sent. By subtracting the time

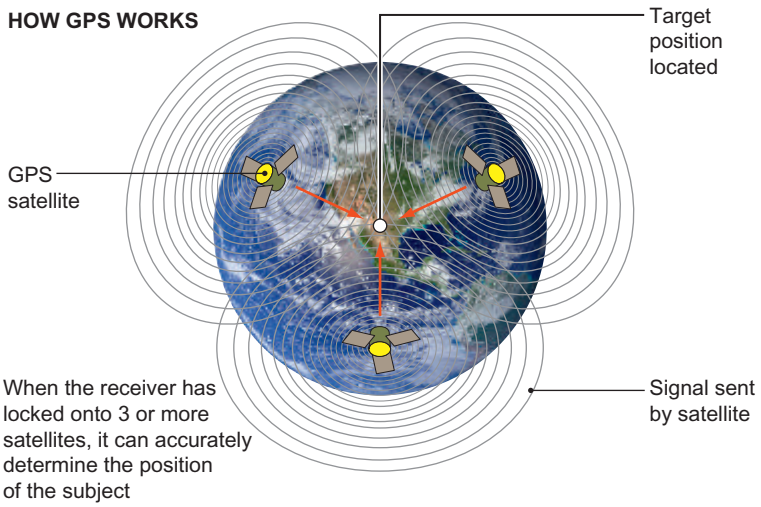

Figure 3.156 How GPS works

Figure 3.157 Four satellites determine vehicle position more accurately

when the signal was transmitted from the time it was received, the GPS can tell how far it is from each satellite. The GPS receiver also knows the exact position in the sky of the satellites, at the moment they sent their signals. So, given the travel time of the GPS signals from three satellites and their exact position in the sky, the GPS receiver can determine position in three dimensions: east/west, north/south and altitude (Fig. 3.156).

To calculate the time the GPS signals took to arrive, the GPS receiver needs to know the time very accurately. The GPS satellites have atomic clocks that keep very precise time, but it is not feasible to equip a GPS receiver with such a device. However, if the GPS receiver uses the signal from a fourth satellite it can solve an equation that lets it determine the exact time, without needing an atomic clock (Fig. 3.157).

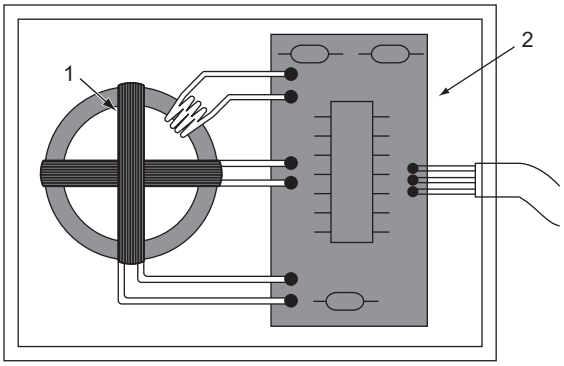

Figure 3.158 Field sensor: 1, crossed coils; 2, control circuit. (Source: Ford)

If the GPS receiver is only able to get signals from three satellites, position can still be calculated, but less accurately. If only three satellites are available, the GPS receiver can get an approximate position by making the assumption that you are at mean sea level. If you really are at sea level, the position will be reasonably accurate, but if you are driving in the mountains, the two-dimensional fix could be several hundreds of metres out.

The magnetic field sensor in a GPS unit is a key component (Fig. 3.158). It determines direction of travel in relation to the Earth's magnetic field. It also senses the changes in direction when driving round a corner or a bend. The two crossed measuring coils sense changes in the Earth's magnetic field because it has a different effect in each of them. The direction of the Earth's field can be calculated from the polarity and voltage produced by these two coils. The smaller excitation coil produces a signal that causes the ferrite core to oscillate. The direction of the Earth's magnetic field causes the signals from the measuring coils to change depending on the direction of the vehicle.

To use most satellite navigation systems, the destination address is entered using a joystick control, cursor keys or something similar. The systems usually 'predict' the possible destination as letters are entered so it is not usually necessary to enter the complete address. Once the destination is set, the unit will calculate the journey. Options may be given for the shortest or quickest routes at this stage. Driving instructions, relating to the route to be followed, are given visually on the display and audibly through speakers.

Even though the satellite information provides a positional accuracy of only about 50 m, using dead-reckoning, intelligent software can still get the driver to their destination with an accuracy of about 5 m in some cases. Dead-reckoning means that the vehicle position is determined from speed and turn signals.

Key fact

Dead-reckoning allows basic navigation when satellite signals are disrupted.

The computer can update the vehicle position from the GPS data by using the possible positions on the stored digital map (Fig. 3.159). This is because in many places on the map only one particular position is possible: it is assumed that short-cuts across fields are not taken! Dead-reckoning even allows navigation when satellite signals are disrupted.

Vehicle global positioning systems use a combination of information from satellites and sensors to accurately determine the vehicle's position on a digital map. A route can then be calculated to a given destination. Like all vehicle systems, GPS continues to develop and will do for some time yet as more features are added to the software. Already it is possible to 'ask' many systems for the nearest fuel station or restaurant, for example.

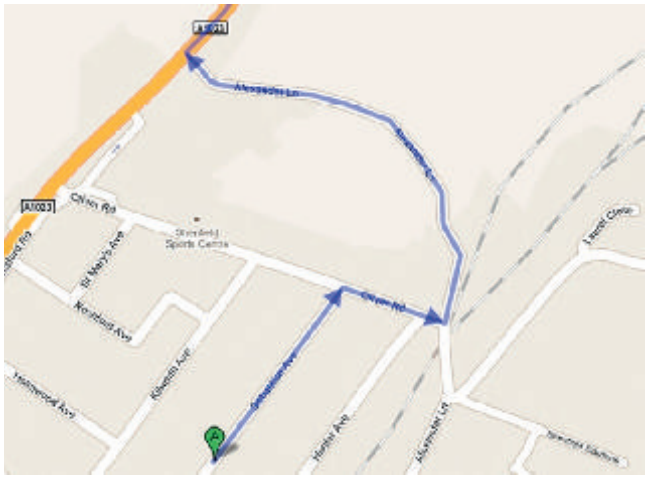

Figure 3.159 As the driver follows the instructions for the first right turn here, the system will 'know' the location to within a metre or so if steering angle is used as an input

3.6 Air conditioning

3.6.1 Air conditioning fundamentals

A vehicle fitted with air conditioning allows the temperature of the cabin to be controlled to the ideal or most comfortable value. This is usually determined by the ambient conditions. Air conditioning can be manually controlled or, as is often the case, combined with some form of electronic control. The system as a whole can be thought of as a type of refrigerator or heat exchanger. Heat is removed from the car interior and dispersed to the outside air. To understand the principle of air conditioning or refrigeration, the terms and definitions described here will be useful:

- Heat is a form of energy.
- Temperature is the degree or intensity of heat of a body, and the condition that determines whether or not it will transfer heat to, or receive heat from, another body.
- Heat will only flow from a higher to a lower temperature.
- Change of state describes the changing of a solid to a liquid, a liquid to a gas, a gas to a liquid or a liquid to a solid.
- Evaporation describes the change of state from a liquid to a gas.
- Condensation describes the change of state from gas to liquid.
- Latent heat describes the energy required to evaporate a liquid without changing its temperature.

Latent heat, in the change of state of a refrigerant, is the key to air conditioning. As an example of this, if you put a liquid such as vodka on your hand it feels cold, particularly if you blow on it. This is because it evaporates and the change of state, from liquid to a gas, uses heat from your body (Fig. 3.160). This is why the process is often thought of as 'unheating' rather than cooling. The refrigerant used in many air conditioning systems changes state from liquid to gas at a much low temperature and works better than vodka!

The refrigerant used in many air conditioning systems is known as R134a (Fig. 3.161). This substance changes state from liquid to gas at −26.3°C. R134a

Definition

Latent heat
Heat that is released or absorbed accompanying a change of state or of phase of a material.

Figure 3.160 A liquid evaporating uses heat

Figure 3.161 R134a refrigerant

Key fact

Low-pressure refrigerant will have a low temperature, and high-pressure refrigerant will have a high temperature.

is hydrofluorocarbon (HFC) based. Earlier types were chlorofluorocarbon (CFC) based and caused problems with atmospheric ozone depletion. The two types of refrigerant are not compatible.

A key to understanding refrigeration is to remember that low-pressure refrigerant will have a low temperature, and high-pressure refrigerant will have a high temperature.

The layout of an air conditioning or refrigeration system is shown in Fig. 3.162. The main components are the evaporator, the condenser and the pump or compressor. The evaporator is situated in the car and, the condenser outside the car, in the air stream, and the compressor is driven by the engine.

As the compressor operates it causes the pressure on its intake side to fall. This allows the refrigerant in the evaporator to evaporate and draw heat from the vehicle interior. The high-pressure or output side of the pump is connected to the condenser. The pressure causes the refrigerant to condense, in the condenser, and it thus gives off heat outside the vehicle as it changes state.

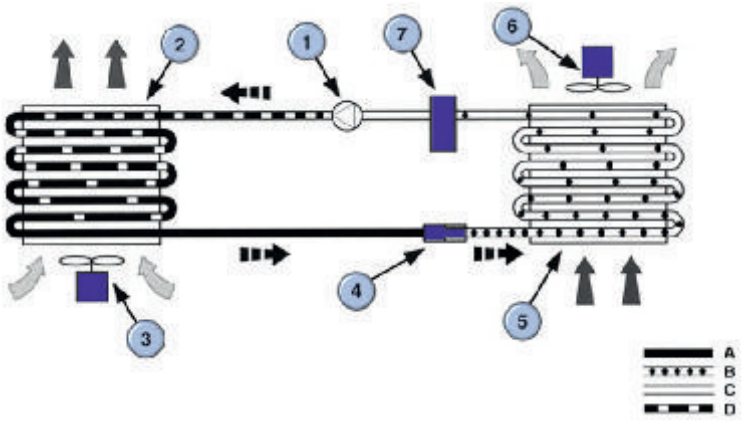

Figure 3.162 Air conditioning system layout: 1, compressor; 2, condenser; 3, auxiliary fan (depending on model); 4, fixed orifice tube; 5, evaporator; 6, heater/air conditioning blower; 7, suction accumulator/drier; A, high-pressure warm liquid; B, low-pressure cool liquid; C, low pressure, gaseous and cool; D, high pressure, gaseous and hot. (Source: Ford Motor Company)

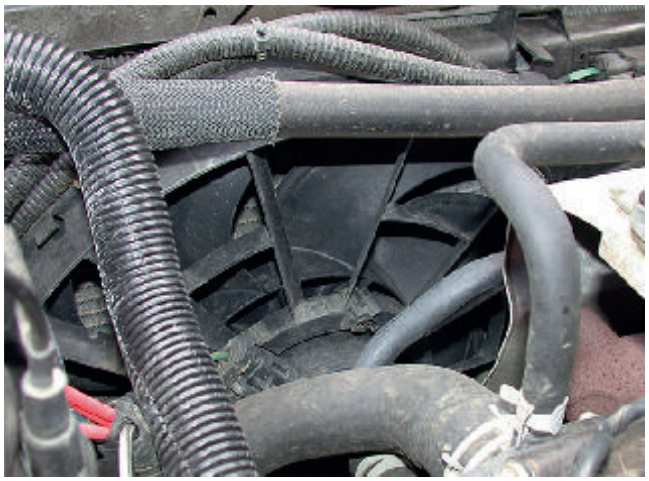

Figure 3.163 Condenser cooling fan

The compressor pumps low-pressure but heat-laden vapour from the evaporator, compresses it and pumps it as a super-heated vapour under high pressure to the condenser. The temperature of the refrigerant at this stage is much higher than the outside air temperature. It therefore gives up its heat via the fins on the condenser, as it changes state back to a liquid. This high-pressure liquid is then passed to a receiver drier, which stores any vapour that has not yet turned back to a liquid. Alternatively, a suction accumulator is used on the low-pressure side.

A desiccant, which is a drying agent, removes any moisture that is contaminating the refrigerant. Refrigerant, like brake fluid, is hygroscopic, which means it absorbs water. The high-pressure liquid is now passed through the thermostatic expansion valve, or a fixed orifice, and is converted back to a low-pressure liquid as it passes through a restriction into the evaporator.

As the liquid changes state to a gas in the evaporator, it takes up heat from its surroundings, thus cooling or 'unheating' the air, which is forced over the fins. The low-pressure vapour leaves the evaporator returning to the pump, thus completing the cycle.

Definition

Desiccant
A drying agent.

If the temperature of the refrigerant increases beyond certain limits the condenser cooling fans can be switched on to supplement the ram air effect (Fig. 3.163).

Changing a liquid into a gas uses energy. This energy, in the form of heat, is taken from inside the vehicle. When the gas is compressed, it gets hotter and the heat can be given off outside the vehicle. This turns the gas back into a liquid and the cycle starts again.

3.6.2 Air conditioning components

The main components of an air conditioning system are:

- a compressor
- a condenser
- an evaporator
- a control valve
- a drier.

An air conditioning system compressor is shown in Fig. 3.164. It is belt driven from the engine crankshaft and it causes refrigerant to circulate through the system. The compressor is controlled by an electromagnetic clutch, which may be under either manual control or electronic control, depending on the type of system.

The shaft is driven by the engine via a multi-V belt. Five double pistons are arranged around the driving shaft. The swash plate, which is mounted on the main shaft, causes the pistons to move backwards and forwards.

Key fact

An air conditioning condenser is fitted in front of the vehicle radiator.

The condenser is fitted in front of the vehicle radiator. It is very similar in construction to the radiator and fulfils a similar role. The heat is conducted through the aluminium pipes and fins to the surrounding air and then by a process of radiation and convection is dispersed by the air movement (Fig. 3.165).

Figure 3.166 shows a typical receiver/drier assembly. It is connected in the high-pressure line between the condenser and the thermostatic expansion valve. This component carries out four tasks:

- It holds refrigerant in a reservoir until a greater flow is required.
- It prevents contaminants circulating through the system by using a filter.

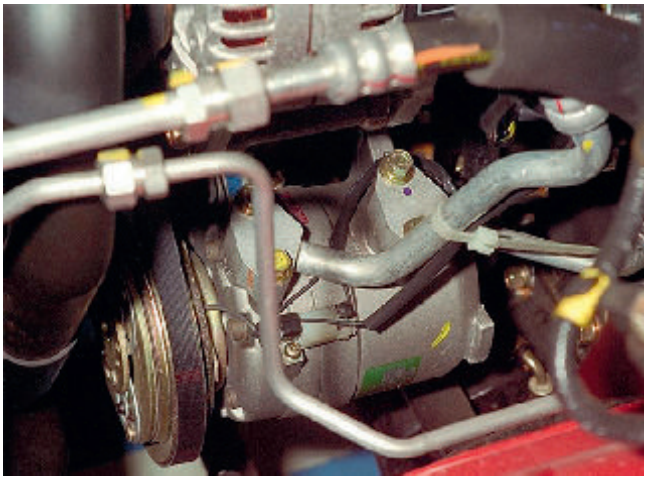

Figure 3.164 Air conditioning system compressor in place

- It enables vapour retention until the vapour converts back to a liquid.
- It removes moisture from the system using a drying agent.

Systems that use a fixed orifice control system usually use a low-pressure accumulator instead of a receiver/drier. This component carries out the same tasks as a receiver/drier.

A sight glass is fitted to some receiver/driers. This gives an indication of refrigerant condition and system operation. The refrigerant generally appears clear if all is in order.

The main function of the thermostatic expansion valve (Fig. 3.167) is to control the flow of refrigerant as demanded by the system. This, in turn, controls the temperature of the evaporator. A temperature sensor is fitted in the evaporator on some systems.

Some systems use a fixed orifice control valve. The operation is quite simple. A fixed orifice, which is a small hole, only allows a certain flow rate. Filters are included to prevent contamination. The fixed orifice is the connection between the low- and high-pressure systems.

The evaporator is similar in construction to the condenser, consisting of fins to maximize heat transfer. It is mounted in the car under the dash panel, forming

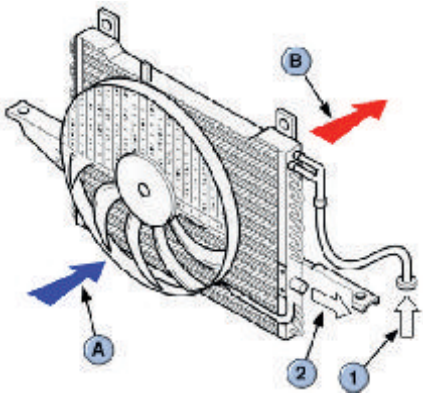

Figure 3.165 The condenser is very similar to the cooling system radiator: A, cooled air; B, heated air; 1, gaseous refrigerant; 2, liquid refrigerant

Figure 3.166 Receiver/drier

Figure 3.167 Thermostatic expansion valve

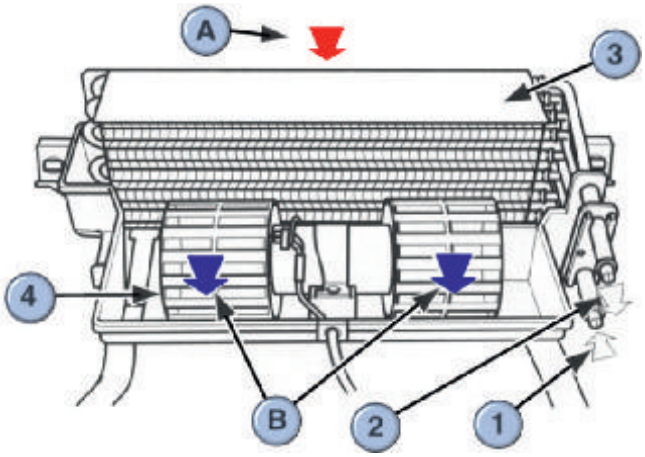

Figure 3.168 Evaporator housing and blower motor: A, hot air; B, cooled air; 1, liquid refrigerant; 2, gaseous refrigerant; 3, evaporator; 4, booster fan

Key fact

The main components of an air conditioning system are the condenser, evaporator and compressor.

part of the heating and ventilation system (Fig. 3.168). As well as cooling the air passed over it, the evaporator removes moisture from the air. This is because the moisture in the air condenses on the fins. The action is much like breathing on a cold pane of glass. A drain is fitted to remove water.

The key components of an air conditioning system are the condenser, evaporator and compressor. Refrigerant takes heat from the car as it evaporates. It is then compressed, and condenses in the condenser. It gives off heat to the atmosphere.

3.7 Formula 1 electrical technology

3.7.1 Introduction

Each Formula 1 (F1) car on the starting grid depends on sophisticated electronics. As with road cars, electronics are now used to control almost all aspects of the vehicle. It is estimated that each F1 car has more than a kilometre of wires, and up to 100 sensors and actuators. Few races are completed without a car retiring with electrical problems.

The role, and reliability, of electrical technology in F1 is therefore vital. The following section will just examine one important aspect: data acquisition, also known as telemetry.

3.7.2 Telemetry

First let's define what this means: Telemetry is a technology that allows remote measurement and transmission of information. The Greek root of the word is that tele means remote, and metron means measure. Telecommand is, in a way, a response to telemetry, as it means sending a command or instruction.

Telemetry is an important factor in F1, because it allows engineers to collect and analyse a huge amount of data during a race. The data can be interpreted and used to ensure that the car and driver are performing at their optimum.
F1 systems in particular have advanced such that even the potential lap time of the car can be calculated. Examples of operating data collected from an F1 car:

- acceleration (G force) in all 3 axis
- temperature readings (brakes, tyres, engine, transmission, etc.)
- wheel speed
- suspension displacement
- hydraulic pressure
- tyre pressures
- track position.

Driver inputs are also recorded so that the team can assess performance and, in the case of an accident, the FIA can determine or rule out driver error as a possible cause. Examples of driver inputs:

- brake pedal movement
- throttle pedal movement
- steering angle
- gear position.

Two-way telemetry (telemetry and telecommand) is possible and was originally developed by three different companies. The system started as a way to send a message to the electronic systems allowing the race engineers to update the car in real time, for example, changing engine mapping. However, the FIA banned two-way telemetry from F1 in 2003.
McLaren Electronic Systems have developed a system called the Advanced Telemetry Linked Acquisition System (ATLAS). This system displays graphs of each of the cars' systems in real time as the car travels round the track. Since the standard ECU (SECU) was introduced in 2008 almost all Formula One teams use the ATLAS data analysis software.

An F1 car can use two types of telemetry:

1. real-time information, which is sent in small packets. Hundreds of channels can be transmitted including track position, sensor readings and much more
2. a data burst, which is sent as the car passes the pits.

With ATLAS, this data burst is to make sure the engineers have all the data in case there were any gaps due to poor coverage. Some other systems have to use the data burst to gather more detailed information. The telemetry is transmitted by a small aerial located in the car sidepod (or on the chassis centreline) to a large aerial often fitted to the truck. Additional data can be

Definitions

Telemetry
Remote measurement and transmission of information

Telecommand
Sending a command or instruction.

Key fact

Telemetry is transmitted by a small aerial located on the car

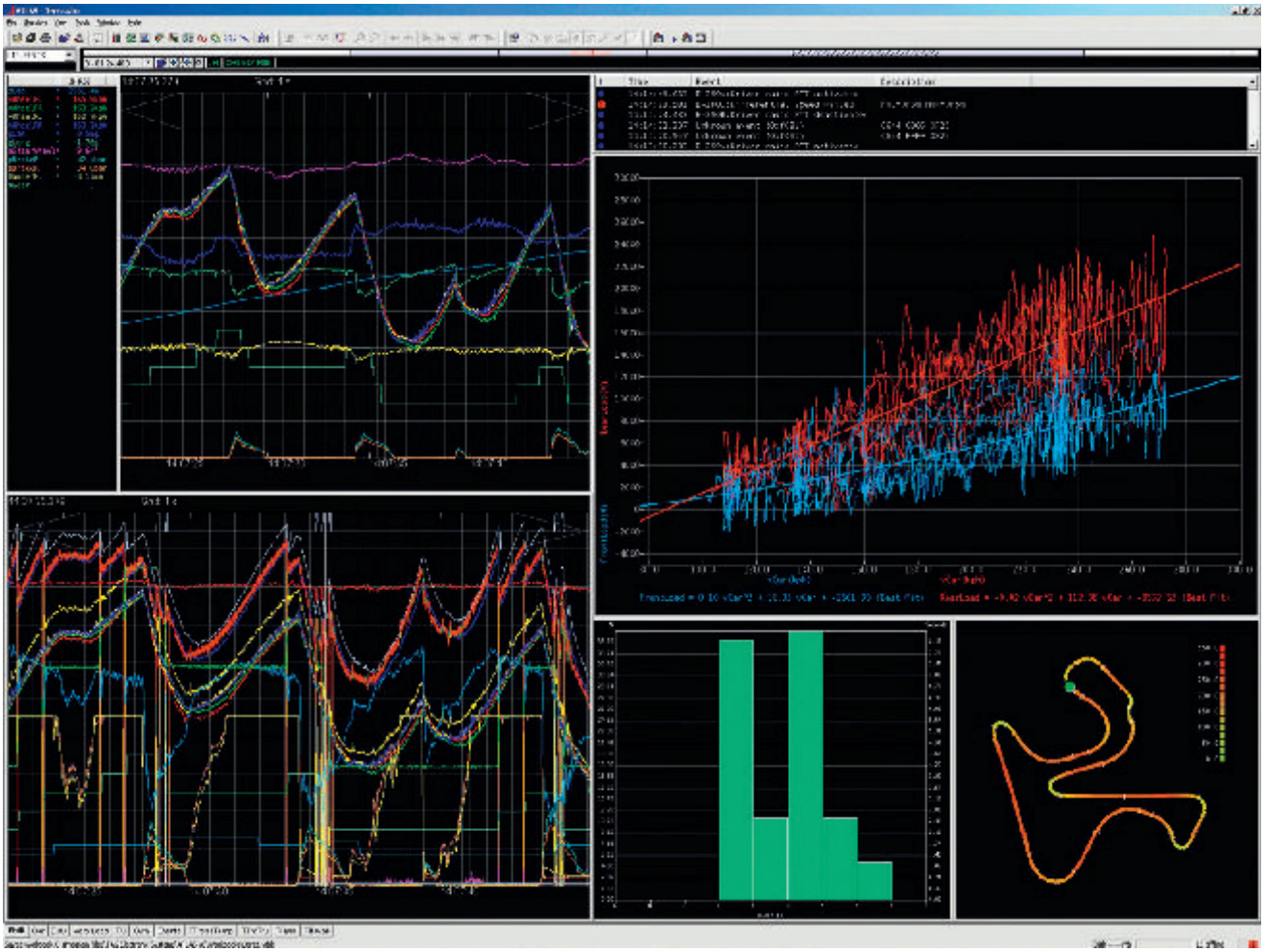

Figure 3.169 ATLAS screenshot showing the track and a range of data and displays. (Source: McLaren Electronic Systems)

downloaded from the car or a test bed by connecting directly to a computer. This is referred to as cable data.

ATLAS uses a single computer to process and distribute the data. A bank of computers is used to allow many engineers to analyse the data. The software displays the information on screens in a way that can be quickly and easily interpreted by the engineers. During a race, readings such as engine temperature and hydraulic pressure are examined in detail to make sure that a major failure is not imminent. If any readings go above or below what is normally expected, the engineers can radio the driver and, for example, ask them to use less engine revs or brake earlier to try and prevent failure.

See http://www.mclarenelectronics.com/Products/All/sw_atlas.asp for more information.

3.7.3 FIA technical regulations

This section gives a simplified overview of the technical regulations as at 2011, which relate to data acquisition and telemetry (source: www.fia.com). Please note that before you design and build your own F1 telemetry system, you should refer to the official FIA technical regulations!

3.7.3.1 Data acquisition

- Any data acquisition system, telemetry system or associated sensors additional to those provided by the ECU and ADR (accident data recorder) must be physically separate and completely isolated from any control electronics, with the exception of the primary regulated voltage supply, car system ground and a single communication link to the ECU and ADR.

3.7.3.2 Telemetry

- Telemetry systems must operate at frequencies which have been approved by the FIA.
- Pit-to-car telemetry is prohibited.

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CHAPTER 4

Chassis systems

4.1 Suspension

4.1.1 Overview of suspension

The suspension system is the link between the vehicle body and the wheels (Fig. 4.1). Its purpose is to:

- locate the wheels while allowing them to move up and down, and steer
- maintain the wheels in contact with the road and minimize road noise
- distribute the weight of the vehicle to the wheels
- reduce vehicle weight as much as possible, in particular the unsprung mass
- resist the effects of steering, braking and acceleration
- work in conjunction with the tyres and seat springs to give acceptable ride comfort.

This list is difficult to achieve completely, so some sort of compromise has to be reached. Because of this, many different methods have been tried, and many are still in use. Keeping these requirements in mind will help you to understand why some systems are constructed in different ways.

Unsprung mass (sometimes described as unsprung weight) is usually the mass of the suspension components, the wheels and the springs. However,

Figure 4.1 Suspension plays a key role

Automobile Mechanical and Electrical Systems.
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Figure 4.2 Spring just before a bump

Figure 4.3 Spring hitting a bump

Definition

Unsprung mass
The mass of the suspension components, wheels and springs.

only 50% of the spring mass and the moving suspension arms is included. This is because they form part of the link between the sprung and unsprung masses. It is beneficial to have the unsprung mass as small as possible in comparison with the sprung mass (main vehicle mass). This is so that when the vehicle hits a bump the movement of the suspension will have only a small effect on the main part of the vehicle. The overall result is therefore improved ride comfort.

A vehicle needs a suspension system to cushion and damp out road shocks (Figs 4.2 and 4.3). This provides comfort to the passengers and prevents damage to the load and vehicle components. A spring between the wheel and the vehicle body allows the wheel to follow the road surface. The tyre plays an important role in absorbing small road shocks. It is often described as the primary form of suspension. The vehicle body is supported by springs located between the body and the wheel axles. Together with the damper (also described as a shock absorber), these components are referred to as the suspension system.

Definition

Damper
A device that reduces vibration.

As a wheel hits a bump in the road, it is moved upwards with quite some force. An unsprung wheel is affected only by gravity, which will try to return the wheel to the road surface. However, most of the energy will be transferred to the body. When a spring is used between the wheel and the vehicle body, most of the energy in the bouncing wheel is stored in the spring and not passed to the vehicle body. The vehicle body only moves upwards through a very small distance compared to the movement of the wheel.

The springs in the suspension system take up the movement or shock from the road. The energy of the movement is stored in the spring. The actual spring can be in many different forms, ranging from a steel coil to a pressurized chamber of nitrogen. Soft springs provide the best comfort, but stiff springs can be better for high performance. Vehicle springs and suspension therefore are made to provide a compromise between good handling and comfort.

Key fact

Modern cars usually use a coil (or helical) spring.

Modern vehicles use a number of different types of spring medium, but the most popular is the coil (or helical) spring. Coil or helical springs used in vehicle suspension systems are made from round spring-steel bars. The heated bar is wound on a special former and then heat-treated to obtain the correct elasticity (springiness). The coil spring can withstand any compression load, but not side thrust. It is also difficult for a coil spring to resist braking or driving thrust. Suspension arms are used to resist these loads.

Coil springs are generally used with independent suspension systems; the springs are usually fitted on each side of the vehicle, between the stub axle assembly and the body (Figs 4.4 and 4.5). The spring remains in the correct position because recesses are made in both the stub axle assembly and body.

Figure 4.4 Details of a coil spring

Figure 4.5 Coil spring in position

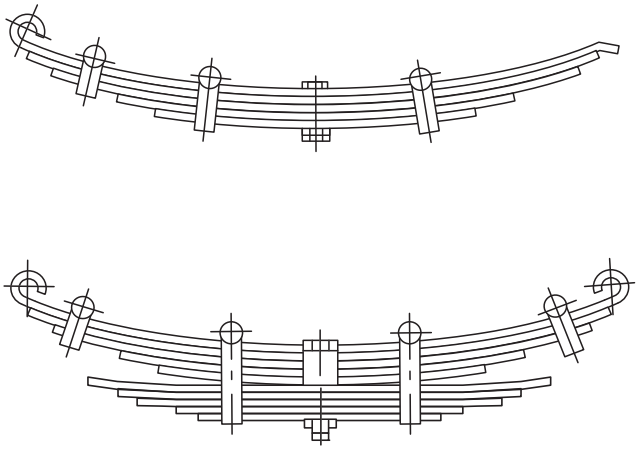

Figure 4.6 Laminated springs

The spring is always under compression owing to the weight of the vehicle and hence holds itself in place.

The leaf spring can provide all the control for the wheels during acceleration, braking, cornering and general movement caused by the road surface. Leaf springs are used with fixed axles and usually on larger vehicles. They can be described as:

- laminated or multileaf springs (Fig. 4.6)
- single-leaf or monoleaf springs.

The multileaf spring was widely used at the rear of cars and light vehicles, and is still used in commercial vehicle suspension systems (Fig. 4.7). It consists of a number of steel strips or leaves placed on top of each other and then clamped together. The length, cross-section and number of leaves are determined by the loads carried.

The top leaf is called the main leaf and each end of this leaf is rolled to form an eye (Fig. 4.8). This is for attachment to the vehicle chassis or body. The leaves of the spring are clamped together by a bolt or pin known as the centre bolt.

Definition

Laminated
Consisting of many thin layers.

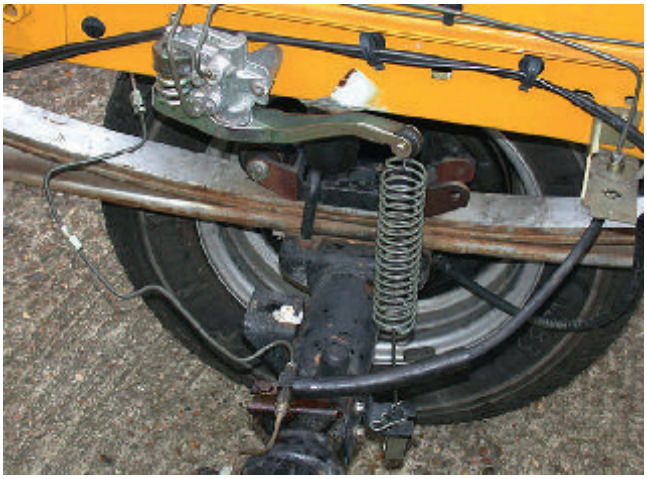

Figure 4.7 Commercial vehicle leaf spring

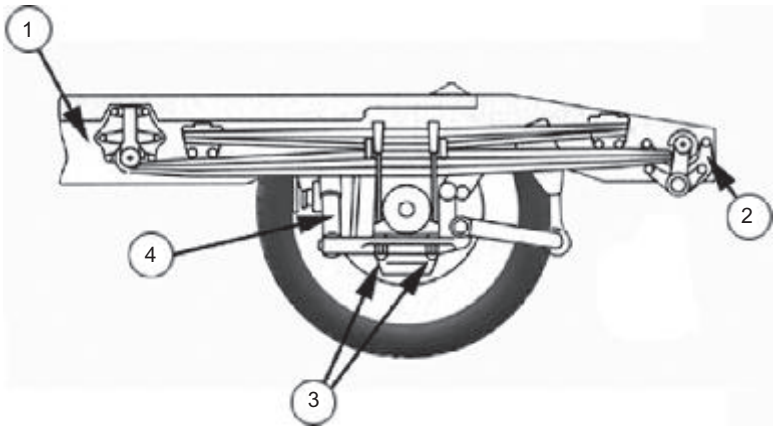

Figure 4.8 Details of a leaf spring: 1, fixed shackle; 2, swinging shackle; 3, U-bolts; 4, damper

Key fact

The curve of leaf springs straightens out when a load is applied to it, and its length changes.

The spring eye allows movement about a shackle and pin at the rear, allowing the spring to flex. The vehicle is pushed along by the rear axle through the front section of the spring, which is anchored firmly to the fixed shackle on the vehicle chassis or body. The curve of leaf springs straightens out when a load is applied to it, and its length changes.

Because of the change in length as the spring moves, the rear end of a leaf spring is fixed by a shackle bolt to a swinging shackle. As the road wheel passes over a bump, the spring is compressed and the leaves slide over each other. As it returns to its original shape, the spring forces the wheel back in contact with the road. The leaf spring is usually secured to the axle by means of U-bolts. As the leaves of the spring move, they rub together. This produces interleaf friction, which has a damping effect.

Figure 4.9 Tapered single leaf

A single-leaf spring, as the name implies, consists of one uniformly stressed leaf (Fig. 4.9). The spring varies in thickness from a maximum at the centre to a minimum at the spring eyes. This type of leaf spring is made to work in the same way as a multileaf spring. Advantages of this type of spring are:

- simplified construction
- constant performance over a period, because interleaf friction is eliminated
- reduction in unsprung mass.

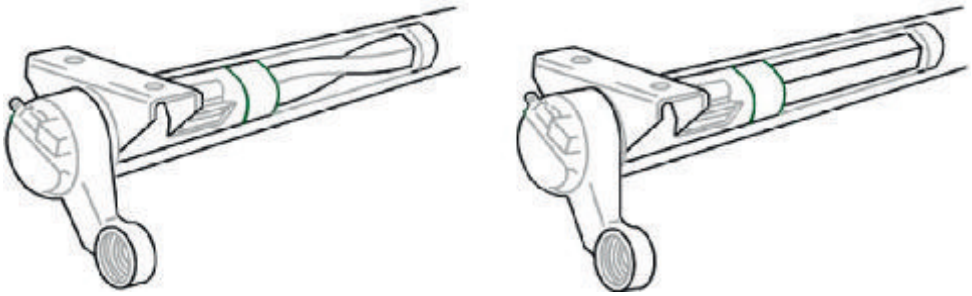

Figure 4.10 Torsion bar in a guide tube

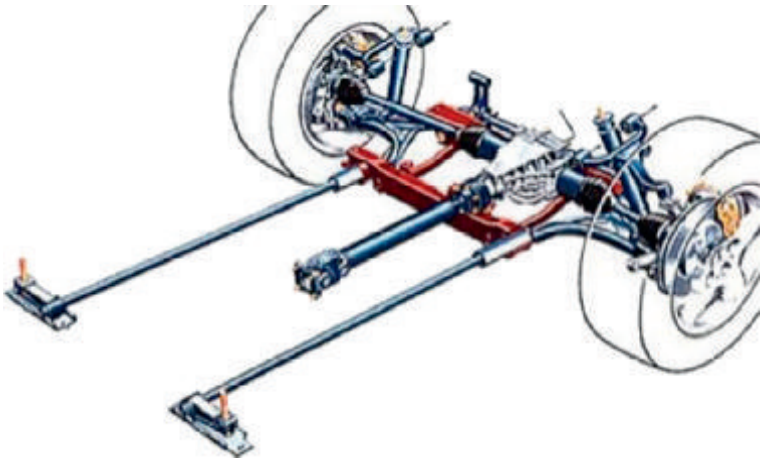

Figure 4.11 Torsion bar spring

Torsion bar suspension uses a metal bar, which provides the springing effect as it is twisted (Fig. 4.10). It has the advantage that the components do not take up too much room. The torsion bar can be round or square section, solid or hollow. The surface must be finished accurately to eliminate pressure points, which may cause cracking and fatigue failure. They can be fitted longitudinally or laterally.

Key fact

A torsion bar can be round or square section, solid or hollow.

Torsion bars are maintenance free but can sometimes be adjusted. They transmit longitudinal and lateral forces and have low mass. However, they have limited self-damping. Their spring rate is linear and their life may be limited by fatigue (Fig. 4.11).

Steel springs must be stiff enough to carry a vehicle's maximum load. However, this can result in the springs being too stiff to provide consistent ride control and comfort when the vehicle is empty. Pneumatic suspension can be made self-compensating. It is fitted to many heavy goods vehicles and buses, but is also becoming popular on some off-road light vehicles.

The pneumatic or air spring is a reinforced rubber bellow fitted between the axle and the chassis or vehicle body (Figs 4.12 and 4.13). An air compressor is used to increase or decrease the pressure depending on the load in the vehicle. This is done automatically, but some manual control can be retained for adjusting the height of the vehicle or stiffness of the suspension. Air springs can be thought of as being like a balloon or football on which the car is supported. The system involves compressors and air tanks. The system is not normally used on light vehicles.

Key fact

Air springs are like a (strong) balloon or football on which the car is supported.

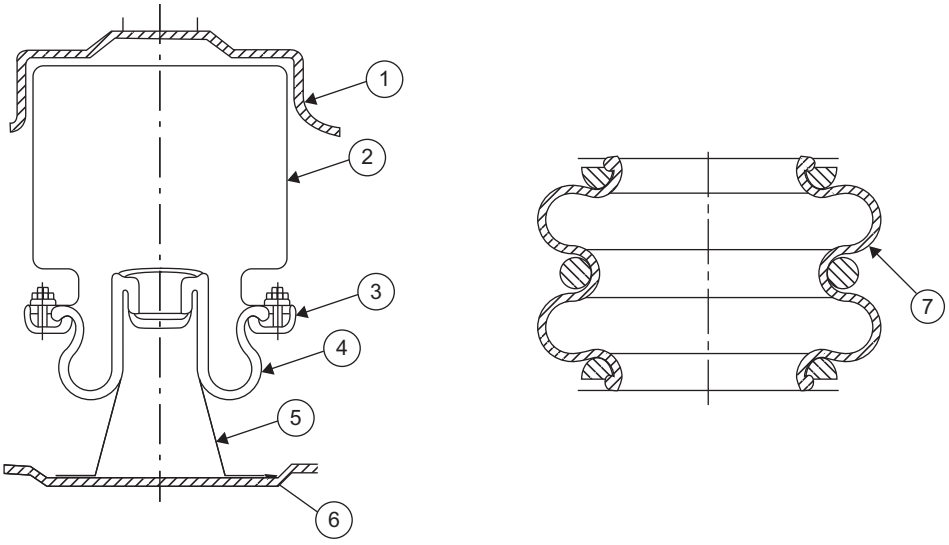

Figure 4.12 Air spring: 1, suspension mounting; 2, air chamber; 3, clamping ring; 4, rolling bellows; 5, piston; 6, suspension arm; 7, concertina bellows

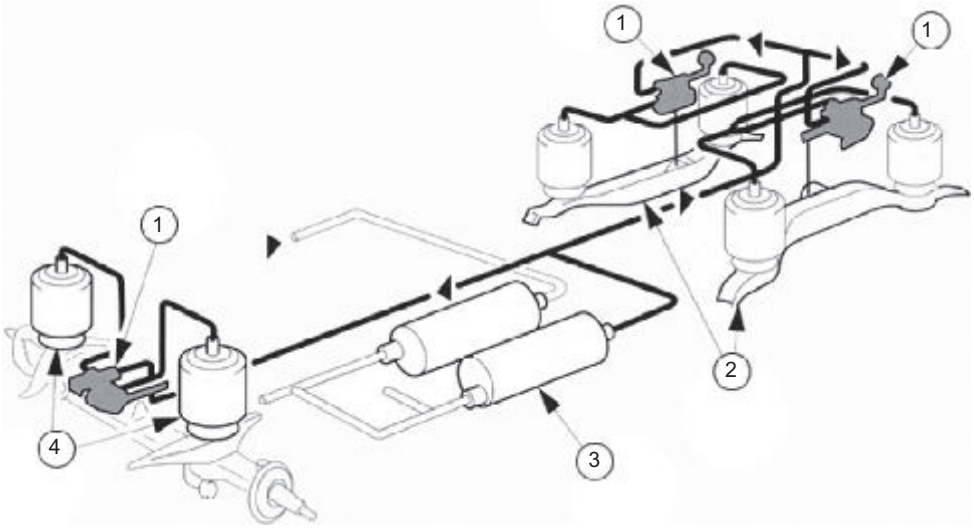

Figure 4.13 Air spring suspension system: 1, air spring valve; 2, axle support; 3, compressed air tank; 4, bellows

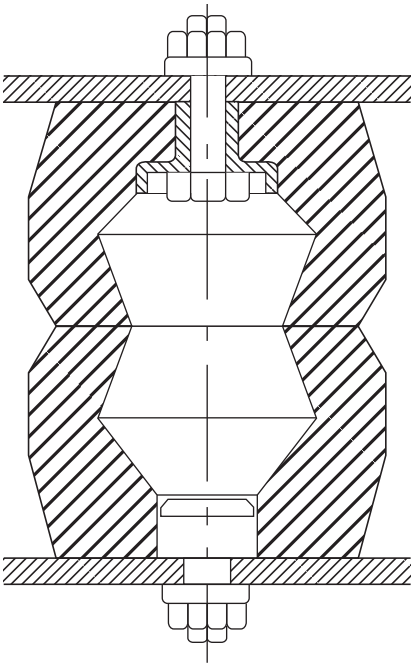

Figure 4.14 Hollow rubber spring

Rubber is now a very old suspension method, but never say never, as old ideas often come back! The suspension medium, or spring, is simply a specially shaped piece of rubber (Figs 4.14 and 4.15). This technique was used on early Mini cars, for example. The rubber did not require damping in most cases. Nowadays, rubber springs are only used as a supplement to other forms of springs. They are, however, popular on trailers and caravans.

Key fact

A hydragas suspension unit contains nitrogen gas under very high pressure.

In a hydragas suspension system, each wheel has a sealed displacer unit (Figs 4.16 and 4.17). This contains nitrogen gas under very high pressure, which works in much the same way as the steel spring in a conventional system. A damper is also incorporated within the displacer unit. The lower part of the displacer unit is filled with a suspension fluid (usually a type of wood alcohol). The units can be joined by pipes or used individually. Linking front to rear makes the rear unit rise

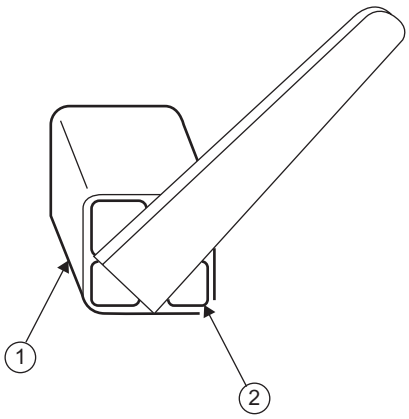

Figure 4.15 Torsion type rubber spring: 1, casing; 2, rubber insert

Figure 4.16 Hydragas suspension unit

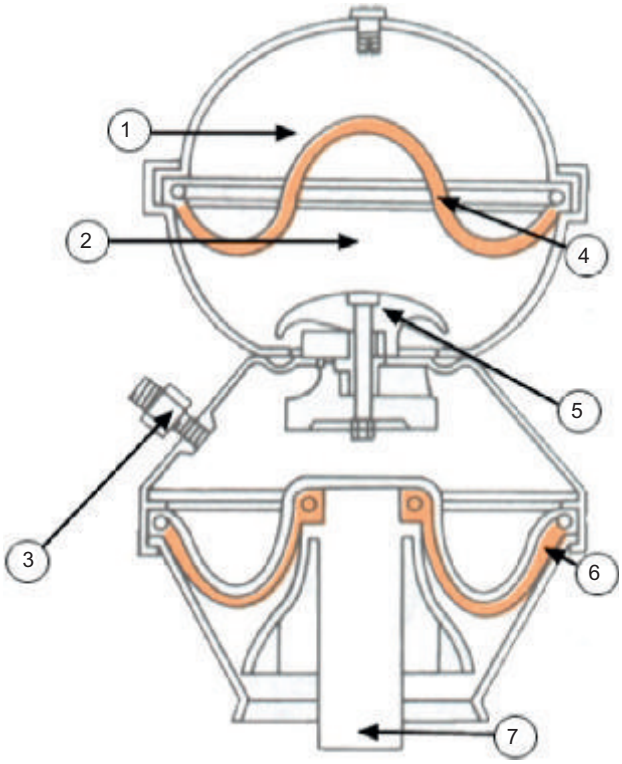

Figure 4.17 Suspension unit: 1, nitrogen gas spring; 2, fluid under high pressure; 3, connector for adding fluid; 4, flexible diaphragm; 5, damper valve; 6, flexible diaphragm; 7, strut connection to suspension

as the front unit is compressed by a bump. This tends to keep the vehicle level and reduce pitch. Ride height control can be achieved by pumping oil into or out of the working chamber.

The energy stored in any type of spring after a bump has to be got rid of or else the spring would oscillate (bounce up and down). A damper damps down these oscillations by converting the energy from the spring into heat. If working correctly, the spring should stop moving after just one bounce and rebound. Shock absorber is a term that is also used to describe a damper (Fig. 4.18).

Key fact

The energy stored in any type of spring after a bump has to be got rid of or else the spring would oscillate (bounce up and down).

Figure 4.18 Telescopic damper

Figure 4.19 MacPherson strut

Figure 4.20 Front suspension wishbone

Figure 4.21 Rubber stop

The combination of a coil spring with a damper inside it, between the wheel stub axle and the inner wing, is often referred to as a strut or, after its inventor, a MacPherson strut (Fig. 4.19). This is a very popular type of suspension.

A wishbone is a triangular shaped component with two corners hinged in a straight line on the vehicle body (Fig. 4.20). The third corner is hinged to the moving part of the suspension.

When a vehicle hits a particularly large bump, or if it is carrying a heavy load, the suspension system may bottom out (reach the end of its travel). A bump stop, usually made of rubber, is used to prevent metal-to-metal contact, which would cause damage (Fig. 4.21).

A link is a very general term used to describe a bar or other similar component that holds or controls the position of another component. Other terms may be used, such as tie-bar or tie-rod.

A beam axle is a solid axle from one wheel to the other. It is not now used on the majority of light vehicles. However, as it makes a very strong construction, it is common on heavy vehicles (Fig. 4.22).

Figure 4.22 Heavy vehicle axle

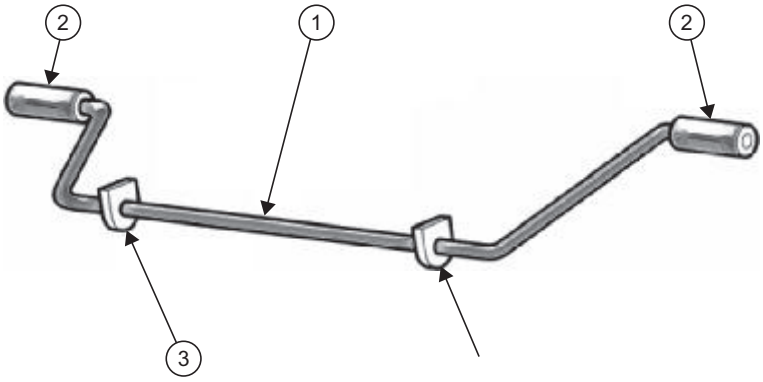

Figure 4.23 Shape of an anti-roll bar: 1, torsion bar; 2, pivots on suspension lower arms; 3, fixings to vehicle body

Independent front and rear suspension (IFS/IRS) was developed to meet the demand for improved ride quality and handling. The main advantages of independent suspension (i.e. not using a beam axle) are as follows:

- When one wheel is lifted or drops, it does not affect the opposite wheel.
- The unsprung mass is lower; therefore, the road wheel stays in better contact with the road.
- Problems with changing steering geometry are reduced.
- There is more space for the engine at the front.
- Softer springing with larger wheel movement is possible.

An anti-roll bar usually forms part of a suspension system (Fig. 4.23). The main purpose of an anti-roll bar is to reduce body roll on corners. The anti-roll bar can be thought of as a torsion bar. The centre is pivoted on the body and each

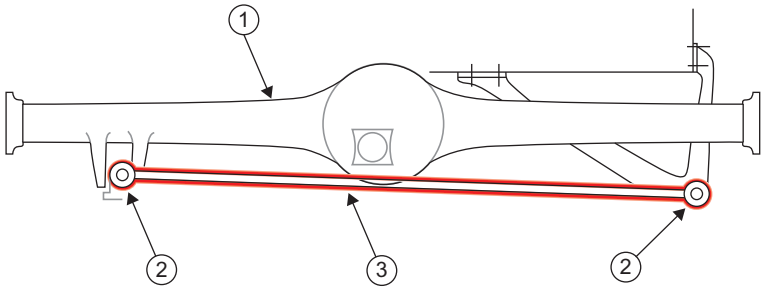

Figure 4.24 Rear axle with Panhard rod: 1, axle; 2, pivots; 3, Panhard rod

Key fact

An anti-roll bar is fitted to reduce body roll on corners.

Definitions

Lateral
Sideways.

Longitudinal
Along the length of a vehicle.

end bends to make connection with the suspension/wheel assembly. When the suspension is compressed on both sides, the anti-roll bar has no effect because it pivots on its mountings. As the suspension is compressed on just one side, a twisting force is exerted on the anti-roll bar. Part of this load is transmitted to the opposite wheel, pulling it upwards. This reduces the amount of body roll on corners.

The Panhard rod was named after a French engineer (Fig. 4.24). Its purpose is to link a rear axle to the body. The rod is pivoted at each end to allow movement. It takes up lateral forces between the axle and body, thus removing load from the radius arms. The radius arms have now to transmit only longitudinal forces.

A wide variety of suspension systems and components is used. Engineers strive to achieve optimum comfort and handling. However, these two main requirements are often at odds with each other. As is common with all vehicle systems, electronic control is one way that developments are now being made.

The requirements of the springs and suspension system can be summarized as follows. They:

- absorb road shocks from uneven surfaces
- control ground clearance and ride height
- ensure good tyre adhesion
- support the weight of the vehicle
- transmit gravity forces to the wheels.

Suspension springs can be made from a variety of materials and in many different ways. However, the most common is the coil spring. This is because it has many advantages and is reasonably inexpensive. A modern front suspension system is shown in Fig. 4.25.

4.1.2 Dampers/shock absorbers

As a spring is deflected, energy is stored in it. If the spring is free to move, the energy is released in the form of oscillations, for a short time, before it comes to rest. This principle can be demonstrated by flicking the end of a ruler placed on the edge of a desk. The function of the damper is to absorb the stored energy, which reduces the rebound oscillation. A spring without a damper would build up dangerous and uncomfortable bouncing of the vehicle.

Hydraulic dampers are the most common type used on modern vehicles (Fig. 4.26). In a hydraulic damper, the energy in the spring is converted into heat. This is caused as the fluid (a type of oil) is forced rapidly through small holes (orifices).

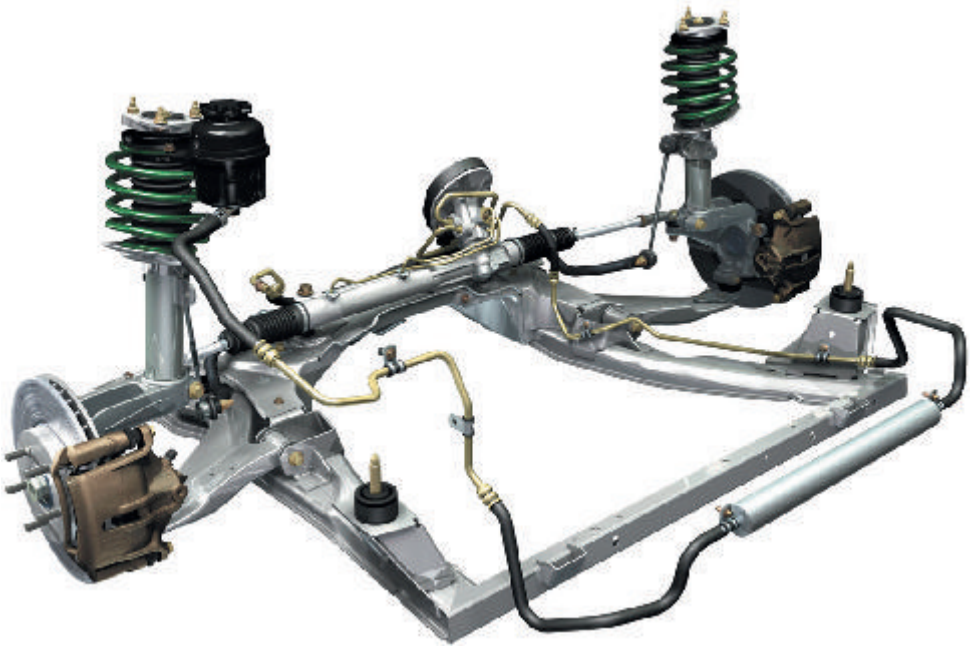

Figure 4.25 Modern front suspension system. (Source: Jaguar/Ford Media)

Figure 4.26 Dampers form part of the struts on this system. (Source: Ford Media)

The oil temperature in a damper can reach over 150°C during normal operation. The functions of dampers can be summarized as follows. They:

- ensure directional stability
- ensure good contact between the tyres and the road
- prevent build-up of vertical movements
- reduce oscillations
- reduce wear on tyres and chassis components.

Safety first

The oil temperature in a damper can reach over 150°C during normal operation.

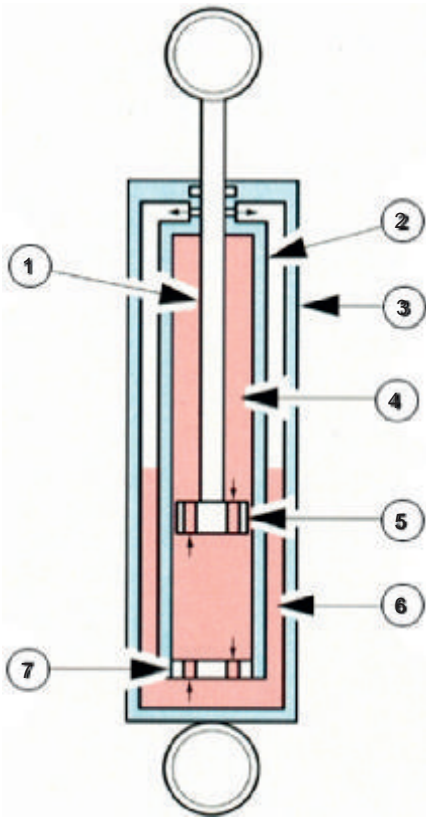

Figure 4.27 Twin-tube damper: 1, piston rod; 2, inner tube; 3, outer tube; 4, oil chamber; 5, piston with valves; 6, reservoir space; 7, inner tube bottom valves. (Source: Ford Motor Company)

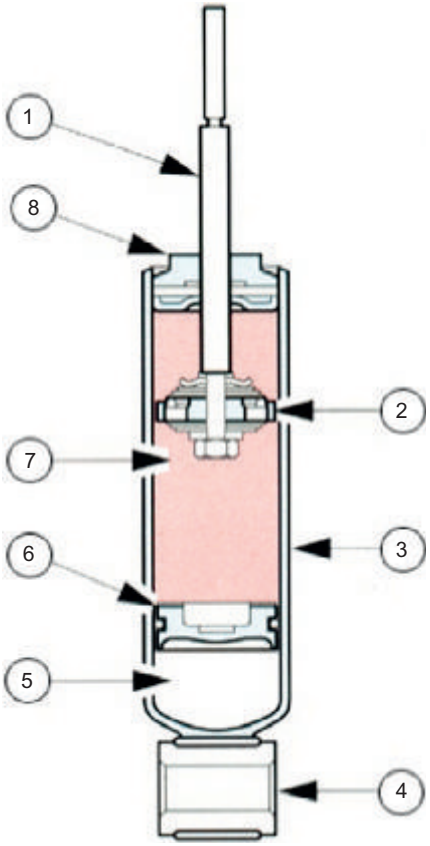

Figure 4.28 Single-tube damper: 1, piston rod; 2, working piston; 3, tube; 4, mounting bush; 5, gas chamber; 6, separator piston; 7, oil chamber; 8, seal. (Source: Ford Motor Company)

The twin-tube telescopic damper is the most commonly used type of telescopic damper (Fig. 4.27). It consists of two tubes. An outer tube forms a reservoir space and contains the oil displaced from an inner tube. Oil is forced through a valve by the action of a piston as the damper moves up or down. The reservoir space is essential to make up for the changes in volume as the piston rod moves in and out.

Key fact

The single-tube telescopic damper is often referred to as a gas damper.

The single-tube telescopic damper is often referred to as a gas damper (Fig. 4.28). However, the damping action is still achieved by forcing oil through a restriction. The gas space behind a separator piston compensates for the changes in cylinder volume, which are caused as the piston rod moves. The gas is at a pressure of about 25 bar.

A twin-tube gas damper is a combination of the standard twin-tube and the single tube gas system. The gas cushion is used in this case to prevent oil foaming. The gas pressure on the oil prevents foaming, which in turn ensures constant operation under all operating conditions. Gas pressure is set at about 5 bar. If bypass grooves are machined in the upper half of the working chamber, the damping rate can be made variable. With light loads the damper works in this area with a soft damping effect. When the load is increased the piston moves lower down the working chamber away from the grooves, resulting in a full damping effect.

There are dampers where the damping rate can be controlled by solenoid valves inside the units. With suitable electronic control, the characteristics can be

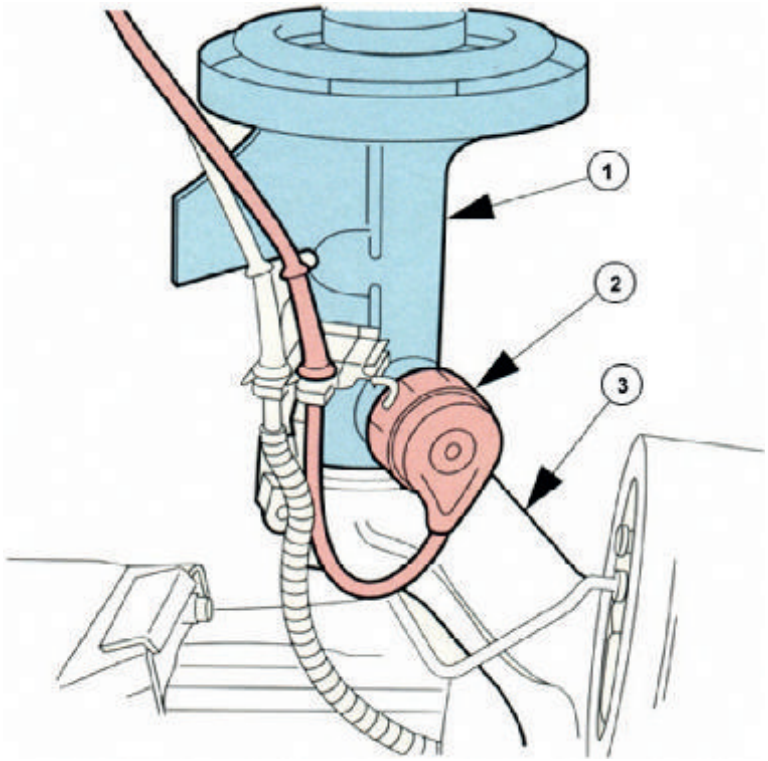

Figure 4.29 Damper with electronic control: 1, damper; 2, solenoid valve; 3, stub axle. (Source: Ford Motor Company)

changed within milliseconds to react to driving and/or load conditions. When it is activated, the solenoid allows some of the oil to be diverted (Fig. 4.29).

Dampers (or shock absorbers) are used to prevent the suspension springs oscillating. This improves handling, comfort and safety.

Key fact

Dampers (or shock absorbers) are used to prevent the springs oscillating.

4.1.3 Suspension layouts

As with most design aspects of the vehicle, compromise often has to be reached between performance, body styling and cost.

Twin, unequal-length wishbone suspension is widely used on light vehicles (Fig. 4.30). A coil spring is fitted between two suspension arms. The suspension arms are 'wishbone' shaped and the bottom end of the spring fits in a plate in the lower wishbone assembly. The top end of the spring is located in a section of the body. The top and bottom wishbones are attached to the chassis by rubber bushes. A damper is fitted inside the spring. The stub axle and swivel pins are connected to the outer ends of the upper and lower wishbones by ball or swivel joints.

This strut type of suspension system has been used now for many years. It is often referred to as the MacPherson strut system. With this system, the stub axle is combined with the bottom section of a telescopic tube, which incorporates a damper. The bottom end of the strut is connected to the outer part of a transverse link by means of a ball joint. The inner part of the link is secured to the body by rubber bushes. The top of the strut is fixed to the vehicle body by a bearing, which allows the complete strut to swivel. A coil spring is located between the upper and lower sections of the strut (Fig. 4.31).

Key fact

A strut type of suspension is often referred to as a MacPherson strut system.

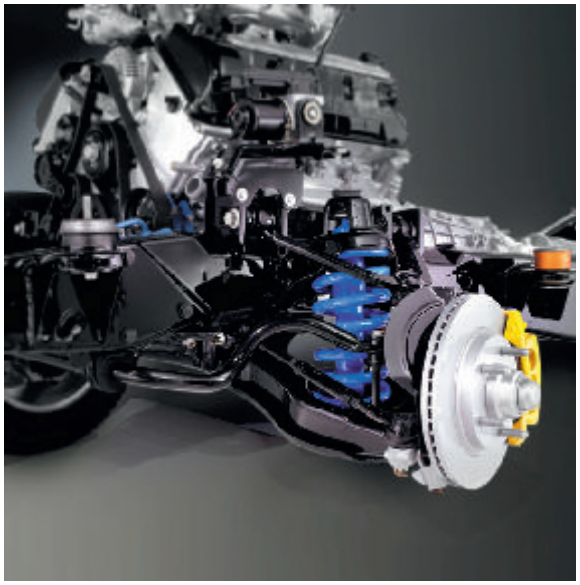

Figure 4.30 Twin, unequal-length wishbone suspension system

Figure 4.31 Suspension strut in position

Figure 4.32 Rear struts

A transverse arm with MacPherson strut is the most popular method in current use. This system uses a combination of the spring, damper, wheel hub, steering arm and axle joints in one unit. There are only slight changes in track and camber with suspension movement. Forces on the joints are reduced because of the long strut. However, the body must be strengthened around the upper mounting and a low bonnet line is difficult.

There are other variations of front suspension layouts. However, the two most popular are the MacPherson strut and the unequal length wishbone systems.

The systems used for the rear suspension of light vehicles vary depending on the requirements of the vehicle. In addition, the systems are different if the vehicle is front- or rear-wheel drive. Older and heavy vehicles use leaf-type springs. The two main types using independent rear suspension are:

- the strut type for front-wheel drive (Fig. 4.32)
- trailing and semi-trailing arms with coil springs for rear-wheel drive (Fig. 4.33).

The strut system on the rear is much the same as used at the front of the vehicle (Fig. 4.34). Note that suitable links are used to allow up-and-down movement but to prevent the wheel moving in any other direction. Some change in the wheel geometry is designed in, to improve handling on corners.

Trailing arm suspension and semi-trailing arm suspension both use wishbone-shaped arms hinged on the body. Trailing arms are at right angles to the vehicle centre line and semi-trailing arms are at an angle (Figs 4.35 and 4.36). This changes the geometry of the wheels as the suspension moves. The final drive and differential unit is fixed with rubber mountings to the vehicle body. Drive shafts must therefore be used to allow drive to be passed from the fixed final drive to the movable wheels. The coil springs and dampers are mounted between the trailing arms and the vehicle body.

Figure 4.33 Rear semi-trailing arm

Key fact

Trailing arm and semi-trailing arm systems both use wishbone-shaped arms hinged on the body.

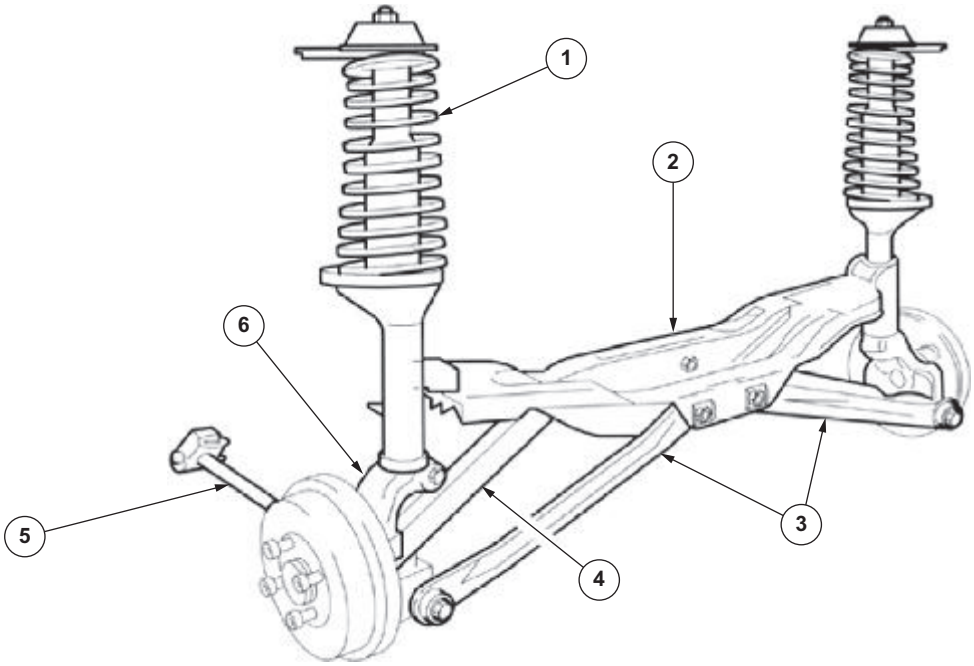

Figure 4.34 Rear suspension struts: 1, coil spring; 2, cross-member; 3, rear transverse arms; 4, front transverse arms; 5, radius arm; 6, stub axle

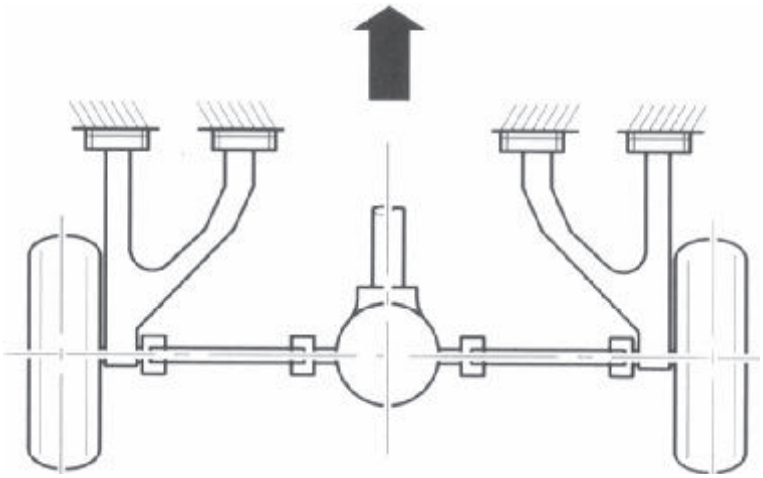

Figure 4.35 Trailing arms pivot at 90° to the length of the vehicle

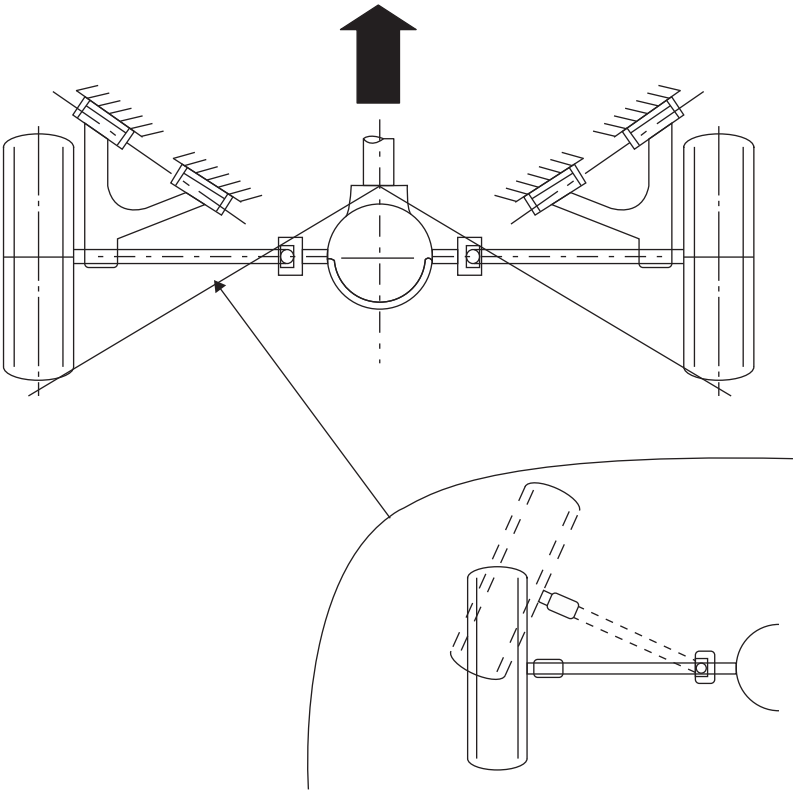

Figure 4.36 Semi-trailing arms are at an angle

Figure 4.37 This method is used on older and larger vehicles with live, fixed rear axles

The final drive, differential and axle shafts are all one unit with a rigid axle and leaf spring layout. With this system, the rear track remains constant, reducing tyre wear. It has good directional stability because there is no camber change due to body roll on corners. This is a strong design for load carrying (Fig. 4.37). However, it has a high unsprung mass. The interaction of the wheels causes lateral movement, reducing tyre adhesion when the suspension is compressed on one side.

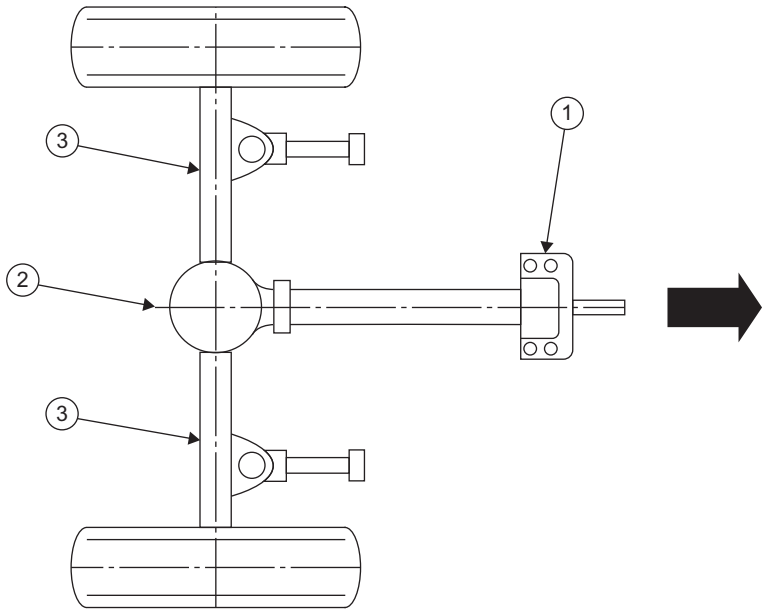

Figure 4.38 'A' bracket system: 1, central joint; 2, final drive; 3, half shafts

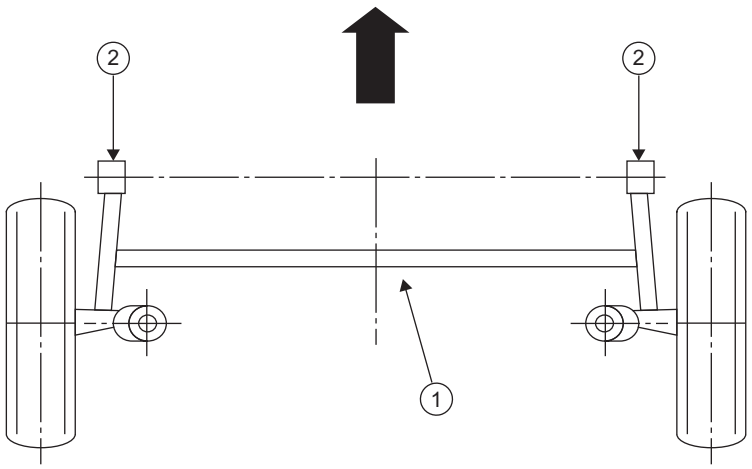

Figure 4.39 Torsion beams twist to provide the spring action: 1, U-section spring; 2, trailing arms mounted to the body

A rigid axle with an A-bracket system has a solid axle with coil springs and a central joint supports the axle on the body (Fig. 4.38). This tends to make the rear of the vehicle pull down on braking, which stabilizes the vehicle. It results in a high unsprung mass.

On a torsion beam trailing arm axle, two links are used, connected by a U-section that has low torsional stiffness but a high resistance to bending (Fig. 4.39). Track and camber do not change as the suspension moves. It has a low unsprung mass and is simple to produce. It is a space-saving design but torsion bar springing on this system can be more expensive than coil springs.

In the system shown in Fig. 4.40 two links are welded to an axle tube or U-section. The lateral forces are taken by a Panhard rod. Track and camber do not change as the suspension moves and simple flexible joints connect it to the bodywork. Torsion bar springing on this system, however, can be more expensive than coil springs.

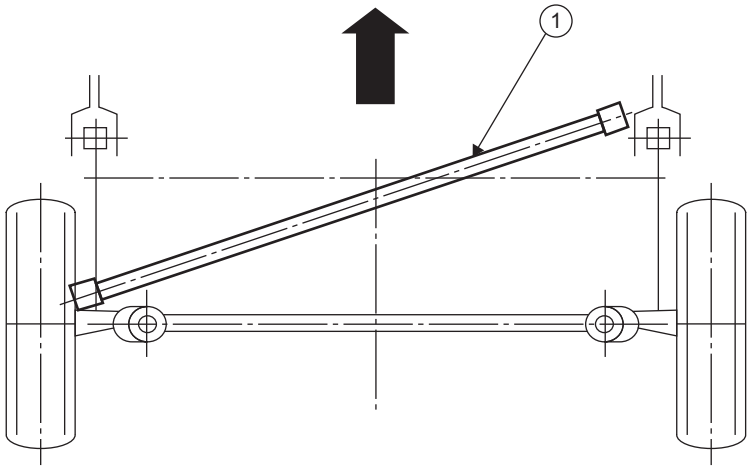

Figure 4.40 Panhard rod and torsion beam system: 1, Panhard rod

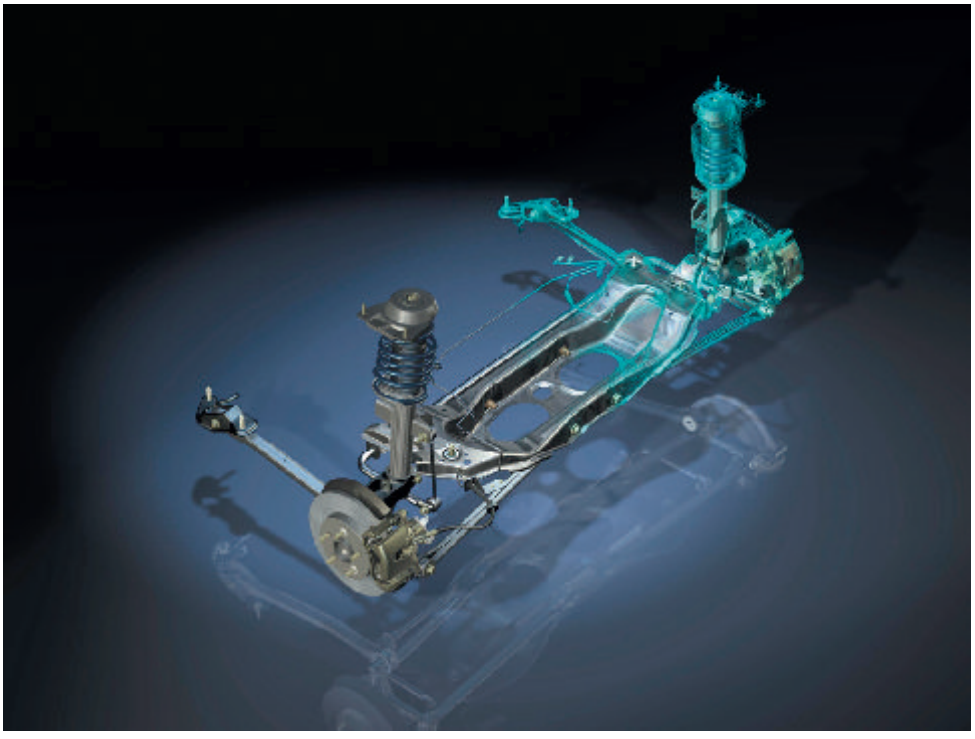

Figure 4.41 'Quadralink' suspension. (Source: Ford Media)

There are various rear suspension systems, each with its advantages and disadvantages, and engineers strive to achieve the optimum design. The system shown in Fig. 4.41 is known as 'quadralink'. It is very similar to front strut systems.

Key fact

Conventional suspension systems are a compromise between soft springs for comfort and hard springs for performance.

4.1.4 Active suspension

Electronic control of suspension or active suspension, like many other innovations, was born in the world of Formula 1 (F1). It is now slowly becoming more popular on production vehicles. Conventional suspension systems are always a compromise between soft springs for comfort and harder springing for

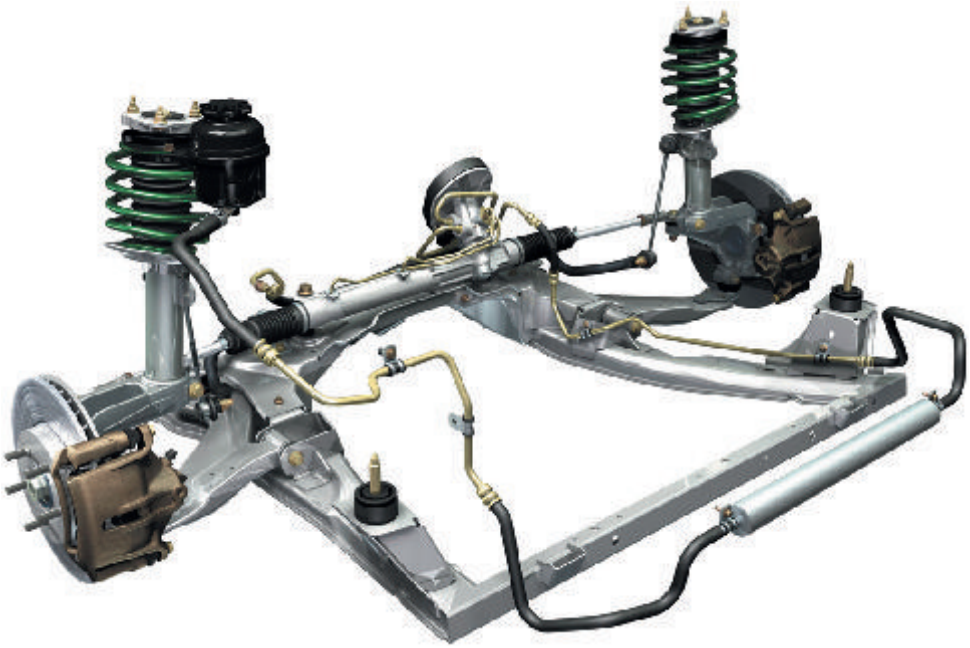

Figure 4.42 Jaguar suspension system. (Source: Jaguar Media)

better cornering capability. Active systems have the ability to switch between the two extremes.

A traditional or a conventional suspension system, consisting of springs and dampers, is passive. In other words, once it has been installed in the car, its characteristics do not change.

The main advantage of a conventional suspension system is its predictability. Over time, the driver will become familiar with a car's suspension and understand its capabilities and limitations. The disadvantage is that the system has no way of compensating for situations beyond its original design. The main benefits of active suspension are:

- improvements in ride comfort, handling and safety
- predictable control of the vehicle under different conditions
- no change in handling between laden and unladen.

The benefits are considerable and as component prices fall, the system will become available on more vehicles. It is expected that more off-road vehicles may be fitted with active suspension in the near future.

An active suspension system (also known as computerized ride control) has the ability to adjust itself continuously (Fig. 4.43). It monitors and adjusts its characteristics to suit the current road conditions. As with all electronic control systems, sensors supply information to an electronic control unit (ECU) which in turn outputs to actuators. By changing its characteristics in response to changing road conditions, active suspension offers improved handling, comfort, responsiveness and safety.

Active suspension systems usually consist of the following components:

- ECU
- adjustable dampers and springs
- sensors at each wheel and throughout the car
- Levelling compressor (some systems).

Definition

Active suspension
A system that can change its properties depending on conditions (also known as computerized ride control).

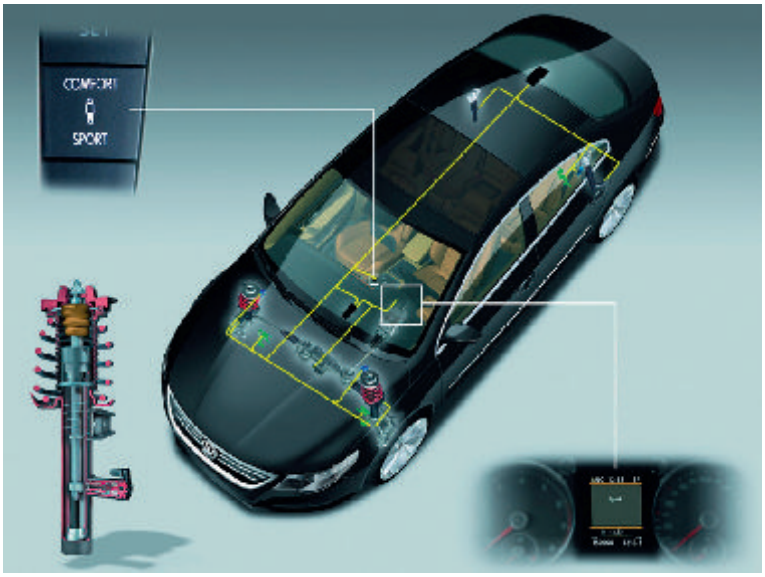

Figure 4.43 Active suspension also allows adjustments, in this case, between sport and comfort settings. (Source: Volkswagen Media)

Figure 4.44 Suspension strut and actuator connection. (Source: Delphi Media)

Key fact

Active suspension works by sensing changes in conditions and feeding that information to the ECU.

Active suspension works by constantly sensing changes in the road surface and feeding that information to the ECU, which in turn controls the suspension springs and dampers. These components then act upon the system to modify the overall suspension characteristics by adjusting damper stiffness, ride height (in some cases) and spring rate.

The suspension can be controlled in a number of ways. However, in most cases it is done by controlling the oil restriction in the damper. On some systems, ride height is controlled by opening a valve and supplying pressurized fluid from an engine-driven compressor. Later systems are starting to use special fluid in the dampers that reacts to a magnetic field, which is applied from a simple electromagnetic coil.

The improvements in ride comfort are considerable, which is why active suspension technology is becoming more popular. In simple terms, sensors provide the input to a control system that in turn actuates the suspension dampers in a way that improves stability and comfort.

4.2 Steering

4.2.1 Introduction to steering

Key fact

On early cars, the entire front axle was steered by way of a pivot (fifth wheel) – like a horse and cart!

The development of steering systems began before cars were invented. On early cars, the entire front axle was steered by way of a pivot (fifth wheel) situated in the centre of the vehicle. The steering accuracy was not very good, there was a serious risk of overturning and the tyre wear was significant.

In 1817, Rudolph Ackermann patented the first stub axle steering system in which each front wheel was fixed to the front axle by a joint. This made it possible to cover a larger curve radius with the wheel on the outside of the curve than with the front wheel on the inside of the curve (Fig. 4.45).

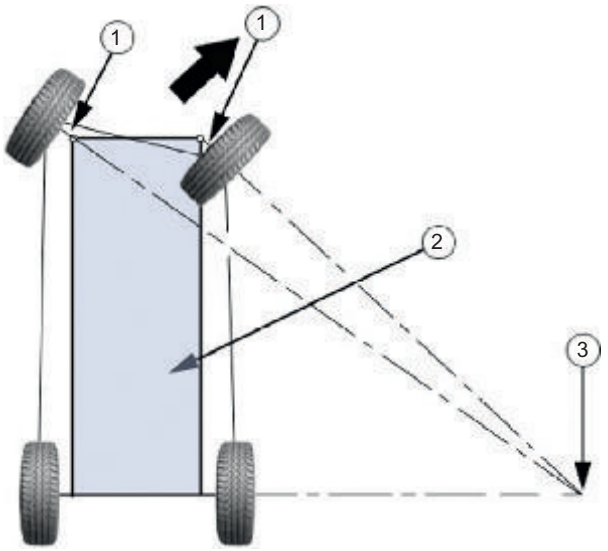

Figure 4.45 Ackermann steering method: 1, stub axles; 2, vehicle support area; 3, imaginary common centre

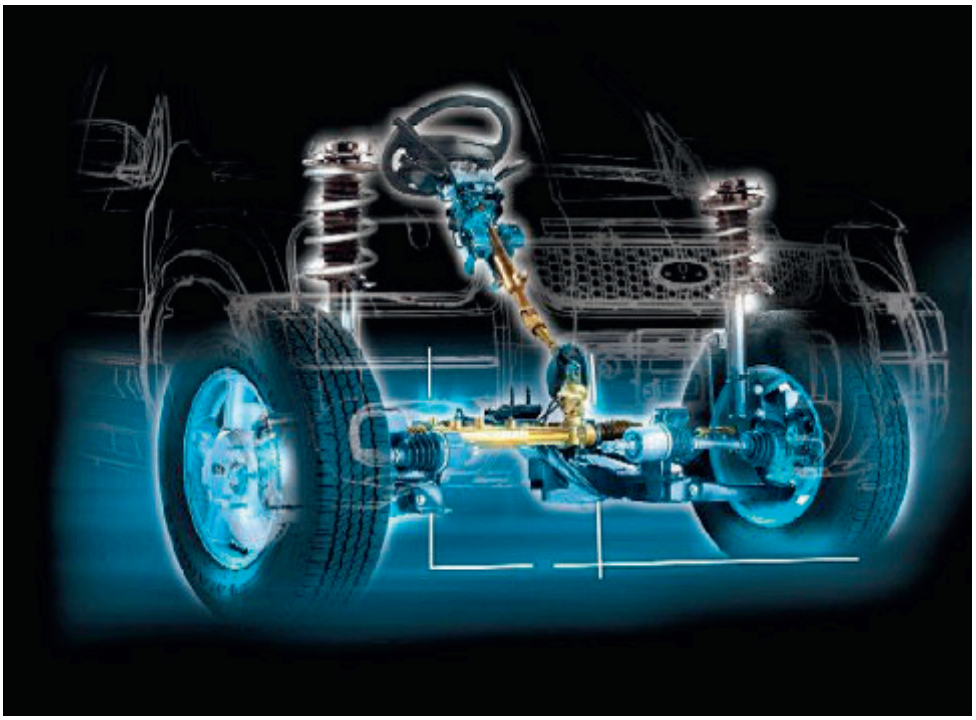

Figure 4.46 Steering rack in position. (Source: Ford Media)

Rack and pinion steering was developed at an early age in the history of the car. However, this became popular when front-wheel drive was used more, since it requires little space and production costs are lower (Fig. 4.46). The first hydraulic power steering was produced in 1928. However, since there was no real demand for this until the 1950s, the development of power steering systems stagnated.

Increasing standards of comfort stimulated the demand for power steering systems. Speed-sensitive or variable-assistant power steering (VAPS) systems were developed using electronic controls. The demand for safety and comfort will lead to further improvements in steering systems.

Definition

Ackermann angle
The angle of the inside wheel in relation to the outside wheel when the front wheels are steered. The inside front wheel turns at a sharper angle than the outside wheel.

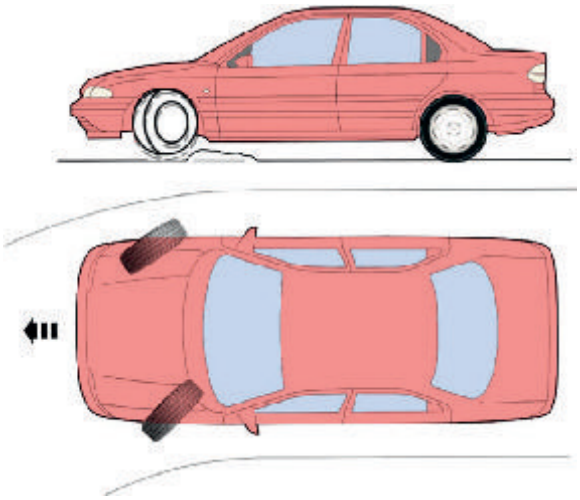

Figure 4.47 Suspension and steering interact

Motor vehicles are generally steered via the front wheels, the rear wheels following the front wheels on a smaller radius. With motor vehicles, two factors have to be taken into account:

- dead weight or axle loading
- the contact area of the steered wheels.

To overcome the friction forces more easily, many different types of steering gear have been developed. Power steering, in particular, reduces the effort required and increases safety and comfort. Steering systems must be capable of:

- automatically returning the steered front wheels to the straight-ahead position after cornering (self-centring action)
- translating the steering wheel rotation so that only about two rotations of the steering wheel are necessary for a steering angle of about 40°.

Key fact

Suspension faults will influence the vehicle's steering characteristics.

Steering and suspension must always be regarded as a unit (Fig. 4.47). If the suspension system is not working correctly, it will have a considerable influence on the vehicle's steering characteristics. For example, defective shock absorbers or dampers reduce the wheel contact with the road, limiting the ability to steer the vehicle. The driving safety of a motor vehicle depends largely on the steering. Reliable steering at high speeds is required, together with easy manoeuvrability.

Crucial to the manoeuvrability of a motor vehicle is the turning circle, which in turn is directly dependent on the track circle. Designers strive for the smallest possible track and turning circle. The wheel housing should enclose the wheels as tightly as possible; however, sufficient clearance must be left so that the tyres do not rub when the wheels are turned.

With the stub axle, Ackerman type of steering, the stub axle of the steered front wheel is swivelled about the steering axis (Fig. 4.48). When steering, the wheelbase remains constant. The space between the steered wheels can be used for the installation of deep-seated components such as the engine. The low centre of gravity contributes to road handling characteristics. Even at large steering angles, the stability of the vehicle is maintained since the area of support is only slightly reduced.

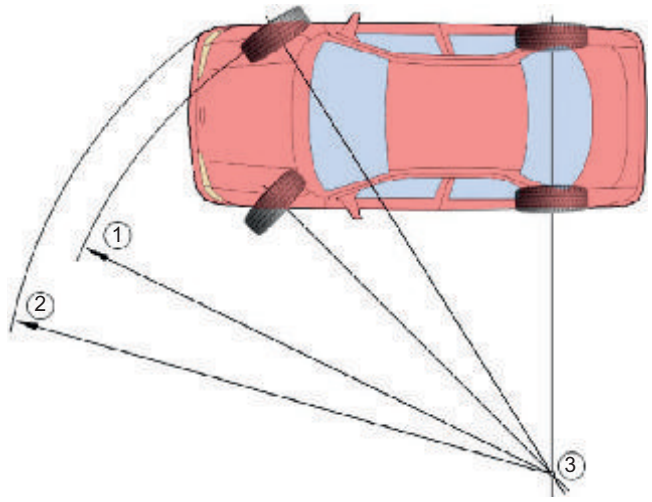

Figure 4.48 Front axle geometry: 1, track circle; 2, turning circle; 3, common centre

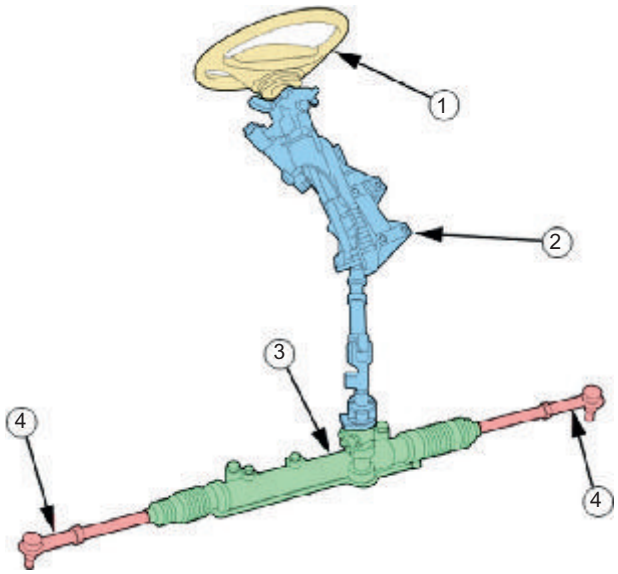

Figure 4.49 Ford steering system: 1, steering wheel; 2, column; 3, rack; 4, track rod ends

4.2.2 Steering racks and boxes

In order to transmit the steering movements of the driver to the wheels, several components are required (Fig. 4.49). The steering movement is transmitted by way of the steering wheel, shaft, gear and linkage to the front wheels. The rotational movement of the steering wheel is transmitted via the steering shaft to the steering pinion in the steering gear. The steering shaft is supported in the steering column tube, which is fixed to the vehicle body.

The steering gear translates (reduces) the steering force applied by the driver. It also converts the rotational movement of the steering wheel into push or pull movements of the track rods. The converted movement is transmitted to the linkage, which in turn moves the wheels in the desired steering direction. Track rods are required to transmit the steering movement from the steering gear to the front wheels. Different track rods are used depending on the type of front axle.

Key fact

The steering gear translates (reduces) the steering force applied by the driver.

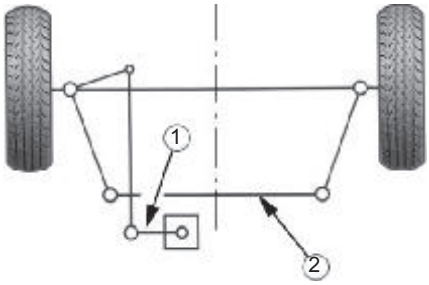

Figure 4.50 One-piece track rod: 1, steering box drop arm; 2, solid track rod

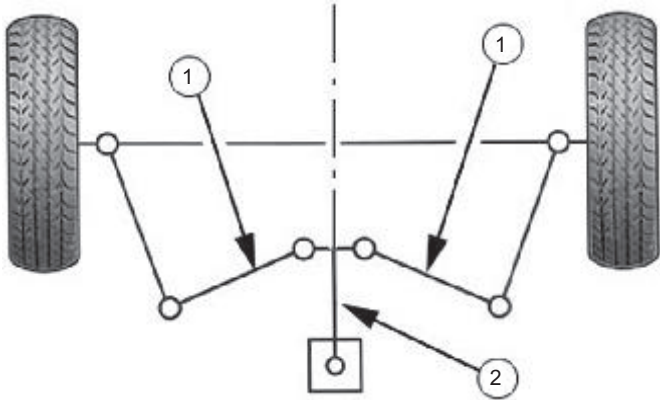

Figure 4.51 Two-piece track rod: 1, track rod; 2, drop arm

The steering rack is the simplest design of steering linkage, needing only three joints. One-piece track rods are found only with rigid axles, since the distance of the steering swivel pins or joints cannot vary (Fig. 4.50).

Two-piece track rods may be split centrally or to one side (Fig. 4.51). They are necessary on vehicles with independent suspension, since the suspensions of the steered wheels are compressed independently of one another. The split reduces the effect of bump steering.

In the type of steering that is now almost universal on light vehicles, the steering linkage is operated by a rack and pinion. Two designs are encountered as shown in Fig. 4.52, number 1 being by far the more common. The rack either forms part of the track rod or acts directly on the split track rod.

Swivels of some sort are necessary for steering movement. The kingpin is the predecessor of the ball joint (Fig. 4.53). It is only fitted in commercial vehicles and a few off-road vehicles, because these generally have rigid front axles in which the distances of the track rods do not vary. The kingpin is not maintenance free–it must be supplied with grease via a grease nipple.

Ball joints allow parts of the steering linkage to rotate about the longitudinal axis of the ball joint (Fig. 4.54). They also allow limited swivel movements transversely to the longitudinal axis. The lubricated ball pivot is supported in steel cups or between preloaded plastic cups. A gaiter prevents lubricant losses. Ball joints are generally maintenance free and must always be renewed if the gaiter is damaged.

There are several different steering box designs. The first, shown in Fig. 4.55, consists of a steering screw on which the steering nut is displaced axially as the steering wheel is moved. Slide rings on the circumference of the steering

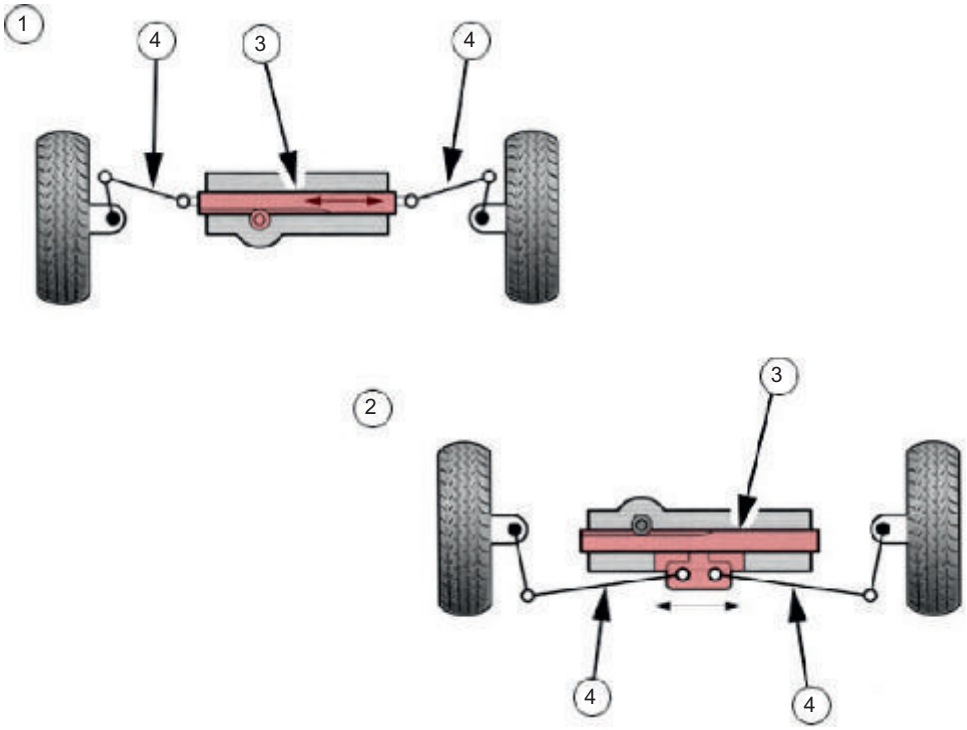

Figure 4.52 Basic steering racks: 1, rack is effectively part of the track rod; 2, rack acts on a split track rod; 3, rack; 4, track rod

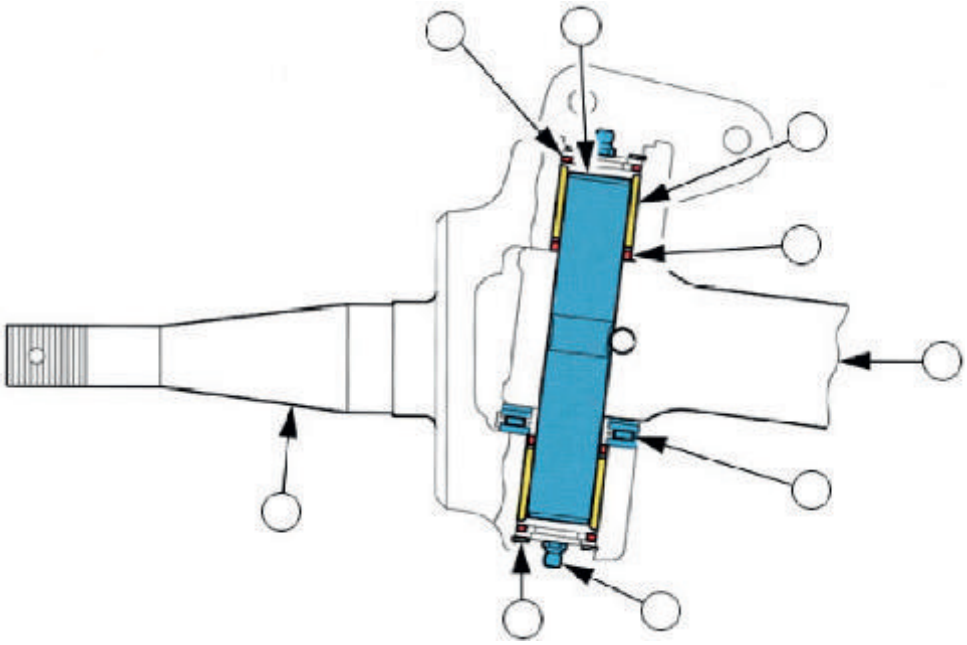

Figure 4.53 Kingpin on a steered front axle: 1, O-ring; 2, kingpin; 3, bush; 4, lip seal; 5, axle; 6, thrust bearing; 7, grease nipple; 8, circlip/snap ring; 9, stub axle

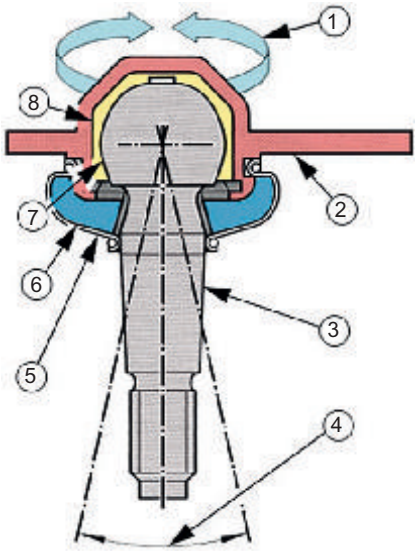

Figure 4.54 Two ball joints are used instead of a kingpin: 1, rotation; 2, connecting flange; 3, taper; 4, possible swivel movement; 5, gaiter; 6, lubricating grease; 7, ball pivot; 8, plastic cup

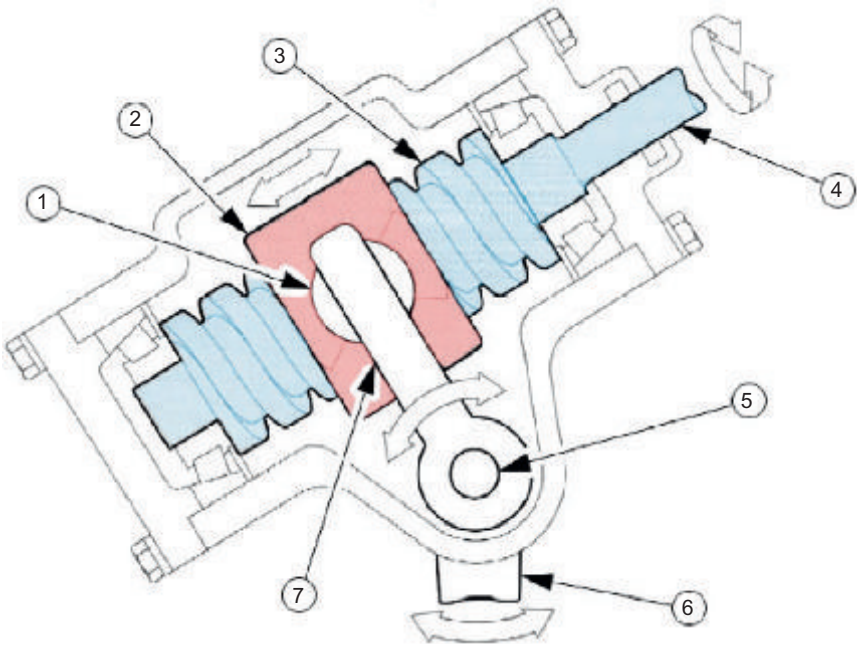

Figure 4.55 Screw and nut steering box: 1, slide rings; 2, steering nut; 3, steering screw; 4, steering shaft; 5, shaft to drop arm; 6, drop arm; 7, steering fork. (Source: Ford Motor Company)

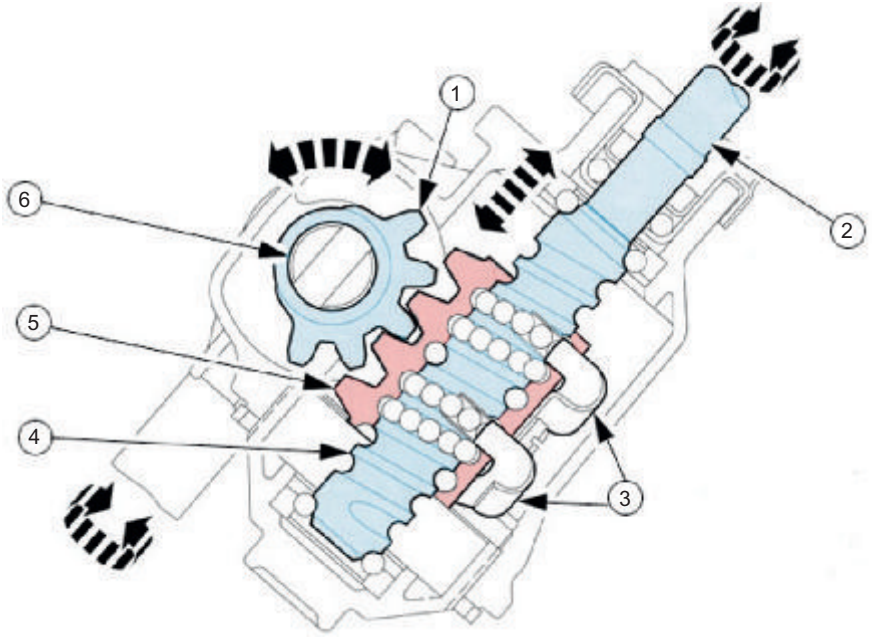

Figure 4.56 Recirculating ball steering box: 1, gear sector; 2, steering shaft; 3, ball return tubes; 4, steering screw; 5, steering nut; 6, shaft to drop arm. (Source: Ford Motor Company)

Key fact

There are a number of different steering box designs: a steering rack is a type of steering box; it just doesn't look like one.

nut transmit the movement to the steering fork and thereby to the drop arm. The drop arm performs a movement of up to 90°. In this type of steering the wear is relatively high. The steering nut play cannot be adjusted, and this is a disadvantage. With this type of steering gear, the steering is linear.

Owing to the high friction in the screw and nut steering gear, gears with roller friction have become more common. In the recirculating ball steering gear, the steering screw and steering nut have ball groove threads (Fig. 4.56). The

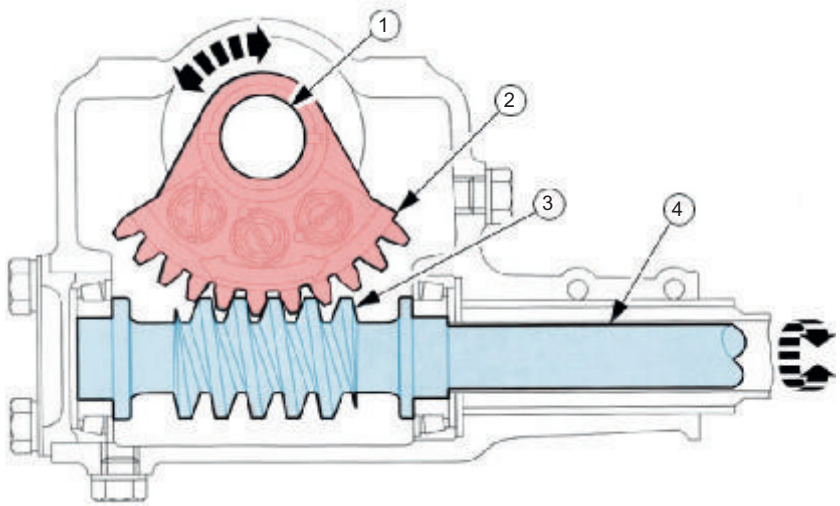

Figure 4.57 Worm and sector steering box: 1, shaft to drop arm; 2, sector; 3, cylindrical worm gear; 4, steering shaft. (Source: Ford Motor Company)

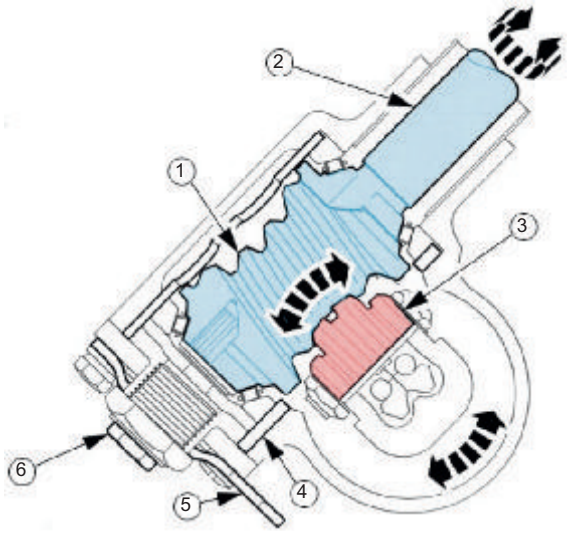

Figure 4.58 Worm and roller steering box: 1, hourglass work gear; 2, steering shaft; 3, roller; 4, eccentric bush; 5, backlash adjustment lever; 6, steering shaft adjustment screw. (Source: Ford Motor Company)

threads do not touch one another because they form channels for the balls. When the steering screw is turned, the balls roll in the ball groove thread in two closed recirculating ball races. The balls are returned by two tubes. The drop arm is moved by means of a gear sector. The advantage of the recirculating ball steering gear is that it functions virtually free of wear.

Key fact

The recirculating ball steering box has very low friction and is therefore virtually free of wear.

The worm and sector steering gear has a cylindrical worm, which, owing to its screw motion, turns a steering sector back and forth (Fig. 4.57). The drop arm is fixed to the sector. It can perform a swivel movement of up to about 70°. Worm steering gears are characterized by high transmission ratios, for example 22:1. One disadvantage is the high wear due to the sliding friction between the sector and the cylindrical worm. In addition, large steering forces are required. In this type of steering gear, the steering is linear.

The worm and roller steering gear has a roller instead of the sector (Fig. 4.58). The steering worm is not cylindrical but tapers towards the middle like an hourglass.

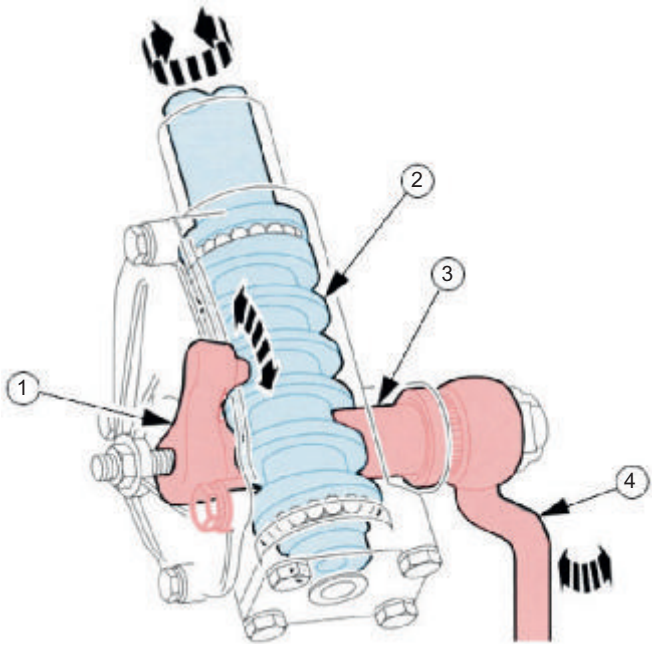

Figure 4.59 Worm and rolling finger steering box: 1, rolling finger; 2, work with progressive pitch; 3, shaft; 4, drop arm. (Source: Ford Motor Company)

The roller, driven by the worm, can thus perform a steering movement about its centre when the steering wheel is turned. The drop arm can perform a swivel movement of up to 90°. Advantages include low wear, ease of steering and that a small space is required. The steering play can be adjusted and the steering is free of play when running in a straight line. With this type of steering gear, the steering is linear.

The worm and rolling finger steering gear has a cylindrical screw with an uneven thread pitch (Fig. 4.59). When the worm is rotated, the tapered rolling finger rolls on the flanks of the worm. The rolling finger is displaced. This movement is converted by the shaft into a swivel movement of the drop arm. This system has low wear and ease of steering. The longitudinal play of the worm and the shaft, and the play between rolling finger and worm thread, are adjustable. In this type of steering gear, the steering is progressive owing to the uneven thread pitch on the worm.

Now back to the most common method used on cars (Fig. 4.60); but remember, old ideas often come back. The steering rack housing contains a toothed pinion, which meshes with the rack. By turning the steering wheel and hence the pinion, the rack is displaced transversely to the direction of travel. A spring-loaded pressure pad presses the rack against the pinion. For this reason, the steering gear always functions without backlash. At the same time, the sliding friction between pressure pad and rack acts as a damper to absorb road shocks. Advantages of rack and pinion steering include the shallow construction, very direct steering, good steering return and the low cost of manufacture.

It is also possible to make a non-linear or progressive pitch steering rack (Fig. 4.61). The basic construction and the advantages are similar to those of a rack and pinion steering gear with constant pitch. In a rack and pinion steering gear with variable pitch, a rack is used which has teeth that diminish in size towards the ends. This makes it possible to increase the transmission ratio

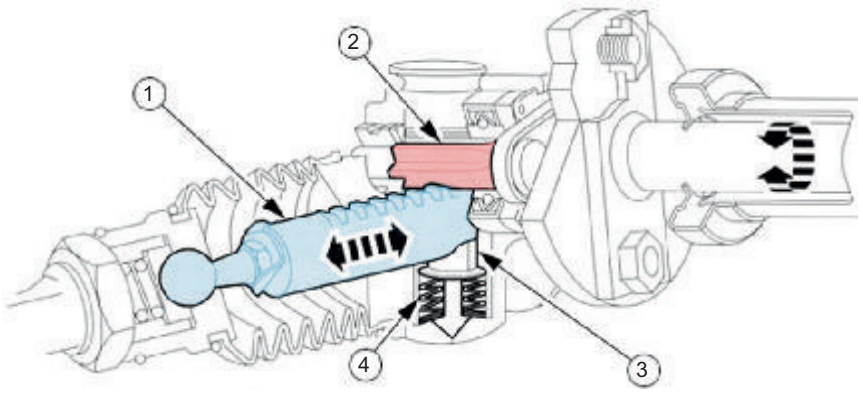

Figure 4.60 Standard linear steering rack: 1, rack; 2, pinion; 3, pressure pad; 4, vibration damper. (Source: Ford Motor Company)

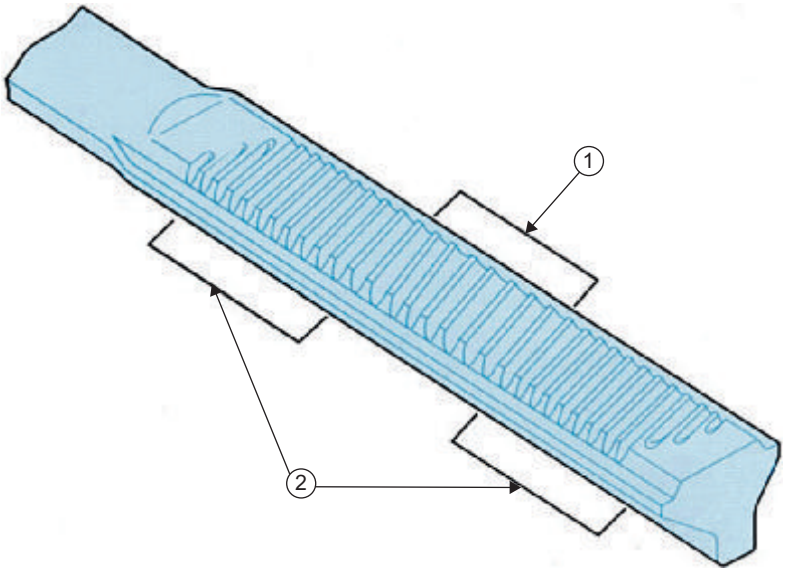

Figure 4.61 Progressive pitch steering rack: 1, large rack movement and larger effort needed; 2, smaller movement and less effort required

constantly. This means, in practice, that more steering wheel turns but less effort is required to turn the wheels. As a result, the steering moves more easily when applying lock than when moving in a straight line. This makes parking considerably easier.

There is a wide range of steering boxes and steering layouts. On light vehicles, the most common by far is the steering rack. This is because it has a shallow construction, is very direct, has good steering return and the cost of manufacture is low.

Key fact

A steering rack is described as being 'direct' because there are fewer joints than in other types of steering box, and hence there is reduced free play.

4.2.3 Steering geometry

The wheels of a vehicle cover different distances when cornering. At low speed, optimum rolling of the wheels is only possible if the centre lines of the stub axles, with the front wheels turned, meet the extended centre line of the rear axle. In this case, the paths covered by the front and rear wheels have a common centre.

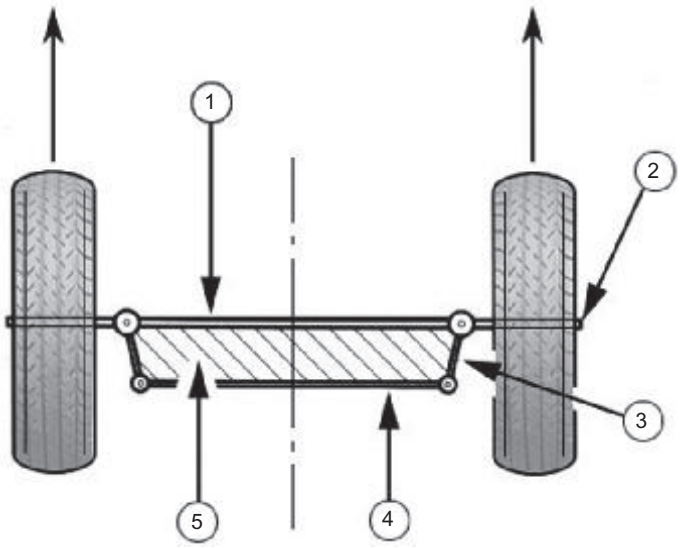

Figure 4.62 The Ackermann principle (straight): 1, front axle; 2, stub axle; 3, steering arm; 4, track rod; 5, trapezium

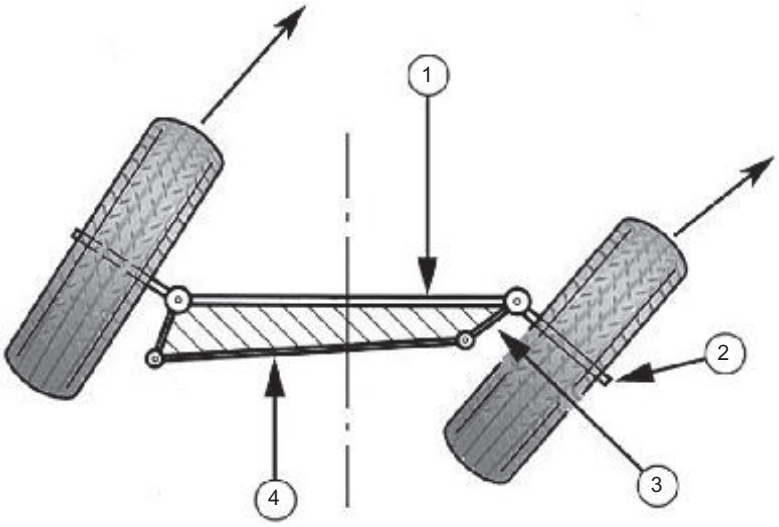

Figure 4.63 The Ackermann principle (cornering): 1, front axle; 2, stub axle; 3, steering arm; 4, track rod

The inside front wheel must, therefore, be turned more than the outside front wheel. This is achieved by the Ackermann trapezium system (Figs 4.62 and 4.63).

Key fact

In an Ackermann steering system, the name 'trapezium' comes from the geometrical shape that the two steering arms and the track rod form with the front axle.

The 'trapezium' name is derived from the geometrical shape that the two steering arms and the track rod form with the front axle. The stub axle and steering arm are rigidly connected to one another. The stub axles are swivel mounted on the kingpins or in ball joints. Track rod and steering arms are movably connected to one another. When in the straight-ahead position, track rod and front axle are parallel. When cornering, the stub axles are swivelled, thereby turning the front wheels. With the front wheels turned, the track rod is no longer parallel to the front axle; this results in the inside front wheel being turned more than the outside front wheel.

There are numerous terms and phrases associated with steering geometry. Wheelbase is the distance between the wheel centres of the front and rear wheels. The track is the distance between the wheels, measured from tyre centre

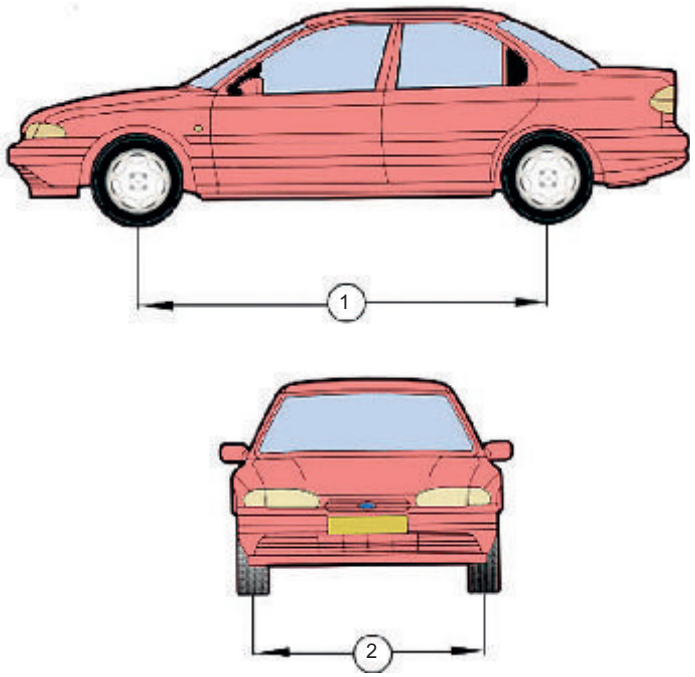

Figure 4.64 Common measurements: 1, wheelbase; 2, track

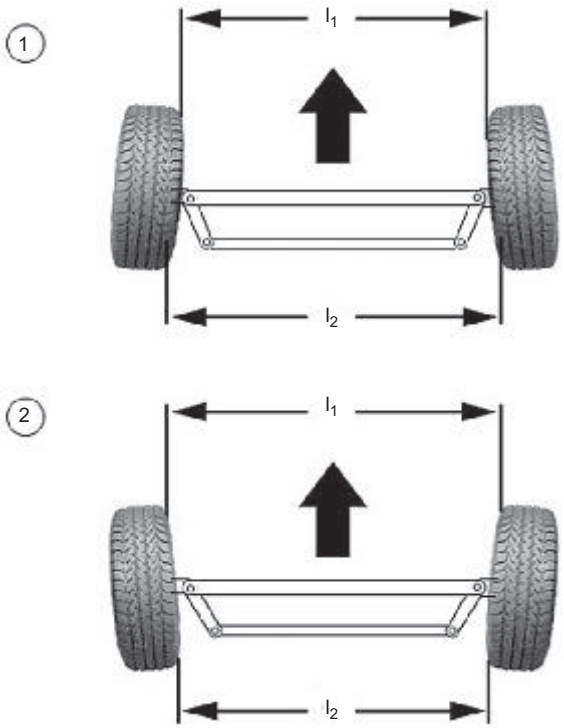

Figure 4.65 Tracking: 1, toe-in; 2, toe-out

to tyre centre on the wheel contact plane. A greater track and wheelbase results in improved safety, especially when cornering.

The wheel toe is the difference in the distance between the rim flanges in front of and behind the axle in the straight-ahead position. If the distance in front of and behind the axle is the same, the vehicle has zero wheel toe. There is generally some toe-in or toe-out (Fig. 4.65). The wheel toe is given in millimetres

Key fact

The wheel toe or tracking setting is given in millimetres, fractions of an inch or angular degrees and minutes.

or angular degrees and minutes. It is often referred to as tracking. Toe-in occurs when the distance between the rim flanges in the direction of travel is smaller in front of the axle than behind the axle. Toe-out occurs when the distance between the rim flanges in the direction of travel is greater in front of the axle than behind the axle.

The ideal running direction of the wheels is parallel to the vehicle's longitudinal axis. Owing to deformations in the suspension elements, however, the front wheels are diverted from their ideal line. In the case of front-wheel drive, they are forced inwards in the toe-in direction and in the case of rear-wheel drive, outwards in the toe-out direction. Undesirable toe-out is counteracted by toe-in and undesirable toe-in by toe-out.

Definition

Camber
The angle between the wheel plane and a line perpendicular to the road.

Camber is the angle between the wheel plane and a line perpendicular to the road (Figs 4.66–4.68). The wheels must be straight ahead. Camber is described as positive when the wheel is inclined out at the top. It has the effect of reducing scrub radius and influences the wheel forces when cornering. Camber is described as negative when the wheel is inclined in at the top. It produces a good cornering force and allows a low vehicle centre of gravity.

Figure 4.66 Positive camber (r = scrub radius)

Figure 4.67 Negative camber (r = scrub radius)

Figure 4.68 F1 cars use negative camber

The scrub radius is the distance between the contact point of the steering axis with the road surface plane and the wheel centre contact point. The functions of the scrub radius are to reduce the steering force, prevent shimmy and stabilize the straight-ahead position.

When the point of contact of the steering axis with the road surface is between the wheel centre and the outside of the wheel, it is termed negative scrub radius (Fig. 4.69). The result of negative scrub radius is that the brake forces acting on the wheel produce a torque, which tends to turn the wheel inwards. As a result, the wheel with the greater braking action is turned inwards, i.e. steered away from the more heavily braked side. This produces automatic counter-steer, stabilizing the vehicle.

When the contact point of the steering axis with the road surface is between the wheel centre and the inside of the wheel, this is termed positive scrub radius (Fig. 4.70). The greater the positive scrub radius, the more easily the wheels can be turned. The result of positive scrub radius is that the brake forces acting on the wheel produce a torque, which tends to turn the wheel outwards. With a large positive scrub radius, the vehicle can be steered very easily. Disturbing forces, such as different road surfaces, act on a long lever and can produce an unwanted steering angle.

When the point of contact of the steering axis with the road surface is in the wheel centre, the scrub radius is zero. With a zero scrub radius, the wheel swivels on the spot (Fig. 4.71). Steering is heavy when the vehicle is stationary, since the wheel cannot roll at the steering angle. In this case no separate torques occur.

Kingpin angle is the angle between the steering axis and the perpendicular to the road surface, viewed in the direction of travel. Scrub radius, wheel camber and kingpin inclination all influence one another. The kingpin inclination mainly affects the aligning torque, which brings the wheels back into the straight-ahead position.

Definition

Scrub radius
The distance between the contact point of the steering axis with the road surface plane and the wheel centre contact point.

Definition

Kingpin angle
The angle between the steering axis and a line perpendicular to the road surface, viewed from the front.

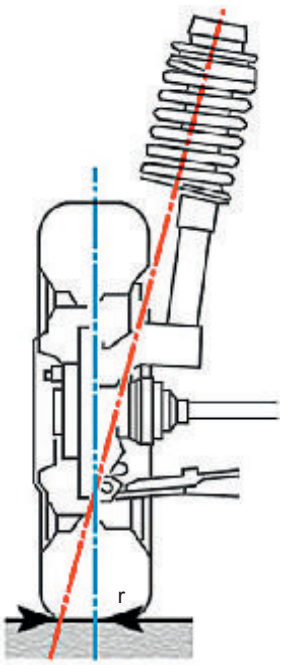

Figure 4.69 Scrub radius: negative

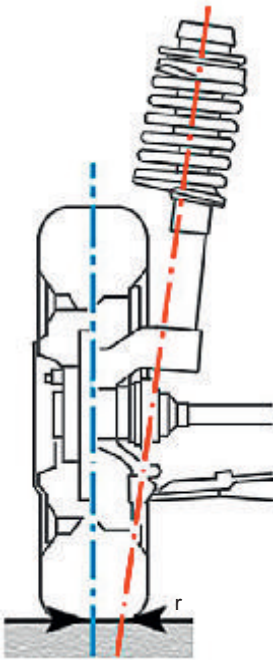

Figure 4.70 Scrub radius: positive

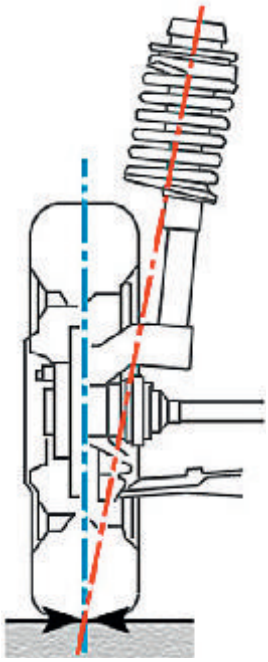

Figure 4.71 Scrub radius: zero

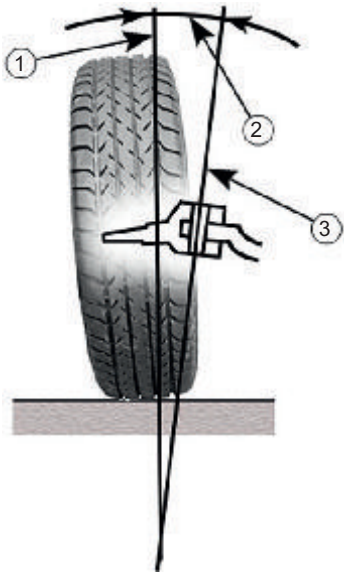

Figure 4.72 Kingpin or swivel axis inclination: 1, perpendicular to road surface; 2, kingpin angle; 3, steering axis

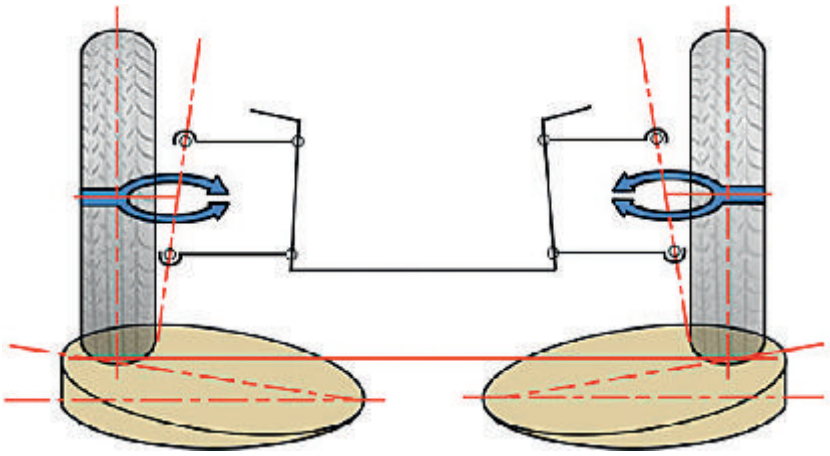

Figure 4.73 Inclined plane effect

Owing to the inclination of the steering axes, the vehicle is raised slightly at the front when the steering is turned. The weight of the vehicle, therefore, forces the wheels back into the straight-ahead position (Fig. 4.72).

If the wheels are turned, they move downwards on the inclined plane. On the road, the wheels obviously cannot penetrate the road surface. Therefore, for the load condition on the road, this means that the vehicle is raised. This is counteracted by the weight of the vehicle. As a result, the steered wheels attempt to return to the straight-ahead position. This self-centring action increases with a greater kingpin angle. After cornering, the vehicle is steered back into the straight-ahead position as a result of this effect and the axle stabilizes itself (Fig. 4.73).

Turning out of the straight-ahead position is made more difficult. This is an advantage when travelling over uneven road surfaces. The restoring forces of the kingpin inclination counteract the disturbing forces. They help the driver to hold a course without heavy counter-steering. The steering therefore becomes smoother. This principle cannot operate if the scrub radius is equal to zero. In this case, the wheel turns on its contact point and does not raise the vehicle body. No steering return forces of any kind are generated. In such a case, the steering return forces are obtained by a positive castor.

Definition

Castor angle
The angle in the vehicle's longitudinal direction between the steering axis and the perpendicular through the wheel centre.

Castor angle is the angle in the vehicle's longitudinal direction between the steering axis and the perpendicular through the wheel centre. The castor trail is the distance between the point of intersection of the steering axis with the road surface plane and the perpendicular through the wheel centre. If the wheel contact point is situated between the point of intersection of the steering axis with the road surface in the direction of travel, the castor angle and castor trail is positive. Positive castor causes the wheels to return to the straight-ahead position. It influences the steering torque when cornering and the straight-ahead stability (Fig. 4.74).

If the wheel contact point is situated in front of the point of intersection of the steering axis with the road surface in the direction of travel, the castor angle and castor trail are negative. Negative castor, or at least only slight positive castor, is frequently present in front-wheel drive vehicles. This is used to reduce the return forces when cornering (Fig. 4.75).

Tyres are a key part of the steering and suspension system. To allow the specially tuned steering and suspension systems in today's cars to operate, there

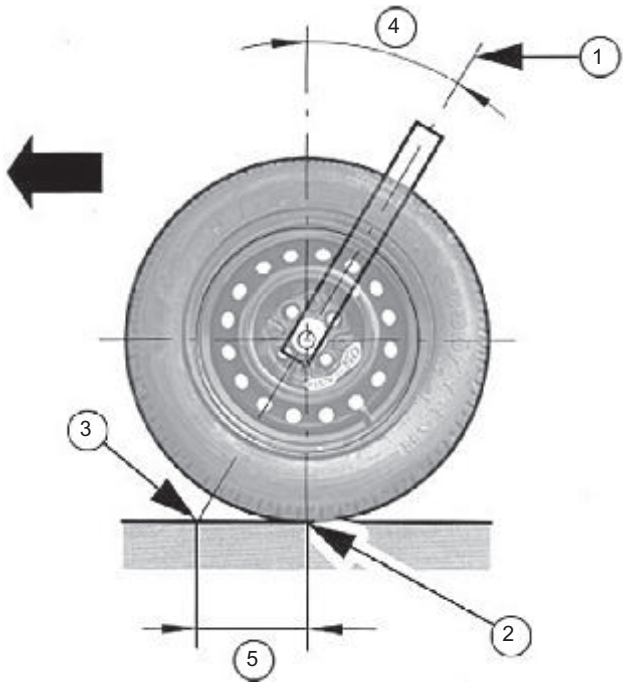

Figure 4.74 Positive castor angle: 1, steering axis; 2, wheel contact point; 3, positive castor point of intersection of steering axis with the road surface; 4, castor angle; 5, trail

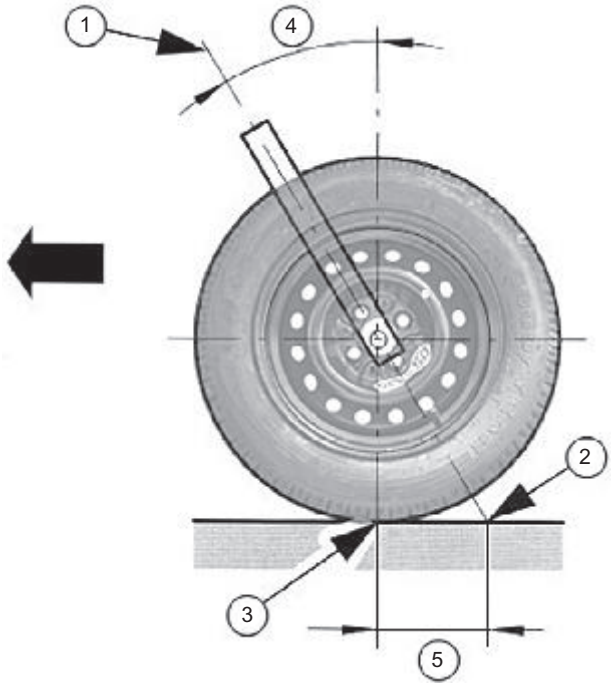

Figure 4.75 Negative castor angle: 1, steering axis; 2, wheel contact point; 3, negative castor point of intersection of steering axis with the road surface; 4, castor angle; 5, trail

must be good contact between vehicle and road surface. The tyres are therefore designed to:

- support the weight of the vehicle
- ensure good road adhesion

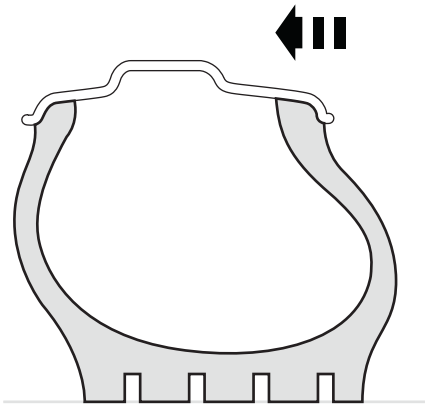

Figure 4.76 Tyre under lateral force loading

Key fact

A tyre can only transmit lateral forces when it is rolling at an angle to the direction of travel.

Definition

Slip angle
The angle between the tyre's longitudinal axis and the actual direction.

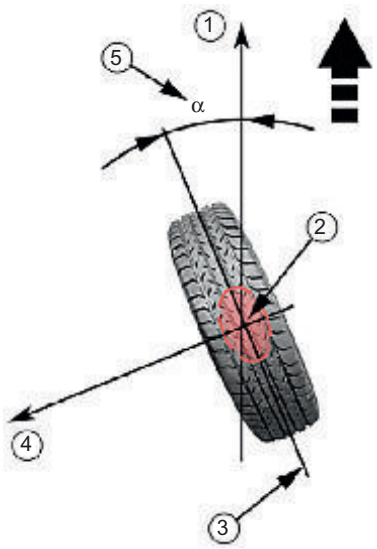

Figure 4.77 Representation of slip angle: 1, direction of movement; 2, contact patch; 3, tyre longitudinal axis; 4, cornering force; 5, slip angle

- transmit the drive, braking, steering and cornering forces
- improve the ride comfort through good suspension
- achieve a high mileage.

When drive force is transmitted at the contact area of a rolling wheel, a relative movement occurs between the tyre and road surface. In this case, the distance covered by the vehicle is shorter than that corresponding to the rolling circumference; in other words, slip occurs. The slip percentage represents the difference between the distance covered by a wheel rolling without power transmission and the distance actually covered with power transmission. When braking with locked wheels the slip is 100%. The slip varies as a function of drive, braking and cornering forces, as well as the friction of tyre and road surface.

A tyre can only transmit lateral forces when it is rolling at an angle to the direction of travel. For this reason, the tyre does not roll straight ahead when cornering, but flexes laterally (Fig. 4.76). As a result of the flexing, the tyre develops a resistance, or a side force, which keeps the vehicle on course. The side deflection of the tyre is introduced by the camber and the toe-in of the wheels. It is necessary to transmit the lateral forces in order to absorb disturbing forces such as side winds or negative lift force. When cornering, the centrifugal force represents an additional disturbing force.

At higher cornering speeds, the centrifugal force drives the vehicle mass towards the outside of the curve. So that the vehicle can be kept on track, the tyres must transmit cornering forces, which counteract the centrifugal force. This is only possible, however, if the tyre flexes laterally. In so doing, the wheels no longer move in their turned direction, but drift off at a certain angle from this direction. This means that the tyre is running at an angle to the direction of travel. This angle, which occurs between the tyre's longitudinal axis and the actual direction, is the slip angle (Fig. 4.77).

Tyres corner best at a slip angle of 15–20°. The lateral adhesion depends on the slip angle, the wheel load and the type of road surface. Steering systems are generally designed so that on bends with radii of more than 20 m, the two steered front wheels lie virtually parallel (that is, not in accordance with the Ackermann principle). On bends with smaller radii, the angles of the stub axles differ significantly from one another, in accordance with the Ackermann principle. In high-speed cornering, this adjustment leads to improved cornering of the wheel due to the greater turning of the outside front wheel.

The centrifugal force acting at the vehicle's centre of gravity is distributed to the front and rear wheels, according to the position of the centre of gravity. This may result in a direction of travel that deviates from the desired direction. A vehicle oversteers when the rear of the vehicle tends to swing outward more than the front during cornering. The slip angle is significantly greater on the rear axle than on the front axle. The vehicle therefore travels in a tighter circle. If the steering angle is not reduced, the vehicle may break away.

A vehicle understeers when the front of the vehicle tends to swing outward more than the rear during cornering. The slip angle is greater on the front axle than on the rear axle. The vehicle therefore travels in a greater circle. It must be forced into the bend with a greater steering angle. Vehicles with understeer can be carried out of the bend. Front-engined vehicles have a

tendency to understeer, since the centre of gravity is situated in front of the vehicle centre.

4.2.4 Power steering

The effort required to steer the front wheels depends primarily on the axle load. This is particularly apparent in the following situations:

- low speed
- low tyre pressures
- large tyre contact area
- tight cornering.

Steering ratio cannot be increased too much, because a large number of steering wheel turns would be necessary for the steering movement. In general, a steering force of 250 N (184 ft lbs) should not be exceeded. Therefore, the need arises for power steering in heavier cars, trucks and buses. The power assistance is generally produced by hydraulic pressures. However, electric systems are now becoming popular. The requirements of a power steering system are:

- precise onset of power assistance
- maintenance of driver feel
- continued ability to steer should the power system fail.

4.2.4.1 Hydraulic power steering

Hydraulic power-assisted steering (PAS) systems use an engine-driven pump to supply pressurized fluid (Fig. 4.78). A control valve directs the fluid to a ram that assists with movement of the steering. If the fluid supply or ram cylinder fails, the steering works like a manual system.

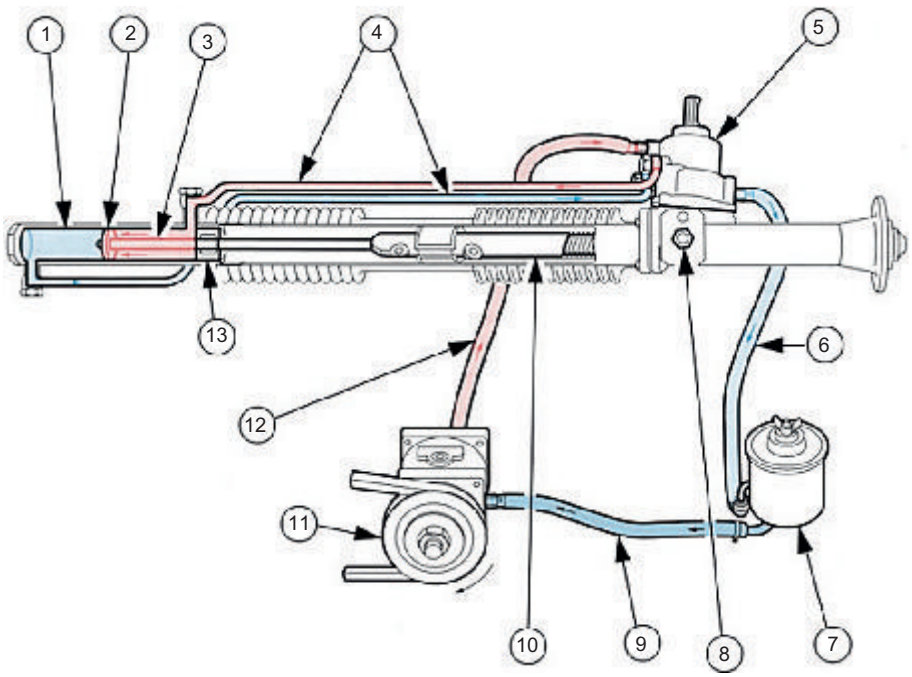

Figure 4.78 Power-assisted steering (PAS) hydraulic system: 1, ram cylinder; 2, piston; 3, piston rod; 4, pressure lines; 5, steering gear; 6, return line; 7, reservoir; 8, pressure pad adjusting screw; 9, suction line; 10, rack; 11, high-pressure pump; 12, high-pressure expansion hose; 13, seal. (Source: Ford Motor Company)

Definitions

Oversteer
This occurs when a car turns by more than the amount commanded by the driver.

Understeer
This occurs when a car steers less than the amount commanded by the driver.

Key fact

The effort required to steer the front wheels depends primarily on the axle load.

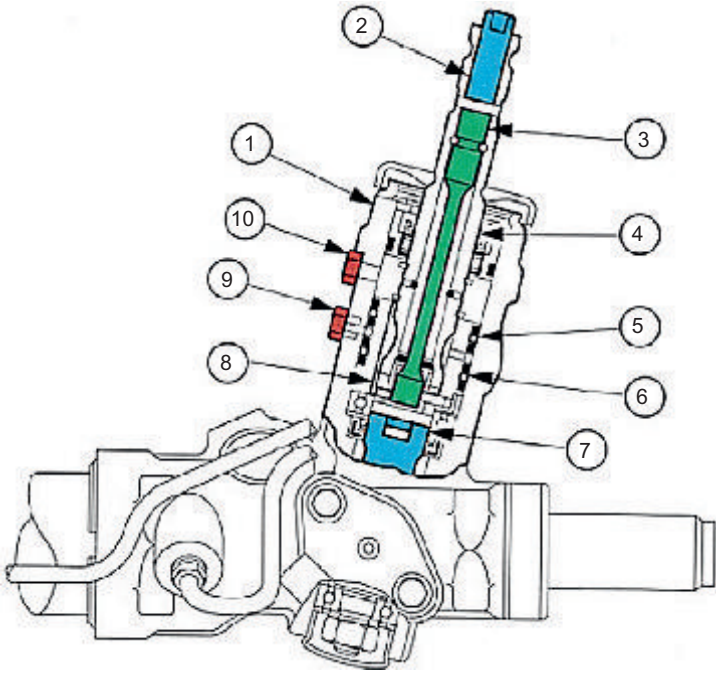

Figure 4.79 Steering rack control unit: 1, control valve housing; 2, input steering shaft; 3, torsion bar; 4, control valve sleeve; 5, upper radial groove feed to right side of piston; 6, lower radial groove feed to left side of piston; 7, pinion shaft; 8, control valve sleeve return groove; 9, pump line connection; 10, return line connection. (Source: Ford Motor Company)

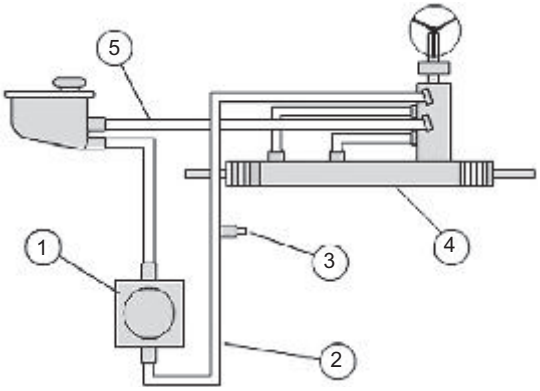

Figure 4.80 Hydraulic circuit: 1, pump; 2, pressure line; 3, pressure switch; 4, rack and ram; 5, return line

Key fact

In most hydraulic power-assisted steering systems, parts of the steering gear take the form of a hydraulic piston and cylinder.

In PAS systems of modular design, parts of the steering gear take the form of a hydraulic piston and cylinder (Fig. 4.79). This gives a compact construction.

Most control valves incorporate a torsion bar. This is designed to twist by a small amount as steering force is exerted. As the torsion bar twists, it allows valves to open and close. These valves supply fluid under pressure to the appropriate side or the ram cylinder. Splines limit the amount of torsion bar twist. In the event of a failure of the hydraulic power assistance, the driver can steer the vehicle by purely mechanical means.

When the steering wheel is turned, the control valve is actuated, admitting hydraulic fluid into the ram cylinder (Fig. 4.80). Hydraulic fluid under pressure in the ram cylinder assists with the steering force exerted by the driver. Return hydraulic fluid flows through the outlet at the other end of the ram cylinder into the reservoir.

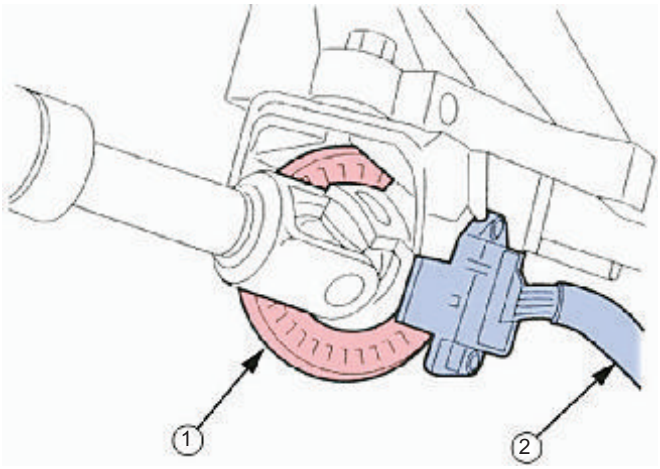

Figure 4.81 This sensor monitors steering position: 1, rotating disc; 2, sensor

When the steering movement is interrupted, the control piston assumes a neutral position. In this neutral position, the pressure in the ram cylinder is reduced.

Variable assist power steering (VAPS) systems are controlled electronically. Variable power steering (sometimes called progressive power steering) makes steering easier at low speeds but provides good driver feel at higher speeds. An electronic control unit monitors the signals from the vehicle speed sensor and the steering position sensor (Fig. 4.81). From this data, it can work out the power assistance required. The solenoid valve controls the amount of assistance, because the valve in turn controls fluid pressure. Maximum power assistance occurs at speeds less than 10 km/h (6 mph) or when the steering wheel is rotated more than 45°.

Hydraulic PAS systems use an engine-driven pump to supply pressurized fluid. A control valve directs the fluid to a ram that assists with the movement of the steering. Variable assistance systems are used. These usually involve some electronic control. Progressive PAS is controlled in this way or by a restrictor valve that changes with road speed. Pressure switches, when used, often inform engine management systems that PAS is in use. This allows idle speed to be increased if necessary.

4.2.4.2 Electric power steering

There are two main ways of using electric power for steering assistance (the second is now the more common):

- replacing the conventional system pump with an electric motor while the ram remains much the same
- using a drive motor, which directly assists with the steering and has no hydraulic components.

With a direct-acting type, an electric motor works directly on the steering via an epicyclic gear train (Fig. 4.82). This completely replaces the hydraulic pump and servo cylinder. This eliminates the fuel penalty of the conventional pump and greatly simplifies the drive arrangements. Engine stall when the power steering is operated at idle speed is also eliminated.

On many systems, an optical torque sensor is used to measure driver effort on the steering wheel (all systems use a sensor of some sort). The sensor works by measuring light from a light-emitting diode (LED), which shines through some holes. These are aligned in discs at either end of a torsion bar, fitted into the steering column. An optical sensor element identifies the twist of two discs

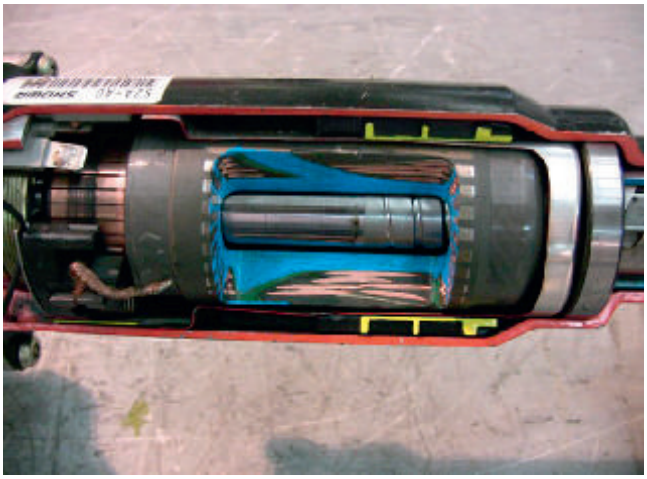

Figure 4.82 Direct acting motor

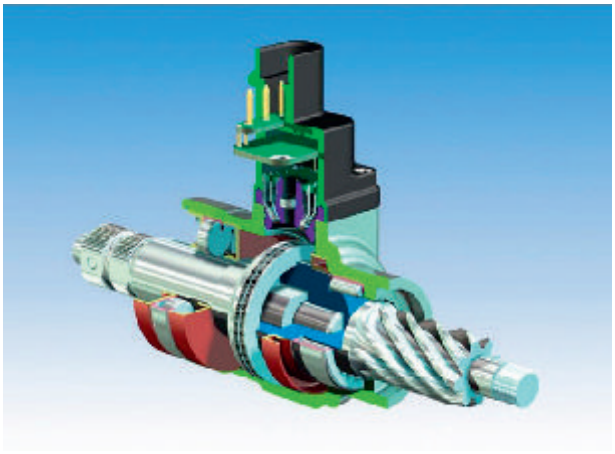

Figure 4.83 Steering sensor. (Source: Bosch Media)

Figure 4.84 Electric power-assisted steering (PAS). (Source: Ford Media)

Key fact

Electrical PAS occupies little under-bonnet space and the motor only averages about 2 A current draw under urban driving conditions.

on the steering axis with respect to each other, each disc being provided with appropriate codes. From this sensor information the system calculates the torque as well as the absolute steering angle (Fig. 4.83).

Electric PAS (Fig. 4.84) occupies little under-bonnet space, something that is at a premium these days, and the 400 W motor only averages about 2 A under urban driving conditions. The cost benefits over conventional hydraulic methods are considerable.

Electric power for steering assistance can be applied in a number of ways. However, using a drive motor, which directly assists with the steering, is the most common. This method uses less power and takes up less space than other methods.

4.3 Brakes

4.3.1 Disc, drum and parking brakes

The main purpose of the braking system is simple: to slow down or stop a vehicle. To do this, the energy in the vehicle movement must be taken away or converted.

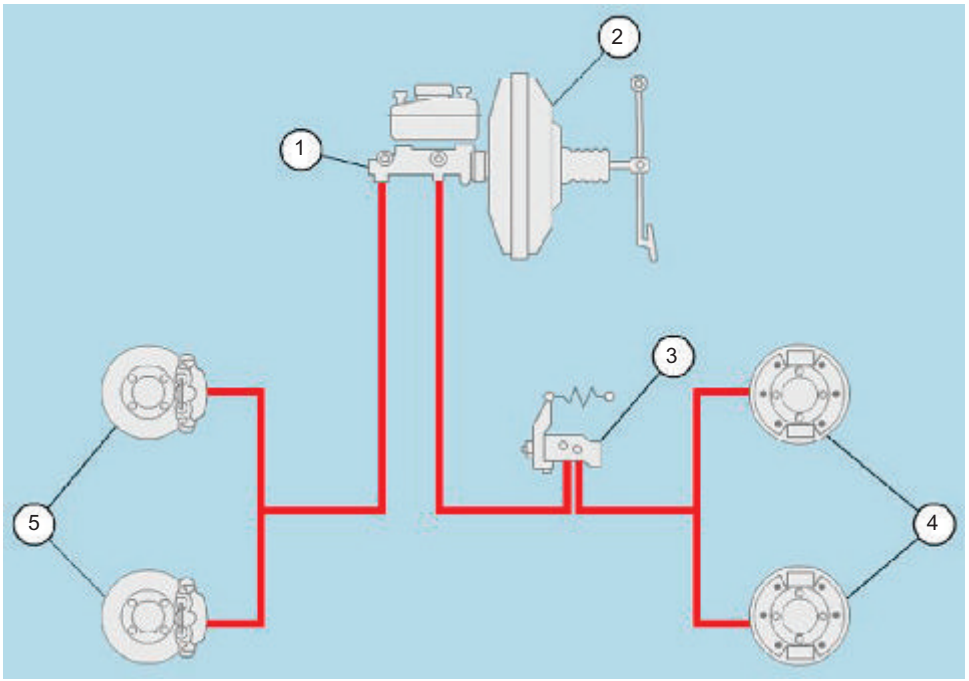

Figure 4.85 Brake system: 1, master cylinder; 2, brake servo or booster; 3, pressure regulator; 4, brake shoes; 5, brake discs (rotors) and pads

Figure 4.86 Brake pads

This is achieved by creating friction. The resulting heat takes energy away from the movement. In other words, kinetic energy is converted into heat energy.

The main braking system of a car works by hydraulics. This means that when the driver presses the brake pedal, liquid pressure forces pistons to apply brakes on each wheel. Disc brakes are used on all wheels of most cars nowadays (Fig. 4.85). Braking pressure forces brake pads against both sides of a steel disc. Drum brakes are fitted on the rear wheels of some cars and on all wheels of older vehicles. Braking pressure forces shoes to expand outwards into contact with a drum. The important part of brake pads and shoes is the friction lining.

Brake pads (Fig. 4.86) are steel-backed blocks of friction material, which are pressed onto both sides of the disc (also known as a brake rotor). Older types were asbestos based, so you must not inhale the dust. Pads should be changed when the friction material wears down to 2 or 3 mm. The circular steel disc

Key fact

To slow down a vehicle its movement energy (kinetic) must be converted to another form.

Figure 4.87 Brake shoes

Figure 4.88 Brake master cylinder on a vehicle

Key fact

Brake pads should be changed when the friction material wears down to 2 or 3 mm, or as specified by the manufacturer.

rotates with the wheel. Some are solid but many have ventilation holes. Modern brake pad and shoe lining material is made from mineral fibres, cellulose, aramid, polyacrylonitrile (a resinous, fibrous or rubbery organic polymer), ceramics, chopped glass, steel, and copper fibres, carbon fibres or a similar material. There is no need to remember all these; just choose the correct replacement types as recommended by the manufacturer.

Brake shoes are steel crescent shapes with a friction material lining (Fig. 4.87). They are pressed inside a steel drum, which rotates with the wheel. The rotating action of the brake drum tends to pull one brake shoe harder into contact. This is known as self-servo action. It occurs on the brake shoe after the wheel cylinder in the direction of wheel rotation. This brake shoe is described as the leading shoe. The brake shoe before the wheel cylinder in the direction of wheel rotation is described as the trailing shoe.

Key fact

Vacuum, from the engine inlet manifold, is used to work most brake servos.

The master cylinder piston is moved by the brake pedal. In its basic form, it is like a pump which forces brake fluid through the pipes. Pressure in the pipes causes a small movement to operate either brake shoes or pads. The wheel cylinders and callipers work like a pump only in reverse (Figs 4.88 and 4.89).

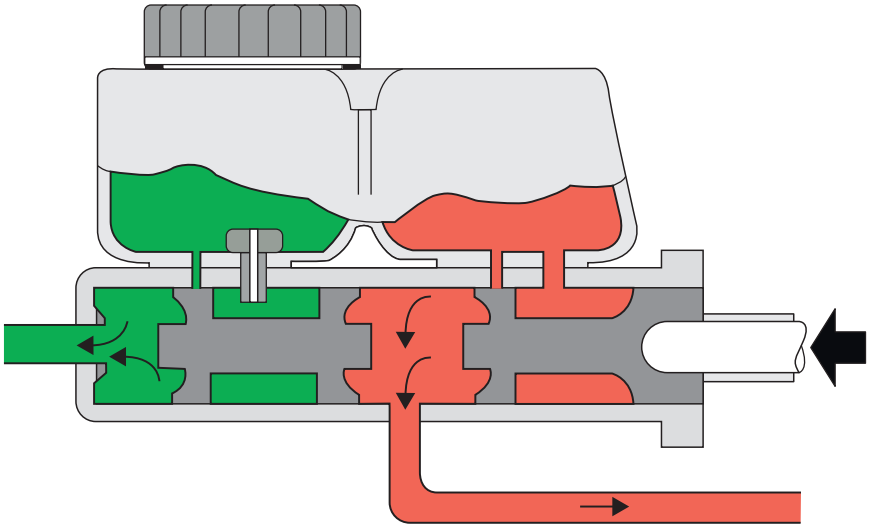

Figure 4.89 Master cylinder operation

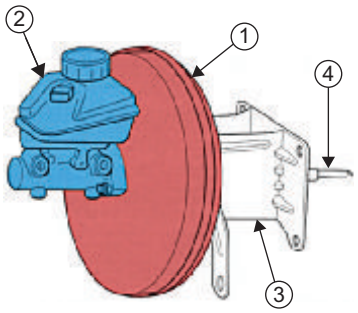

Figure 4.90 Servo unit: 1, brake servo (booster); 2, master cylinder and fluid reservoir; 3, bracket; 4, diaphragm rod connection to brake pedal

Figure 4.91 Flexible and metal brake pipes

The brake servo (booster) increases the force applied by the driver on the pedal. It makes the brakes more effective. Vacuum, from the engine inlet manifold, is used to work most brake servos (Fig. 4.90).

Strong, high-quality pipes are used to connect the master cylinder to the wheel cylinders. Fluid connection, from the vehicle body to the wheels, has to be through flexible pipes to allow suspension and steering movement (Fig. 4.91). As a safety precaution (because brakes are important!), brake systems are split into two sections. If one section fails, say by a pipe breaking, the other will continue to operate.

If the brakes cause the wheels to lock and make them skid, steering control is lost. In addition, the brakes will not stop the car as quickly. ABS (anti-lock braking system) uses electronic control to prevent this happening.

On most car braking systems, about 70% (or more) of the braking force is directed to the front wheels. This is because, under braking, the weight of the vehicle transfers to the front wheels. Load compensation, however, allows the braking pressure to the rear wheels to increase as load in the vehicle increases.

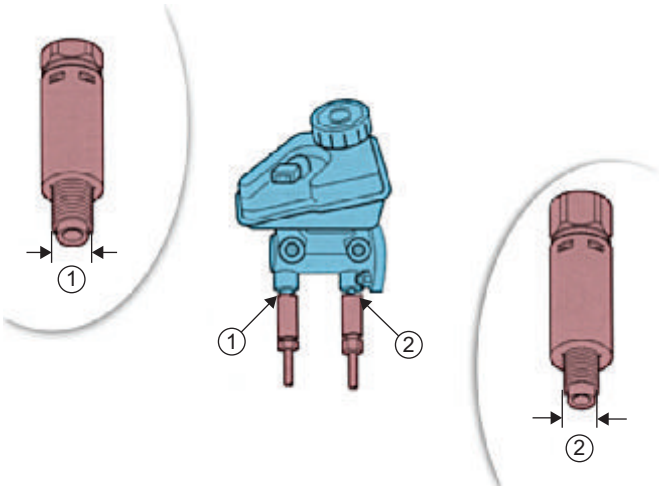

Figure 4.92 Pressure-conscious regulator (PCR) valves: 1, PCR valve for circuit one with larger thread diameter; 2, PCR valve for circuit two with smaller thread diameter

Safety first

If brakes become so hot that they cannot convert energy rapidly enough, they become much less efficient. This is known as brake fade.

Key fact

Service brake minimum efficiency: 50%; second line brake efficiency: 25%; parking brake efficiency: 16%.

Definition

DOR
Direction of rotation.

Devices such as pressure-conscious regulator (PCR) valves (Fig. 4.92) to may be used to control the braking force.

If brakes become so hot that they cannot convert energy rapidly enough, they become much less efficient, or in other words, fade away! This is described as brake fade. A more serious form of brake fade can also be caused if the heat generated is enough to melt the bonding resin in the friction material. This reduces the frictional value of the linings or pads.

All components of the braking system must be in good working order, in line with most other vehicle systems. Braking efficiency means the braking force compared to the weight of the vehicle. For example, the brakes on a vehicle with a weight of 10 kN (1000 kg $\times$ 10 ms^{-2} [g]) will provide a braking force of, say, 7 kN. This is said to be 70% efficiency. During an annual test this is measured on brake rollers. The current efficiency requirements in the UK are as follows: service brake efficiency 50%, second line brake efficiency 25% and parking brake efficiency 16%.

Disc brakes are less prone to brake fade than drum brakes (Fig. 4.93). This is because they are more exposed and can get rid of heat more easily. They also throw off water better than drum brakes. Brake fade occurs when the brakes become so hot they cannot transfer any more energy, and they stop working. Disc brakes are self-adjusting. When the pedal is depressed, the rubber seal is preloaded. When the pedal is released, the piston is pulled back owing to the elasticity of the rubber sealing ring.

Brake shoes, when used, are mounted inside a cast iron drum (Fig. 4.94). They are mounted on a steel backplate, which is rigidly fixed to a stationary part of the axle. The two curved shoes have friction material on their outer faces. One end of each shoe bears on a pivot point. The other end of each shoe is pushed out by the action of a wheel cylinder when the brake pedal is pressed. This puts the brake linings in contact with the drum inner surface. When the brake pedal is released, the return spring pulls the shoes back to their rest position.

Drum brakes are more adversely affected by wet and heat than disc brakes, because both water and heat are trapped inside the drum. However, they are easier to fit with a mechanical handbrake linkage (Fig. 4.95).

Figure 4.93 Sliding disc brake calliper

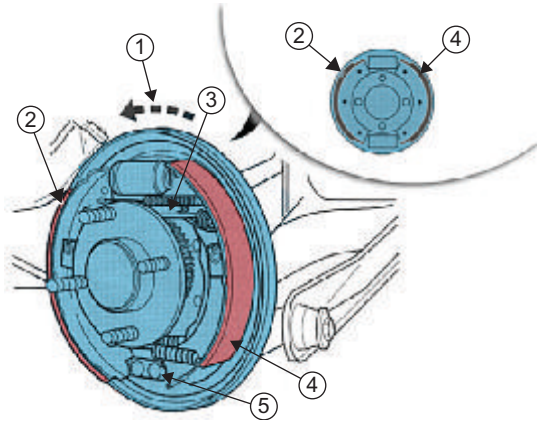

Figure 4.94 Rear drum brake: 1, direction of rotation; 2, leading shoe; 3, self-adjusting device; 4, trailing shoe; 5, lower bracket

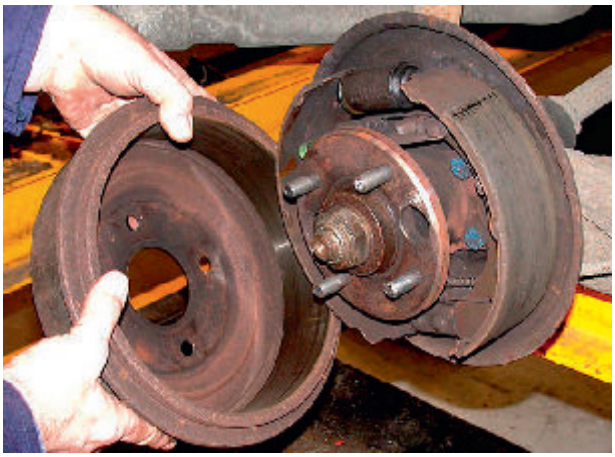

Figure 4.95 Brake drum being removed

Brakes must be adjusted so that the minimum movement of the pedal starts to apply the brakes. The adjustment in question is the gap between the pads and disc and the shoes and drum. Disc brakes are self-adjusting because as pressure is released it moves the pads just away from the disc (Fig. 4.96). Drum brakes are different because the shoes are moved away from the drum to a set position by a pull-off spring. Self-adjusting drum brakes are almost universal now on light vehicles. A common type uses an offset ratchet, which clicks to a wider position if the shoes move beyond a certain amount when operated.

Safety first

Brake shoes must not be rubbing (binding) as this builds up heat and wears the friction material very quickly, and prevents the brakes working properly.

If an automatic adjuster is not used, manual adjustment through a hole in the back plate is often employed (Fig. 4.97). This involves moving a type of nut on a threaded bar, which pushes the shoes out as it is screwed along the thread. This method is similar to the automatic adjusters. An adjustment screw on the back plate is now quite an old method. A screw or square head protruding from the back plate moves the shoes by a snail cam. As a guide, tighten the adjuster until the wheels lock, and then move it back until the wheel is just released. You must ensure that the brakes are not rubbing as this would build up heat and wear the friction material very quickly.

The precise way in which the shoes move into contact with the drum affects the power of the brakes. If the shoes are both hinged at the same point then the

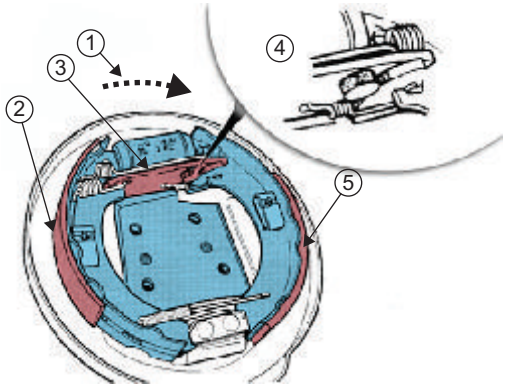

Figure 4.96 Self-adjusting device: 1, direction of rotation; 2, trailing shoe; 3, thrust link; 4, toothed cam and pawl mechanism; 5, leading shoe

Figure 4.97 Drum brake adjustment hole

system is said to have one leading and one trailing shoe. As the shoes are pushed into contact with the drum, the leading shoe is dragged by the drum rotation harder into contact, whereas the rotation tends to push the trailing shoe away. This 'self-servo' action on the leading shoe can be used to increase the power of drum brakes. This is required on the front wheels of all-round drum brake vehicles.

The shoes are arranged so that they both experience the self-servo action. The shoes are pivoted at opposite points on the backplate and two wheel cylinders are used. The arrangement is known as twin leading shoe brakes (Fig. 4.98). It is not suitable for use on the rear brakes because if the car is travelling in reverse then it would become a twin trailing shoe arrangement, which means the efficiency of the brakes would be seriously reduced. The leading and trailing layout is therefore used on rear brakes, as one shoe will always be leading no matter in what direction the vehicle is moving.

The standard layout of drum brake systems on a vehicle is normally:

- twin leading shoe brakes on the front wheels
- leading and trailing shoe brakes on the rear wheels.

Disc brakes are now used on the front wheels of all light vehicles and the rear wheels of most. However, some retain leading and trailing shoe brakes on the rear (Fig. 4.99). In most cases, it is easier to attach a handbrake linkage to the system with shoes on the rear. This method will also provide the braking performance required when the vehicle is reversing.

Inside a brake drum, the handbrake linkage is usually a lever mechanism as shown in Fig. 4.100. This lever pushes the shoes against the drum and locks the wheel. The handbrake lever pulls on one or more cables and has a ratchet to allow it to be locked in the 'on' position. There are several ways in which the handbrake linkage can be laid out to provide equal force, or compensation, for both wheels:

- two cables, one to each wheel
- equalizer on a single cable pulling a U-section to balance effort through the rear cable (as shown in Fig. 4.100)
- single cable to a small linkage on the rear axle.

Some sliding calliper disc brakes incorporate a handbrake mechanism. The footbrake operates as normal. Handbrake operation is by a moving lever. The

Key fact

The handbrake lever pulls on one or more cables to operate both rear brakes (in most cars).

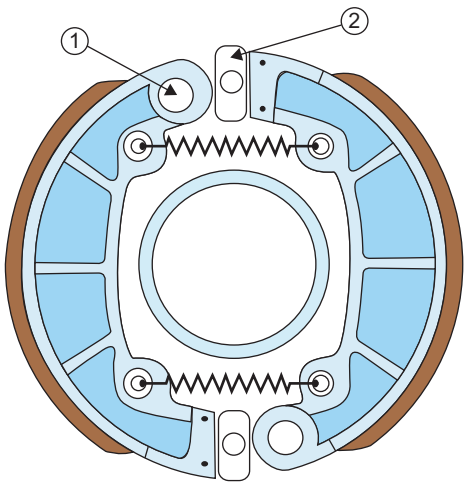

Figure 4.98 Twin leading shoe principle: an expander at the top and the bottom: 1, pivot; 2, actuator

Figure 4.99 Leading and trailing system

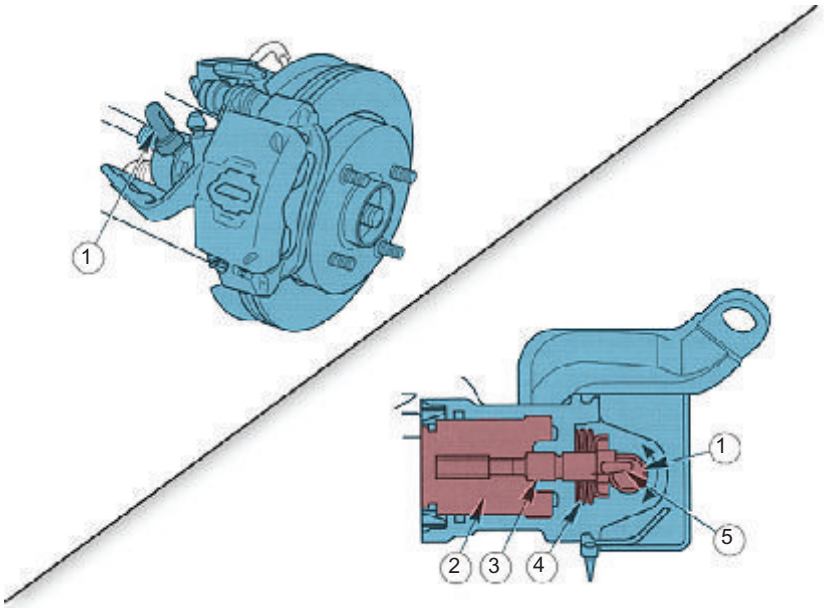

Figure 4.100 Sliding calliper parking brake: 1, moving lever; 2, piston; 3, adjusting screw; 4, spring washers; 5, cam

lever acts through a shaft and cam, which works on the adjusting screw of the piston. The piston presses one pad against the disc and, because of the sliding action, the other pad also moves.

Some manufacturers use a set of small brake shoes inside a small drum, which is built in to the brake disc. The calliper is operated as normal by the footbrake. The small shoes are moved by a cable and lever.

In summary, remember that the purpose of the braking system is to slow down or stop a vehicle. This is achieved by converting the vehicle's movement energy into heat using friction.

4.3.2 Hydraulic components

A complete braking system includes a master cylinder, which operates several wheel cylinders (Fig. 4.101). The system is designed to give the power

Figure 4.101 Master cylinder and fluid reservoir fitted on to the servo

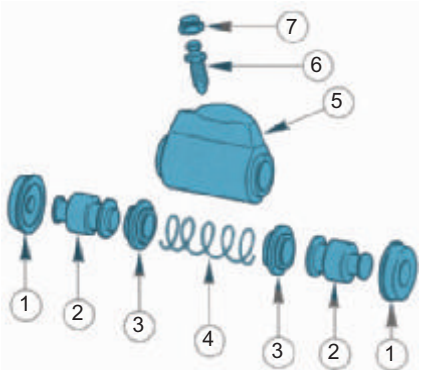

Figure 4.102 Slave cylinder components: 1, dust seal; 2, piston; 3, piston seal; 4, spring; 5, cylinder; 6, bleed nipple; 7, dust cap

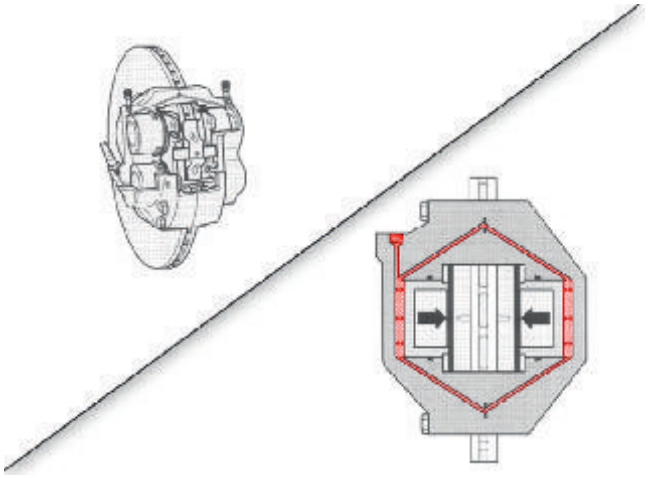

Figure 4.103 Fixed calliper

amplification needed for braking the particular vehicle. On any vehicle when braking, a lot of the weight is transferred to the front wheels. Most braking effort is therefore designed to work on the front brakes. Some cars have special hydraulic valves to limit rear wheel braking. This reduces the chance of the rear wheels locking and skidding.

Key fact

Most braking effort is directed to the front wheels.

Brake shoes can be moved by double- (Fig. 4.102) or single-acting wheel cylinders. A common layout is to use one double-acting cylinder and brake shoes on each rear wheel of the vehicle and disc brakes on the front wheels. A double-acting cylinder simply means that as fluid pressure acts through a centre inlet, pistons are forced out of both ends.

Disc brake callipers are known as fixed, floating or sliding types (Figs 4.103–4.105). The pistons are moved by hydraulic pressure created in the master cylinder. A number of different callipers are used. Some high-performance callipers include up to four pistons. However, the operating principle remains the same. The sliding calliper tends to be used most.

Key fact

Some high-performance callipers include up to four pistons.

Always use new and approved brake fluid when topping up or refilling the system. Manufacturers' recommendations must always be followed. Brake fluid

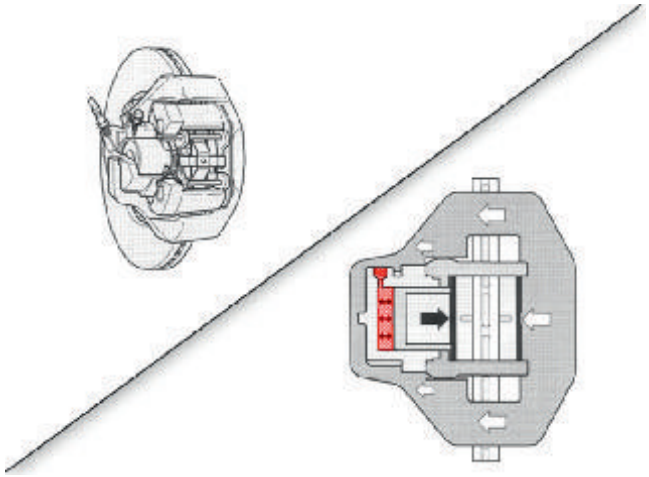

Figure 4.104 Floating calliper

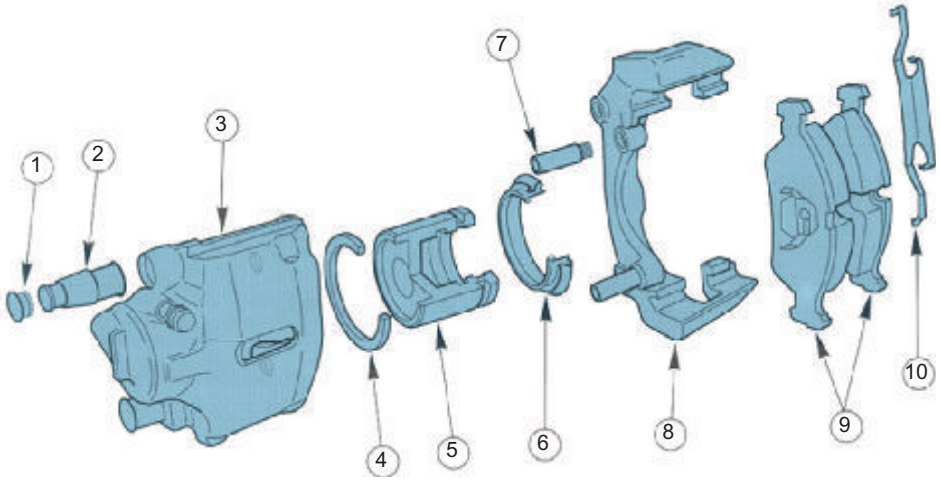

Figure 4.105 Sliding disc brake calliper components: 1, dust cap; 2, bleed nipple; 3, piston housing (calliper assembly); 4, piston seal; 5, piston; 6, dust seal; 7, locating stud; 8, housing bracket; 9, pads; 10, retaining clip

Safety first

Many manufacturers recommend that the brake fluid is changed at regular intervals.

is hygroscopic, which means that, over time, it absorbs water. This increases the risk of the fluid boiling owing to the heat from the brakes. Pockets of steam in the system would not allow full braking pressure to be applied. Many manufacturers recommend that the fluid be changed at regular intervals. Make sure the correct grade of fluid is used. The current recommended types are known as DOT4 and DOT5.

Key fact

A tandem master cylinder is like two separate cylinders but inside one housing.

Safety is built into braking systems by using a double-acting master cylinder. This is often described as tandem and can be thought of as two master cylinders inside one housing. The pressure from the pedal acts on both cylinders but fluid cannot pass from one to the other. Each cylinder is then connected to a separate circuit. These split lines can be connected in a number of ways. Under normal operating conditions, the pressure developed in the first part of the master cylinder is transmitted to the second. This is because the fluid in the first chamber acts directly on the second piston (Fig. 4.107).

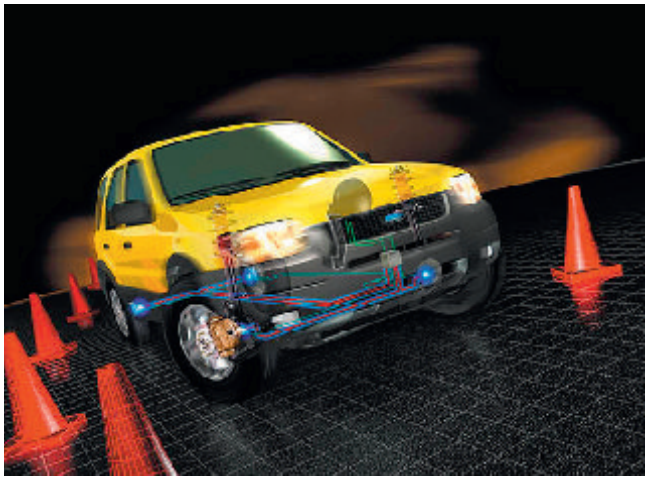

Figure 4.106 Braking and other components

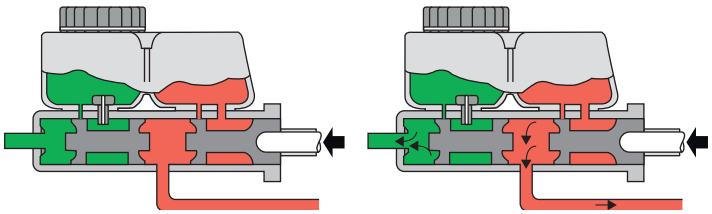

Figure 4.107 Master cylinder operation: left, not operating; right, normal operation

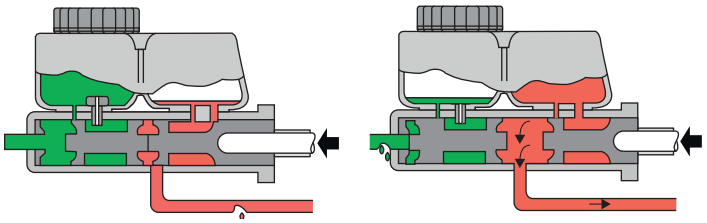

Figure 4.108 Tandem master cylinder showing the operation when there is a failure in different circuits

If one line fails, the first piston meets no restriction and closes up to the second piston. Further movement will now provide pressure for the second circuit. The driver will notice that pedal travel increases, but some braking performance will remain. If the fluid leak is from the second circuit, then the second piston will meet no restriction and close up the gap. Braking will now be just from the first circuit. Diagonal split brakes are the most common and are used on vehicles with a negative scrub radius. Steering control is maintained under brake failure conditions (Fig. 4.108).

Three common 'splits' or multicircuit systems are used on braking systems. The first two types listed are the most common:

- diagonal split type, where, if a fault occurs, the driver loses half of the front and half of the rear brakes (Fig. 4.109)
- separate front and rear, where, if a fault occurs, the driver loses all of the front or all of the rear brakes (Fig. 4.110)

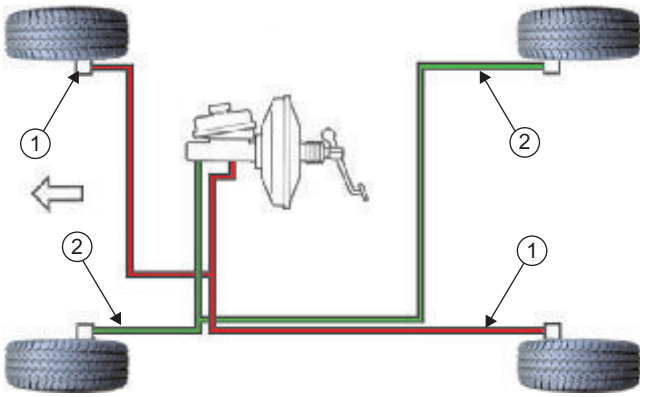

Figure 4.109 Diagonal split: 1, circuit 1; 2, circuit 2

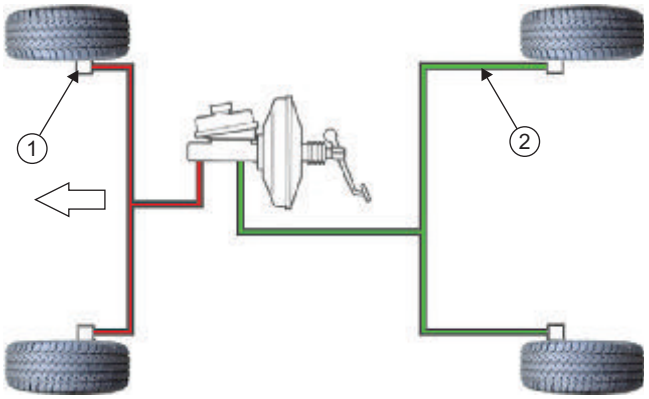

Figure 4.110 Front/rear split: 1, circuit 1; 2, circuit 2

- duplicated front, where, if a fault occurs, the driver loses the rear and part of the front brakes only. Special front callipers are required when using this method.

4.3.3 Brake servo operation

The brakes of a vehicle must perform well, while keeping the effort required by the driver to a reasonable level. This is achieved by the use of a brake servo. It is also called a brake booster. Vacuum-operated systems are commonly used on light vehicles (Fig. 4.111).

Hydraulic power brakes use the pressure from an engine-driven pump. The pump will often be the same as the one used to supply the PAS. Pressure from the pump is made to act on a plunger in line with the normal master cylinder. As the driver applies force to the pedal, a servo valve opens in proportion to the force applied by the driver. The hydraulic assisting force is therefore also proportional. This maintains the all-important 'driver feel'.

A hydraulic accumulator (a reservoir for fluid under pressure) is incorporated into the system (Fig. 4.112). This is because the pressure supplied by the pump varies with engine speed. The pressure in the accumulator is kept between set pressures in the region of 70 bar. A warning, therefore: if you have to disconnect any components from the braking system on a vehicle fitted with an accumulator, you must follow the manufacturer's recommendations on releasing the pressure first.

Figure 4.111 Vacuum servo and master cylinder

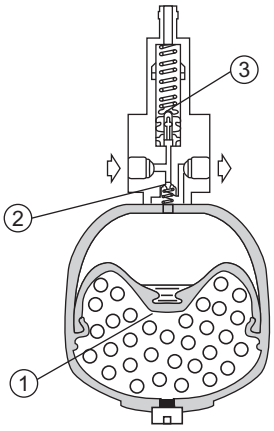

Figure 4.112 Accumulator with arrows showing the inlet and outlet: 1, diaphragm; 2, check valve; 3, pressure-relief valve

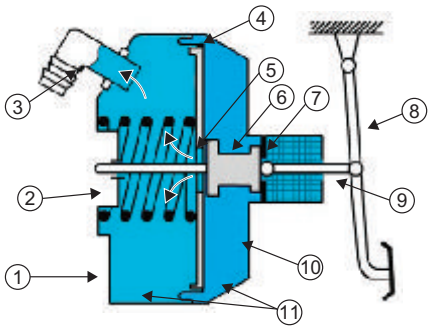

Figure 4.113 Servo construction: 1, vacuum chamber; 2, compression spring; 3, vacuum line; 4, diaphragm; 5, vacuum passage; 6, poppet valve; 7, exterior air passage; 8, brake pedal; 9, filter; 10, working chamber; 11, chambers

The more common servo system uses low pressure (vacuum) from the manifold on one side, and the higher atmospheric pressure on the other side of a diaphragm (Fig. 4.113). The low pressure is taken via a non-return safety valve from the engine inlet manifold. A pump is often used on diesel-engined vehicles as most do not have a throttle butterfly and hence do not develop any significant manifold vacuum. The pressure difference, however created, causes a force, which is made to act on the master cylinder.

The vacuum servo is fitted in between the brake pedal and the master cylinder. The main part of the servo is the diaphragm. The larger this diaphragm, the greater the servo assistance provided. A vacuum is allowed to act on both sides of the diaphragm when the brake pedal is in its rest position. When pedal force is applied to the piston a valve cuts the vacuum connection to the rear chamber and allows air at atmospheric pressure to enter. This causes a force to act on the diaphragm, so assisting with the application of the brakes.

Once the master cylinder piston moves, the valve closes again to hold the applied pressure. Further effort by the driver on the brake pedal will open the valve again and apply further vacuum assistance. In this way, the driver can ‘feel’ the amount of braking effort being applied. The cycle continues until the driver effort reaches a point where the servo assistance remains fully on.

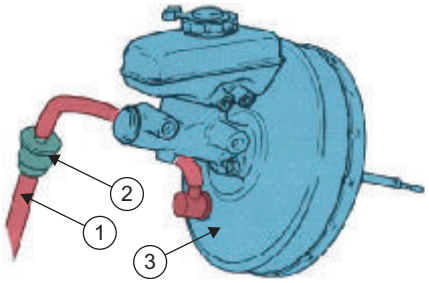

Figure 4.114 A check valve is fitted in the vacuum supply: 1, vacuum connection to inlet manifold; 2, check (non-return valve); 3, chamber

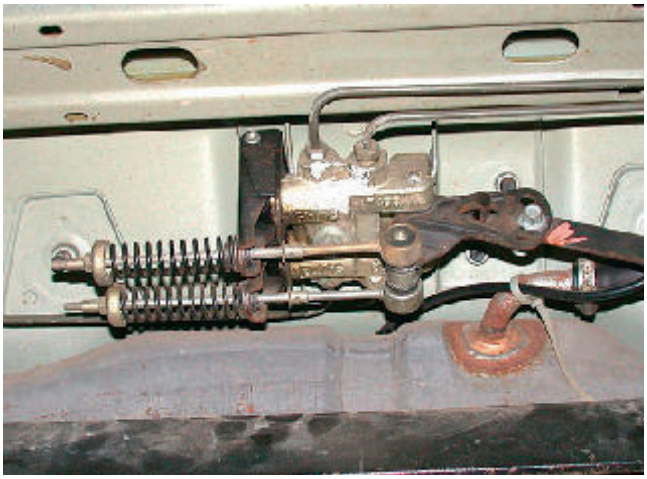

Figure 4.115 Load apportioning valve

Safety first

If the vacuum servo (booster) stops working the brakes will still operate, but extra force will be required from the driver.

A non-return valve is fitted in the line to keep a vacuum in the servo chamber. This means that it is possible to carry out three or four braking operations, with servo assistance, without the engine running. The valve also prevents fuel vapours getting in the servo and damaging the diaphragm (Fig. 4.114).

If the vacuum servo (booster) stops working the brakes will still operate, but extra force will be required from the driver. The connection to the inlet manifold will normally be via a check valve as an extra safety feature.

A brake servo assists the driver when the brakes are applied. The 'feel' must be maintained during operation. Most servos are vacuum operated.

4.3.4 Braking force control

Some cars use devices to control the braking force. There are three main types:

- load-apportioning valve (Fig. 4.115)
- pressure-conscious regulator (Fig. 4.116)
- deceleration-sensing brake pressure reducer.

The purpose of these devices is to ensure braking force is distributed so that most of the force goes to the front brakes. This improves performance and stability.

Load-apportioning valves are fitted between the rear axle and vehicle floor assembly. A single valve is used for vehicles with front to rear split lines, and two valves are used when the split is diagonal. A lever and tension spring changes the force necessary to make a plunger move. The lever and spring adjust position depending on the vehicle load. Fluid pressure moves the plunger; however, the position of the lever limits the movement. Load in the vehicle sets the valve position. Pressure, and therefore braking force, is controlled by the valve.

The pressure-conscious regulator is simply fitted in the line, or lines, to the rear brakes. It reduces braking pressure by a fixed amount. An internal control spring is used to set the operating pressure.

Where used, one deceleration sensor is used in each brake circuit (Fig. 4.117). The sensors are mounted on the vehicle floor at a set angle to the horizontal.

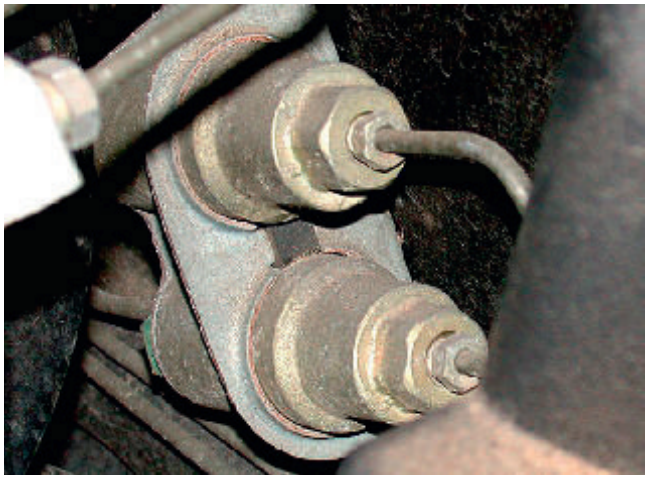

Figure 4.116 Electronic control unit for the brakes

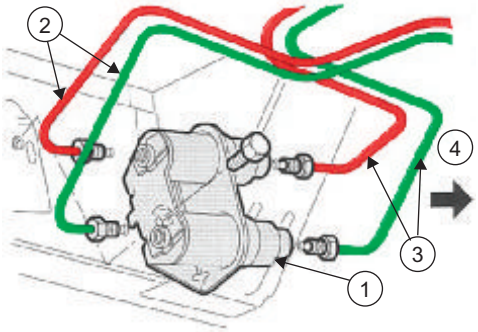

Figure 4.117 Pressure reducer location: 1, brake pressure reducers (2); 2, pipes from master cylinder; 3, pipes to rear axle; 4, direction of travel

When the deceleration is greater than about 0.5*g*, the valves allow the pressure to the rear brakes to rise more slowly than the front. During deceleration (usually above 0.5*g*), a ball moves against a spring and a valve, which reduces the pressure to the rear brakes. When deceleration reduces, the ball rolls back against the washer.

Controlling brake pressure ensures that braking force is distributed so that most of the force goes to the front brakes. As a guide, more than 70% of the braking takes place on the front wheels. This improves performance, control and stability.

Key fact

About 70% of the braking takes place on the front wheels.

4.3.5 Anti-lock brake systems

The reason for the development of the anti-lock braking system (ABS) (Fig. 4.118) is simple. Under braking conditions, if one or more of the vehicle's wheels locks (begins to skid), then this has serious consequences:

- Braking distance increases.
- Steering control is lost.
- Tyre wear is abnormal.

The maximum deceleration of a vehicle is achieved when maximum energy conversion is taking place in the brake system. This is the conversion of kinetic energy to heat energy at the discs and brake drums. The potential for this

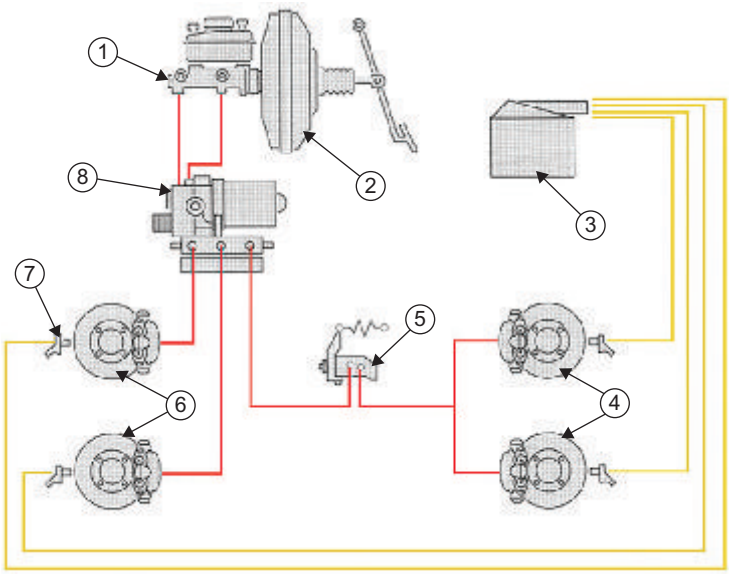

Figure 4.118 Anti-lock braking system (ABS) layout: 1, master cylinder; 2, brake servo or booster; 3, electronic control unit; 4, rear disc brakes; 5, load apportioning valve (if used); 6, front disc brakes; 7, wheel speed sensor; 8, hydraulic modulator

Figure 4.119 Electronic control unit control of the brakes

Key fact

The maximum deceleration of a vehicle is achieved when maximum energy conversion is taking place in the brake system, rather than between skidding tyres and the road.

conversion process between a tyre skidding and the road, even a dry road, is far less. A good driver can pump the brakes on and off to prevent locking (cadence braking) but electronic control can achieve even better results (Fig. 4.119).

ABS is now common on lower price vehicles, which should be a contribution to safety. It is important to remember, however, that for normal use, the system is not intended to allow faster driving and shorter braking distances. It should be viewed as operating in an emergency only. Good steering and road holding must continue when ABS is operating. This is arguably the key issue, as being able to swerve round a hazard, while still braking hard, is often the best course of action.

In the event of the ABS failing, then conventional brakes must still operate to their full potential. In addition, a warning must be given to the driver. This is normally in the form of a simple warning light (Fig. 4.120).

Figure 4.120 Anti-lock braking system (ABS) warning light

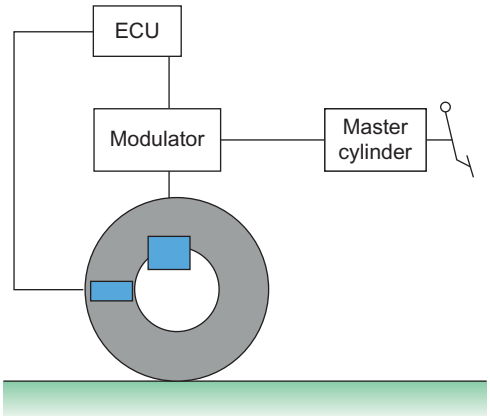

Figure 4.121 Representation of an anti-lock braking system (ABS)

The system must operate under all speed conditions above walking pace. At this very slow speed, even when the wheels lock, the vehicle will come to rest quickly. If the wheels did not ever lock then in theory the vehicle would never stop!

ABS must be able to recognize aquaplaning and react accordingly. It must also operate on an uneven road surface. The one operating condition that has still not been perfected is braking from slow speed on snow. The ABS can actually increase stopping distances in snow. However, steering control will be improved and this is considered a suitable trade-off.

An ABS is represented by the closed loop system block diagram shown in Fig. 4.121. The most important of the inputs are the wheel speed sensors. The main output is some form of brake system pressure control (the modulator). The task of the ECU is to compare signals from each wheel sensor. From these signals, it can determine the acceleration or deceleration of an individual wheel. Brake pressure can be reduced, held constant or allowed to increase. The maximum pressure is determined by the driver's pressure on the brake pedal.

A vehicle reference speed is determined from the combination of two diagonal wheel sensor signals (Fig. 4.122). After the start of braking, the ECU uses

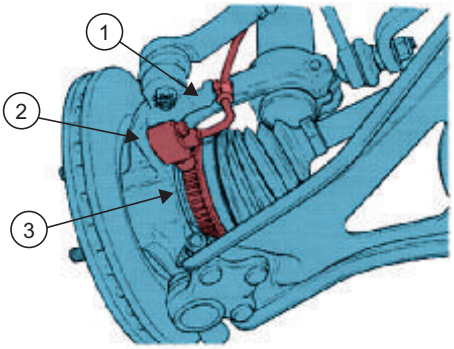

Figure 4.122 Front wheel sensor: 1, carrier; 2, wheel speed sensor; 3, pulse rotor (toothed wheel)

Figure 4.123 Wheel speed sensors

this value as its reference. The acceleration and deceleration values are live measurements, which are constantly changing.

Although brake slip cannot be measured directly, a value can be calculated from the vehicle reference speed. This figure is then used to determine whether and when ABS should take control of the brake pressure. There are variations between manufacturers involving a number of different components. However, for the majority of systems, there are three main components:

- wheel speed sensors (Fig. 4.123)
- electronic control unit (Fig. 4.124)
- hydraulic modulator (Fig. 4.125).

Most wheel speed sensors are inductance sensors and work in conjunction with a toothed wheel. They consist of a permanent magnet and a soft iron rod around which is wound a coil of wire. As the toothed wheel rotates the changes in inductance of the magnetic circuit generates a signal. The frequency and voltage of the signal are proportional to wheel speed. The frequency is the signal used by the ECU. Some systems now use Hall effect sensors, which are more accurate at lower speed. The main parts of the sensor are a magnet and an integrated circuit containing the sensing element.

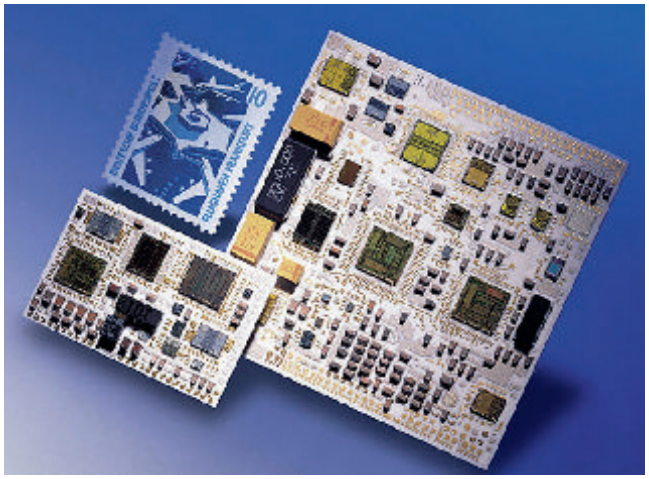

Figure 4.124 Electronic control unit

Figure 4.125 Hydraulic modulators

The ECU takes in information from the wheel sensors and calculates the best course of action for the hydraulic modulator. At the heart of an ABS ECU are two microprocessors, which run the same program independently of each other. This ensures greater security against any fault that could adversely affect braking performance. If a fault is detected, the ABS disconnects itself and operates a warning light. Both processors have non-volatile memory into which fault codes can be written for later service and diagnostic access. The ECU performs a self-test after the ignition is switched on. A failure results in disconnection of the system.

A hydraulic modulator has three operating positions:

- pressure release, where the brake line is open to the reservoir
- pressure holding, where the brake line is closed
- pressure build-up, where the brake line is open to the pump.

The start of ABS engagement is known as ‘first control cycle smoothing’. This smoothing stage is necessary in order not to react to minor disturbances such

Key fact

A hydraulic modulator has three operating positions:

- pressure release
- pressure holding
- pressure build-up.

as an uneven road surface, which can cause changes in the wheel sensor signals. The threshold of engagement is critical. If it started too soon, it would be distracting to the driver and cause unnecessary component wear. If too late, steering and stability could be lost on the first control cycle.

When braking on a road surface with different adhesion under the left and right wheels, the vehicle will yaw or start to twist. The driver can control this with the steering if time is available. This can be achieved if, when the front wheel with poor adhesion becomes unstable, the pressure to the other front wheel is reduced. This acts to reduce the vehicle yaw, which is particularly important when the vehicle is cornering.

Wheel speed instability occurs frequently and at random because of axle vibration on rough roads. Because of this instability, brake pressure tends to be reduced more than it is increased during ABS operation. This could lead to loss of braking under certain conditions. A slight delay in the reaction of the ABS due to delay in signal smoothing, the time taken to move control valves and a time lag in the brake lines, helps to reduce the effect of axle vibration.

The control strategy of the anti-lock brake system can be summarized as follows:

- a rapid brake pressure reduction during wheel speed instability. The wheel will therefore reaccelerate without too much pressure reduction and avoid underbraking
- a rapid rise in brake pressure during and after a reacceleration to a value just less than the instability pressure
- a discrete increase in brake pressure in the event of increased adhesion
- sensitivity suited to the prevalent conditions
- anti-lock braking not initiated during axle vibration.

The application of these five main requirements leads to the need for compromise. Optimum programming and prototype testing can reduce the level of compromise but some disadvantages have to be accepted. The best example of this is braking on uneven ground in deep snow, because deceleration is less effective unless the wheels are locked up. In this example, priority is given to stability rather than stopping distance, as directional control is favoured under these circumstances.

Definition

ESP
Electronic stability program.

An interesting further development in braking systems is the electrohydraulic brake (EHB) (Figs 4.126–4.128). In this system, when the brakes are activated, the EHB control unit calculates the desired target brake pressures at the individual wheels. Braking pressure for each of the four wheels is regulated individually via a wheel pressure modulator, which consists of one inlet and one outlet valve controlled electronically. Normally, the brake master cylinder is detached from the brake circuit, with a pedal travel simulator creating normal pedal feedback. If the electronic stability program (ESP) intervenes, the high-pressure reservoir supplies the required brake pressure quickly and precisely to the wheel brakes.

Key fact

Even in complex systems, the brakes still use pads and discs to cause friction, which creates heat, therefore taking energy away from the movement.

With EHB, the driver's brake pedal input is translated into an electrical signal that is calculated by the EHB control unit and transferred to a central hydraulic unit. The central hydraulic unit develops a hydraulic braking pressure in line with the driver's input and transfers the pressure to the wheel cylinders.

In summary, the principle of operation of all anti-lock brake systems is the same. Three discrete operating phases have to be achieved: pressure reduction, pressure holding and pressure decrease. There are further developments such as EHB and stability control, but the actual brakes still work in the same way, with pads and discs.

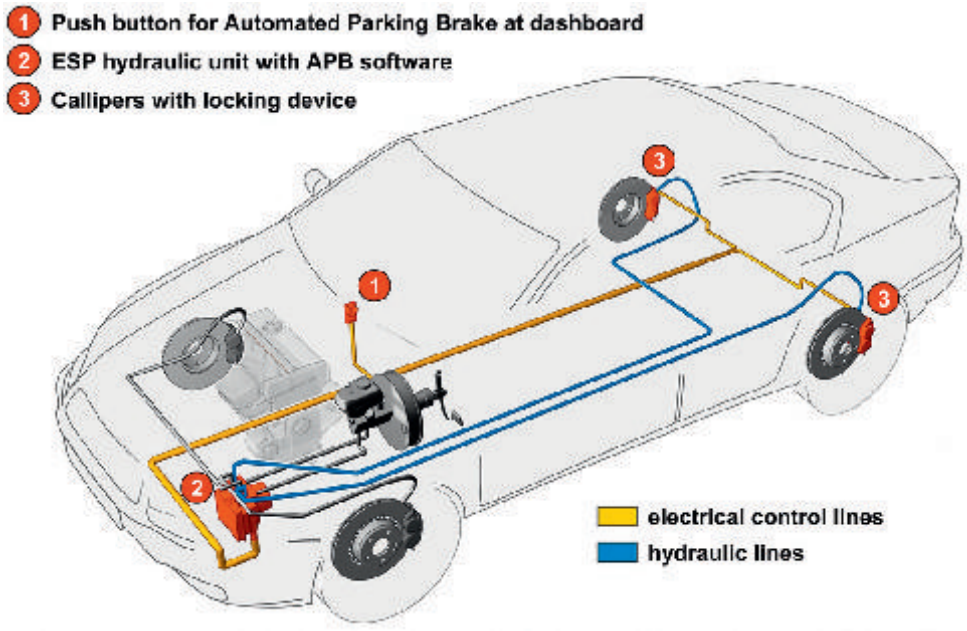

Figure 4.126 Electrohydraulic brake (EHB) system

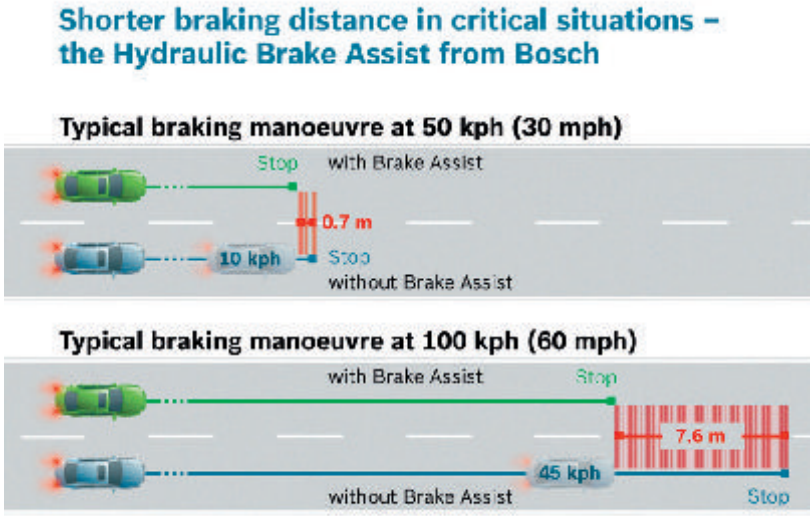

Figure 4.127 Electrohydraulic brake (EHB) system

4.3.6 Traction control

The 'steerability' of a vehicle is lost if the wheels spin when driving off under severe acceleration. Electronic traction control has been developed as a supplement to ABS (Fig. 4.129). This control system prevents the wheels from spinning when moving off or when accelerating sharply while on the move. In this way, an individual wheel that is spinning is braked in a controlled manner. If both or all of the wheels are spinning, the drive torque is reduced by means of an engine control function. The traction control system (TCS) is also known as anti-slip regulation (ASR).

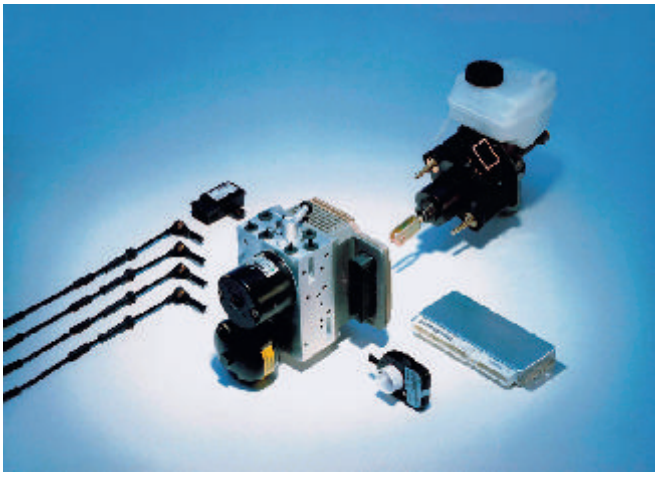

Figure 4.128 Brake by wire: components of Bosch's electrohydraulic brake (EHB) with electronic stability program (ESP). (Source: Bosch Media)

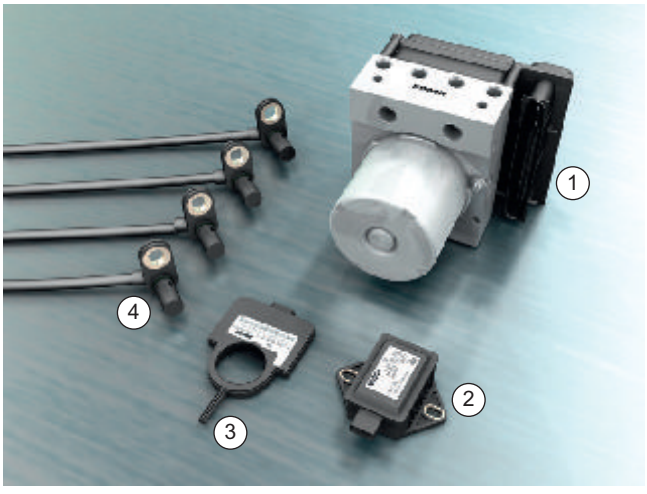

Figure 4.129 Components of an electronic stability program (ESP): 1, Anti-lock braking system and traction control modulator with built-in electronic control; 2, position sensor; 3, steering sensor; 4, wheel speed sensors

Key fact

Traction control is not normally available as an independent system, but is available in combination with ABS.

Traction control is not normally available as an independent system, but is available in combination with ABS. This is because many of the components required are the same for each. A traction control system is linked to the ABS and the engine control system. Traction control will intervene to achieve the following:

- driving stability
- reduction of yawing moment reactions
- optimum propulsion at all speeds
- reduced driver workload.

An automatic control system can intervene more quickly and precisely than the driver of the vehicle. This allows stability to be maintained at a time when the driver might not be able to cope with the situation.

Tractive force can be controlled by a number of methods:

- throttle control
- ignition control
- braking effect.

Figure 4.130 Standard wheel used on many cars

When wheel spin is detected, the throttle position and ignition timing are adjusted. However, better results are gained when the brakes are applied to the spinning wheel. When the brakes are applied, a valve in the hydraulic modulator assembly moves over to allow traction control operation. This allows pressure from the pump to be applied to the brakes on the offending wheel. The valves, in the same way as for ABS, can provide pressure build-up, pressure hold and pressure reduction. This all takes place without the driver touching the brake pedal.

Traction control is designed to prevent wheel spin when a vehicle is accelerating. This improves traction and ensures vehicle stability. Anti-lock brakes and traction control have now developed into complex stability control systems.

ESPs intervene to ensure stability under a wide range of situations. Sensors supply an ECU with information on vehicle movement such as rotation about a vertical axis (yaw). By controlling the driving force from the engine and the braking force to individual wheels, the vehicle can be kept in a stable condition.

4.4 Wheels and tyres

4.4.1 Wheels

Together with the tyre, a road wheel must support the weight of the vehicle. It must also be capable of withstanding a number of side thrusts when cornering, and torsional forces when driving. Road wheels must be strong, but lightweight. They must be cheap to produce, easy to clean, and simple to remove and refit.

Old spoked wheels are attractive but tend only to be used on older sports cars. They have a smaller diameter than, but are a stronger version of, a bike wheel. These wheels must have tyres with an inner tube. Spoked wheels allow good ventilation and cooling for the brakes but can be difficult to keep clean.

The centre of the more common steel wheel is made by pressing a disc into a dish shape, to give it greater strength (Figs 4.130 and 4.131). The rim is a rolled section, which is circled and welded. The rim is normally welded to the flange of the centre disc. The centre disc has a number of slots under the rim to allow ventilation for the brakes as well as the wheel itself.

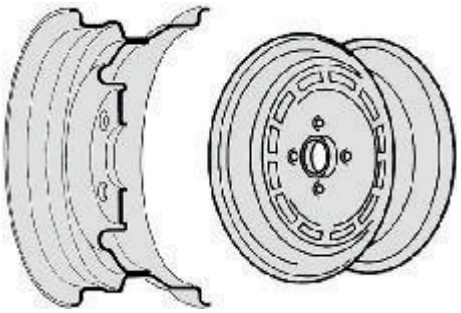

Figure 4.131 Standard wheel design

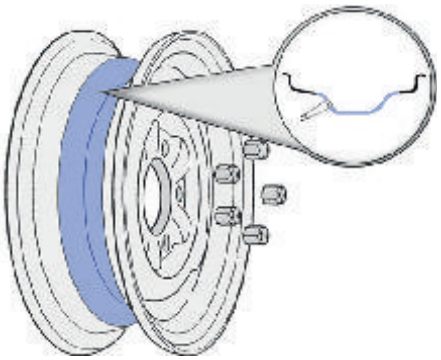

Figure 4.132 Wheel 'well' profile

This type of wheel is cheap to produce and strong. The bead of a tyre is made from wire, which cannot be stretched for fitting or removal. The wheel rim, therefore, must be designed to allow the tyre to be held in place, but also allow for easy removal and replacement.

Key fact

To allow fitting and removal of a tyre, a 'well-base' is manufactured into the rim.

To facilitate fitting and removal a 'well-base' is manufactured into the rim (Fig. 4.132). For tyre removal, one bead must be forced into the well. This then allows the other bead to be levered over the edge of the rim. The bead seats are made with a taper so that as the tyre is inflated the bead is forced up the taper by the air pressure. This locks the tyre on to the rim, making a good seal.

Steel wheels are a very popular design. They are very strong and cheap to produce. Steel wheels are usually covered with plastic wheel trims, which are available in many different styles (Fig. 4.133).

Key fact

The main advantage of cast alloy wheels is reduced weight.

Alloy wheels, or 'alloys', are good, attractive looking wheels (Fig. 4.134). They tend to be fitted to higher specification vehicles and many designs are used. They are strong and lightweight but can be difficult to clean. Wheels of this type are generally produced from aluminium alloy castings, which are then machine finished. Alloy wheels, however, can be damaged by 'kerbing' (Fig. 4.135).

The main advantage of cast alloy road wheels is their reduced weight and, of course, they look good. Disadvantages are their lower resistance to corrosion and that they are more prone to accidental damage. The general shape of the wheel, as far as tyre fitting is concerned, is much the same as the pressed steel type's.

Safety first

Do not remove tyres from or fit tyres on split or divided rim wheels unless you have received proper instruction.

Many larger vehicles use split rims, of either a two- or three-piece construction (Fig. 4.136). The tyre is held in place by what could be described as a very large circlip (also known as a C-clip or snap ring). Do not remove tyres from or fit tyres on this type of wheel unless you have received proper instruction.

Figure 4.133 Plastic trim

Figure 4.134 Alloy wheel

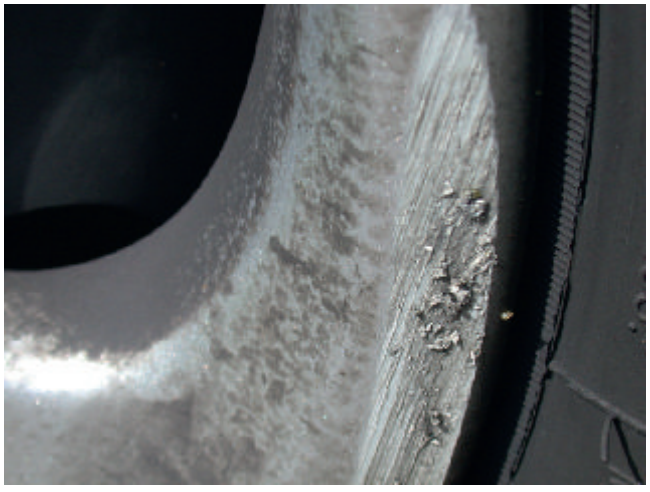

Figure 4.135 Damaged alloy wheel

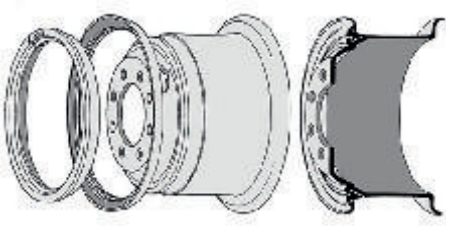

Figure 4.136 Three-piece wheel construction

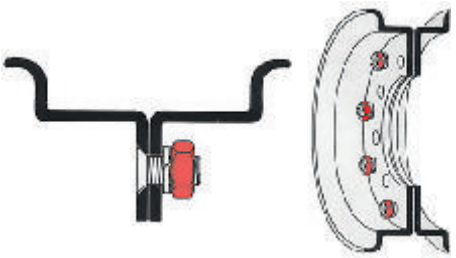

Figure 4.137 Divided rim

Figure 4.138 Space saver

On a few specialist vehicles, the rims are made in two halves, which are bolted together (Fig. 4.137). The nuts and bolts holding them together should be specially marked. Undoing them with the tyre inflated would be very dangerous.

To save space in the vehicle and to save on costs, some cars with large and expensive alloy wheels use a small thin steel wheel as the spare (Fig. 4.138). The speed of the vehicle is restricted when this type of wheel is used. It is intended for emergency use only.

Light vehicle road wheels are usually held in place by four or five nuts or bolts (more on some vehicles) (Fig. 4.139). The fixing holes in the wheels are stamped or machined to form a cone-shaped seat. The wheel nut or bolt heads fit into this seat (Fig. 4.140). This ensures that the wheel fits in exactly the right position. In the case of the steel pressed wheels, it also strengthens the wheel centre around the stud holes.

Figure 4.139 Four stud fixings

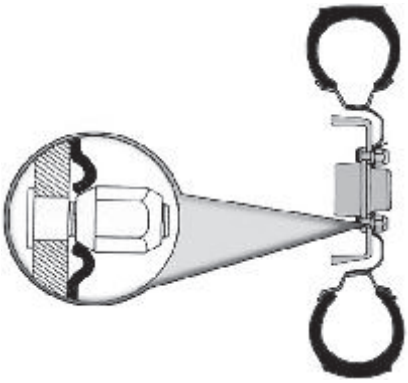

Figure 4.140 Wheel fixing

When fitting a wheel, the nuts or bolts must be tightened evenly in a diagonal sequence (Fig. 4.141). It is also vital that they are set to the correct torque. Ensure that the cone-shaped end of the wheel nuts is fitted towards the wheel.

Car wheel rim measurement consists of three main dimensions (Fig. 4.142). The nominal rim diameter is the distance between the bead seats. The inside rim width is the distance between rims. It is not possible to measure this when the tyre is fitted. The flange height can be determined by subtracting the nominal diameter from the outside rim diameter.

There are many types of car wheel rims and Fig. 4.143 shows a selection of those in common use. The arrows indicate the side of the rim over which the tyre should be removed or fitted.

Some rims now allow 'run flat' capability. Conventional rims, which have a well for tyre removal and fitting, also have the disadvantage that the tyre can roll off the rim in the event of a puncture when driving. The rim shown in Fig. 4.144 prevents this by the use of two circumferential grooves into which the specially shaped tyre bead fits. In the event of a puncture, the 'run flat' facility is intended to be used for bringing the vehicle to a safe stop, not for continued driving.

A valve is used to allow the tyre to be inflated with air under pressure, prevent air from escaping after inflation, and allow the release of air for adjustment of

Key fact

Run flat rims use two circumferential grooves into which the specially shaped tyre bead fits so that it will not come off the rim.

Figure 4.141 Torque sequences

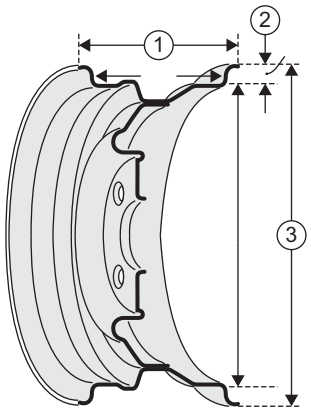

Figure 4.142 Rim sizes: 1, outside and inside rim; 2, flange height; 3, outside and nominal rim diameter

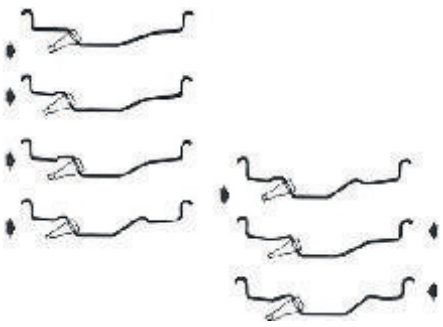

Figure 4.143 A variety of rim designs showing tyre fitting directions

Figure 4.144 Run flat rim profile

Figure 4.145 Valve on a tubeless wheel rim

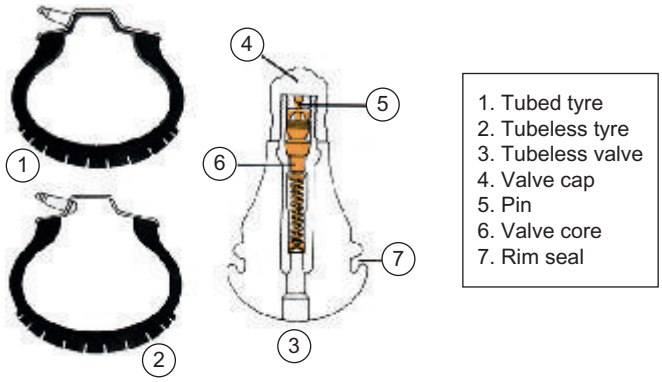

Figure 4.146 Tyres and valves

pressure (Fig. 4.145). The valve assembly is contained in a brass tube, which is bonded into a rubber sleeve and mounting section.

The valve core consists of a centre pin, which has metal and rubber disc valves. When the tyre is inflated, the centre pin is depressed, and the disc valve moves away from the bottom of the seal tube and allows air to enter the tyre. To release air, or for pressure checking, the centre pin is depressed. During normal operation, the disc valve is held onto its seat by a spring and by the pressure of air. If all the air needs to be released, the valve core assembly can be removed. The upper part of the valve tube is threaded to accept a valve cap. This prevents dirt and grit from entering and acts as a secondary seal.

The tubeless valve body must be made so that when fitted into the wheel an airtight seal is formed. Wheel rims used for tubeless tyres must be sealed and airtight. Most wheels and tyres in use are of the tubeless design (Fig. 4.145).

Figure 4.147 Tubeless tyre construction: 1, inner sealing layer; 2, radial plies; 3, sidewall; 4, bead; 5, kerb band; 6, bracing layers; 7, tread

4.4.2 Tyres

Key fact

The tyre performs two basic functions:

- primary suspension
- frictional contact with the road.

The tyre performs two basic functions. It acts as the primary suspension, cushioning the vehicle from the effects of a rough surface. It also provides frictional contact with the road surface. This allows the driving wheels to move the vehicle. The tyres allow the front wheels to steer and the brakes to slow or stop the vehicle.

The tyre has a flexible casing, which contains air and is manufactured from reinforced synthetic rubber. The tyre is made from an inner layer of fabric plies, which are wrapped around bead wires at the inner edges. The bead wires hold the tyre in position on the wheel rim. The fabric plies are coated with rubber, which is moulded to form the side walls and the tread of the tyre. Behind the tread is a reinforcing band, usually made of steel, rayon or glass fibre. Modern tyres are mostly tubeless, so they also have a thin layer of rubber coating on the inside to act as a seal (Fig. 4.147).

An innermost sheet of airtight synthetic rubber performs the 'inner tube' function. The carcass ply is made up of thin textile fibre cables, laid out in straight lines and bonded into the rubber. These cables are largely responsible for determining the strength of the tyre structure. The carcass ply of a car tyre has about 1400 cables, each capable of withstanding 15 kg. A lower filler is responsible for transferring propulsion and braking torques from the wheel rim to the road surface.

Beads clamp the tyre firmly against the wheel rim. The beads can withstand forces up to 1800 kg. The tyre has supple rubber walls, which protect it against impacts (with kerbs, etc.) that might otherwise damage the carcass. There is also a hard rubber link between the tyre and the rim. Crown plies consist of oblique overlapping layers of rubber reinforced with very thin, but very strong, metal wires. The overlap between these wires and the carcass cables forms a series of non-deformable triangles. This arrangement lends great rigidity to the tyre structure.

Safety first

Different types of tyre construction should not be used on the same vehicle.

There are two main types of tyre construction, cross-ply and radial, and as a general rule these different types should not be mixed on a vehicle.

Cross-ply tyres are not used on any mass-produced modern cars. However, the construction details are useful to show how tyre technology has developed. Several textile plies are laid across each other, running from bead to bead in alternate directions. The number of plies depends on the size of the tyre and the load it has to carry. The same number of plies is used on the crown and the sidewalls.

The overlaid plies are embedded in interposed layers of rubber (Fig. 4.148). This thick mass is subject to internal shearing movements. There is no difference between the sidewalls and crown, because each has the same plies.

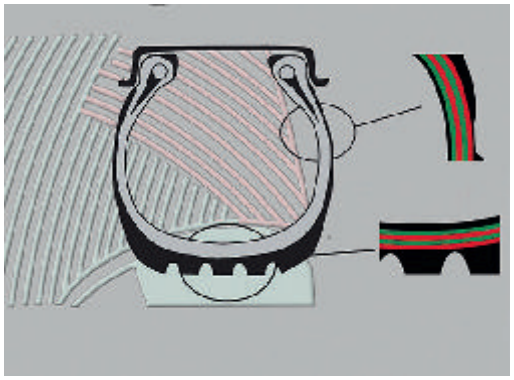

Figure 4.148 Plies embedded in layers of rubber

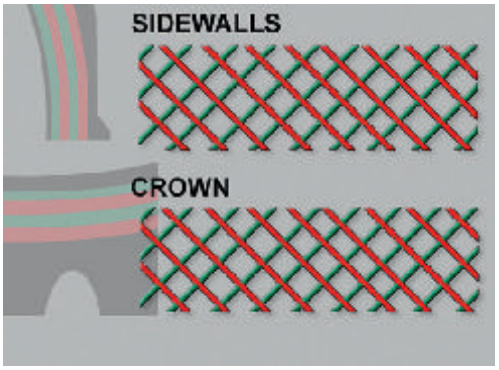

Figure 4.149 Honeycomb of superimposed layers

Inside the reinforcing, a honeycomb of superimposed layers forms a grid with a square mesh (Fig. 4.149). With a longitudinal pulling movement, each of the diamond shapes stretches and compacts easily. This repeated deformation results in a lot of friction in the surrounding rubber. This friction leads to energy loss in the form of heat. Over time, this damages the tyre and reduces its lifetime.

When it is not carrying a load, the cross-ply tyre presents a very rounded profile to the ground (Fig. 4.150). Only a small elliptical area makes road contact. As load is applied, the tyre flattens. The greater the load, the more the shoulders flatten to the ground. The tread in the middle tends to lift up and grip is reduced overall.

When the tyre is rolling along a straight road and it undergoes a temporary overload, the contact area increases. Once the suspension takes the load the contact area decreases. The path of the cross-ply tyre is therefore a succession of increasing and decreasing contacts. When subjected to a lateral force, the structure of the cross-ply tyre cannot remain flat on the ground. This is because of its rigid sidewalls. One of the shoulders is compacted against the ground while the other tends to lose contact. This results in a strong drift effect.

The radial architecture (which is used for most modern tyres) consists of a carcass ply formed by textile arcs running from one bead to the other. Each arc is laid at an angle of 90° to the direction in which the tyre rolls. At the top of the tyre a crown belt, made up of several plies reinforced with metal wire, is laid on top

Definition

Radial
At an angle of 90° to the direction in which a tyre rolls.

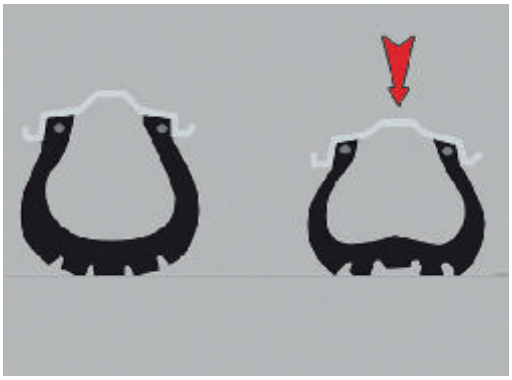

Figure 4.150 Cross-ply tyre profile

Figure 4.151 Radial tyre: thickness of the crown and sidewall

of the carcass ply. These crown plies, laid one on top of another, overlap at an angle determined by the type of tyre.

The thicknesses of the radial tyre crown and sidewall plies are different, so that the work of each part of the tyre is more specialized (Fig. 4.151). The sidewall reinforcement consists of a single thin layer of textile. The rubber covering of this reinforcement is also thin. At the crown, there is a textile reinforcing near the inside of the tyre, overlaid with the belt of metal plies. This construction gives an inextensible crown and flexible sidewalls.

In the sidewall of the radial tyre, the arcs of the carcass ply, with its wires, are laid independently of each other and embedded in the rubber (Fig. 4.152). The crown is made up of the arcs of the carcass ply, continuing up from the sidewalls, plus the metal wires of the crown plies. This forms a grid with a triangular mesh.

In the sidewalls, the shearing movement between the parallel wires is slight and the rubber is not very thick. As a result, there is little friction and less heat is generated. At the crown, the triangular mesh is virtually impossible to deform. The structure therefore maintains its equilibrium, and when rolling, spreads flat on the ground. The tyre lasts longer because there is less deformation (Fig. 4.153).

Even without a load, the radial tyre is almost flat on the ground and the contact area is already very wide. As load is applied, this area grows longer without losing width. The tread blocks remain flat against the road surface and grip is at a maximum (Fig. 4.154). When rolling, the flexibility of the sidewalls allows them to absorb many of the bumps.

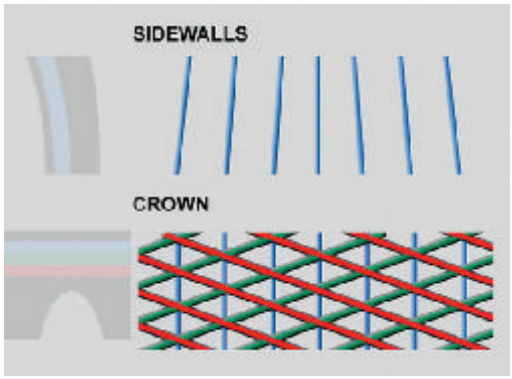

Figure 4.152 Radial tyre: sidewall and crown construction

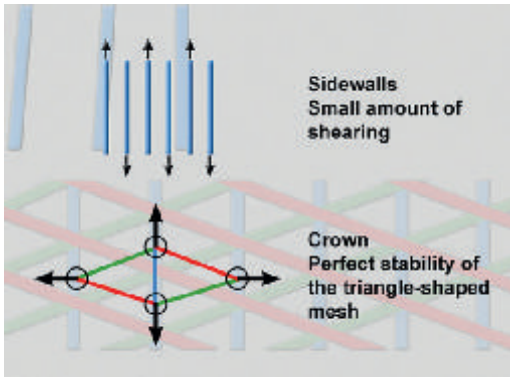

Figure 4.153 Radial construction reduces deformation

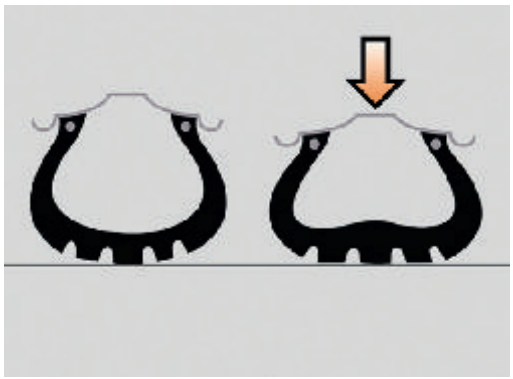

Figure 4.154 Radial tyre: contact remains constant

The width of the contact area when rolling remains constant. Only the length of the radial tyre can increase under load. The width of its path is therefore not affected by uneven road surfaces. In a way, the radial tyre functions like a tank track moving across the ground.

As the sidewalls of the radial tyre are very flexible, they stretch in proportion to an increase in force. The sidewall acts like a moving hinge between the wheel and the crown, and this allows the crown to remain flat against the ground. The path of the radial tyre therefore remains constant, even when subject to lateral forces.

Key fact

A radial tyre functions much like a tank track moving across the ground.

Safety first

The rubber compound of a tyre, not the tread, provides grip. However, without the tread to disperse water, very little grip can be achieved.

Figure 4.155 Side of a tyre showing markings

Markings on the sides of tyres are quite considerable and can be a little confusing. For example, the tyre in Fig. 4.155 shows:

195/55 R 15 84 H

This translates as:

- 195–tyre section width (the width of the tyre tread) in millimetres
- 55–aspect ratio (height of the sidewall divided by the width of the tyre) in %
- R–construction type, in this case a radial tyre
- 15–rim diameter in inches
- 84–load index
- H–speed rating.

All tyres are produced with a serial tyre identification number (TIN) that shows the date of manufacture of a tyre. The last three digits (for tyres made before 2000) or four digits (for post-2000 tyres) of the serial TIN indicate the week and year that the tyre was made. For example, a tyre made in the 23th week of 1996 would show 236 and a tyre made in the 34th week of 2011 will show 3411.

Other markings used on tyres are as follows:

- M&S–mud and snow tyres
- DOT codes–coding satisfying the requirements of the US Department of Transportation contain a mixture of letters and numbers (e.g. DOT DVDE MTA 129), which identify the place of manufacture
- E-Marks–tyres for sale in the European Union must carry an E-mark in accordance with ECE Regulation 30 (e.g. E4 027550).

The speed rating was traditionally shown as a part of the tyre's size (e.g. 195/55VR15). Since the inclusion of load ratings, many manufacturers now show the speed rating after the size in combination with the load rating (e.g. 195/55R15 84V). Commonly used speed ratings are shown in Table 4.1.

The load index indicates the maximum weight the tyre can carry at the maximum speed indicated by its speed rating. Some load rating indices are listed in Table 4.2 (the full range extends to index 119).

Current tread depth and MOT legislation in the UK requires that car tyres must have a minimum of 1.6 mm of tread in a continuous band throughout the central three-quarters of the tread width and over the whole circumference of the tyre. The legislation is the same in Australia and New Zealand.

Table 4.1 Tyre speed ratings

Speed symbol	Maximum speed	
	(km/h)	(mph)
N	140	87
P	150	93
Q	160	99
R	170	106
S	180	112
T	190	118
H	210	130
V	240	149
W	270	168
Y	300	186

Table 4.2 Tyre load index ratings (examples)

Load index	kg
65	290
66	300
67	307
68	315
69	325
70	335
71	345
72	355
73	365
74	375
75	387
76	400
77	412
78	425
79	237
80	450
81	462
82	475
83	487
84	500

The current regulations are:

- The tyre must be suitable for the purpose the vehicle is being used.
- The tyre must be suitably inflated for the purpose the vehicle is being used.
- The tyre must not have a cut in excess of 25 mm or 10% of the tyre section width, whichever is the greater, which is deep enough to reach the tyre's internal structure.
- The tyre must not have a lump, bulge or tear caused by separation or partial failure of its structure.
- The tyre must not have any ply or cord exposed.
- The tyre tread depth must be a minimum of 1.6 mm measured in a band comprising the central 75% of the tread width and continuous around the tyre circumference.
- The tyre must be maintained in a condition so that it is fit for the purpose the vehicle or trailer is being used and must not have any defect which may cause danger to the road surface or damage to persons in or on the vehicle, or other road users.

Safety first

Industry testing has shown that when a tyre reaches around 3.5 mm in tread depth, the level of performance in the wet, in particular, starts to deteriorate.

In the USA, to prevent aquaplaning and skidding, it is recommended that tyres must have proper tread depth. The minimum tread depth is 1/16th of an inch. However, legislation is less clear, so always check state and local requirements.

Despite the laws and recommendations, it is recognized that the legal limit is an extreme. Industry testing has shown that when a tyre reaches around 3.5 mm in tread depth, the level of performance in the wet, in particular, starts to deteriorate. This is because the main function of the tread pattern of a tyre is to evacuate water. As the tread depth decreases it gradually loses the ability to evacuate all water from the road surface under the tyre and the car will eventually aquaplane.

Tyre tests have shown that the wet braking distances of a new tyre compared with a tyre with only 1.6 mm of tread left on it are significant and can be the difference between life and death. In addition, tyres should always be inflated to the pressure recommended by the car manufacturer.

4.5 Formula 1 chassis technology (brakes)

4.5.1 Brakes overview

An average F1 car will decelerate from 100 to 0 km/h (62 to 0 mph) in about 17 m (55 ft). When braking from higher speeds, aerodynamic downforce enables an eye-popping (literally!) deceleration of between 4.5 and 5.5 *g*. Contrast this with the Bugatti Veyron, which is claimed to be able to brake at 1.3 *g*. An F1 car can also brake from 200 km/h (124 mph) to a complete stop in just 2.9 seconds and 65 m (213 ft).

F1 disc brakes consist of a rotor and calliper inside each wheel, just like most road cars. However, carbon composite discs (rotors) are used instead of steel or cast iron. This is because this material has superior frictional, thermal and anti-warping properties. It also results in significant weight savings. F1 brakes are designed to work at temperatures up to 1000°C (1800°F). The driver can control brake force distribution front the rear (bias) to compensate for changes in track conditions or fuel load. Regulations specify that this control must be mechanical, so it is typically operated by a lever inside the cockpit. The front brakes have a priority to within 51–60%, depending on track conditions. During a race, reducing the rear braking force allows for reduced rear tyre wear.

Key fact

F1 cars use carbon composite discs (rotors).

Although the braking performance is unbelievable, the drivers say that carbon-fibre brakes can take some time to get used to. This is because it feels like nothing is happening during the first few milliseconds after pressing the pedal. After this very short time, deceleration is immediate and fierce. The delay is the time required by the disc and calliper to reach operating temperature. This increases by about 500°C during the first half-second of braking, after which it can reach up to 1200°C.

Even though carbon fibre can withstand high temperatures, cooling is vital to ensure that the brakes continue to work effectively during a race. Air ducts are therefore created on the inside of the wheel to provide a constant airflow onto the calliper pads and disc. Current cooling systems are complicated and differ among different teams, but all use perforated brake discs.

4.5.2 FIA technical regulations

This section gives a simplified overview of the technical regulations as at 2011, which relate to the brakes (source: www.fia.com). Please note that before you design and build your own F1 car, you should refer to the official FIA technical regulations!

4.5.2.1 Brake circuits and pressure distribution

- All cars must be equipped with only one brake system. This system must comprise solely two separate hydraulic circuits operated by one pedal, one circuit operating on the two front wheels and the other on the two rear wheels. This system must be designed so that if a failure occurs in one circuit the pedal will still operate the brakes in the other.
- The brake system must be designed in order that the force exerted on the brake pads within each circuit are the same at all times.
- Any powered device which is capable of altering the configuration or affecting the performance of any part of the brake system is forbidden.
- Any change to, or modulation of, the brake system whilst the car is moving must be made by the driver's direct physical input, may not be preset and must be under his complete control at all times.

4.5.2.2 Brake callipers, discs and pads

- All brake callipers must be made from aluminium materials and no more than two attachments may be used to secure each brake calliper to the car.
- No more than one calliper, with a maximum of six pistons, is permitted on each wheel and no more than one brake disc is permitted on each wheel.
- No brake disc may be more than 28 mm thick with maximum and minimum diameters of 305 mm and 300 mm, respectively, and no more than two brake pads are permitted on each wheel.

4.5.2.3 Brake pressure modulation

- No braking system may be designed to prevent wheels from locking when the driver applies pressure to the brake pedal.
- No braking system may be designed to increase the pressure in the brake callipers above that achievable by the driver applying pressure to the pedal under static conditions.

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CHAPTER 5

Transmission systems

5.1 Manual transmission clutch

5.1.1 Clutch operation

A clutch is a device for disconnecting and connecting rotating shafts. In a vehicle with a manual gearbox, the driver pushes down the clutch when changing gear, thus disconnecting the engine from the gearbox. It allows a temporary neutral position for gear changes and also a gradual way of taking up drive from rest.

The exact location of the clutch varies with vehicle design. However, the clutch is always fitted between the engine and the transmission (Fig. 5.1). With few exceptions, the clutch and flywheel are bolted to the rear of the engine crankshaft.

The driver operates the clutch by pushing down a pedal. This movement has to be transferred to the release mechanism. The two main methods used are cable and hydraulic. The cable method is the most common (Fig. 5.2). Electrohydraulic or electric clutch operation is used on direct shift gearboxes (DSGs).

A steel cable, which runs inside a plastic-coated steel tube, is used on most cars. The cable 'outer' must be fixed at each end. The cable 'inner' transfers the movement. One problem with cable clutches is that movement of the

Key fact

The clutch is always fitted between the engine and the transmission.

Key fact

A steel clutch cable, which runs inside a plastic-coated steel tube, is used on most cars.

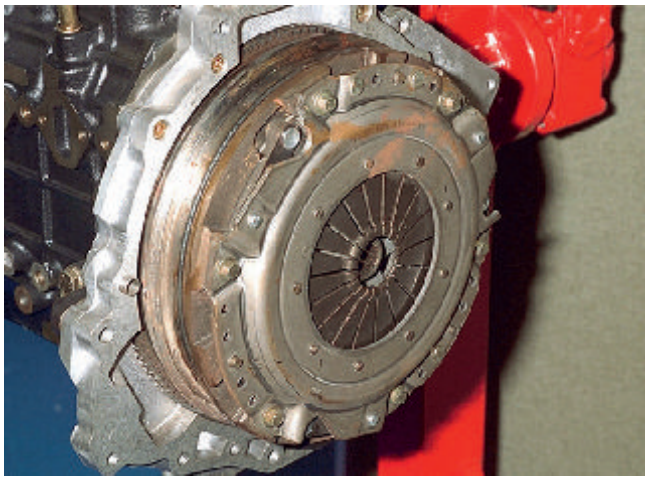

Figure 5.1 The clutch cover is bolted to the engine flywheel

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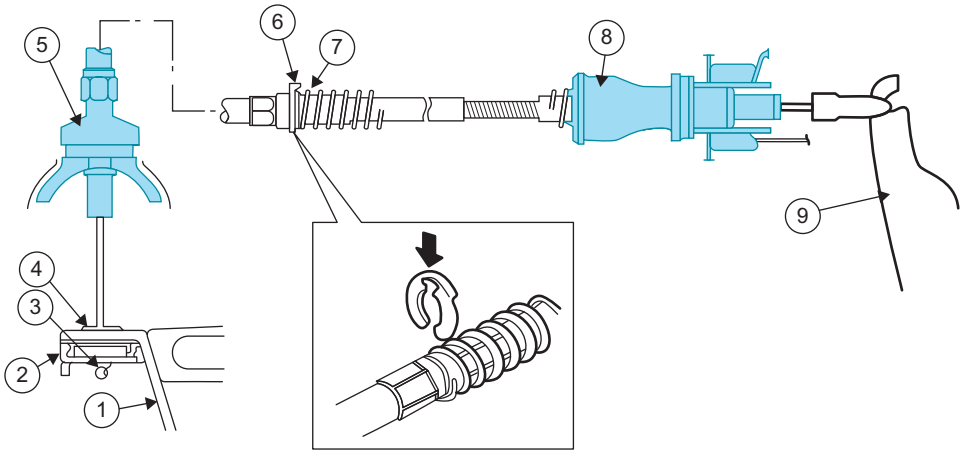


Figure 5.2 Clutch cable: 1, clutch release lever; 2, retaining clip; 3, seating plate; 4, rubber pad; 5, cable end fixed to gearbox or clutch housing; 6, spring retaining clip; 7, self-adjusting spring; 8, cable end fixed to bulkhead; 9, clutch pedal

Figure 5.3 Clutch release bearing

engine, with respect to the vehicle body, can cause the length to change. This results in a judder when the clutch is used. This problem has been almost eliminated by careful positioning and quality engine mountings.

This clutch cable works on a simple lever principle. The clutch pedal is the first lever. Movement is transferred from the pedal to the second lever, which is the release fork. The fork, in turn, moves the release bearing to operate the clutch (Fig. 5.3).

A hydraulic mechanism involves two cylinders (Fig. 5.4). These are termed the master and slave cylinders. The master cylinder is connected to the clutch pedal. The slave cylinder is connected to the release lever. The clutch pedal moves the master cylinder piston. This pushes fluid through a pipe, which in turn forces a

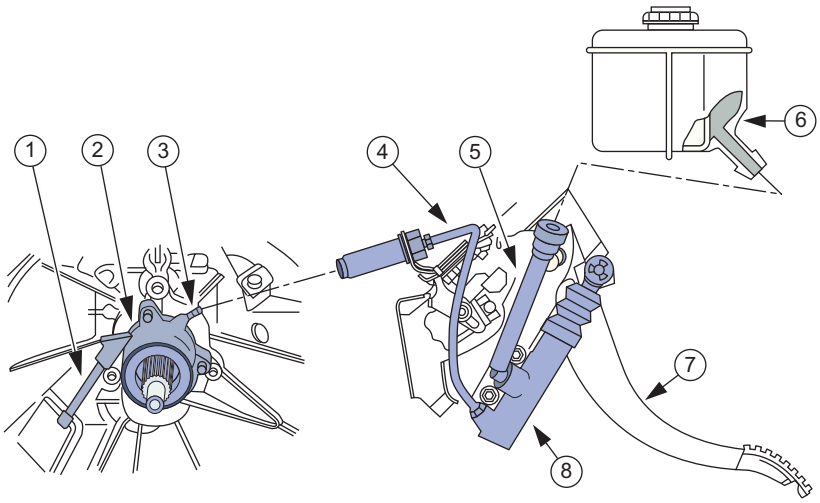


Figure 5.4 Clutch hydraulic components: 1, bleed valve; 2, slave cylinder; 3, pressure pipe connection; 4, pressure pipe; 5, replenishing pipe; 6, fluid reservoir; 7, clutch pedal; 8, master cylinder

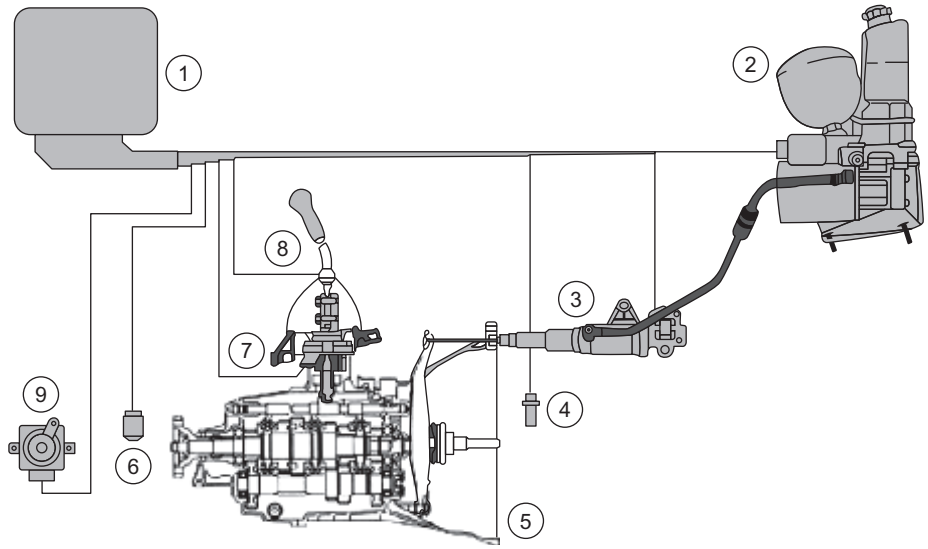


Figure 5.5 Electronic control of the clutch: 1, electronic control unit; 2, hydraulic power unit; 3, slave cylinder with position sensor; 4, engine speed sensor; 5, transmission; 6, vehicle speed sensor; 7, gear selection sensor; 8, gear lever; 9, accelerator pedal position sensor

piston out of the slave cylinder. The movement ratio can be set by the cylinder diameters and the lever ratios.

An electronic clutch was developed for racing vehicles to improve the getaway performance. For production vehicles (Fig. 5.5), a strategy has been developed to interpret the driver's intention. With greater throttle openings, the strategy changes to prevent abuse and driveline damage. Electrical control of the clutch release bearing position is by a solenoid actuator, which can be modulated by signals from the electronic control unit (ECU). This allows the time to reach the ideal take-off position to be reduced and the ability of the clutch to transmit torque to be improved. The efficiency of the whole system can therefore be increased.

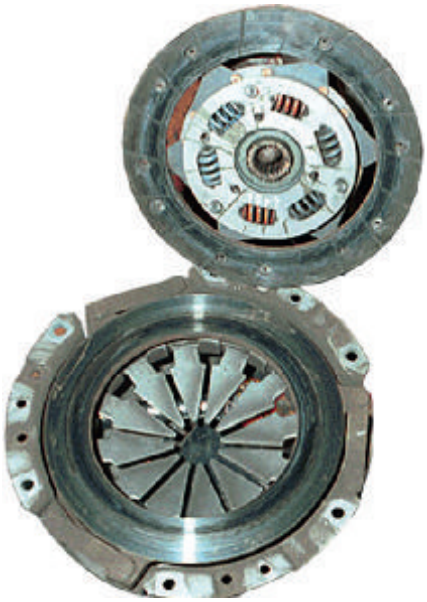


Figure 5.6 Driven plate and pressure plate

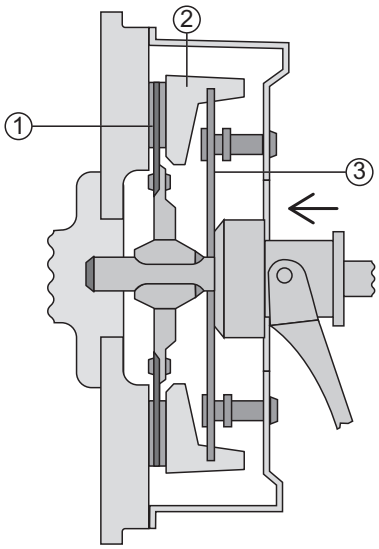


Figure 5.7 Clutch engaged: 1, driven (friction) plate; 2, pressure plate; 3, release levers

5.1.2 Types of clutch

Key fact

The clutch consists of two main parts, a pressure plate and a driven plate.

The clutch is made of two main parts: a pressure plate and a driven plate (Fig. 5.6). The driven plate, often termed the clutch disc, is fitted on the shaft, which takes the drive into the gearbox.

When the clutch is engaged, the pressure plate, inside the cover, presses the driven plate against the engine flywheel. This allows drive to be passed to the gearbox. Pushing down the clutch pedal moves the pressure plate away, which frees the driven plate.

The movement of the diaphragm during clutch operation is represented by Figs 5.7 and 5.8. The method of controlling the clutch is quite simple. The mechanism consists of either a cable or hydraulic system.

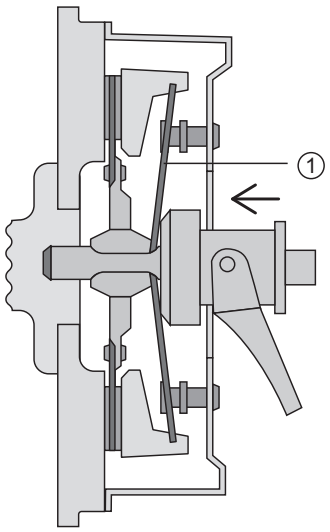


Figure 5.8 Clutch disengaged: 1, release levers (fingers)

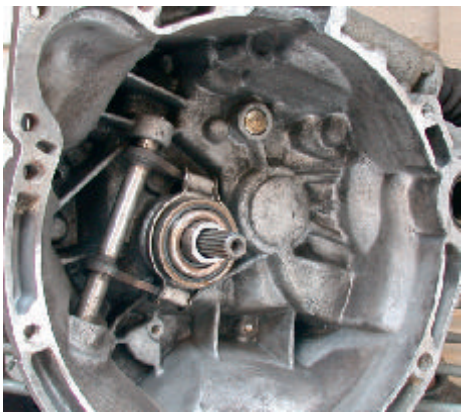


Figure 5.9 Gearbox input shaft around which is the release bearing and its operating lever

The clutch shaft, or gearbox input shaft, projects from the front of the gearbox (Fig. 5.9). Most shafts have a smaller section or spigot, which projects from its outer end. This rides in a spigot bearing in the engine crankshaft flange. The splined area of the shaft allows the clutch disc to move along the splines. When the clutch is engaged, the disc drives the gearbox input shaft through these splines.

The clutch disc is a steel plate covered with frictional material (Fig. 5.10). It fits between the flywheel face and the pressure plate. In the centre of the disc is the hub, which is splined to fit over the splines of the input shaft. As the clutch is engaged, the disc is firmly squeezed between the flywheel and pressure plate. Power from the engine is transmitted by the hub to the gearbox input shaft. The width of the hub prevents the disc from rocking on the shaft as it moves along the shaft.

The clutch disc has frictional material riveted or bonded on both sides. These frictional facings are either woven or moulded. Moulded facings are preferred because they can withstand high-pressure plate loading forces. Grooves are cut across the face of the friction facings to allow for smooth clutch action and increased cooling. The cuts also make a place for the facing dust to go as the clutch lining material wears.

Key fact

The splined area of the gearbox input shaft allows the clutch disc to move but still transmit drive.

Key fact

The clutch disc has frictional material riveted or bonded on both sides.

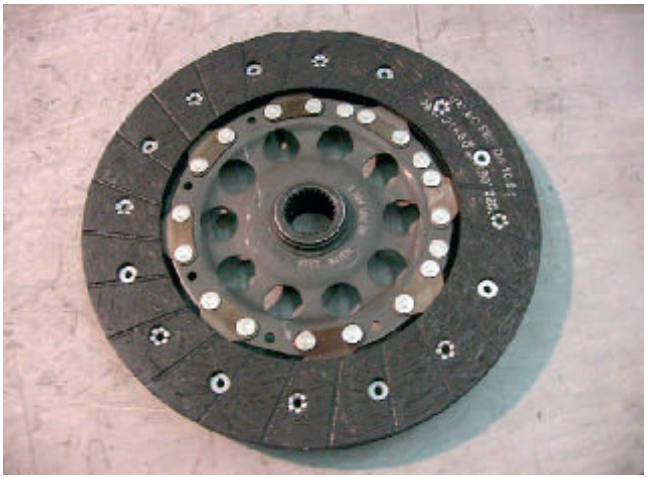


Figure 5.10 Clutch disc or driven plate

Figure 5.11 Wave springs eliminate chatter

The frictional material wears as the clutch is engaged. At one time asbestos was in common use. Owing to awareness of the health hazards resulting from asbestos (asbestosis and mesothelioma, for example) new lining materials have been developed. The most commonly used types are paper-based and ceramic materials. They are strengthened by the addition of cotton and brass particles, and wire. These additives increase the torsional strength of the facings and prolong the life of the clutch.

The facings are attached to wave springs, which cause the contact pressure on the facings to rise gradually. This is because the springs flatten out when the clutch is engaged. These springs eliminate chatter when the clutch is engaged (Fig. 5.11). They also help to move the disc away from the flywheel, when it is disengaged. The wave springs and facings are attached to the steel disc.

There are two types of clutch discs: rigid and flexible (Fig. 5.12). A rigid clutch disc is a solid circular disc fastened directly to a centre splined hub. The flexible clutch disc has torsional dampener springs that circle the centre hub.

The dampener is a shock-absorbing feature built into a flexible clutch disc (Fig. 5.13). The primary purpose of the flexible disc is to absorb power impulses

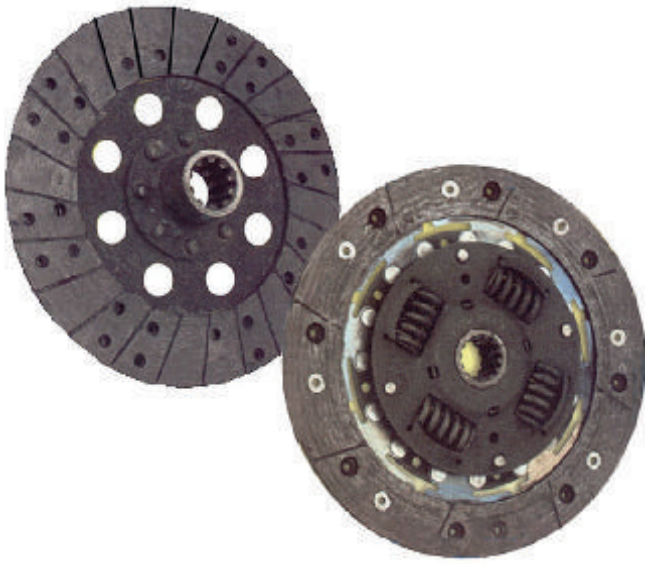


Figure 5.12 Solid and flexible discs

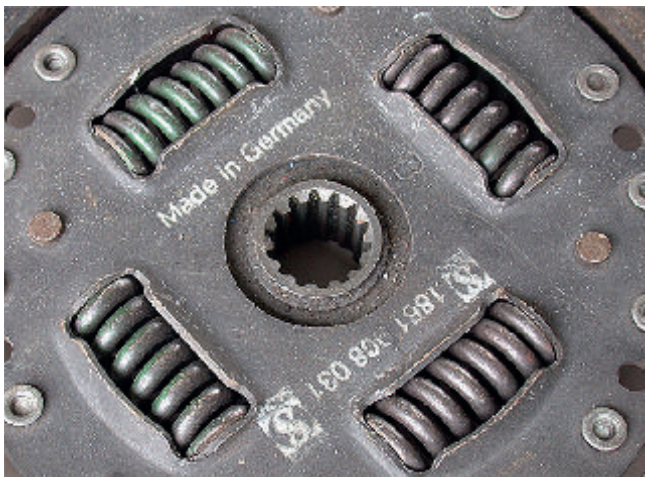


Figure 5.13 Damping springs

from the engine that would otherwise be transmitted directly to the gears in the transmission. A flexible clutch disc has torsion springs and friction discs between the plate and hub of the clutch.

When the clutch is engaged, these springs cushion the sudden loading by flexing and allowing twist between the hub and plate. When the loading is over, the springs release and the disc transmits power normally. The number and tension of these springs are determined by the amount of engine torque and the weight of the vehicle. Stop pins limit the torsional movement to a few millimetres.

The pressure plate and cover assembly squeezes the clutch disc onto the flywheel when the clutch is engaged. It moves away from the disc when the clutch is disengaged. These actions allow the clutch disc to transmit, or not transmit, the engine's torque to the gearbox.

A pressure plate is a large spring-loaded clamp, which is bolted to, and rotates with, the flywheel (Fig. 5.14). The assembly includes a metal cover, heavy release springs

Key fact

The pressure plate and cover assembly squeezes the clutch disc onto the flywheel when the clutch is engaged.

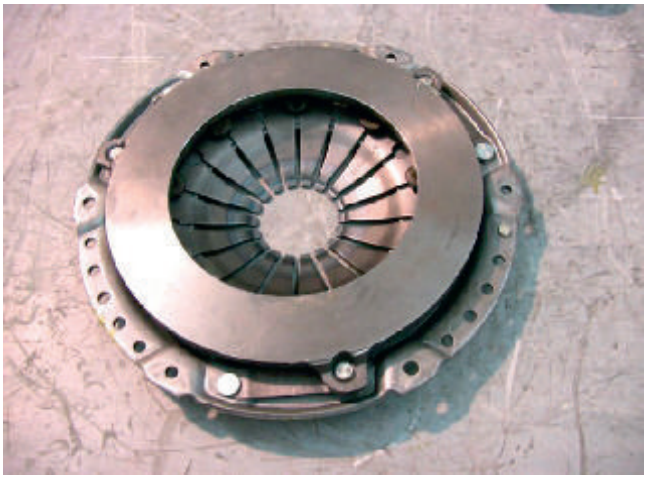


Figure 5.14 Pressure plate

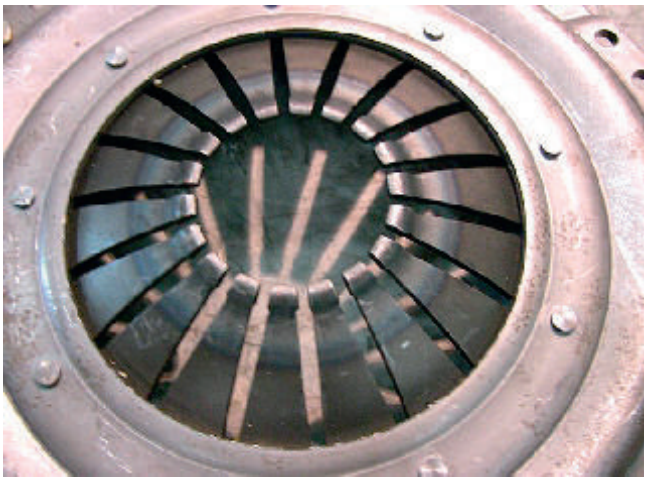


Figure 5.15 Cone-shaped diaphragm spring

and a metal pressure ring that provides a friction surface for the clutch disc. It also includes a thrust ring or fingers for the release bearing, and release levers.

The release levers release the holding force of the springs when the clutch is disengaged. Some pressure plates are of a 'semi-centrifugal' design. They use centrifugal weights, which increase the clamping force on the thrust springs as engine speed increases.

The diaphragm spring assembly is a cone-shaped diaphragm spring between the pressure plate and the cover (Fig. 5.15). Its purpose is to clamp the pressure plate against the clutch disc. This spring is normally secured to the cover by rivets. When pressure is exerted on the centre of the spring, the outer diameter of the spring tends to straighten out. When pressure is released, the spring resumes its normal cone shape.

The centre portion of the spring is slit into a number of fingers that act as release levers (Fig. 5.16). When the clutch is disengaged, these fingers are depressed by the release bearing. The diaphragm spring pivots over a fulcrum ring. This makes its outer rim move away from the flywheel. The retracting springs pull the pressure plate away from the clutch disc, to disengage the clutch.

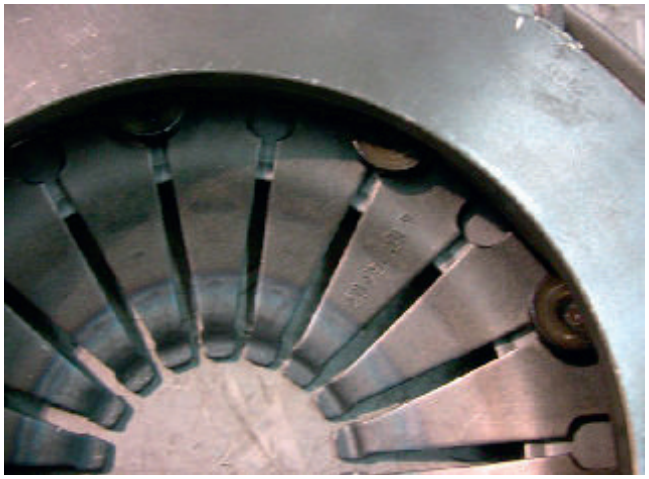


Figure 5.16 Fingers

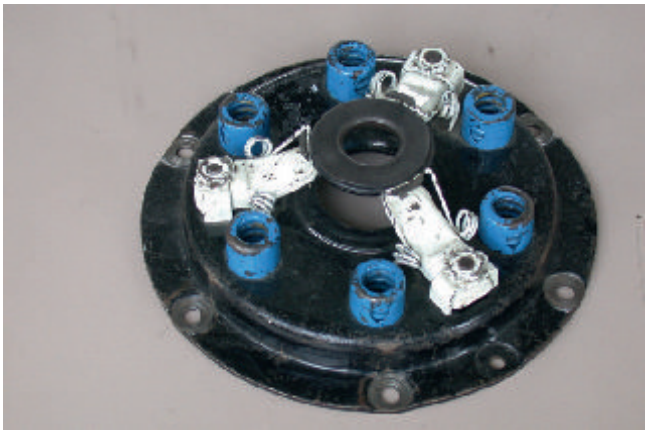


Figure 5.17 Coil spring clutch assembly

Key fact

As the clutch is engaged, the release bearing is moved away from the release fingers.

As the clutch is engaged, the release bearing is moved away from the release fingers. As the spring pivots over the fulcrum ring, its outer rim forces the pressure plate tightly against the clutch disc. At this point, the clutch disc is clamped between the flywheel and pressure plate.

The individual parts of a pressure plate assembly are contained in the cover. Most covers are vented to allow heat to escape and air to enter. Other covers are designed to provide a fan action to force air circulation around the clutch assembly. The effectiveness of the clutch is affected by heat. Therefore, by allowing the assembly to cool, it works better.

Earlier clutches, and some heavy-duty types, used coil springs instead of a diaphragm (Fig. 5.17). However, the diaphragm clutch has replaced the coil spring type because the diaphragm type has the following advantages:

- It is not affected by high speeds (coil springs can be thrown outwards).
- The low pedal force makes for easy operation.
- It is light and compact.
- The clamping force increases or at least remains constant as the friction lining on the plate wears.

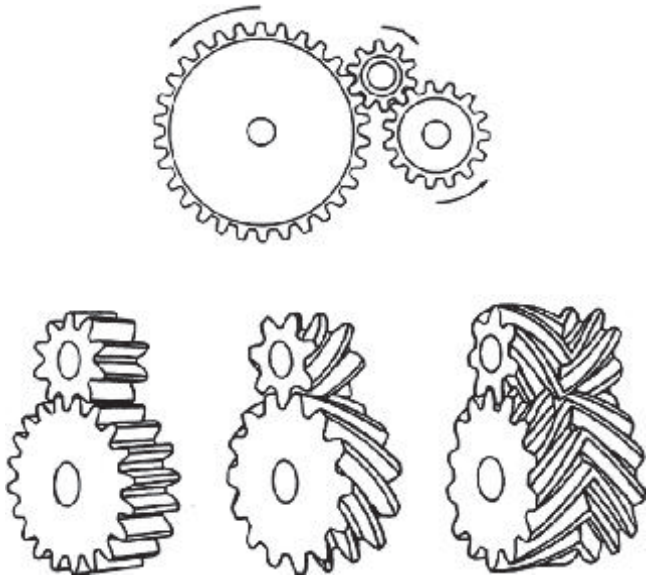


Figure 5.18 Straight cut and helical gears and at the top, the principle of gear operation

5.2 Manual transmission gearbox

5.2.1 Gearbox operation

Key fact

A transmission system gearbox is required because torque from an engine changes at different speeds.

A transmission system gearbox is required because the power of an engine consists of speed and torque. Torque is the twisting force of the engine's crankshaft and speed is its rate of rotation. The transmission can adjust the proportion of torque and speed that is delivered from the engine to the drive shafts. When torque is increased, speed decreases, and when speed is increased, the torque decreases. The transmission also reverses the drive and provides a neutral position when required.

Helical gears are used for almost all modern gearboxes (Fig. 5.18). They run more smoothly and are quieter in operation. Earlier sliding-mesh gearboxes used straight-cut gears, as these were easier to manufacture. Helical gears do produce some sideways force when operating, but this is dealt with using thrust bearings.

For most light vehicles, a gearbox has five forward gears and one reverse gear (Fig. 5.19). It is used to allow operation of the vehicle through a suitable range of speeds and torque. A manual gearbox needs a clutch to disconnect the engine crankshaft from the gearbox while changing gears. The driver changes gears by moving a lever, which is connected to the box by a mechanical linkage. Alternatively, gears can be changed by electrohydraulic methods in response to paddle switches located behind the steering wheel.

The gearbox converts the engine power by a system of gears, providing different ratios between the engine and the wheels. When the vehicle is moving off from rest, the gearbox is placed in first, or low gear. This produces a high torque but low wheel speed. As the car speeds up, the next higher gear is selected. With each higher gear, the output turns more quickly but with less torque.

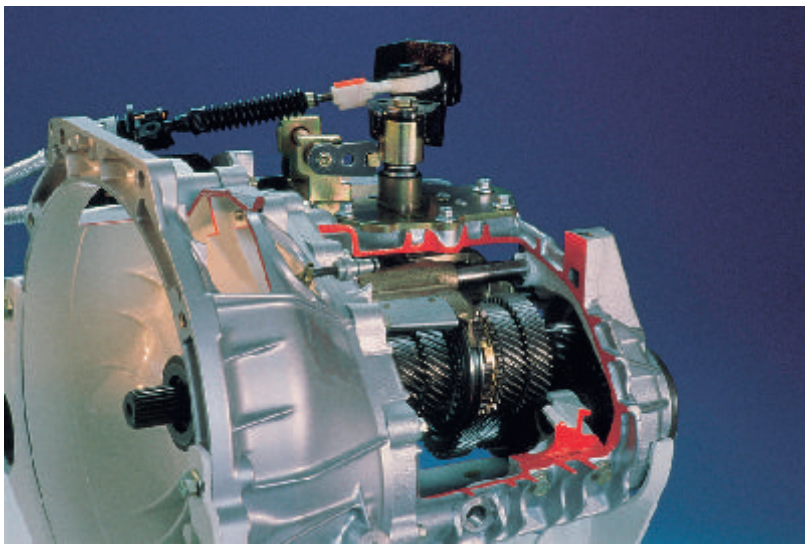


Figure 5.19 Front-wheel drive gearbox. (Source: Ford Media)

Figure 5.20 Pontiac six-speed gear selector

Fourth gear on most rear-wheel drive light vehicles is called direct drive, because there is no gear reduction in the gearbox (Fig. 5.21). In other words, the gear ratio is 1:1. The output of the gearbox therefore turns at the same speed as the crankshaft. For front-wheel drive vehicles, the ratio can be 1:1 or slightly different. Most modern light vehicles now have a fifth gear. This can be thought of as a kind of overdrive because the output turns more quickly than the engine crankshaft.

Power comes into the gearbox via the input shaft. A gear at the end of this shaft drives a gear on another shaft called the countershaft or layshaft. A number of gears of various sizes are mounted on the layshaft. These gears drive other gears on a third motion shaft, also known as the output shaft.

Key fact

Power comes into the gearbox via the input shaft.

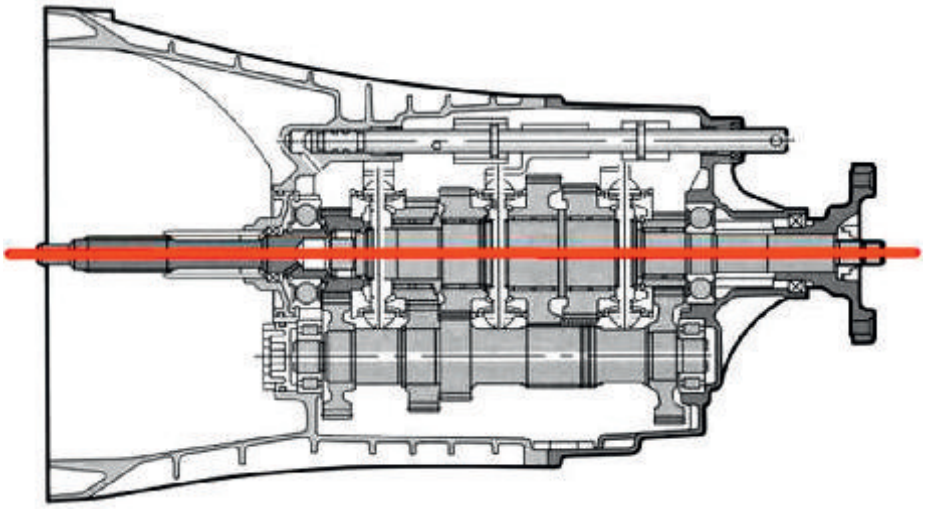


Figure 5.21 Fourth gear is often 'straight through'

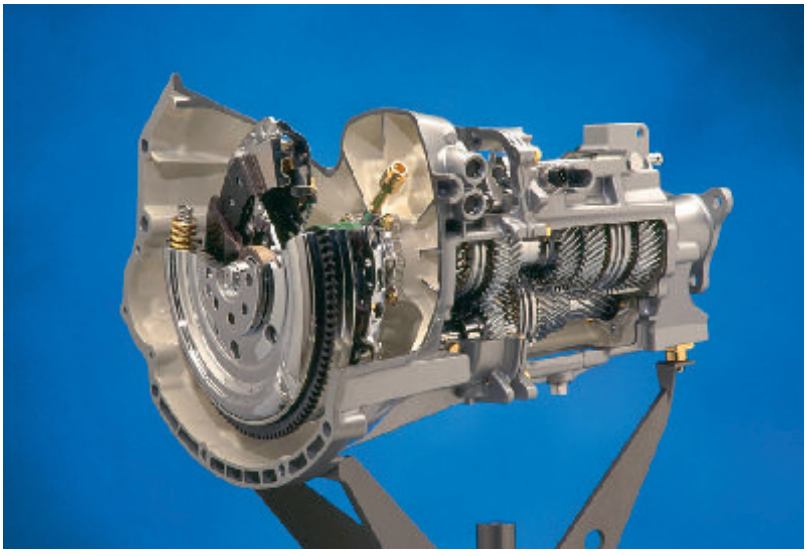


Figure 5.22 Lincoln five-speed rear-wheel drive gearbox. (Source: Ford Media)

Older vehicles used sliding-mesh gearboxes. With these gearboxes, the cogs moved in and out of contact with each other. Gear changing was, therefore, a skill that took time to master. These have now been replaced by constant mesh gearboxes. The modern gearbox still produces various gear ratios by engaging different combinations of gears. However, the gears are constantly in mesh. For reverse, an extra gear called an idler operates between the countershaft and the output shaft. It turns the output shaft in the opposite direction to the input shaft.

With the exception of reverse, the gears do not move. This is why this type of gearbox has become known as constant mesh. In other words, the gears are running in mesh with each other at all times. In constant mesh boxes, dog clutches are used to select which gears will be locked to the output shaft. These clutches, which are moved by selector levers, incorporate synchromesh mechanisms.

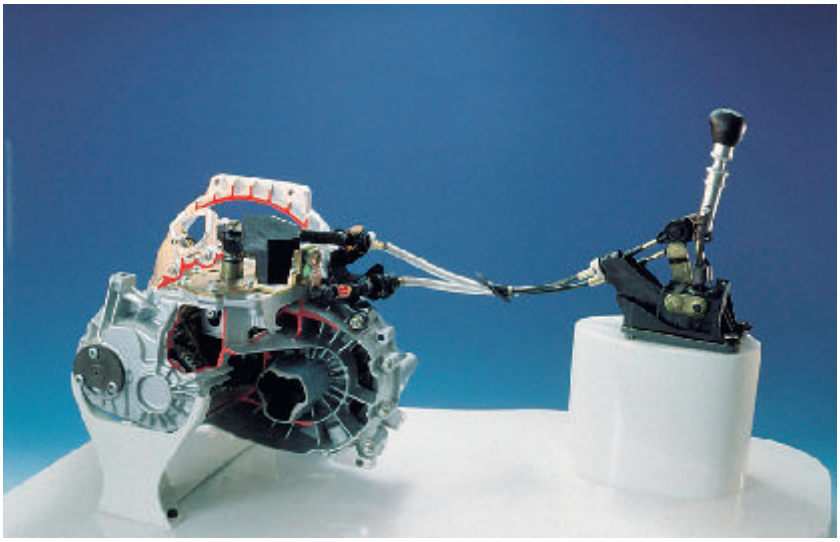


Figure 5.23 Front-wheel drive transaxle gearbox with cable shift. (Source: Ford Media)

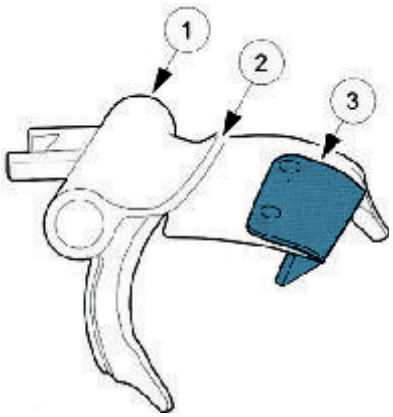


Figure 5.24 Gear shift or selector fork: 1, shift fork; 2, fluid guide edge (for lubrication); 3, fluid baffle

A manual gearbox allows the driver to select the gear appropriate to the driving conditions. Low gears produce low speed but high torque; high gears produce higher speed but lower torque.

Key fact

Low gears produce low speed but high torque; high gears produce higher speed but lower torque.

5.2.2 Gear change mechanisms

On all modern manual change (shift) gearboxes, the selection of different ratios is achieved by locking gears to the mainshaft. A synchromesh and clutch mechanism does this when moved by a selector fork (Fig. 5.24). The selector fork is moved by a rod, or rail, which in turn is moved by the external mechanism and the gearstick.

To save space, some manufacturers use a single selector shaft. This means the shaft has to twist and move lengthways. The twisting allows a finger to contact with different selector forks. The lengthways movement pushes the synchronizers into position. All selector forks are fitted on the same shaft.

Key fact

On all modern manual lever change (shift) gearboxes, the selection of different ratios is achieved by locking gears to the mainshaft.

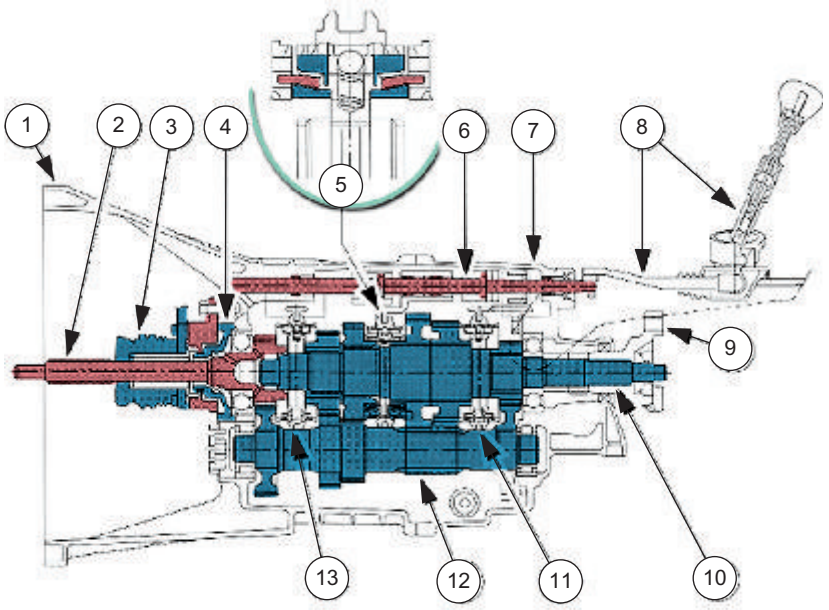


Figure 5.25 Double selector shaft: 1, clutch (bell) housing; 2, input shaft; 3, clutch mechanism; 4, seal housing; 5, interlock; 6, two shift shafts (rails) one behind the other; 7, housing; 8, external change mechanism; 9, output drive flange; 10, output shaft; 11, shaft, 5th gear and reverse gear; 12, countershaft (layshaft); 13, 3rd and 4th gears. (Source: Ford Motor Company)

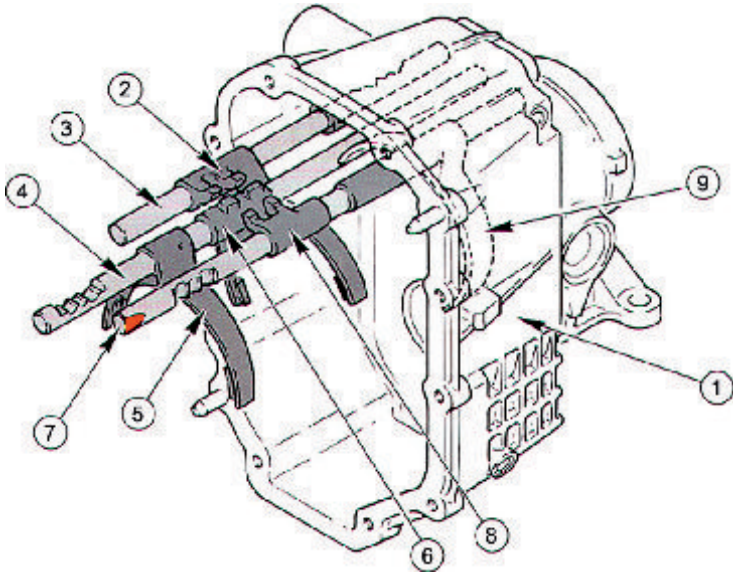


Figure 5.26 Triple selector shaft: 1, housing; 2, 1st/2nd gear selector; 3, 1st/2nd selector shaft; 4, 3rd/4th selector shaft; 5, 3rd/4th selector fork; 6, 3rd/4th gear driver; 7, 5th/reverse gear selector shaft; 8, 5th/reverse gear driver; 9, 5th/reverse gear selector fork. (Source: Ford Motor Company)

On a two-shaft system, the main selector shaft often operates the first/second gear selector fork. An auxiliary shaft operates the third/fourth selector fork (Fig. 5.25).

The three-rail, or three-shaft system, is similar to the two-shaft type (Fig. 5.26). However, each individual shaft can be moved lengthways. In turn, the shafts will move the first/second, third/fourth or fifth/reverse forks.

A common external linkage is shown in Fig. 5.27. Movement of the lever is transferred to the gearbox by a shift rod. The rod will only move to select

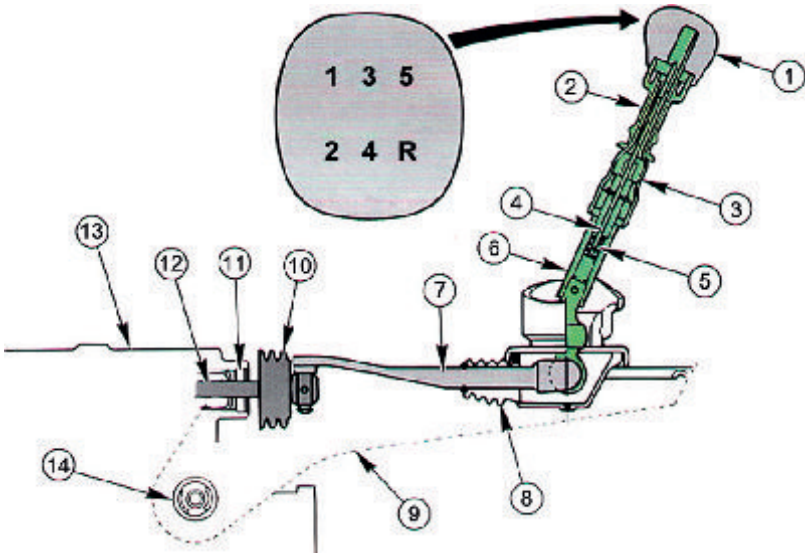


Figure 5.27 Rod-operated shift mechanism: 1, gear knob; 2, reverse lock mechanism; 3, gaiter; 4, reverse lock cable; 5, spring; 6, gear lever; 7, external shift rod; 8, gaiter; 9, housing gaiter; 10, bellows gaiter; 11, selector shaft radial lip oil seal; 12, internal selector shaft; 13, transmission housing; 14, insulator (noise vibration and harshness)

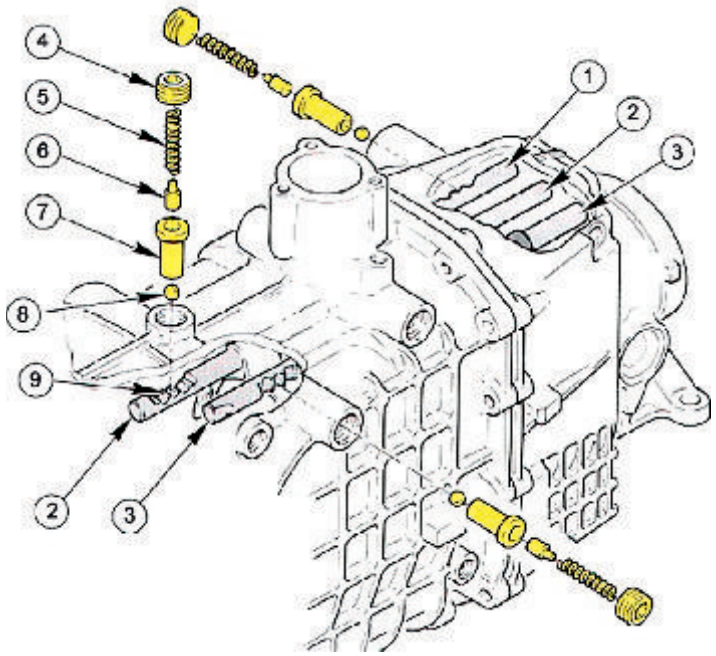


Figure 5.28 Ball and spring detent: 1, 1st/2nd gear selector shaft; 2, 3rd/4th gear selector shaft; 3, 5th/reverse gear selector shaft; 4, threaded plug; 5, spring; 6, pin; 7, sleeve; 8, ball; 9, detent notches

reverse gear when the lock sleeve is lifted. This prevents accidental selection of reverse gear.

A more recent development is the cable shift mechanism. The advantage of this system is that the shift lever does not have to be fixed to the gearbox or in a set position. This allows designers more freedom (see Fig. 5.23).

A detent mechanism is used necessary to hold the selected gear in mesh. In most cases, this is just a simple ball and spring acting on the selector shaft(s). Figure 5.28 shows a gearbox with the detent mechanisms highlighted.

Definition

NVH
Noise vibration and harshness.

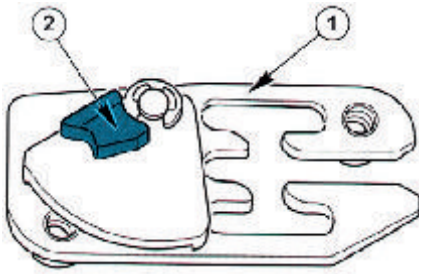


Figure 5.29 Gate and reverse gear lock: 1, gate; 2, reverse gear lock

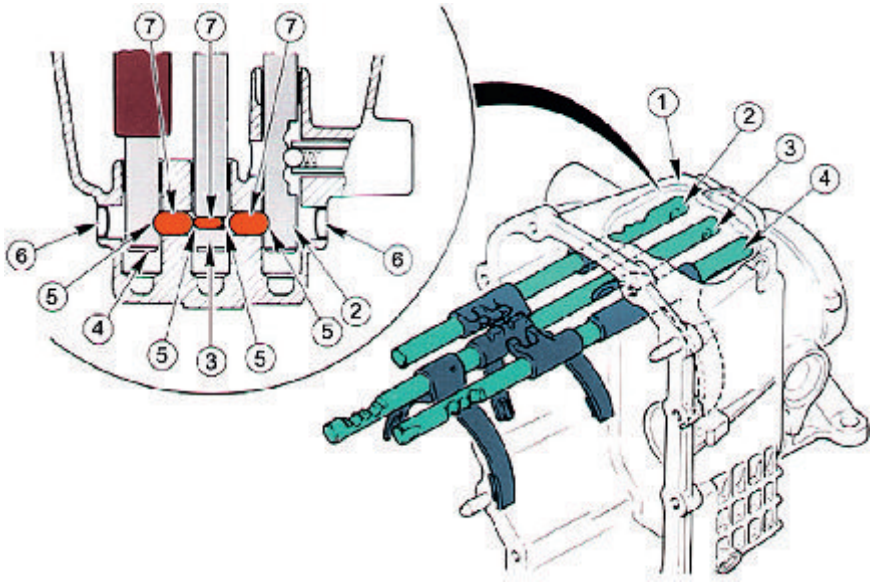


Figure 5.30 Plunger type interlock: 1, housing; 2, 1st/2nd gear selector shaft; 3, 3rd/4th gear selector shaft; 4, 5th/reverse gear selector shaft; 5, locking notch; 6, plug; 7, locking pin

Key fact

A detent system holds the selected gear in place.

Key fact

A gearbox mechanism must only allow selection of one gear at a time by the use of an interlock.

Gear selection interlocks are a vital part of a gearbox. They prevent more than one gear from being engaged at any one time. When any selector clutch is in mesh, the interlock will not allow the remaining selectors to change position. As the main selector shaft is turned by side-to-side movement of the gear stick, the gate restricts the movement. The locking plate, shown in Fig. 5.29, will only allow one shaft to be moved at a time. Because the gate restricts the movement, selection of more than one gear is prevented.

When three rails are used to select the gears, plungers or locking pins can be used (Fig. 5.30). These lock the two remaining rails when one has moved. In the neutral position, each of the rails is free to move. When one rail (rod or shaft) has moved, the pins move into the locking notch, preventing the other rails from moving.

Gear selection must be a simple process for the driver. To facilitate changing, several mechanical components are needed. The external shift mechanism must transfer movement to the internal components. The internal mechanism must only allow selection of one gear at a time by the use of an interlock. A detent system helps to hold the selected gear in place.

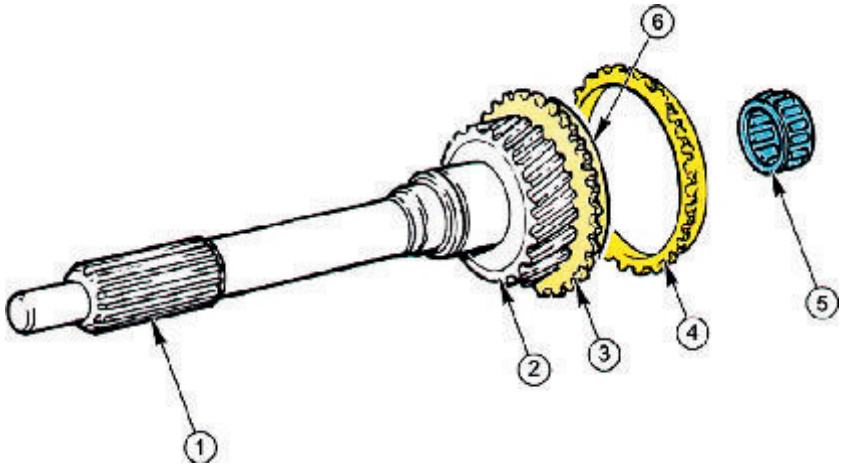


Figure 5.31 Input shaft components: 1, input shaft; 2, countershaft drive gear; 3, 4th gear synchronizing teeth; 4, 4th gear synchronizing ring; 5, mainshaft pilot bearing; 6, synchronizing cone

5.2.3 Gears and components

There is a wide range of gearboxes in use. However, although the internal components differ, the principles remain the same. The examples in this section are, therefore, useful for learning the way in which any gearbox works.

The input shaft transmits the torque from the clutch, via the countershaft (or layshaft) to the transmission output shaft. It runs inside a bearing at the front and has an internal bearing, which runs on the mainshaft, at the rear. The input shaft carries the countershaft driving gear and the synchronizer teeth and cone for fourth gear (Fig. 5.31).

Key fact

The input shaft transmits the torque from the clutch, via the countershaft (or layshaft) to the transmission output shaft.

The mainshaft is mounted in the transmission housing at the rear and the input shaft at the front. This shaft carries all the main forward gears, the selectors and clutches. All the gears run on needle roller bearings. The gears run freely unless selected by one of the synchronizer clutches.

The countershaft is sometimes called a layshaft (Fig. 5.32). It is usually a solid shaft containing four or more gears. Drive is passed from here to the output shaft, in all gears except fourth. The countershaft runs in bearings, fitted in the transmission case, at the front and rear.

Definition

Countershaft
The layshaft.

An extra gear has to be engaged to reverse the direction of the drive. A low ratio is used for reverse, even lower than first gear in many cases. The reverse idler connects the reverse gear to the countershaft (Fig. 5.33).

Power travels in to the gearbox via the input shaft. A gear at the end of this shaft drives a gear on the countershaft (layshaft). Gears of various sizes are mounted on the layshaft. These gears drive other gears on a third motion shaft, also known as the output shaft.

The gearbox produces various gear ratios by engaging different combinations of gears. For reverse, an extra gear called an idler operates between the countershaft and the output shaft. It turns the output shaft in the opposite direction to the input shaft. Figure 5.34 shows a front-wheel drive gearbox and the power flows through it in each of the different gears. Note how in each case (with the exception of reverse) the gears do not move. This is why this type of

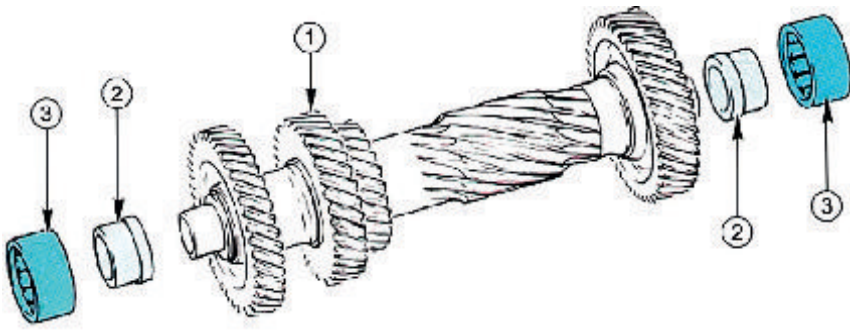
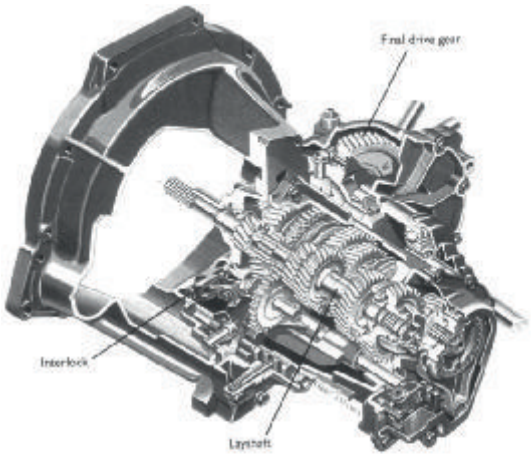
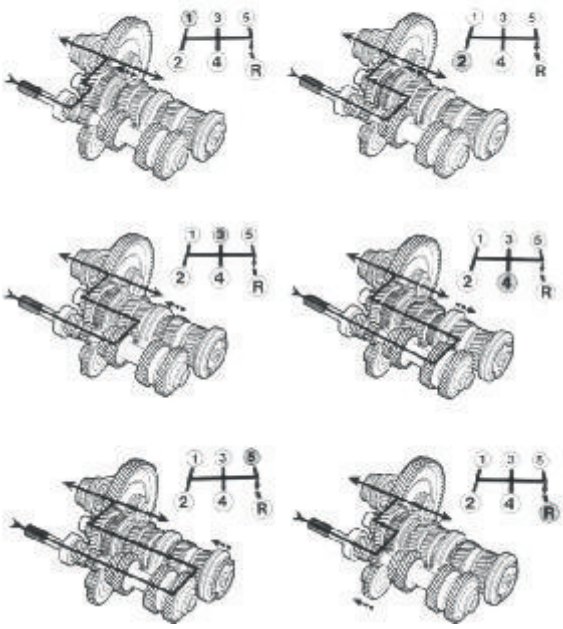


Figure 5.32 Countershaft/layshaft: 1, gears fixed to the countershaft; 2, inner race; 3, roller bearing





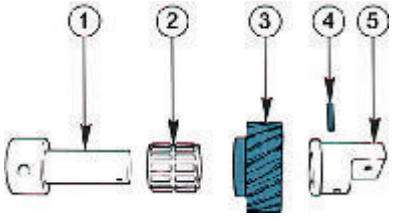


Figure 5.33 Reverse gear idler: 1, shaft; 2, needle roller bearing; 3, reverse gear idler; 4, roll pin; 5, mounting

Figure 5.34 Gearbox operation and power flows

gearbox has become known as constant mesh. In other words, the gears are running in mesh with each other at all times. Dog clutches are used to select which gears will be locked to the output shaft. These clutches are moved by selector levers and incorporate synchromesh mechanisms.

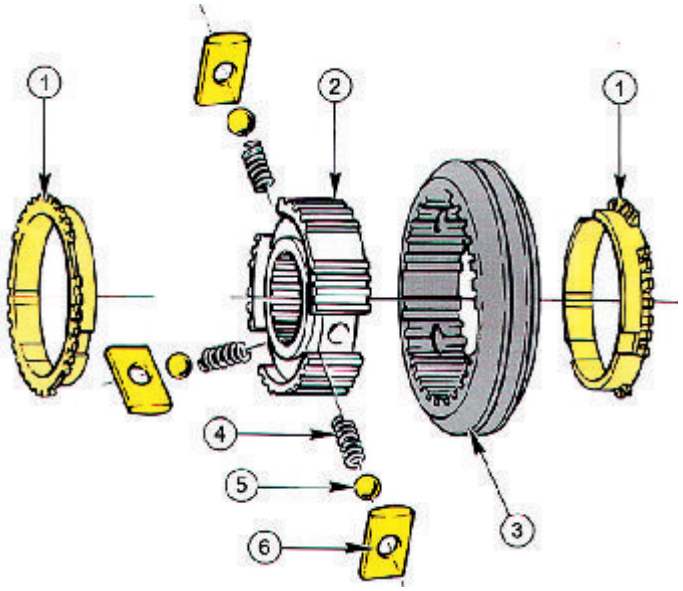


Figure 5.35 Synchronizer components: 1, synchronizer; 2, hub; 3, selector sleeve; 4, spring; 5, ball; 6, blocker bar

Key fact

A synchromesh mechanism is needed because the teeth of dog clutches clash if they meet at different speeds.

A synchromesh mechanism is needed because the teeth of dog clutches clash if they meet at different speeds. A synchromesh system synchronizes the speed of two shafts before the dog clutches are meshed; hence the name.

There are three stages of engagement:

- neutral
- synchronizing
- shift position.

The system works like a friction-type cone clutch. The collar is in two parts and contains an outer toothed ring, which is spring-loaded to sit centrally on the synchromesh hub. When the outer ring, or synchronizer sleeve, is made to move by the action of the selector mechanism, the cone clutch is also moved because of the blocker bars (Fig. 5.35).

In the neutral position the shift ring and blocker bars are centralized (Fig. 5.36). There is no connection between the shift ring and the gear wheel. The gear wheel can turn freely on the shaft.

When the shift fork is moved by the driver, the shift ring is slid towards the gear wheel. In the process, the shift ring carries three blocker bars, which move the synchronizer ring axially and press it onto the friction surface (cone clutch) of the gear wheel. As long as there is a difference in speed, the shift ring cannot move any further. This is because the frictional force turns the synchronizer ring, causing the tooth flanks to rest on the side of the synchronizer body (Fig. 5.37).

Once the shift ring and gear are turning at the same speed, circumferential force no longer acts on them. The force still acting on the shift ring turns it until it slides onto the teeth of the gear wheel. The gear wheel is now locked to its shaft (Fig. 5.38).

For two rotating shafts to mesh using a dog clutch, they should ideally be rotating at the same speed. Early motorists had to be skilled in achieving this through a process known as double-declutching. However, all modern gearboxes make life much easier for us by the use of synchromesh systems (Fig. 5.39).

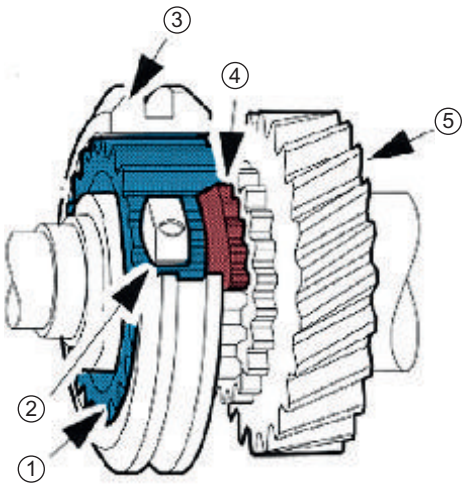


Figure 5.36 Synchronizer in neutral: 1, synchronizer body; 2, blocker bars; 3, shift/selector ring; 4, synchronizer ring; 5, gearwheel

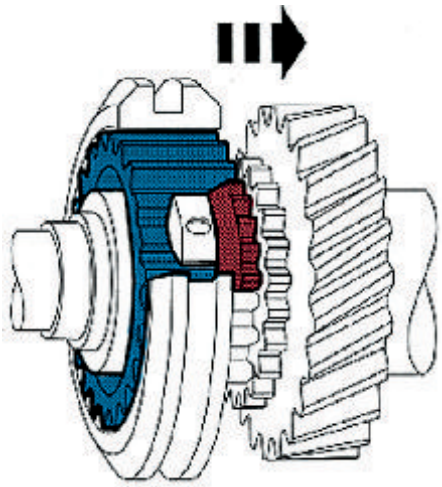


Figure 5.37 Synchronizer synchronizing

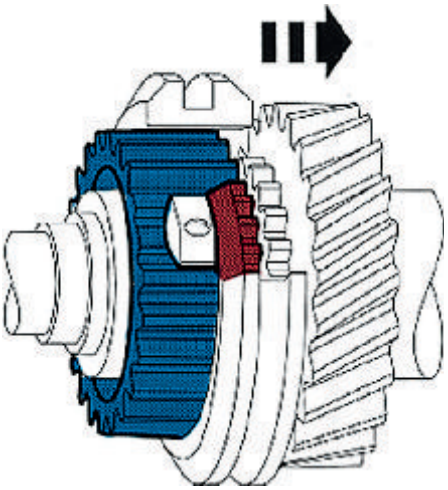


Figure 5.38 Synchronizer shift position

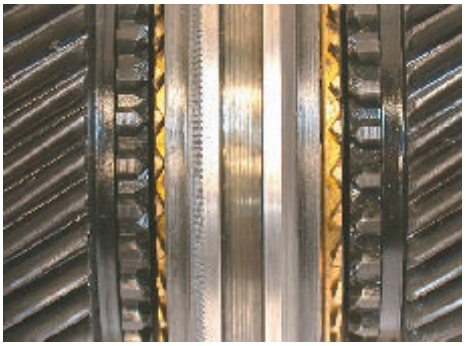


Figure 5.39 Synchromesh components

Transmission fluid is an important component of any gearbox and must meet the following requirements:

- Viscosity must be largely unaffected by temperature.
- It must have a high ageing resistance (gearboxes are usually filled for life).
- It must have a minimal tendency to foaming.
- It must be compatible with different sealing materials.

Only the specified transmission fluid should be used when topping up or filling after dismantling and reassembly. Bearing and tooth flank damage can occur if this is disregarded.

On earlier vehicles, a four-speed gearbox was the norm. Further improvements in operation could be gained by fitting an overdrive. This was mounted on the output of the gearbox (rear-wheel drive). In fourth gear, the drive ratio is usually 1:1. Overdrive would allow the output to rotate more quickly than the input, hence the name. Most gearboxes now incorporate a fifth gear, which is effectively an overdrive but does not form a separate unit.

The transmission gearbox on all modern cars is a sophisticated component. However, the principle of operation does not change because it is based on simple gear ratios and clutch operation. Most current gearboxes are five-speed, constant mesh, and use helical gears.

5.3 Automatic transmission

5.3.1 Introduction and torque converter

An automatic gearbox contains special devices that automatically provide various gear ratios as they are needed. Most automatic gearboxes have three or four forward gears and one reverse gear. Instead of a gearstick, the driver moves a lever called a selector. Some automatic gearboxes have selector positions for park, neutral, reverse, drive, 2 and 1 (or 3, 2 and 1 in some cases). Some more sophisticated types with electronic control just have drive, park and reverse positions. The fluid flywheel or torque converter is the component that makes automatic operation possible.

Key fact

A torque converter is the component that makes automatic operation possible.

The engine will only start if the selector is in either the park or neutral position. In park, the drive shaft is locked so that the drive wheels cannot move (Fig. 5.40). It is also now common, when the engine is running, to only be able to move the selector out of park if you are pressing the brake pedal. This is a very good safety feature as it prevents sudden, uncontrolled movement of the vehicle.

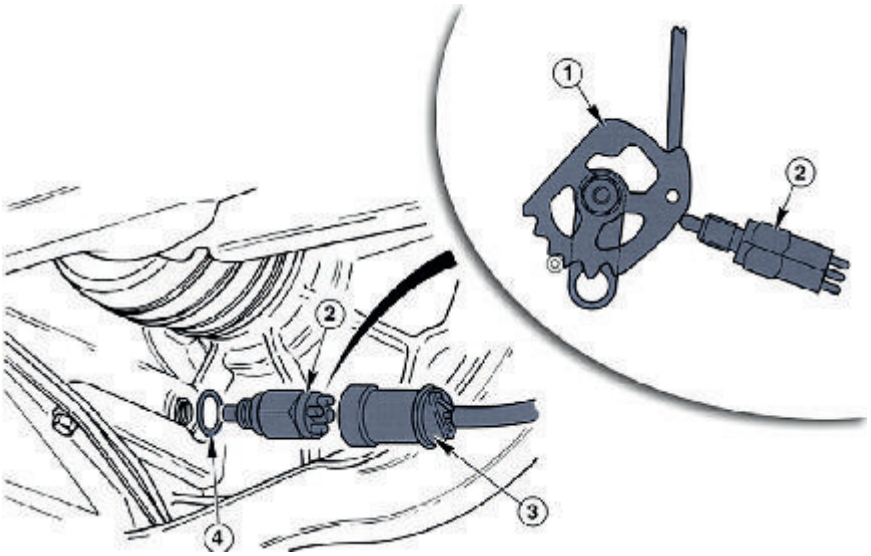


Figure 5.40 Starter circuit with inhibitor switch: 1, selector mechanism; 2, interlock switch; 3, connector; 4, sealing washer

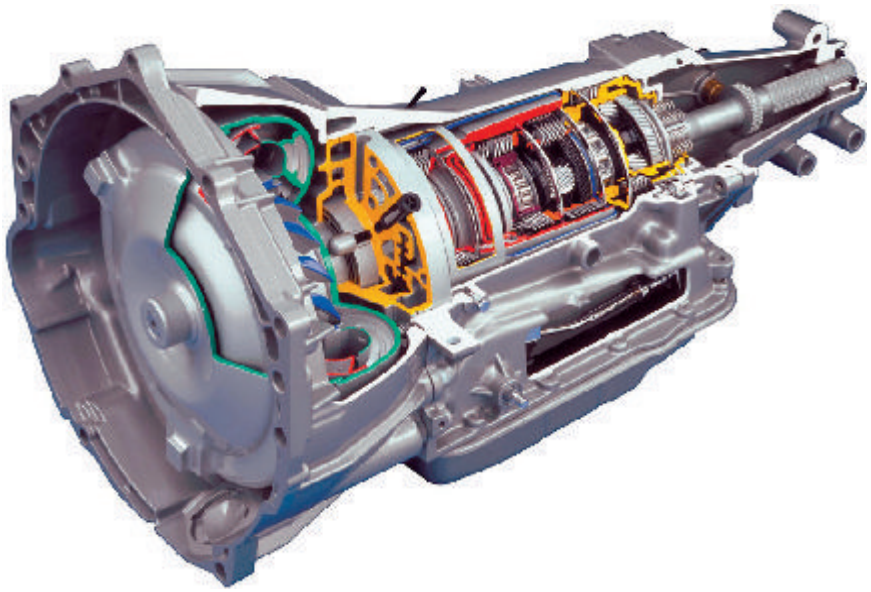


Figure 5.41 Modern auto-box. (Source: GM Media)

For ordinary driving, the driver moves the selector to the 'drive' position. The transmission starts out in the lowest gear and automatically shifts into higher gears as the car picks up speed. The driver can use the lower positions of the gearbox for going up or down steep hills or driving through mud or snow. When in position 3, 2 or 1, the gearbox will not change above the lowest gear specified (Fig. 5.41).

A fluid flywheel consists of an impeller and turbine, which are immersed in oil (Fig. 5.42). They transmit drive from the engine to the gearbox. The engine-driven impeller faces the turbine, which is connected to the gearbox. Each of the parts, which are bowl-shaped, contains a number of vanes. They are both a little like half of a hollowed out orange facing each other. When the engine is running at

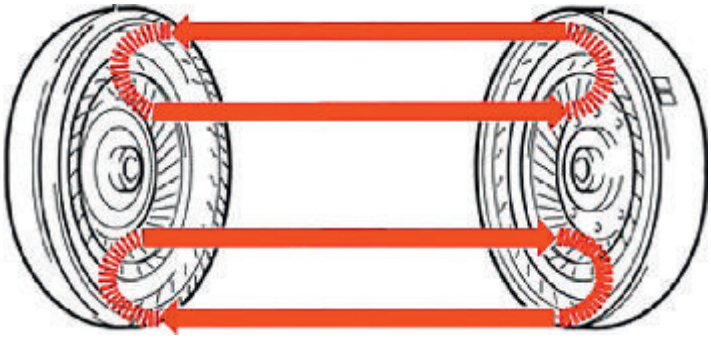


Figure 5.42 Fluid flywheel principle

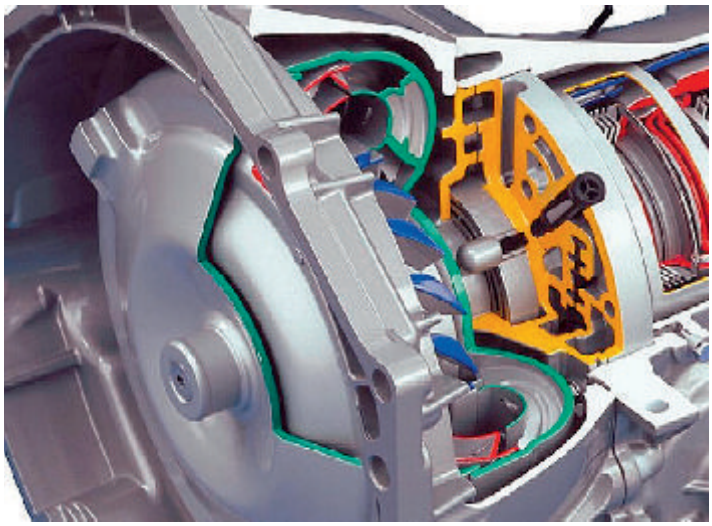


Figure 5.43 Torque converter in position (in green and blue)

idle speed oil is flung from the impeller into the turbine, but not with enough force to turn the turbine.

As engine speed increases so does the energy of the oil. This increasing force begins to move the turbine and hence the vehicle. The oil gives up its energy to the turbine and then recirculates into the impeller at the centre, starting the cycle over again. As the vehicle accelerates the difference in speed between the impeller and turbine reduces until the slip is about 2%.

A good analogy for a fluid flywheel that you can try for yourself is to place two desktop-type cooling fans facing each other. Switch one on (the impeller) and the air it blows will drive the blades of the other (the turbine).

A problem with a basic fluid flywheel is that it is slow to react when the vehicle is moving off from rest. This can be improved by fitting a reactor or stator between the impeller and turbine. We now know this device as a torque converter. All modern cars fitted with automatic transmission use a torque converter (Fig. 5.43).

The torque converter delivers power from the engine to the gearbox like a basic fluid flywheel, but also increases the torque when the car begins to move. Similar to a fluid flywheel, the torque converter resembles a large doughnut sliced in half. One half, called the pump impeller (Fig. 5.44), is bolted to the drive plate or flywheel. The other half, called the turbine, is connected to the gearbox-input shaft. Each half is lined with vanes or blades. The pump and the turbine

Definition

Analogy
Using an analogy means drawing a comparison in order to show a similarity.

Key fact

All modern cars fitted with automatic transmission use a torque converter.

Figure 5.44 Impeller

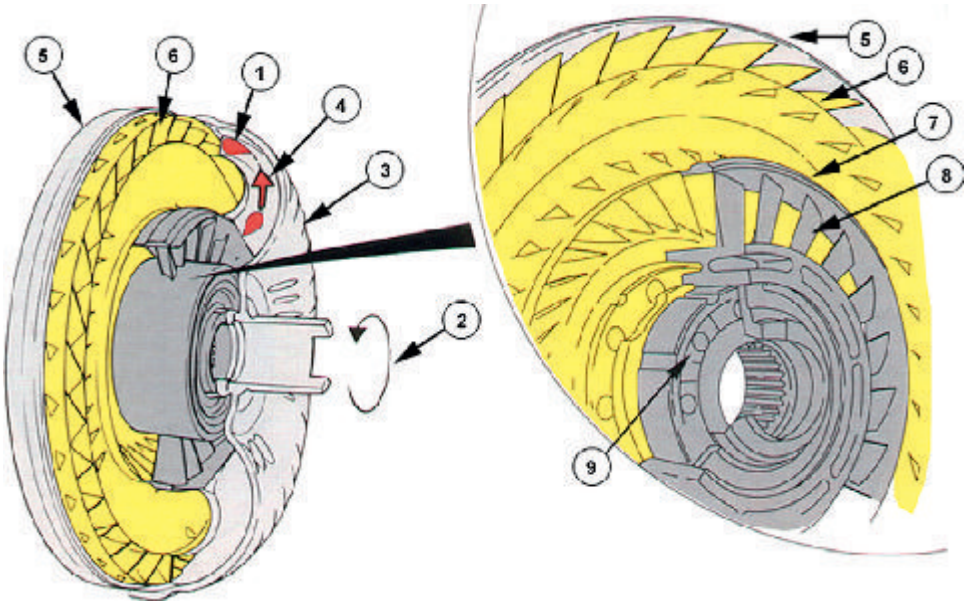


Figure 5.45 Torque converter components and operation–idle speed: 1, automatic transmission fluid (red, ATF); 2, direction of engine rotation; 3, impeller; 4, impeller blade; 5, turbine; 6, turbine blade; 7, reactor; 8, reactor blade; 9, one-way clutch

face each other in a case filled with oil. A bladed wheel called a stator is fitted between them. The components and operation of the torque converter are shown in Figs 5.45–5.48.

The engine causes the pump (impeller) to rotate and throw oil against the vanes of the turbine. The force of the oil makes the turbine rotate and send power to the transmission. After striking the turbine vanes, the oil passes through the stator and returns to the pump. When the pump reaches a specific rate of rotation, a reaction between the oil and the stator increases the torque. In a fluid flywheel, oil returning to the impeller tends to slow it down. In a torque converter, the stator or reactor diverts the oil towards the centre of the impeller for extra thrust.

When the engine is running slowly, the oil may not have enough force to rotate the turbine. However, when the driver presses the accelerator pedal, the engine runs more quickly and so does the impeller. The action of the impeller increases the force of the oil. This force gradually becomes strong enough to rotate the turbine and moves the vehicle. Torque converters can double the applied torque when moving off from rest. As engine speed increases, the torque multiplication

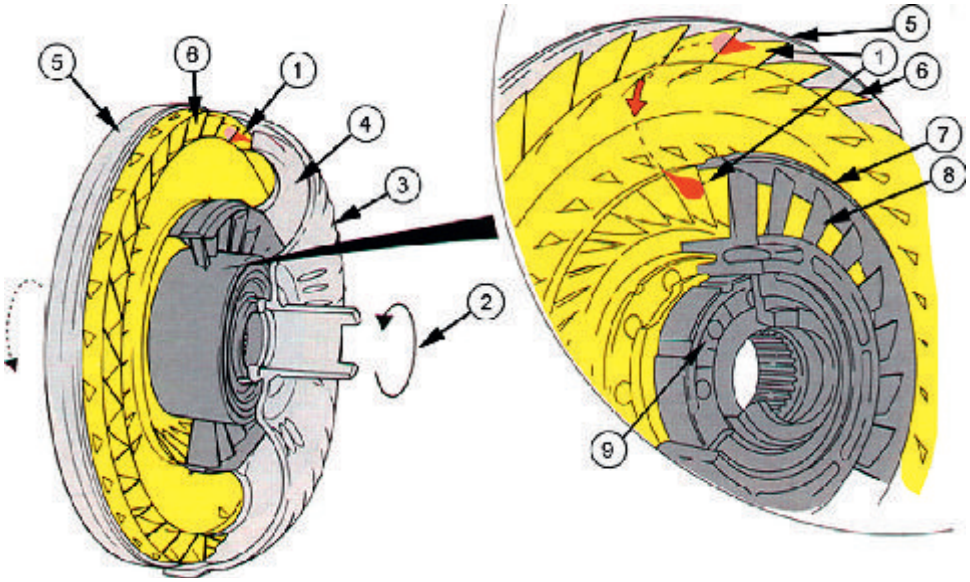


Figure 5.46 Torque converter components and operation–speed starts to increase: 1, automatic transmission fluid (red, ATF); 2, direction of engine rotation; 3, impeller; 4, impeller blade; 5, turbine; 6, turbine blade; 7, reactor; 8, reactor blade; 9, one-way clutch

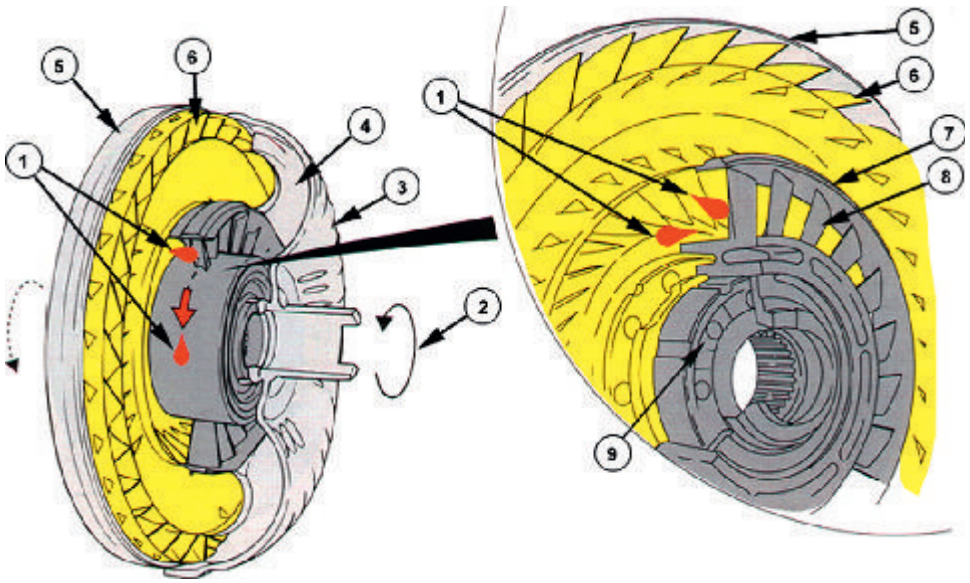


Figure 5.47 Torque converter components and operation–stator comes in to use: 1, automatic transmission fluid (red, ATF); 2, direction of engine rotation; 3, impeller; 4, impeller blade; 5, turbine; 6, turbine blade; 7, reactor; 8, reactor blade; 9, one-way clutch

tapers off until at cruising speed there is no increase in torque. The reactor or stator then freewheels on its one-way clutch at the same speed as the turbine.

The converter housing is bolted to the crankshaft and driven directly. It is welded to the impeller and filled with automatic transmission fluid. The impeller:

- is welded to the converter housing
- has blades arranged radially
- turns at the same speed as the engine
- conveys fluid to the turbine blades and, as a result, produces a radial force at the turbine.

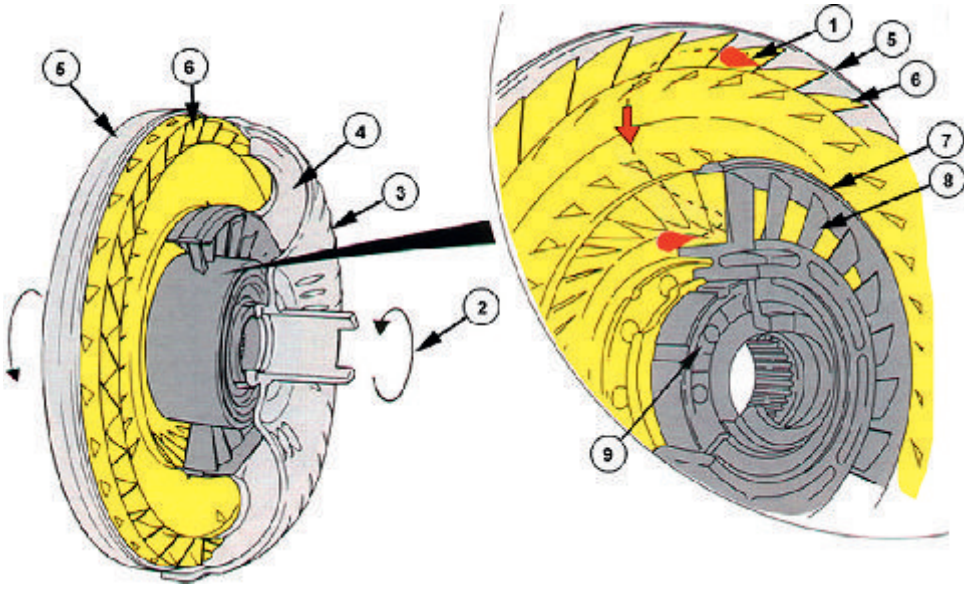


Figure 5.48 Torque converter components and operation–drive is transmitted: 1, automatic transmission fluid (red, ATF); 2, direction of engine rotation; 3, impeller; 4, impeller blade; 5, turbine; 6, turbine blade; 7, reactor; 8, reactor blade; 9, one-way clutch

The turbine is splined to, and drives, the transmission input shaft. It has blades arranged in a curved pattern, which allows fluid to flow inwards owing to the reduced centrifugal force compared with the impeller. The fluid is then passed to the stator.

The purpose of the stator is to deflect the stream of fluid into the impeller until the coupling speed ratio is reached. The stator and one-way clutch assembly is located between the impeller and the turbine. It is splined on the stator support, which is locked to the fluid pump housing and hence to the transmission housing. The stator has blades arranged in a curved pattern. It locks, counter to the normal direction of rotation of the engine, and runs freely in the normal direction of rotation of the engine. The purpose is to boost torque, through ram pressure, up to the coupling point. It is exposed to flow from the rear until a turbine to impeller speed ratio of 85% is reached. The stator now rotates with the converter.

Key fact

The purpose of the stator is to deflect the stream of fluid into the impeller until the coupling speed ratio is reached.

The fluid flywheel action of a torque converter or fluid flywheel reduces efficiency because the pump tends to rotate more quickly than the turbine. In other words, some slip will occur. This is usually about 2%. To improve efficiency, many transmissions now include a lock-up facility. When the pump reaches a specific rate of rotation, the pump and turbine are locked together, allowing them to rotate as one.

A converter lock-up clutch allows slip-free and hence loss-free transmission of the engine torque to the automatic transmission. When engaged, it creates a frictional connection between the converter housing and the turbine. It consists of a clutch pressure plate with a friction lining, and a torsional vibration damper to damp the crankshaft torsional vibrations. It is connected positively to the turbine and is exposed to fluid pressure from one side for clutch disengagement and engagement. A modulating valve is often used to allow controlled pressure build-up and reduction. This is to ensure smooth opening and closing. The valve is controlled electronically by means of the transmission ECU.

Key fact

A converter lock-up clutch allows loss-free transmission of engine torque.

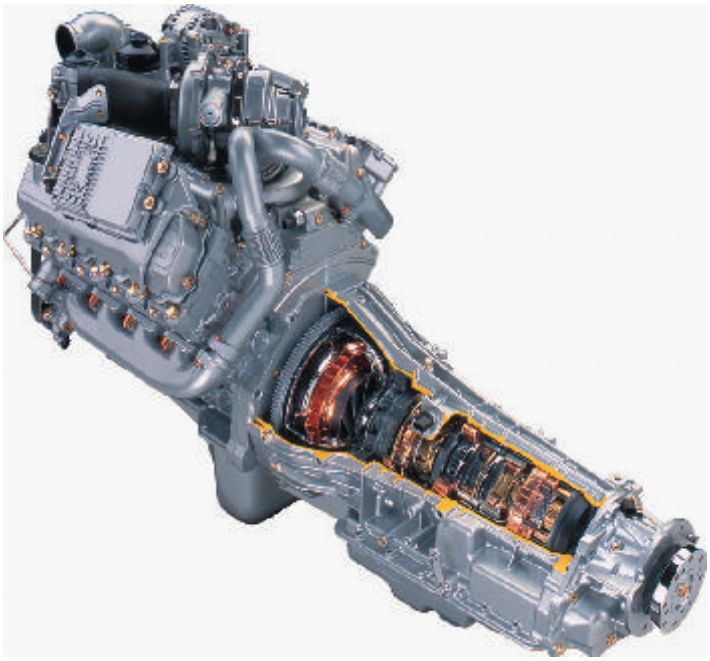


Figure 5.49 Cutaway transmission mounted on an engine. (Source: Ford Media)

5.3.2 Automatic transmission components

All standard automatic transmission gearboxes (Fig. 5.49) use epicyclic gearing. Epicyclic gears are a special set of gears that are part of most automatic gearboxes. In their basic form they consist of three main elements:

- a sun gear, located in the centre
- a carrier that holds two, three or four planet gears, which mesh with the sun gear and revolve around it
- an internal gear or annulus, which is a ring with internal teeth; it surrounds the planetary gears and meshes with them.

Any part of a set of planetary gears can be held stationary or locked to one of the others. This will produce different gear ratios. Most automatic gearboxes have two or more sets of planetary gears that are arranged in line. This provides the necessary number of gear ratios. As the gear selector is moved (automatically) into different positions, the power flow through the gearbox changes. Figures 5.50–5.53 show four power flows; in each case the drive comes in on the sun gear shaft and is taken out on the annulus.

Key fact

Most automatic gearboxes have two or more sets of planetary gears that are arranged in line.

A special feature of some transmission systems is a Ravigneaux planetary gearset (Fig. 5.54). This gearset has the following features:

- It offers the possibility of more gears than a conventional planetary gearset.
- It has a compact design (space-saving) in relation to the available transmission ratios.
- It has two sun gears with different diameters.
- It has two sets of planetary gears, inner and outer. The inner planetary gears are in constant mesh with the smaller, rear sun gear and with the outer

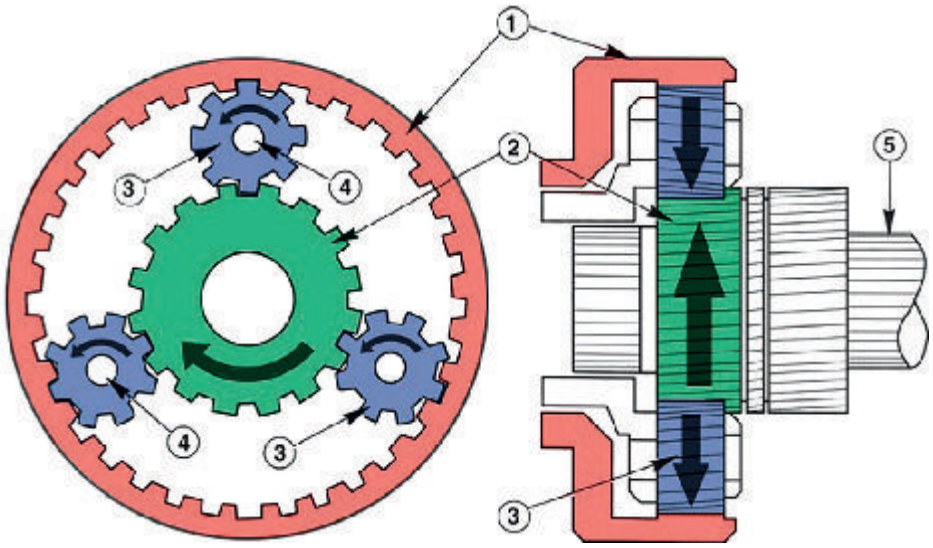


Figure 5.50 Epicyclic gears in direct drive: 1, annulus; 2, sun gear; 3, planet gears; 4, planet carrier; 5, sun gear shaft

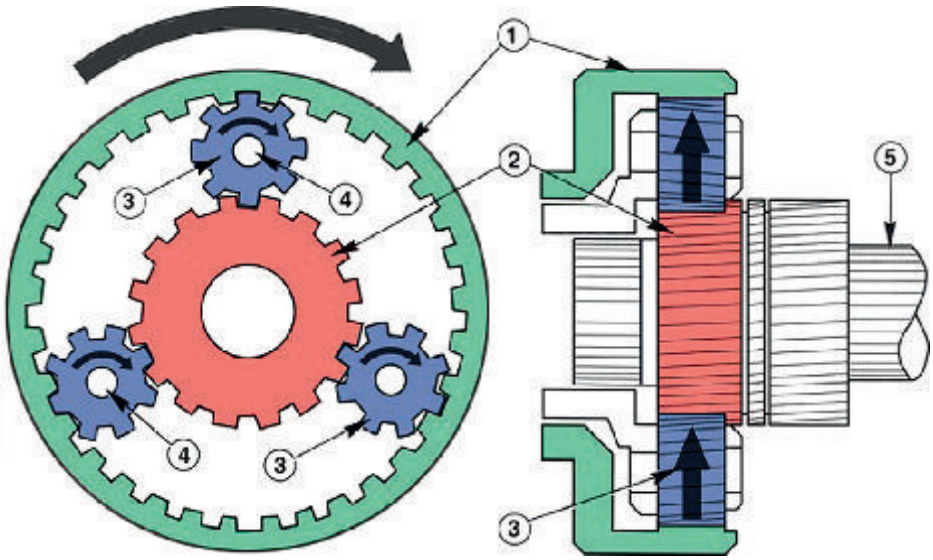


Figure 5.51 Epicyclic gears in high transmission ratio: 1, annulus; 2, sun gear; 3, planet gears; 4, planet carrier; 5, sun gear shaft

planetary gears. The outer planetary gears are in constant mesh with the ring gear and the larger, front sun gear.

- The planetary gears are all fitted on a joint planetary gear holder.

The transmission ratios are achieved via the combinations of locked and/or coupled components listed in Table 5.1. On many transmission systems the Ravigneaux planetary gearset is connected in series with a conventional epicyclic gearset. The conventional gearset can generate a speed reduction from the two sun gears of the Ravigneaux planetary gearset for all gears.

The power flows shown in Figs 5.55–5.63 are a representation of what occurs in one type of automatic gearbox. Note in particular that only the top half is shown in section. In other words, the complete picture would include a reflection of what is represented here.

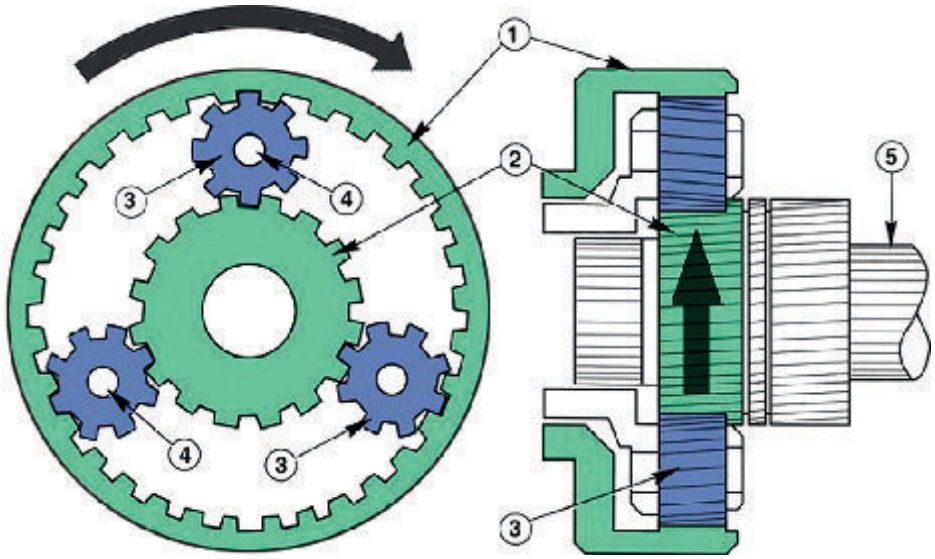


Figure 5.52 Epicyclic gears in low transmission ratio: 1, annulus; 2, sun gear; 3, planet gears; 4, planet carrier; 5, sun gear shaft

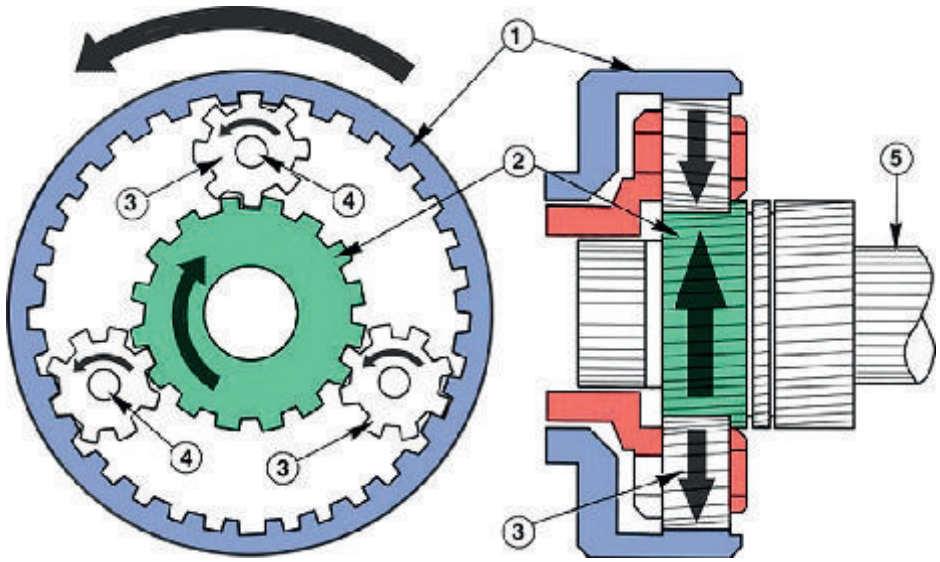


Figure 5.53 Epicyclic gears in reverse: 1, annulus; 2, sun gear; 3, planet gears; 4, planet carrier; 5, sun gear shaft

The appropriate elements in the gear train of an automatic gearbox are held stationary by a system of hydraulically operated brake bands and clutches (Fig. 5.64). These are worked by a series of hydraulically operated valves, usually in the lower part of the gearbox. In most systems these are now electrically controlled.

Oil pressure to operate the clutches and brake bands is supplied by a pump (Fig. 5.65). The supply for this is the oil in the sump (pan) of the gearbox.

A cable from the throttle also allows a facility known as 'kick down'. This allows the driver to change down a gear such as for overtaking, by pressing the throttle all the way down. Alternatively, electronic controls determine when this downshift is needed.

Key fact

Different parts of a gear train in an automatic gearbox are held stationary by a system of hydraulically operated brake bands and clutches.

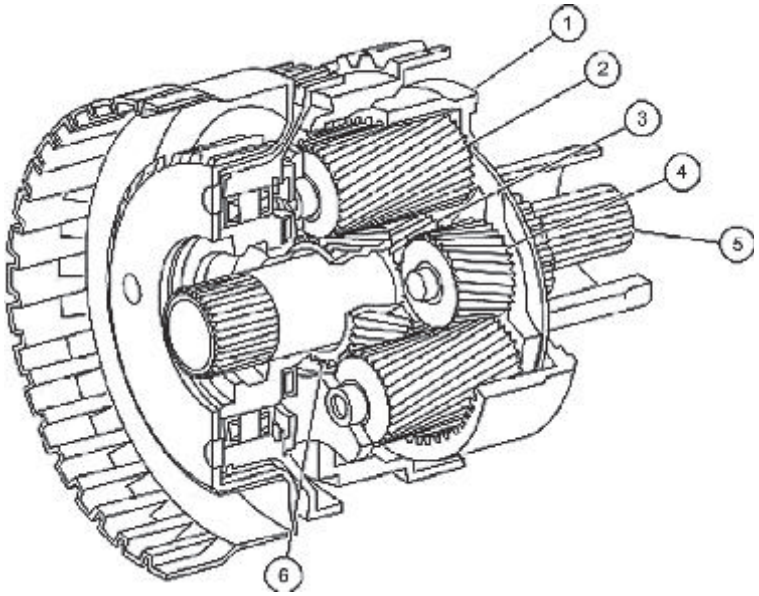


Figure 5.54 Ravigneaux gearset: 1, ring gear; 2, long planet gear; 3, small planet gear; 4, short planet gear; 5, transmission input shaft; 6, large sun gear. (Source: Ford Motor Company)

Table 5.1 Gear ratios in the Ravigneaux gearset shown in Fig. 5.54

Gear/ratio	Input torque (output is always on the ring gear)	Locked
1	Small sun gear	Planetary gear holder
2	Small sun gear	Large sun gear
3	Small sun gear and large sun gear	No component
4	Small sun gear and planetary gear holder	No component
5	Large sun gear and planetary gear holder	No component
6	Planetary gear holder	Large sun gear
Reverse	Large sun gear	Planetary gear holder

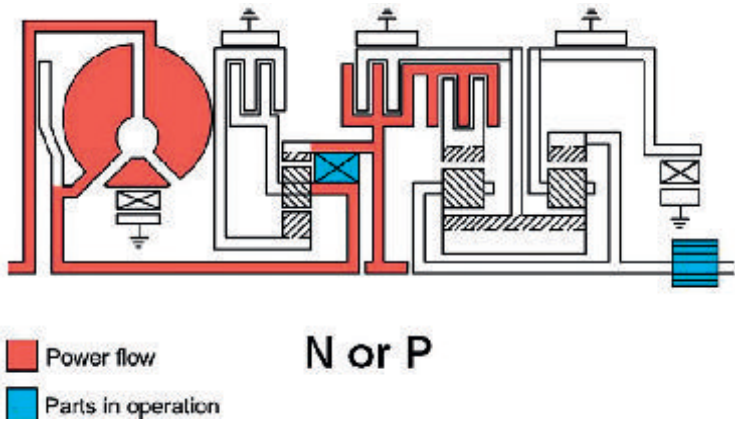


Figure 5.55 Neutral or park with selector in position N or P

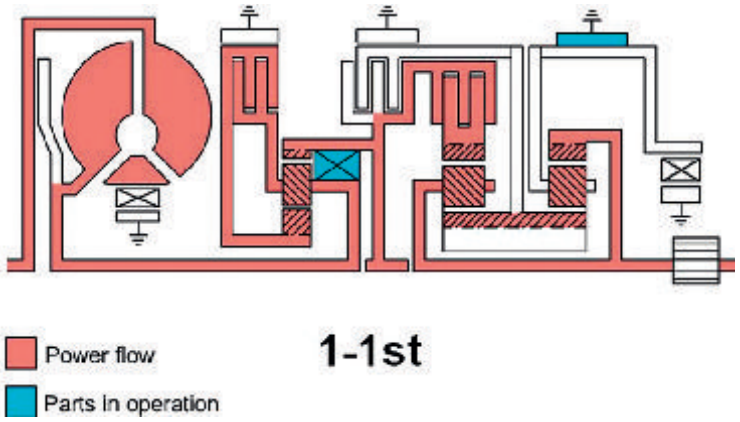


Figure 5.56 First gear with selector in position 1

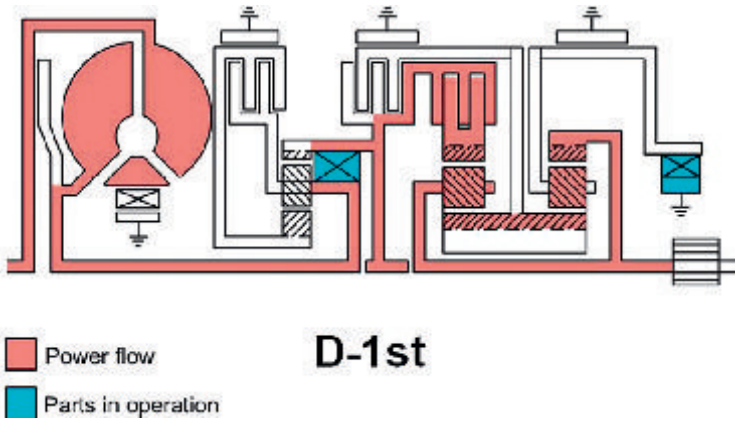


Figure 5.57 First gear with selector in position D

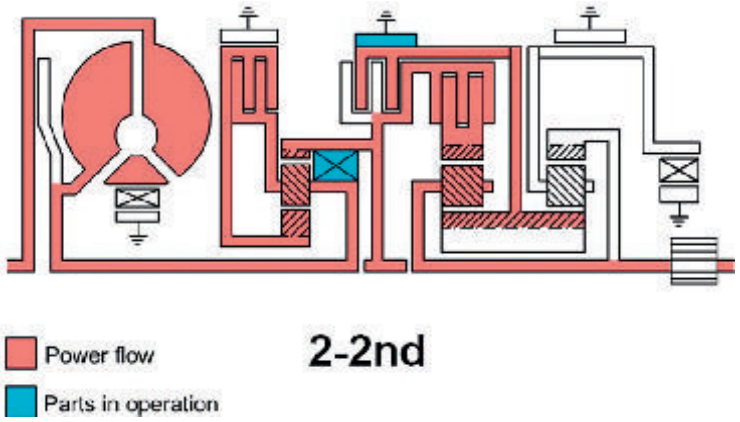


Figure 5.58 Second gear with selector in position 2

The main aim of electronically controlled automatic transmission (ECAT) is to improve on conventional automatic transmission in the following ways:

- smoother and quieter gear changes
- improved performance
- reduced fuel consumption

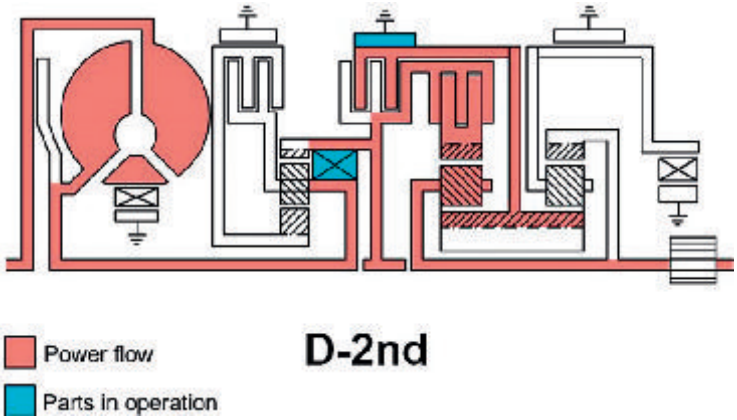


Figure 5.59 Second gear with selector in position D

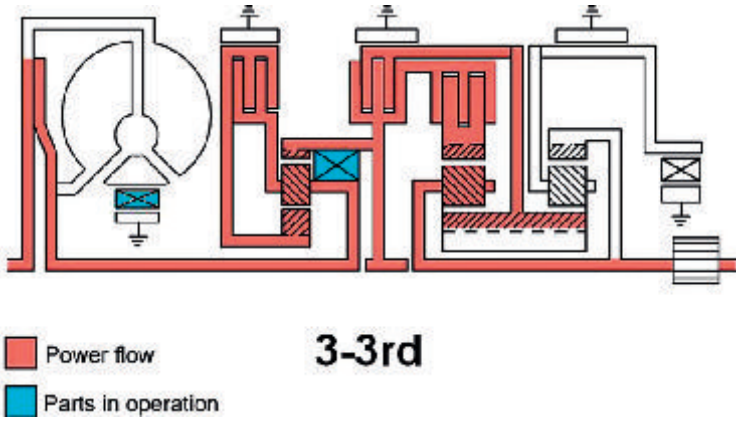


Figure 5.60 Third gear with selector in position 3

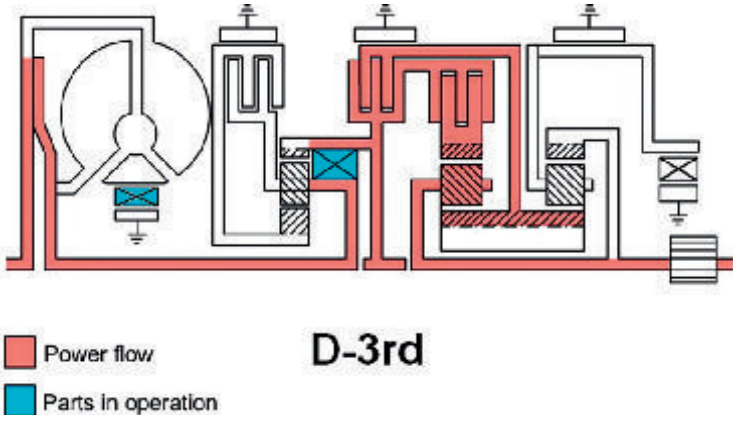


Figure 5.61 Third gear with selector in position D

- reduction of characteristic changes over system life
- increased reliability.

Gear changes and lock-up of the torque converter are caused by hydraulic pressure, but under electronic control. In an ECAT system, electrically controlled solenoid valves can influence this hydraulic pressure. Most ECAT systems

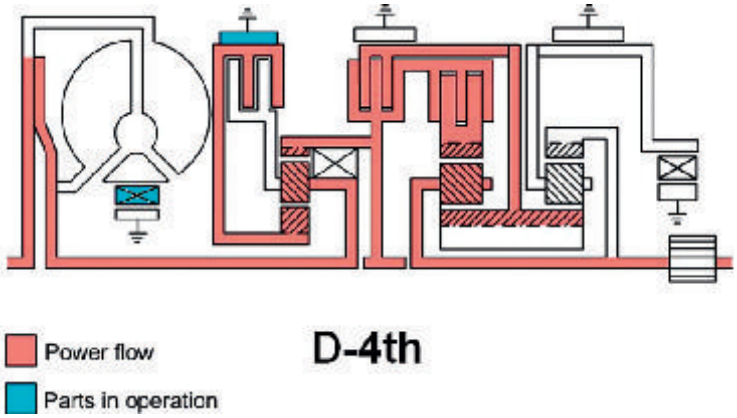


Figure 5.62 Fourth gear with selector in position D

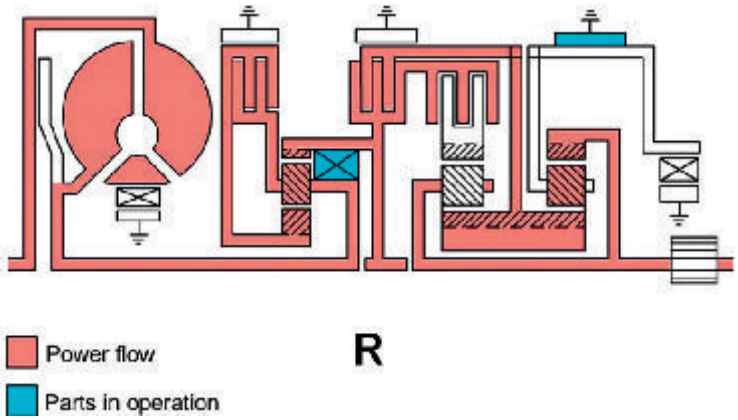


Figure 5.63 Reverse gear with selector in position R

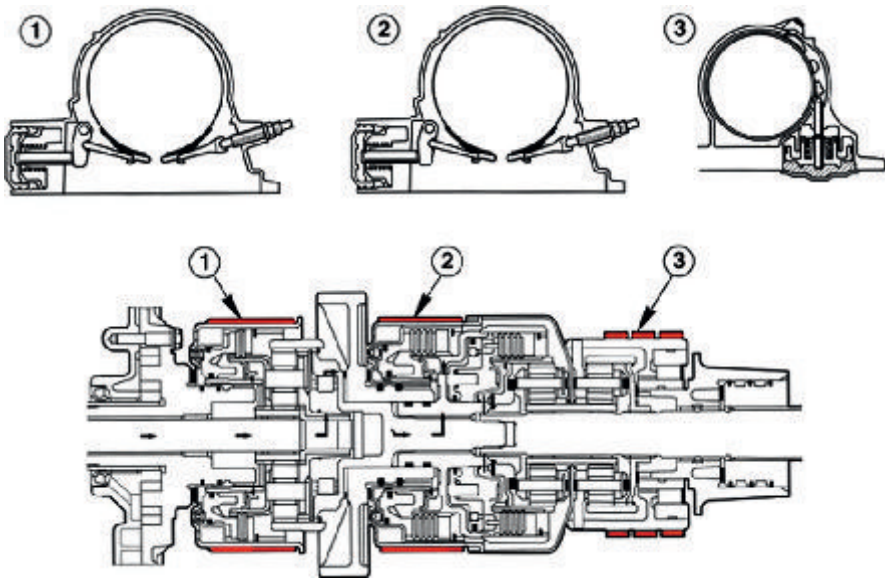


Figure 5.64 Brake bands lock different components in the gear train: 1, front band; 2, centre band; 3, rear band

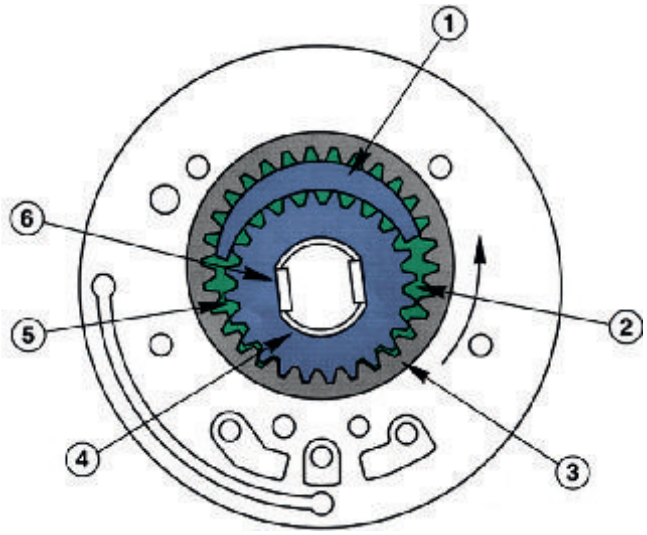


Figure 5.65 Oil pump and governor: 1, pump crescent; 2, intake side; 3, driven gear; 4, driving gear; 5, delivery side; 6, pump drive

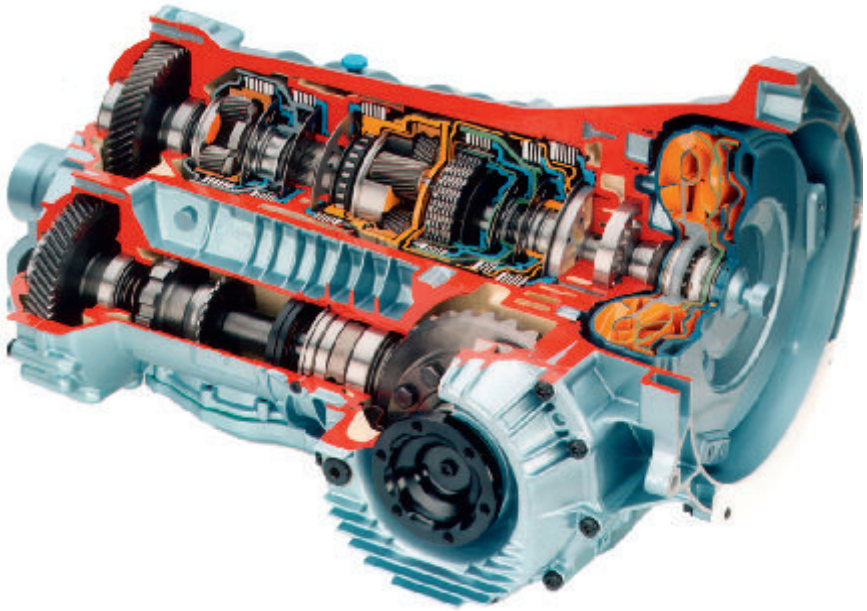


Figure 5.66 Porsche Carrera four-wheel drive auto-gearbox. (Source: Porsche Media)

now have a transmission ECU that is in communication with the engine control system. Control of gearshift and torque converter lockup is determined by the ECU. With an ECAT system, the actual point of gearshift is determined from preprogrammed memory within the ECU. Data from other sensors is also taken into consideration. Actual gearshifts are initiated by changes in hydraulic pressure, which are controlled by solenoid valves.

Typical components of a modern ECAT system are listed here:

- transmission control module (TCM), which controls activation and deactivation of the solenoid valves by processing the input signals from, among others, the speed sensor and rotational speed sensor of the transmission, as well as the temperature sensor; it also saves adaptive data, diagnostic trouble codes (DTCs) and frozen values for diagnosis

- gearshift position sensor, integrated in the TCM
- solenoid valves to control engine braking in first gear
- solenoid valve to control the lock-up function, and also used during certain gearshift processes
- solenoid valve to controls the transmission system pressure
- solenoid valves to control which clutches are used
- solenoid valve to control the use of a brake band
- rotational speed sensor, input shaft
- output shaft rotational speed sensor
- oil temperature sensor
- gear selector module (GSM) in the gear selector housing, which provides information to the TCM about the desired driving mode, etc.; shift select mode and sport mode
- hydraulic system with oil pump, torque converter, hydraulic control housing and oil cooler
- a front planetary gearset and a rear planetary gearset, the transmission ratios of which are controlled by clutches and brakes.

The two main control functions of this system are hydraulic pressure and engine torque. A temporary reduction in engine torque during gear shifting allows smooth operation. This is because the peaks of gearbox output torque, which cause the characteristic surge during gear changes on conventional automatics, are suppressed. Because of control functions smooth gearshifts are possible, and because of the learning ability of some ECUs, the characteristics remain throughout the life of the system.

The ability to lock up the torque converter has been used for some time even on vehicles with more conventional automatic transmission. This gives better fuel economy and quietness and improved driveability. Lock-up is carried out using a hydraulic valve, which can be operated gradually to produce a smooth transition. The timing of lock-up is determined from ECU memory in terms of the vehicle speed and acceleration (Fig. 5.67).

Figure 5.68 shows a modern electronically controlled valve block. The ECU is built in to the system. A connection to other ECUs is made via a controller area network (CAN) connection.

Oil pressure is used to actuate clutches and brake bands to change the ratio of the epicyclic gears, just like on a system with no electronic control.

There is a wide range of electronic and hydraulic control systems. All types, however, serve to operate brake bands and/or clutches. Electronically controlled system operation is determined by ECU programming. Other systems work by sensing a combination of road speed (governor pressure) and throttle (throttle pressure). The transmission (main line pressure) is then used to operate clutches and bands, which are under the control of valves.

5.3.3 Constantly variable transmission

The constantly variable transmission (CVT) uses a pair of cone-shaped pulleys connected by a metal belt (Fig. 5.69). The key to the operation of a CVT system is a high-friction drive belt (Fig. 5.70). The belt, made from high performance steel, transmits drive by thrust rather than tension. The ratio of the rotations, or the gear ratio, is determined by how far the belt rides from the centres of two

Definitions

CVT
Constantly variable transmission.

CTX
Constantly variable transaxle.

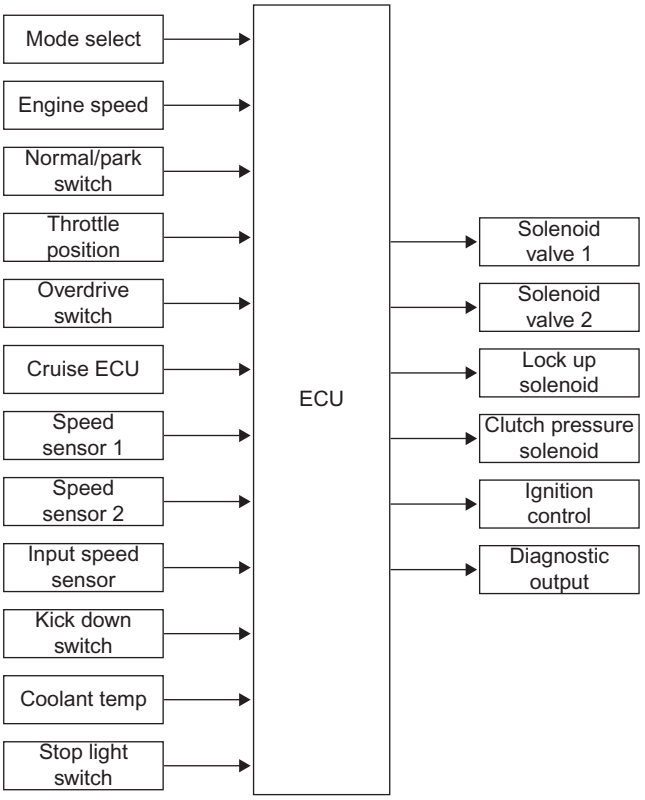


Figure 5.67 Generic electronically controlled automatic transmission (ECAT) system block diagram

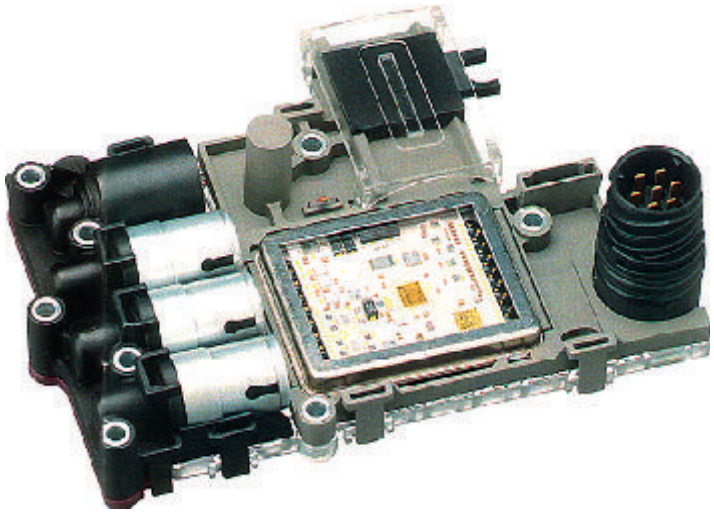


Figure 5.68 Electrohydraulic valve block. (Source: Bosch Media)

Key fact

A key component of a CVT system is a high-friction drive belt.

pulleys. The transmission can produce an unlimited number of ratios. As the car changes speed, the ratio is continuously adjusted.

Cars with this system are said to use fuel more efficiently than cars with set gear ratios. In the gearbox, hydraulic control is used to move the pulleys and hence change the ratio. To achieve forward and reverse, a standard epicyclic gear set is used.

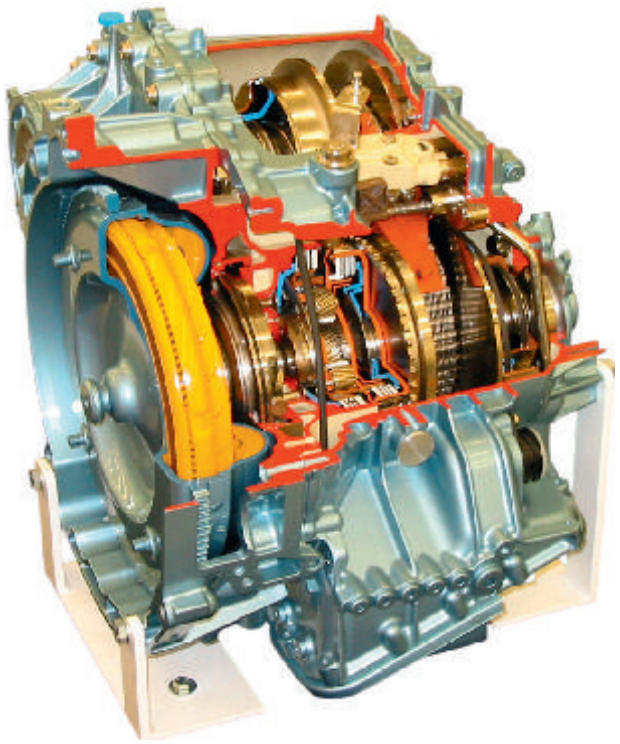


Figure 5.69 Constantly variable transmission (CVT) cutaway. (Source: Ford Media)

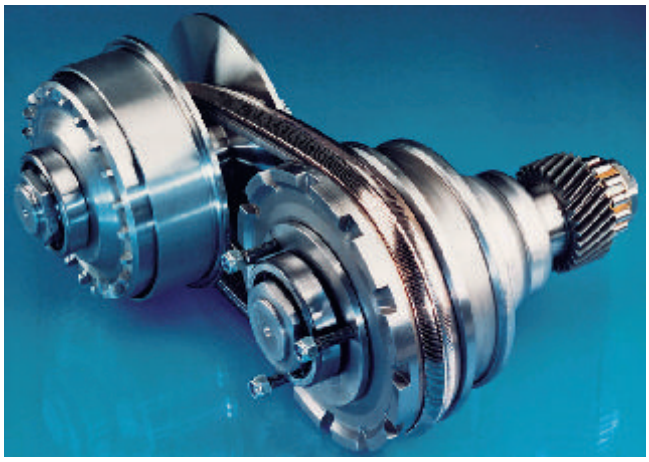


Figure 5.70 Constantly variable transmission (CVT) components. (Source: Bosch Media)

The drive belt transmits torque from the primary cone pulley to the secondary cone pulley unit (Fig. 5.71). The belt is V-shaped and consists of several hundred steel elements held together by steel strips.

5.3.4 Direct shift gearbox

The DSG (Fig. 5.72) is an interesting development as it could be described as a manual gearbox that can change gear automatically. It can be operated by 'paddles' behind the steering wheel, by a lever in the centre console or in a fully automatic mode. The gear train and synchronizing components are similar to those of a normal manual change gearbox.

Definition

DSG
Direct shift gearbox.

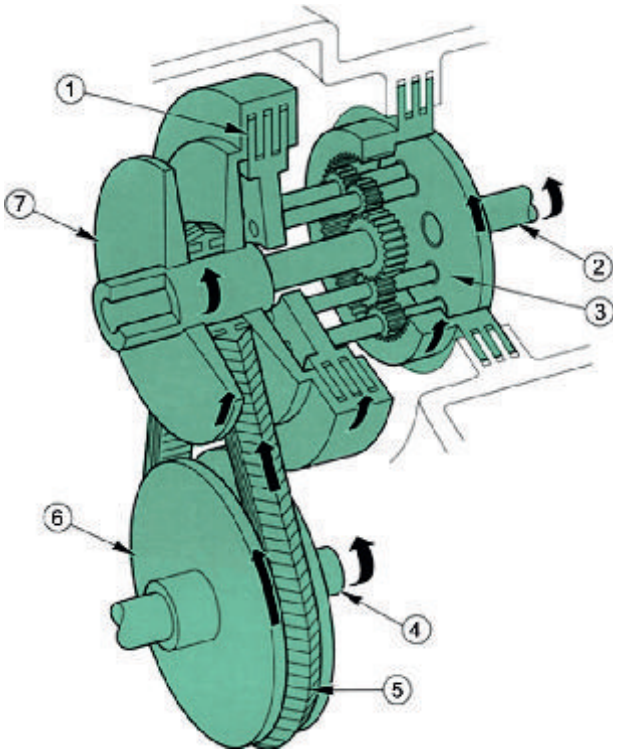


Figure 5.71 Drive belt and cone pulleys: 1, forward and reverse clutch assembly; 2, input shaft; 3, planetary gearset; 4, output shaft; 5, drive belt; 6, secondary cone pulley; 7, primary cone pulley. (Source: Ford Motor Company)

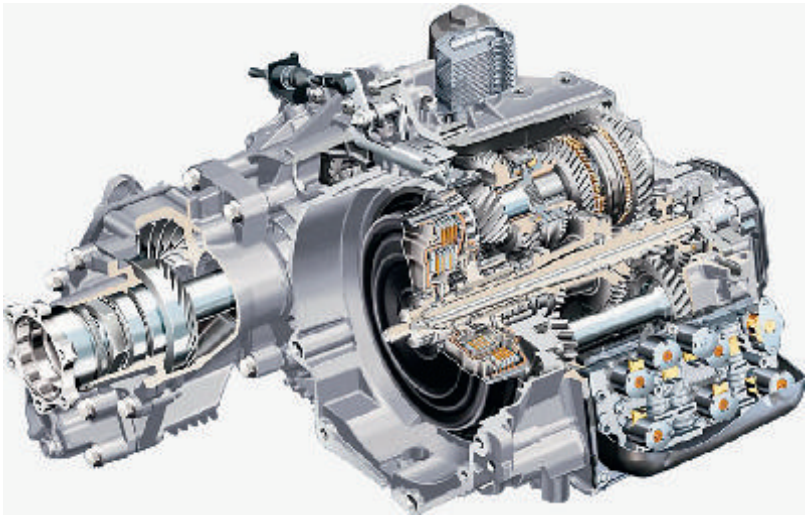


Figure 5.72 Direct shift gearbox (DSG). (Source: Volkswagen Media)

Key fact

A DSG can be operated by 'paddles' behind the steering wheel.

The DSG is made of two transmission units that are independent of each other. Each transmission unit is constructed in the same way as a manual gearbox and is connected by a multiplate clutch. They are regulated, opened and closed by a mechatronics system. On the system outlined in this section:

- first, third, fifth and reverse gears are selected via multiplate clutch 1
- second, fourth and sixth gears are selected via multiplate clutch 2.

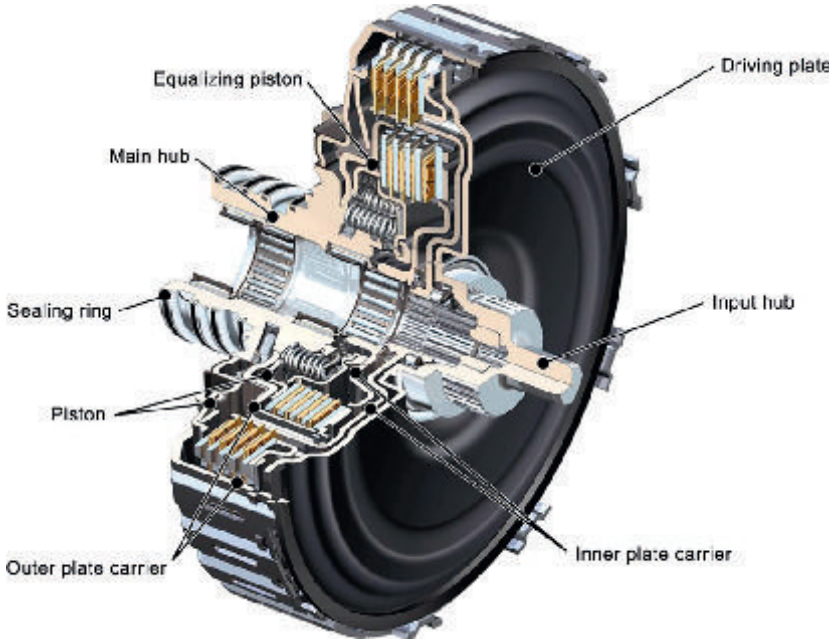


Figure 5.73 Multiplate twin clutch: clutch 1 is the outer. (Source: Volkswagen Media)

One transmission unit is always in gear and the other transmission unit has the next gear selected ready for the next change, but with its clutch still in the open position.

Torque is transmitted from the crankshaft to a dual-mass flywheel. The splines of the flywheel, on the input hub of the double clutch, transmit the torque to the drive plate of the multiplate clutch. This is joined to the outer plate carrier of clutch 1 with the main hub of the multiplate clutch. The outer plate carrier of clutch 2 is also positively joined to the main hub.

Torque is transmitted into the relevant clutch through the outer plate carrier. When the clutch closes, the torque is transmitted further into the inner plate carrier and then into the relevant gearbox input shaft. One multiplate clutch is always engaged.

Clutch 1 is the outer clutch and transmits torque into input shaft 1 for first, third, fifth and reverse gears (Fig. 5.73). To close the clutch, oil is forced into the pressure chamber. Plunger 1 is therefore pushed along its axis and the plates of clutch 1 are pressed together. Torque is then transmitted via the plates of the inner plate carrier to input shaft 1. When the clutch opens, a diaphragm spring pushes plunger 1 back into its start position.

Clutch 2 is the inner clutch and transmits torque into input shaft 2 for second, fourth and sixth gears. As with clutch 1, oil is forced into the pressure chamber so that plunger 2 then joins the drive via the plates to input shaft 2. The coil springs press plunger 2 back to its start position when the clutch is opened.

Input shaft 2 is shown in relation to the installation position of input shaft 1. It is hollow and is joined via splines to multiplate clutch 2. The helical gear wheels for sixth, fourth and second gear can be found on input shaft 2. For sixth, fourth and second gear, a common gear wheel is used. A pulse wheel is used to measure the speed of input shaft 2. The sender is adjacent to the gear wheel for second gear.

Input shaft 1 rotates inside shaft 2 and it is joined to multiplate clutch 1 via splines. Located on input shaft 1 are the helical gear wheels for fifth gear, the

Key fact

One transmission unit is always in gear and the other transmission unit has the next gear selected ready for the next change.

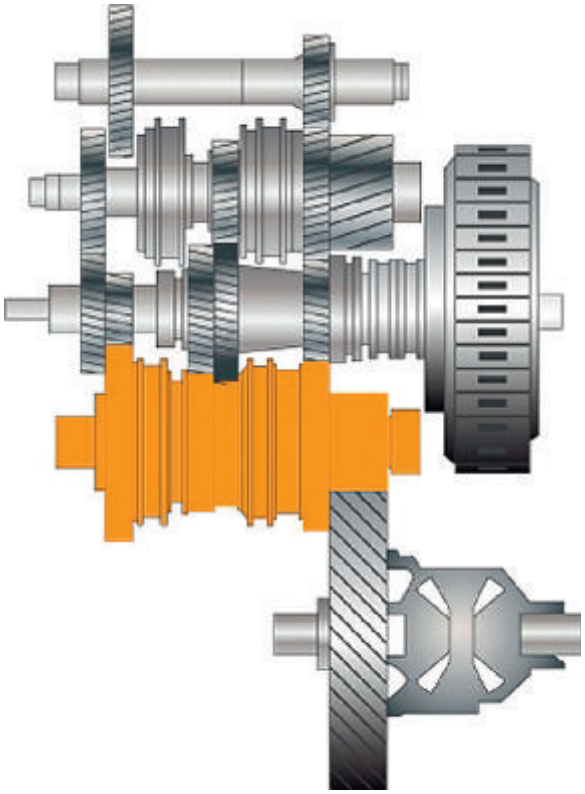


Figure 5.74 Output shaft 1

common gear wheel for first and reverse gear and the gear wheel for third gear. A second pulse wheel is used to measure the speed of input shaft 1. The sender is between the gear wheels for first/reverse gear and third gear.

In line with the two input shafts, the DSG also has two output shafts (Figs 5.74 and 5.75). Because the gear wheels for first and reverse gear are the same, and fourth and sixth gear are on the input shafts, it was possible to reduce the length of the gearbox.

The reverse shaft changes the direction of rotation of output shaft 2 and therefore the direction of rotation of the final drive in the differential (Fig. 5.76). It engages in the common gear wheel for first gear and reverse gear on input shaft 1 and the selector gear for reverse gear on output shaft 2. Both output shafts transmit the torque to the input shaft of the differential (Fig. 5.77). The differential transmits the torque via the drive shafts to the road wheels.

A parking brake is integrated in the differential to secure the vehicle in the parked position and to prevent the vehicle from creeping forwards or backwards unintentionally, when the handbrake is not applied. Engagement of the locking pawl is by mechanical means via a cable between the selector lever and the parking brake lever on the gearbox.

The mechatronics are housed in the gearbox, surrounded by oil. They comprise an ECU and an electrohydraulic control unit (Fig. 5.78). The mechatronics form the central control unit in the gearbox. Housed in this compact unit are twelve sensors. Only two sensors are located outside the mechatronics system.

The mechatronic control unit uses hydraulics to control or regulate eight gear actuators via six pressure valves. It also controls the pressure and flow of cooling

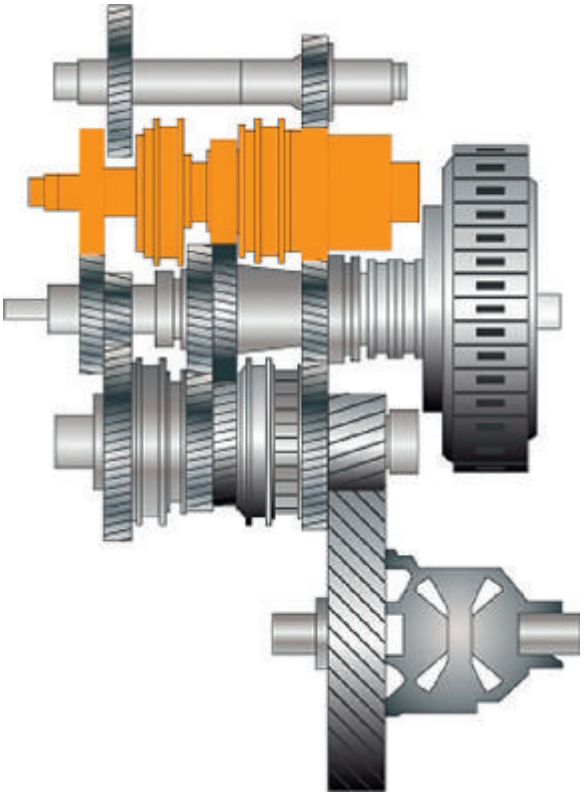


Figure 5.75 Output shaft 2

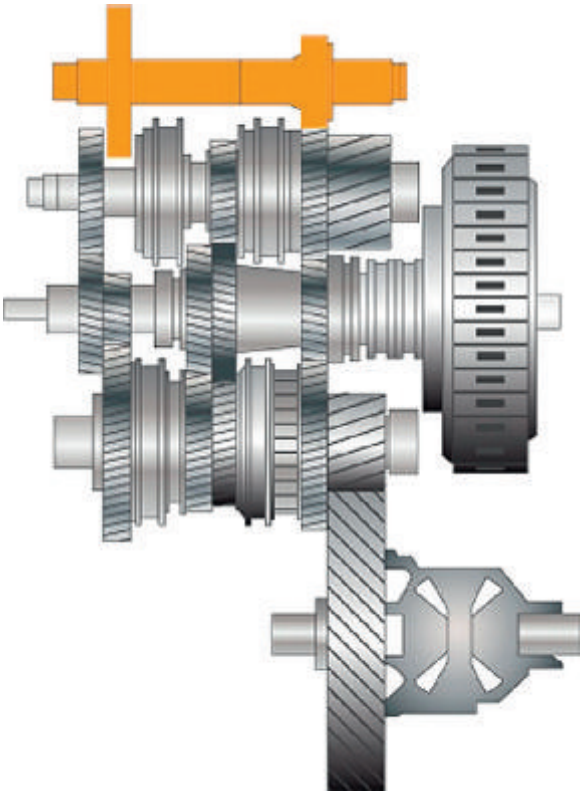


Figure 5.76 Reverse shaft

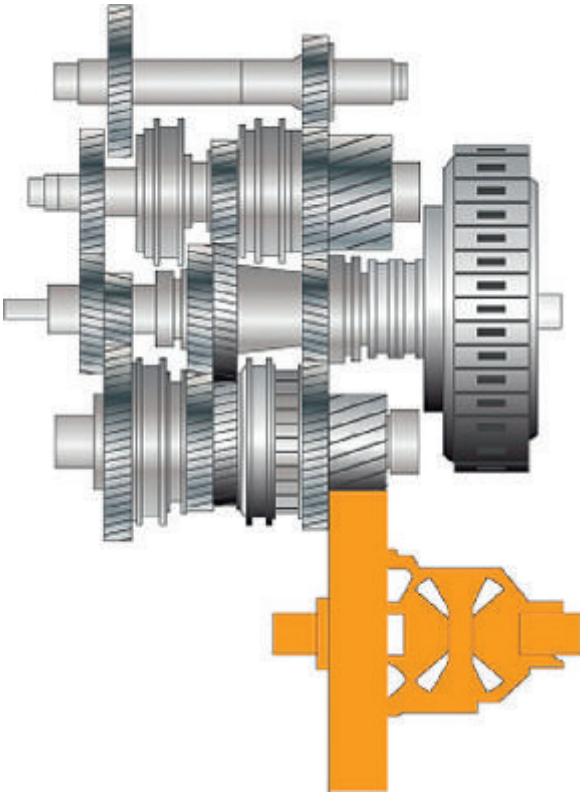


Figure 5.77 Final drive and differential

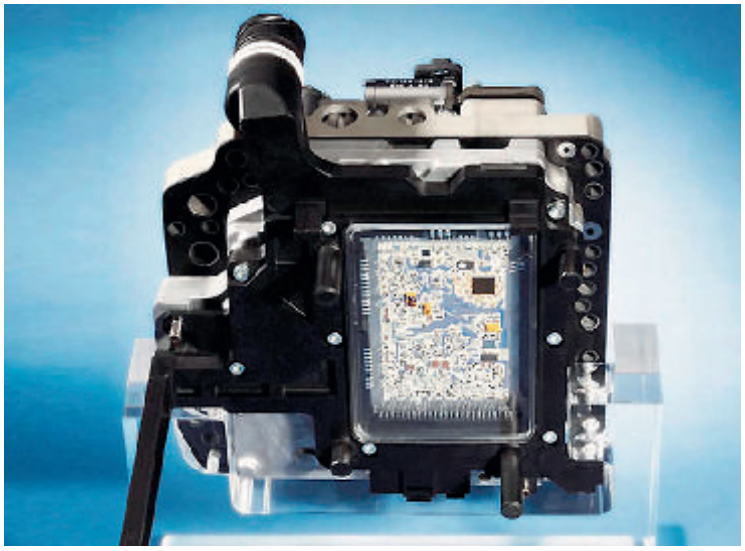


Figure 5.78 Electronic control. (Source: Volkswagen Media)

oil from both clutches. The mechatronics control unit learns and remembers (adapts) the position of the clutches, the positions of the gear actuators, when a gear is engaged, and the main pressure.

A variation on the system described above is shown in Fig. 5.79. I am unsure whether to describe the DSG as a manual or an automatic box, so the only thing to do is to make up a new word. This section has therefore outlined the operation of an 'auto-man gearbox' (AMG)!

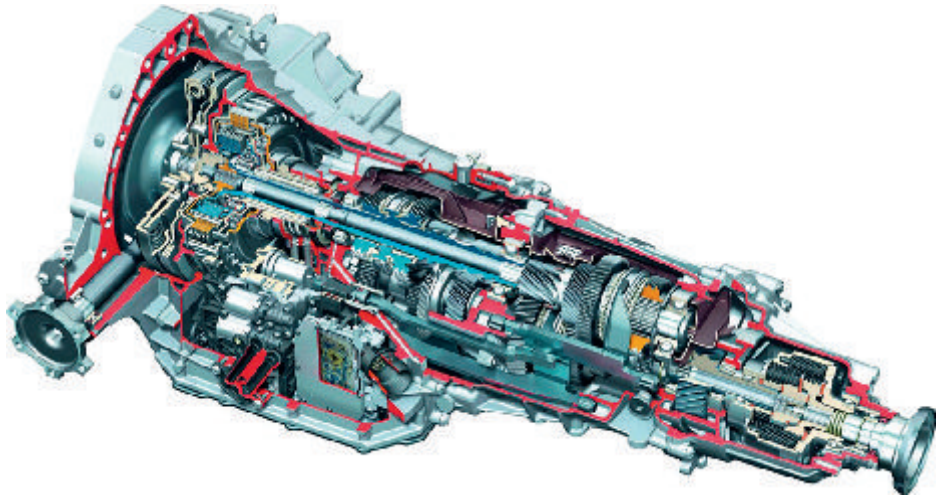


Figure 5.79 Audi four-wheel drive direct shift gearbox. (Source: Audi Media)

5.4 Transmission driveline

5.4.1 Propshafts and driveshafts

Propshafts, with universal joints (UJs), are used on rear- or four-wheel drive vehicles (Fig. 5.80). They transmit drive from the gearbox output to the final drive in the rear axle. Drive then continues through the final drive and differential, via two half shafts to each rear wheel. A hollow steel tube is used for the main shaft (Fig. 5.81). This is lightweight, but will still transfer considerable turning forces and resist bending forces.

Key fact

A hollow steel tube is used for a propshaft because it is lightweight, but will still transfer considerable turning forces and resist bending.

Universal joints allow for the movement of the rear axle with the suspension, while the gearbox remains fixed. Two joints are used on most systems and must always be aligned correctly (Fig. 5.82).

Because of the angle through which the drive is turned by UJs, a speed variation results. This is caused because two arms of the UJ rotate in one plane and two in another. The cross of the UJ, therefore, has to change position twice on each revolution. This problem can be overcome by making sure the two UJs are aligned correctly (Fig. 5.83). If the two UJs on a propshaft are aligned correctly, the variation in speed caused by the first can be cancelled out by the second. However, the angles through which the shaft works must be equal. The main body of the propshaft will run with variable velocity but the output drive will be constant.

Key fact

Two joints are used on most propshafts and must always be aligned correctly.

The simplest and most common type of UJ consists of a four-point cross, which is sometimes called a spider. Four needle roller bearings are fitted, one on each arm of the cross. Two bearings are held in the driver yoke and two in the driven yoke (Fig. 5.84).

Several types of UJ have been used on vehicles (Figs 5.85–5.88). These developed from the simple ‘Hooke’ type joint to the later cross-type, sometimes known as a Hardy Spicer. Rubber joints are also used on some vehicles.

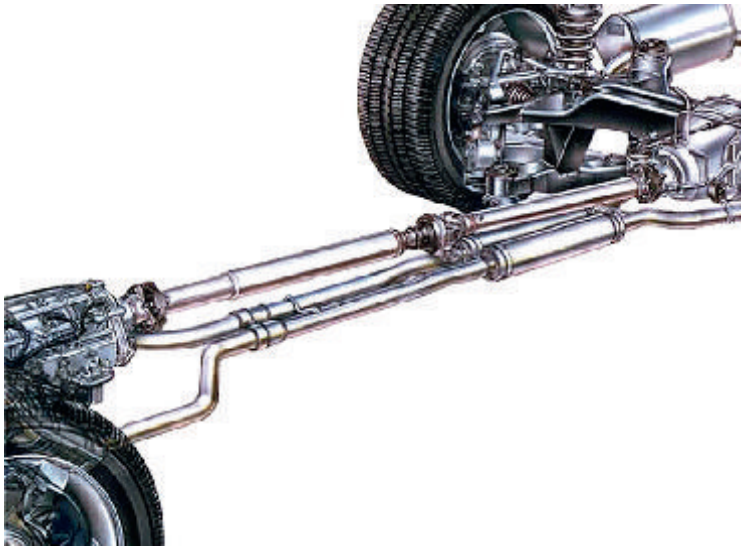


Figure 5.80 Propshaft

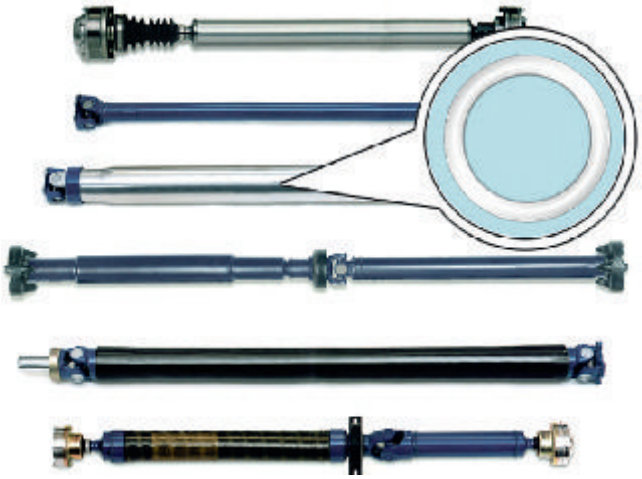


Figure 5.81 Section of a propshaft

Figure 5.82 Universal joint in position

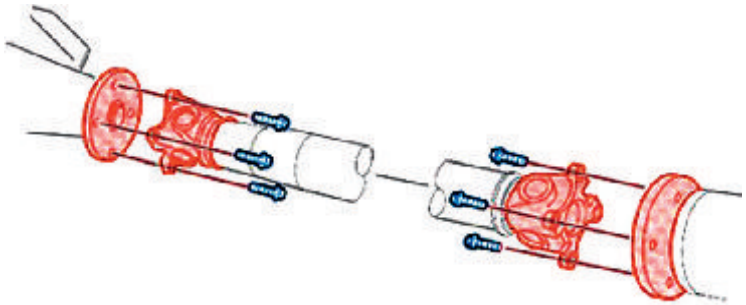


Figure 5.83 These joints are aligned correctly

Figure 5.84 Detail of a universal joint

Figure 5.85 Hooke-type joint

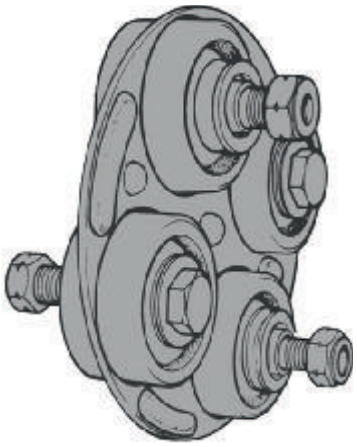


Figure 5.86 Layrub joint

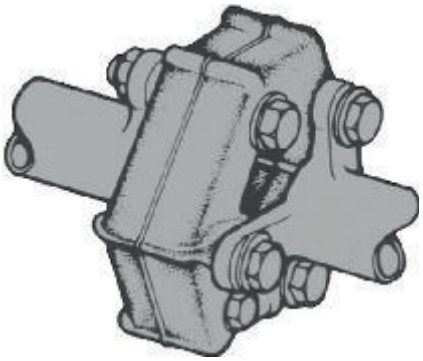


Figure 5.87 Rubber 'doughnut' joint

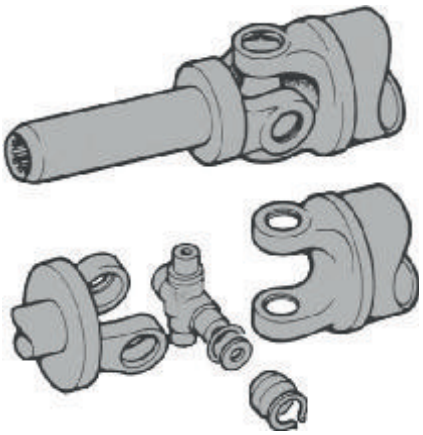


Figure 5.88 Modern cross-type joint

Figure 5.89 A splined joint connects to the gearbox

The 'doughnut' coupling has the advantage that it is flexible and absorbs torsional shocks. It will also tend to reduce vibrations caused by other joints. Its other main advantage is that it allows some axial (back and forth) movement.

As the suspension moves up and down, the length of the driveline changes slightly. As the rear wheels hit a bump, the axle moves upwards. This tends to shorten the driveline. The splined sliding joint allows for this movement. However, it will also transfer the rotational drive. Internal splines are used on the propshaft so that the external surface is smooth (Fig. 5.89). This allows an oil seal to be fitted in to the gearbox output casing.

Key fact

As a car's suspension moves up and down, the length of the driveline changes.

Figure 5.90 This rubber mounted bearing prevents propshaft whip

Figure 5.91 Inner constant velocity (CV) joint

Figure 5.92 Outer constant velocity (CV) joint

When long propshafts are used, there is a danger of vibration. This is because the weight of the propshaft can cause it to sag slightly and therefore 'whip' (like a skipping rope) as it rotates. Most centre bearings are standard ball bearings mounted in rubber (Fig. 5.90).

Propshafts are used on rear- or four-wheel drive vehicles. They transmit drive from the gearbox output to the rear axle. Most propshafts contain two UJs. A single joint produces rotational velocity variations, but this can be cancelled out if the second joint is aligned correctly. Centre bearings are used to prevent vibration due to propshaft whip.

On front-wheel drive cars, driveshafts with constant velocity (CV) joints transmit drive from the output of the final drive and differential, to each front wheel. They must also allow for suspension and steering movements.

Key fact

Constant velocity (CV) joints allow for suspension and steering movements.

A CV joint is a universal joint. However, it is constructed so that the output rotational speed is the same as the input speed. The speed of rotation remains constant even as the suspension and steering move the joint.

The inner and outer joints (Figs 5.91 and 5.92) have to perform different tasks. The inner joint has to plunge in and out, to take up the change in length as the suspension moves. The outer joint has to allow suspension and steering movement up to about 45°. A solid steel shaft transmits the drive.

When a normal UJ operates, the operating angle of the cross changes as described above. This is what causes the speed variations. A CV joint spider

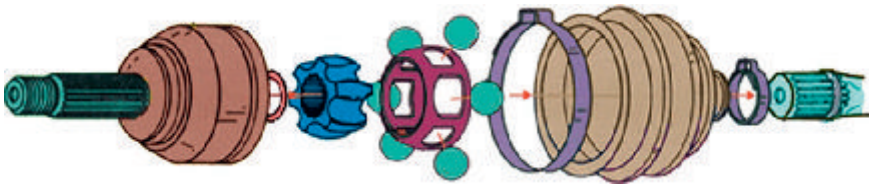


Figure 5.93 Details of a constant velocity (CV) joint (Rzeppa type)

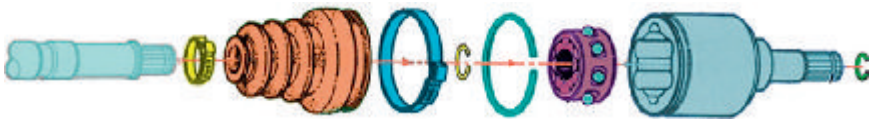


Figure 5.94 Constant velocity (CV) joint: double offset type

(or cross) operates in one plane because balls or rollers are free to move in slots. The cross therefore bisects the driving and driven planes.

The rubber boot or gaiter keeps out dirt and water, and keeps in lubricant. Usually, a graphite or molybdenum grease is used, but check the manufacturer's specifications to be sure.

There are a number of different types of CV joint (Fig. 5.93). The most common is the Rzeppa (pronounced reh-ZEP-ah). The inner joint must allow for axial movement due to changes in length as the suspension moves. It has six steel balls held in a cage between an inner and outer race inside the joint housing. Each ball rides in its own track on the inner and outer races. The tracks are manufactured into an arch shape so that the balls stay in the mid-point at all times, ensuring that the angle of the drive is bisected. This joint is used on the outer end of a driveshaft and can handle steering angles of up to 45°.

The other common CV joint is the double offset joint, which is a variation of the Rzeppa type (Fig. 5.94). The main difference is that the outer race has long straight tracks. This allows a plunge (axial movement) of about 50 mm (2 in.) and a steering angle of up to 24°. This makes it ideal as the inner joint on the driveshaft.

Driveshafts with CV joints are used on front-wheel drive vehicles. They transmit drive from the differential to each front wheel. They must also allow for suspension and steering movements. Inner joints must 'plunge' to allow for changes in length of the shaft.

Key fact

The two main types of bearing are ball and roller.

5.4.2 Wheel bearings

Two main types of bearing are used in rear wheel hubs: ball and roller (or tapered roller) bearings (Figs 5.95 and 5.96).

Key fact

Different bearing layouts are used on the fixed live axle of rear-wheel drive vehicles.

Axle shafts transmit drive from the differential to the rear wheel hubs. An axle shaft has to withstand:

- torsional stress due to driving and braking forces
- shear and bending stress due to the weight of the vehicle
- tensile and compressive stress due to cornering forces.

A number of bearing layouts are used on the fixed live axle (driven) of a rear-wheel drive car, to handle these stresses.

Figure 5.95 Ball bearing

Figure 5.96 Tapered roller bearing

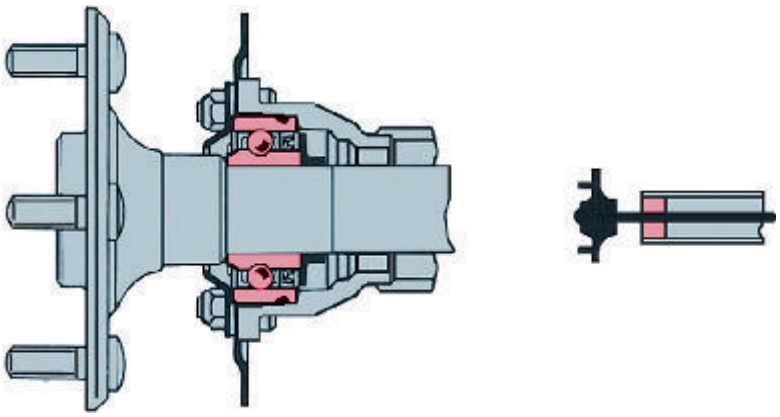


Figure 5.97 Wheel bearing: semi-floating

Figure 5.97 shows a typical axle mounting used on many rear-wheel drive cars. A single bearing is used, which is mounted in the axle casing. With this design, the axle shaft has to withstand all the operating forces. The shaft is therefore strengthened and designed to do this. An oil seal is incorporated because oil from the final drive can work its way along the shaft. The seal prevents the brakes being contaminated.

The three-quarter floating bearing shown in Fig. 5.98 reduces the main shear stresses on the axle shaft but the other stresses remain. The bearing is mounted

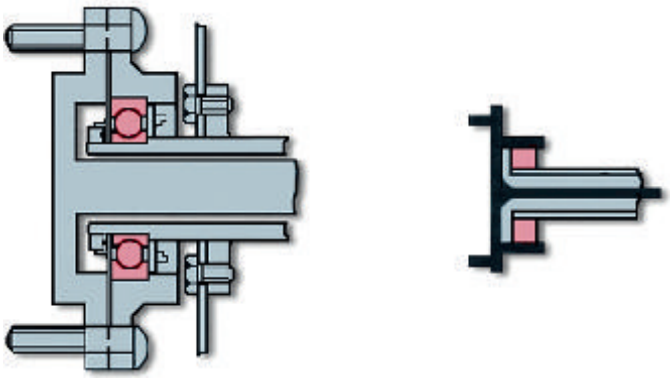


Figure 5.98 Wheel bearing: three-quarter floating

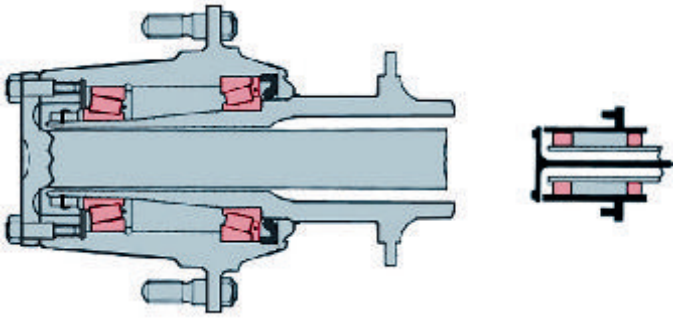


Figure 5.99 Wheel bearing: fully floating

on the outside of the axle tube. An oil seal is included to prevent the brake linings from being contaminated.

Fully floating systems are generally used on heavy or off-road vehicles (Fig. 5.99). This is because the stresses on these applications are greater. Two widely spaced bearings are used, which take all the loads, other than torque, off the axle shaft. Bolts or studs are used to connect the shaft to the wheel hub. When these are removed, the shaft can be taken out without jacking up the vehicle.

The front hubs on rear-wheel drive cars consist of two bearings. These are either ball or tapered roller types (Figs 5.100 and 5.101). The roller types are generally used on earlier vehicles. They have to be adjusted by tightening the hub nut and then backing it off by about half a turn. The more modern hub bearings, known as contact-type ball races, do not need adjusting. This is because the hub nut tightens against a rigid spacer. This nut must always be set at a torque specified by the manufacturer.

Key fact

Wheel bearings must allow smooth rotation of the wheel and withstand high suspension and steering stresses.

The most common systems for rear-wheel drive cars are semi-floating rear bearings at the rear and twin ball bearings at the front. The front bearings are designed to withstand side forces as well as vertical loads. Front-wheel drive cars have a dead axle at the rear so, typically, two taper bearings are used, or a double-race ball bearing (Fig. 5.102).

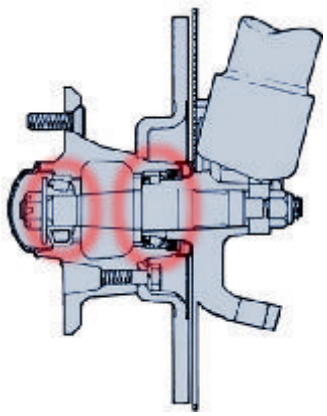


Figure 5.100 Front hub (rear-wheel drive) with tapered roller bearings

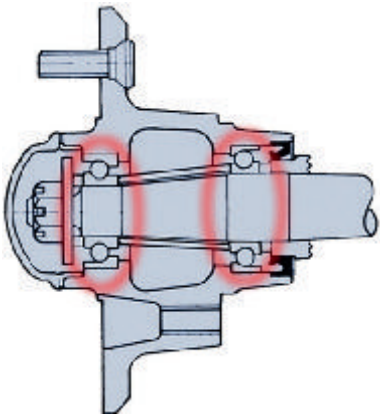


Figure 5.101 Front hub with ball bearings

Wheel bearings must allow smooth rotation of the wheel but also be able to withstand high stresses such as when cornering. In addition, front-wheel drive arrangements must allow the drive to be transmitted via the driveshafts.

A front hub works as an attachment for the suspension and steering as well as supporting the bearings (Fig. 5.103). It supports the weight of the vehicle at the front, when still or moving. Ball or roller bearings are used for most vehicles with specially shaped tracks. This is so that the bearings can stand side loads when cornering. The bearings support the driveshaft as well as the hub.

The stub axle, which is solid-mounted to the suspension arm, fits in the centre of two bearings. The axle supports the weight of the vehicle at the rear, when still or moving. Ball bearings are used for most vehicles, with specially shaped tracks for the balls, so that the bearings can stand side loads when cornering. A spacer is used to ensure the correct distance between, and pressure on, the two bearings.

On front-wheel drive vehicles, the hub and bearing arrangement on the front must bear weight, withstand driving forces and support the driveshaft. The rear hub and bearings (Fig. 5.104) must support the vehicle and withstand side forces.

Figure 5.102 Rear hub (dead axle) with taper bearing

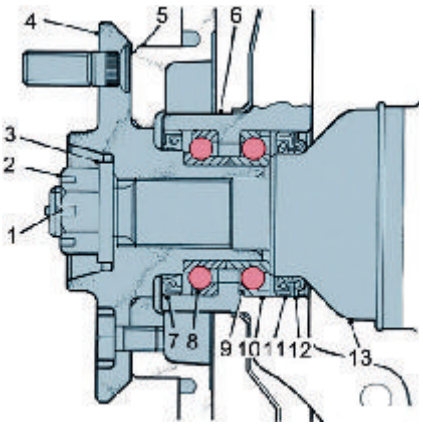


Figure 5.103 Front hub and bearings: 1, split pin; 2, hub nut; 3, flat washer; 4, drive flange; 5, brake disc; 6, hub; 7, outlet oil seal; 8, outer bearing; 9, inner bearing; 10, spacer; 11, inner oil seal; 12, bearing water shield; 13, drive shaft

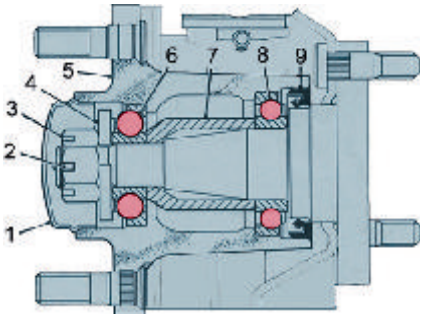


Figure 5.104 Rear hub and bearings: 1, grease retaining cap; 2, split pin; 3, hub nut; 4, flat washer; 5, hub and brake drum assembly; 6, outer bearing; 7, spacer; 8, inner bearing; 9, oil seal

5.4.3 Four-wheel drive

Four-wheel drive (4WD) systems can be described as part-time or full-time. All 4WD systems must include some type of transfer gearbox. The main components of a 4WD system are shown in Fig. 5.105. Each axle must be fitted with a differential. A transfer box takes drive from the output of the normal gearbox and distributes it to the front and rear. The transfer box may also include gears to allow the selection of a low ratio. High ratio is a straight-through drive.

A 4WD system, when described as part-time, means that the driver selects 4WD only when the vehicle needs more traction. When the need no longer exists, the driver reverts to the normal two-wheel drive. This keeps driveline friction, and therefore the wear rate, to a minimum.

When a 4WD system is described as full-time, it means that the drive is engaged all the time. To prevent 'wind-up', which occurs if the front and rear axles rotate at different speeds, a centre differential or viscous drive is used.

An all-wheel drive (AWD) system automatically transfers drive to the axle with better traction (Fig. 5.106). It is designed for normal road use. The drive, on full-time systems, is passed to the rear via a viscous coupling. When the front wheels spin, the viscous coupling locks and transfers drive to the rear.

If used, a transfer box on a part-time 4WD system may allow the driver to choose from four options:

- neutral
- 2WD high

Key fact

Four-wheel drive systems can be described as part-time or full-time.

Key fact

The drive, on full-time four-wheel drive systems, is passed to the rear via a viscous coupling to prevent wind-up.

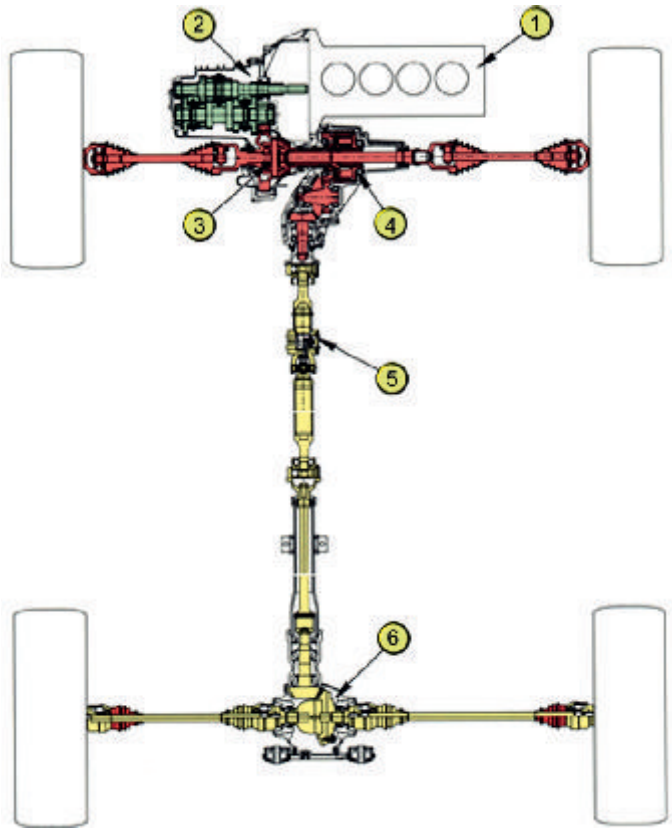


Figure 5.105 The main components of a four-wheel drive system: 1, engine; 2, transmission; 3, front axle differential and final drive; 4, transfer box with longitudinal differential; 5, two-piece driveshaft; 6, rear final drive and differential

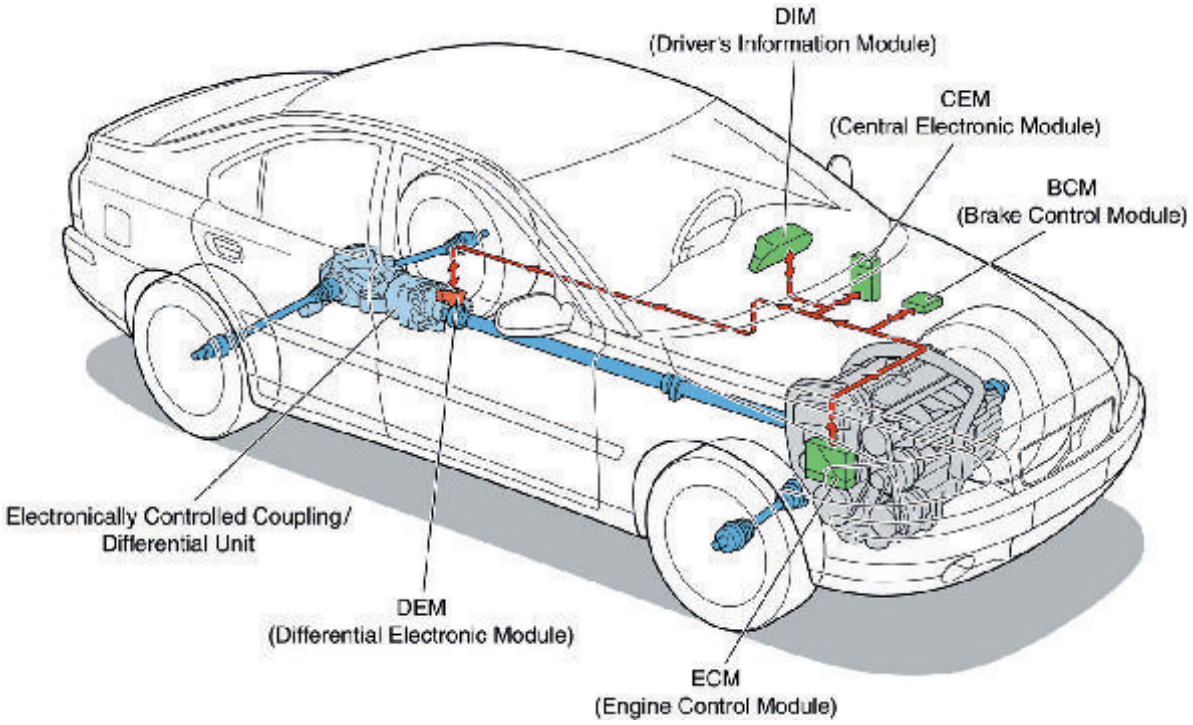


Figure 5.106 Electronically controlled all-wheel drive vehicle. (Source: Volvo Media)

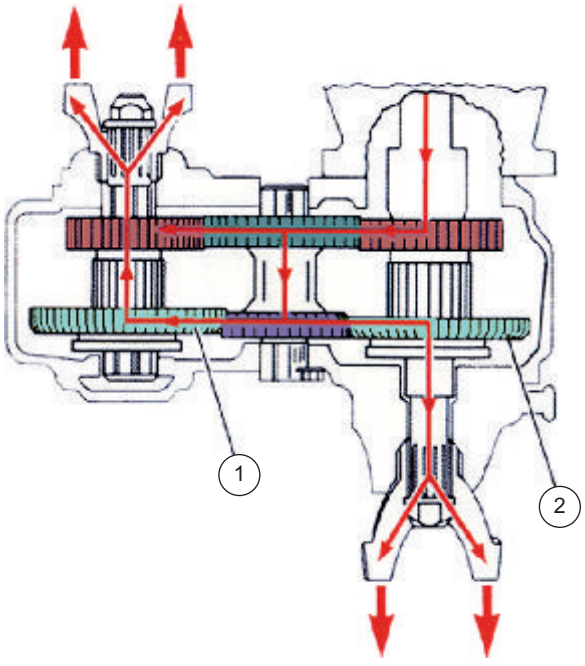


Figure 5.107 Transfer box four-wheel drive low ratio selected: 1, low ratio gear selector; 2, high ratio gear selector

- 4WD high
- 4WD low (Fig. 5.107).

A typical system will have the transfer box, attached to the normal rear-wheel drive gearbox, in place of the extension housing. This arrangement is more often used for off-road vehicles.

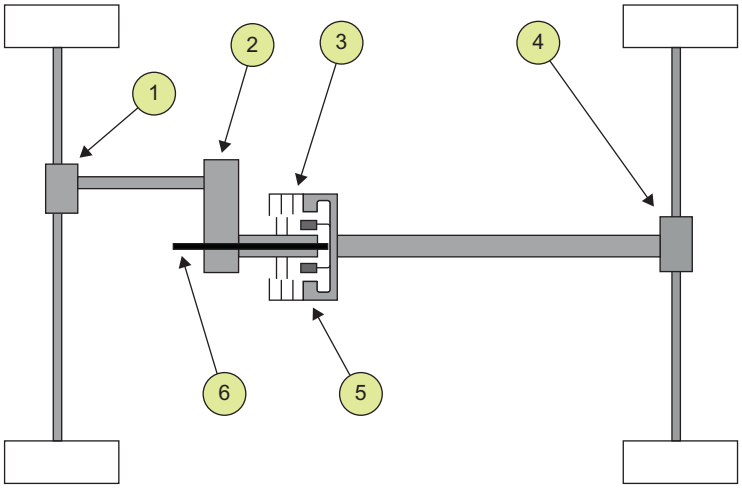


Figure 5.108 A viscous coupling transfers torque when axle speeds differ: 1, front differential; 2, drive chain transfer box; 3, viscous coupling; 4, rear differential; 5, planetary gear train; 6, transmission gearbox output shaft

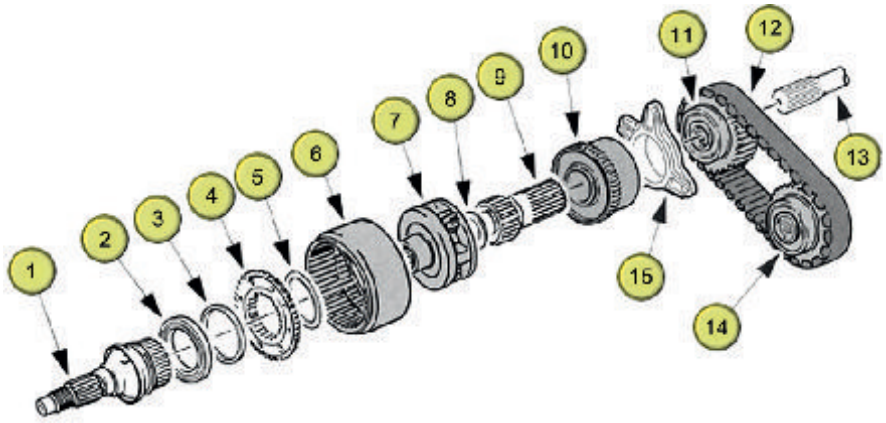


Figure 5.109 Transfer box using planetary gears and a 'silent' drive chain: 1, output shaft; 2, ball bearing; 3, spacer; 4, drive plate; 5, spacer; 6, annulus; 7, planet carrier and planet gears; 8, thrust washer; 9, sun wheel shaft; 10, viscomatic locking unit; 11, driving sprocket and bearing; 12, drive chain; 13, transmission gearbox output shaft; 14, driven sprocket and bearing; 15, bracket

A differential in a transfer box allows its two outputs to be driven at different speeds. In 4WD systems, it is possible that, for example, the front axle could rotate more quickly than the rear axle. This would produce driveline wind-up, so centre differentials or viscous couplings are used. On modern vehicles, they often consist of planetary gears.

A viscous coupling is designed to transmit drive when the axle speeds differ (Fig. 5.108). This occurs because the difference in speed of the two axles increases the friction in the coupling. This results in greater torque transmission, which in turn reduces the speed difference. As the speed difference reduces, less torque is transmitted. In this way, the torque is shared proportionally between the two axles.

A 'silent' drive chain is used on many vehicles to pass the drive to the auxiliary output shaft (Fig. 5.109). The chain takes up less space than do gears. It is designed to last the life of the vehicle and adjustment is not normally possible.

Key fact

A differential in a transfer box allows its two outputs to be driven at different speeds.

Four-wheel drive systems use a combination of propshafts and driveshafts together with viscous couplings and transfer boxes. A number of variations are possible and may be described as full- or part-time.

5.5 Final drive and differential

5.5.1 Final drive

Key fact

The final drive consists of two gears and provides a fixed speed reduction.

Because of the speed at which an engine runs, and in order to produce enough torque at the road wheels, a fixed gear reduction is required. This is known as the final drive and it consists of just two gears. The final drive is fitted on the output of the gearbox on front-wheel drive vehicles, and in the rear axle after the propshaft on rear-wheel drive vehicles. The ratio is normally a speed reduction of between about 2:1 and about 4:1. For example, at 4:1, when the gearbox output is turning at 4000 rpm, the wheels will turn at 1000 rpm.

Many cars now have a transverse engine, which drives the front wheels. The final drive contains ordinary helical gears. When a transaxle system is used as in Fig. 5.110, it always consists of the final drive and two driveshafts.

On rear-wheel drive vehicles, the final drive gears also turn the drive through 90° (Fig. 5.111). This is done using bevel gears known as a crown wheel and pinion. Four-wheel drive vehicles also have a similar arrangement as part of the rear axle. The crown wheel and pinion are special types of bevel gears, which mesh at right angles to each other (Fig. 5.112). They carry power through a right angle to the drive wheels. The crown wheel is driven by the pinion, which receives power from the propeller shaft.

Final drive gears reduce the speed from the propeller shaft and increase the torque. The reduction in the final drive multiplies any reduction that has already taken place in the transmission.

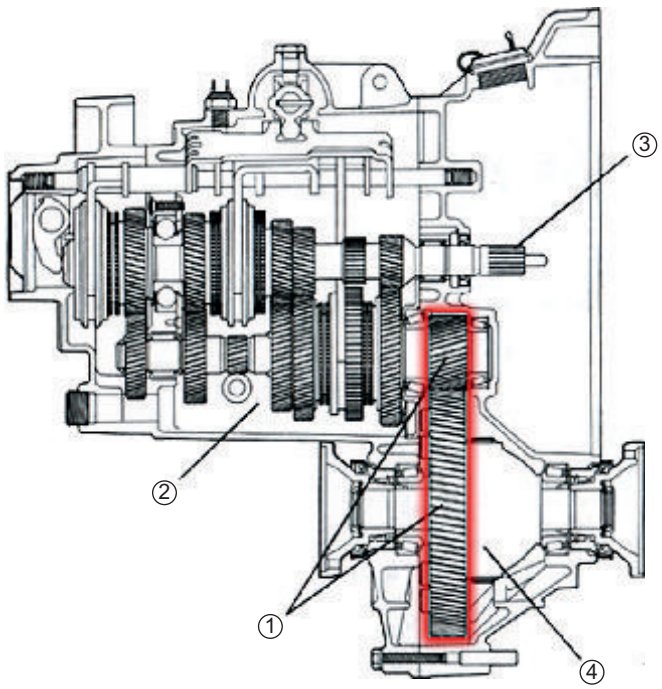


Figure 5.110 Transaxle final drive gears: 1, gearbox output shaft; 2, input shaft; 3, differential; 4, final drive gears (highlighted)

The crown wheel gear (and pinion) of a rear-wheel drive system is usually a hypoid type, and is named after the way the teeth are cut (Fig. 5.113). As well as quiet operation, this allows the pinion to be set lower than the crown wheel centre, thus saving space in the vehicle because a smaller transmission tunnel can be used. Some early vehicles used spiral-cut gears, which had the advantage of running more quietly but still had to be set at the centre line.

Because the teeth of hypoid gears cause 'extreme pressure' on the lubrication oil, a special type is used. This oil may be described as 'hypoid gear oil' or 'EP', which stands for extreme pressure. As usual, refer to manufacturers' recommendations when topping up or changing oil.

The rigid rear axle assembly consists of other components as well as the final drive gears. The other main components are the differential, halfshafts and bearings. On split axle types, as in Fig. 5.111, the final drive is mounted to the chassis and driveshafts are used to connect to the wheels.

Key fact

A crown and pinion hypoid gear set allows the propshaft to be set lower.

Key fact

Because the teeth of hypoid gears cause 'extreme pressure', special oil is used.

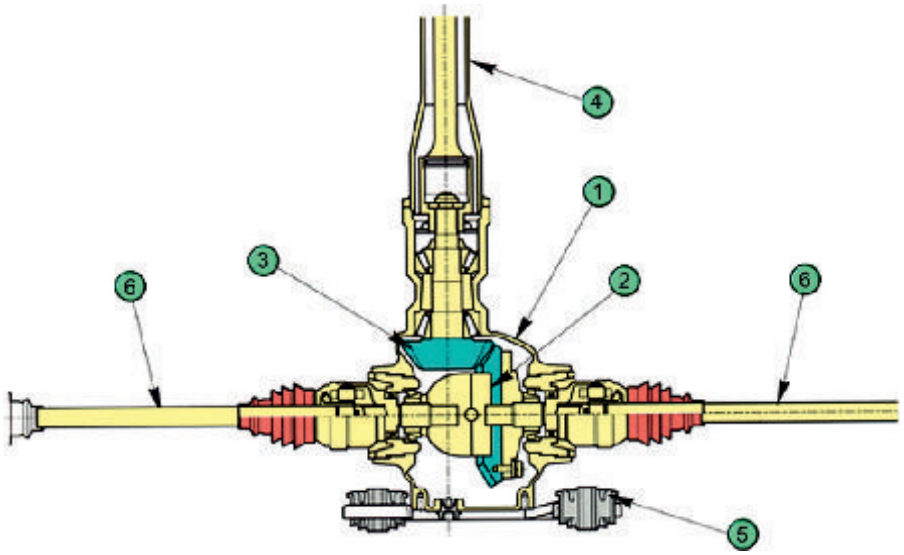


Figure 5.111 Rear axle final drive gears: 1, rear axle housing; 2, differential; 3, crown wheel and pinion final drive gears; 4, extension tube; 5, mounting; 6, driveshafts

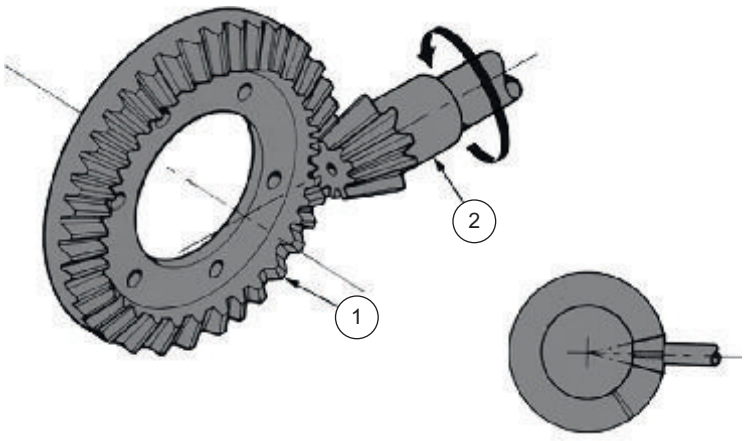


Figure 5.112 Bevel gears change ratio and drive angle: 1, crown wheel; 2, pinion (both on centre line)

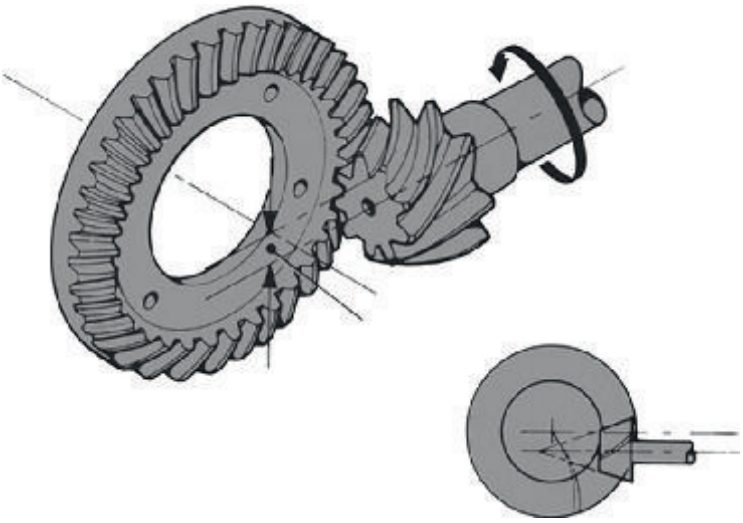


Figure 5.113 The hypoid design allows a lower propshaft to be used (the offset is shown by the arrows)

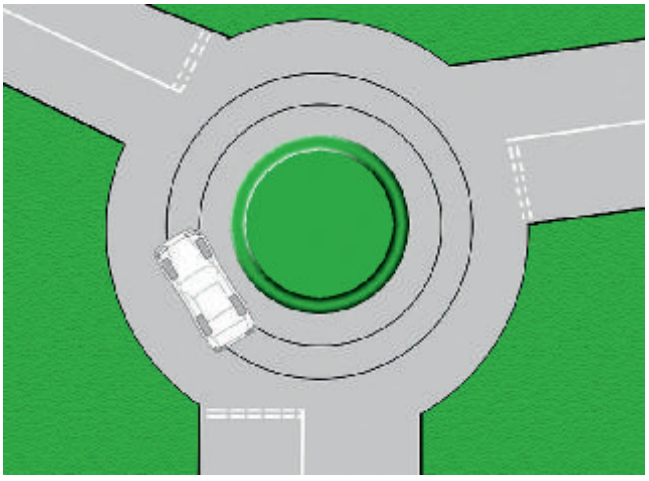


Figure 5.114 The outer wheels travel a greater distance

To produce enough torque at the road wheels, a fixed gear reduction is required. This is known as the final drive. It consists of just two gears. On rear-wheel drive systems, the gears are bevelled to turn the drive through 90°. On front-wheel drive systems, this is not necessary. The drive ratio is similar for front- and rear-wheel drive cars.

5.5.2 Differential

Key fact

A differential is a set of gears that divides torque evenly between two drive wheels.

The differential is a set of gears that divides the torque evenly between the two drive wheels. The differential allows one wheel to rotate more quickly than the other. As a car goes around a corner, the outside driven wheel travels further than the inside one (Fig. 5.114). The outside wheel must therefore rotate faster than the inside one to cover the greater distance in the same time. Tyre scrub and poor handling would be the result if a fixed axle were used.

The differential consists of sets of bevel gears, and pinions within a cage, attached to the large final drive gear. The bevel gears can be described as sun

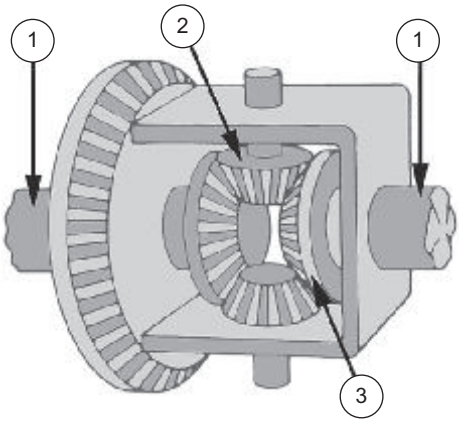


Figure 5.115 All the drive is transferred to the free wheel: 1, driveshaft; 2, planet gears; 3, sun gears

Figure 5.116 This differential is described as an open type

and planet gears. The sun gears provide the drive to the wheels via halfshafts or driveshafts. The planet gears either rotate with the sun gears or rotate around them, depending on whether the car is cornering or not.

Bearings support the differential casing, which is in turn bolted to the final drive gear. The casing transmits the drive from the final drive gear, to the planet gear pinion shaft. The planet gears are pushed round by this shaft. The sun gear pinions, which are splined to the drive shafts, take their drive from the planet gears. The sun gears always rotate at the same speed as the road wheels.

The planet shaft is secured in the differential casing so that it pushes the planet gears. If the sun gears, which are attached to the road wheels via the driveshafts, are moving at the same speed, the planet gears do not spin on their shaft. However, when the vehicle is cornering, the sun gears need to move at different speeds. In this case, the planet gears rotate on their shaft to make up for the different wheel speeds.

When the vehicle is travelling in a straight line, the planet gears turn with the sun gears, but do not rotate on their shaft. This occurs because the two sun gears attached to the driveshafts are revolving at the same speed.

A standard differential can be described as a torque equalizer. This is because the same torque is always provided to each wheel, even if they are revolving at different speeds. At greater speeds, more power is applied to the wheel, so the torque remains the same.

A good way to understand the differential action is to consider the extreme situation. This is when a corner is so sharp that the inner wheel would not move at all! Although this is impossible, it can be simulated by jacking up one wheel of the car. All the drive is transferred to the free wheel (Fig. 5.115). The planets roll around the stationary sun wheel but drive the free wheel because they are rotating on their shaft.

The previous extreme example highlights the problem with a differential. If one of the driven wheels is stuck in the mud, all the drive is transferred to that wheel and it normally spins. Of course, in this case, drive to the wheel on the hard ground would be more useful. The solution to this problem is the limited slip differential (LSD).

Some higher-performance vehicles use an LSD to improve traction. Clutch plates, or similar, are connected to the two output shafts and can, therefore, control the amount of slip. This can be used to counteract the effect of one wheel losing traction when high power is applied.

Key fact

The planet gears either rotate with the sun gears or rotate around them, depending on whether the car is cornering or not.

Key fact

The planet shaft is secured in the differential casing so that it pushes the planet gears.

Definition

Standard differential

This can be described as a torque equalizer.

Key fact

A problem with a standard differential is that if one of the driven wheels is stuck in the mud, all the drive is transferred to that wheel.

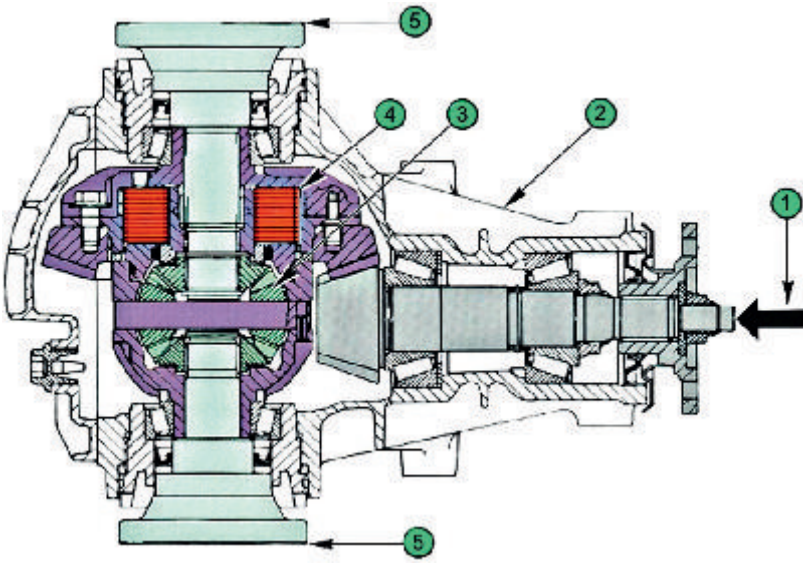


Figure 5.117 Limited slip differential (LSD) using clutch plates: 1, input drive from propshaft; 2, housing; 3, differential; 4, clutch plates; 5, output drive flanges. (Source: Ford Motor Company)

A standard differential always applies the same amount of torque to each wheel. Two factors determine how much torque can be applied to a wheel. In dry conditions, when there is plenty of traction, the amount of torque applied to the wheels is limited by the engine and gearing. When the conditions are slippery, such as on ice, the torque is limited by the available grip. LSDs allow more torque to be transferred to the non-slipping wheel.

The clutch-type LSD is the most common (Fig. 5.117). It is the same as a standard differential, except that it also has a spring pack and a multiplate clutch. The spring pack pushes the sun gears against the clutch plates, which are attached to the cage and both sun gears spin with the cage. When both wheels are moving at the same speed, the clutches have little or no effect. However, the clutch plates try to prevent either wheel from spinning more quickly than the other. The stiffness of the springs and the friction of the clutch plates determine how much torque it takes to make the clutch slip.

If one drive wheel is on a slippery surface and the other one has good traction, drive can be transmitted to the wheel with good traction. The torque supplied to the wheel not on the slippery surface is equal to the amount of torque it takes to overpower the clutches. The result is that the car will move, but not with all the available power.

The viscous coupling often found in all-wheel-drive vehicles acts like an LSD (see Fig. 5.108). It is commonly used to link the back wheels to the front wheels so that when one set of wheels starts to slip, torque will be transferred to the other set. The viscous coupling has two sets of plates inside a sealed housing that is filled with a thick fluid. One set of plates is connected to each output shaft. Under normal conditions, both sets of plates and the viscous fluid spin at the same speed. However, when one set of wheels spins more quickly, there will be a difference in speed between the two sets of plates.

The viscous fluid between the plates tries to catch up with the faster discs, dragging the slower discs along. This transfers more torque to the slower wheels. When a vehicle is cornering, the difference in speed between the wheels is not as large as when one wheel is slipping. The faster the plates spin, relative to each other, the more torque the coupling transfers.

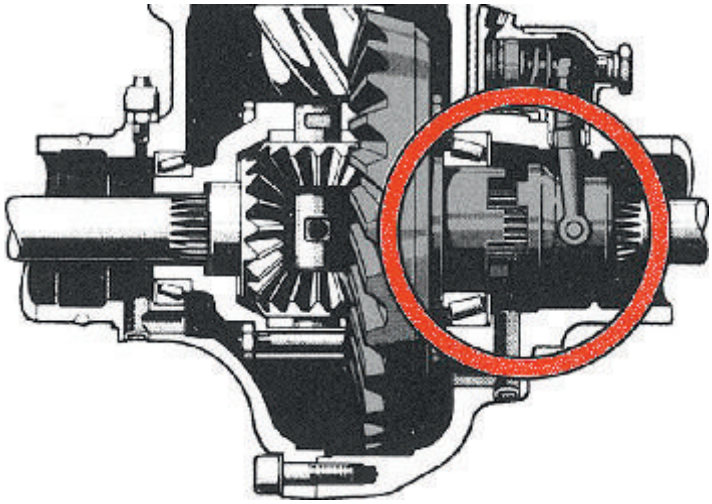


Figure 5.118 Differential locking mechanism

This effect can be demonstrated by spinning an egg. Spin the egg on a table top and then stop it. Let go, and it will start to spin again because the viscous fluid inside is still spinning and drags the shell around with it.

Conventional LSDs cannot be designed for optimum performance because of the effect on the vehicle when cornering and on the steering. These issues prompted the development of electronic control. The slip limiting action is controlled by a multidisc clutch, as discussed previously. The pressure on the clutch plates is controlled by hydraulic pressure, which in turn is controlled by a solenoid valve under the influence of an ECU. The ECU is able, if required, to fully lock the axle. Data is provided to the ECU from standard ABS-type wheel sensors.

Differential locks are used on many off-road type vehicles. A simple dog clutch or similar device prevents the differential action. This allows far better traction on slippery surfaces. An electric, hydraulic or pneumatic mechanism is used to lock the two output pinions together (Fig. 5.118).

This mechanism is usually activated manually by switch and, when activated, both wheels will spin at the same speed. If one wheel ends up off the ground, the other wheel will continue to spin at the same speed.

5.6 Formula 1 transmission technology

5.6.1 Clutch

A Formula 1 (F1) clutch is a multiplate carbon design with a diameter of about 100 mm (4 in.). It weighs in at between 1 and 1.5 kg (2.1–3 lb) and can handle something like 720 h.p. (540 kW). Clutch control is electrohydraulic, except when moving off or coming to a standstill. In this situation, the driver operates the clutch using a lever on the back of the steering wheel.

The engine is linked directly to the clutch, which is fitted between the engine and gearbox as on a road car. The clutch plates and discs are both carbon compounds and must be able to work in temperatures of up to 500°C. The multiplate design is arranged to give enhanced drive pick-up. Being lightweight it has a low inertia, which allows faster gear changes. When the driver initiates a

Key fact

The F1 clutch plates and discs are both carbon compounds and must be able to work in temperatures of up to 500°C.

gear change with the steering wheel-mounted paddles, the on-board computer automatically cuts the engine, disengages the clutch, changes the gear and then engages the clutch again, all in less than 40 ms.

5.6.2 Gearbox

F1 cars use semi-automatic sequential gearboxes (Fig. 5.119), with regulations stating a maximum of seven forward gears and one reverse gear, using rear-wheel drive. The gearbox is constructed of carbon fibre or titanium, and is bolted onto the back of the engine. Fully automatic gearboxes and systems such as launch control and traction control are illegal. This is to maintain the importance of driver skill in controlling the car. The driver initiates gear changes using paddles mounted on the back of the steering wheel and electrohydraulics perform the actual change as well as throttle control.

Key fact

Because there is no synchromesh in an F1 gearbox, the engine electronics synchronize the speed of the engine with the speed of the gearbox, before engaging a gear.

F1 car gearboxes are semi-automatic and have no synchromesh. They are sequential and the gears are changed by a rotating barrel with selector forks around it. Because there is no synchromesh, the engine electronics synchronize the speed of the engine with the speed of the gearbox, before engaging a gear. Most have six or seven forward gears. The gearbox is fixed to the back of the engine via four or six high-strength studs. The engine and gearbox are fully stressed members of the car structure and the suspension for the rear wheels bolts directly onto the gearbox casing. The gearbox casing is made from fully stressed magnesium alloy so it can withstand the resulting loads.

Gear cogs (often referred to in racing as ratios) are used only for one race. They are subjected to very high degrees of stress so are replaced regularly during the race weekend to prevent failure. The teams adjust top gear so that the car will just be approaching the rev limit at the end of the main straight of the particular circuit. First gear is adjusted to give the best acceleration out of a corner; often the one at the end of the straight. The other gears are then set so as to be equally spaced between the first and top gears. The gearbox is designed so that the mechanics can change the ratios in about 40 minutes in the pits.

F1 cars do have a reverse gear because it is required by the regulations. However, it is usually small and flimsy, on the outside of the gearbox to help keep the weight down, as reverse gear is rarely used.

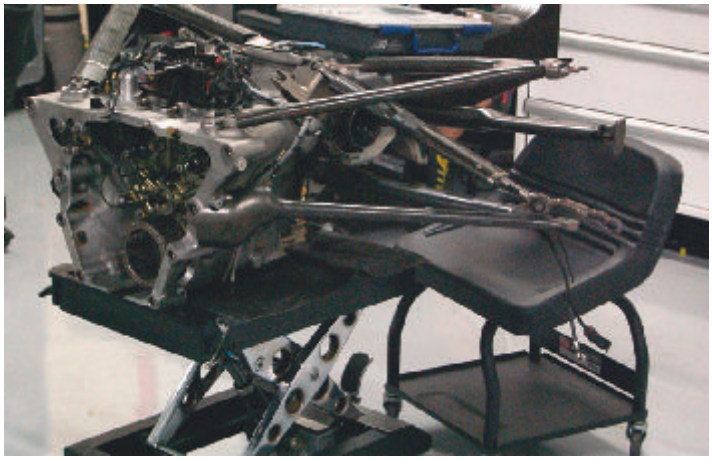


Figure 5.119 A gearbox from the Lotus T127 F1 car, 2010. (Source: John O'Nolan, Flickr)

5.6.3 Differential

LSDs maximize the traction, particularly out of corners. During cornering, electrohydraulic actuators change friction settings so the torque acting on both of the drive wheels changes. This torque relationship can be varied to help steer the car through corners, and prevent the inside rear wheel from spinning under hard acceleration.

5.6.4 FIA technical regulations

This section gives a simplified overview of the technical regulations as of 2011, which relate to the transmission (source: www.fia.com). Please note that before you design and build your own F1 car, you should refer to the official FIA technical regulations!

5.6.4.1 Clutch control

- If multiple clutch operating devices are used, they must all have the same mechanical travel characteristics and be mapped identically.
- Designs which allow specific points along the travel range of the clutch operating device to be identified by the driver or assist him to hold a position are not permitted.
- The minimum and maximum travel positions of the clutch operating device must correspond to the clutch fully engaged normal rest position and fully disengaged (incapable of transmitting any usable torque) positions, respectively.

5.6.4.2 Gearboxes

- The maximum number of forward gear ratios is seven, and all gear ratios must be made from steel.
- The maximum number of numerical change gear ratio pairs a competitor has available to him during a championship season is 30. All such gear ratio pairs must be declared to the FIA technical delegate at or before the first event of the championship.
- Continuously variable transmission systems are not permitted to transmit the power of the engine.
- All cars must have a reverse gear operable at any time during the event by the driver when the engine is running.

5.6.4.3 Kinetic energy recovery system (KERS)

- The KERS must connect at any point in the rear-wheel drivetrain before the differential.
- The system will be considered shut down when all energy is contained within the KERS modules and no high voltage is present on any external or accessible part of any KERS module.

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CHAPTER 6

Learning activities

6.1 Introduction

This section contains information, activities and ideas to help you learn more about automotive engineering, in a fun and interesting way. The best place to start is, of course, to read the content of the book. However, do remember when you are doing this to be active; in other words, make some notes, underline or highlight things and don't expect to understand something straight away–work at it!

I have created lots of useful online material that you can use. If you are at a school or college that is licensed to use my full blended eLearning package you already have access to everything. However, if not at a licensed school or college, I have created a special area for you to use free of charge. Just go to: www.automotive-technology.co.uk and follow the links from there.

You will find:

- multimedia (that includes some amazing animations)
- practical activities
- multiple-choice questions
- short answer questions
- glossaries
- virtual toolboxes
- and more …

Figure 6.1 Launch of the McLaren MP4-26 in early 2011. (Source: Vodafone McLaren Mercedes)

Automobile Mechanical and Electrical Systems.
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Figure 6.2 So, Lewis, do you have the ignition key or did Jenson bring it? (Source: Vodafone McLaren Mercedes)

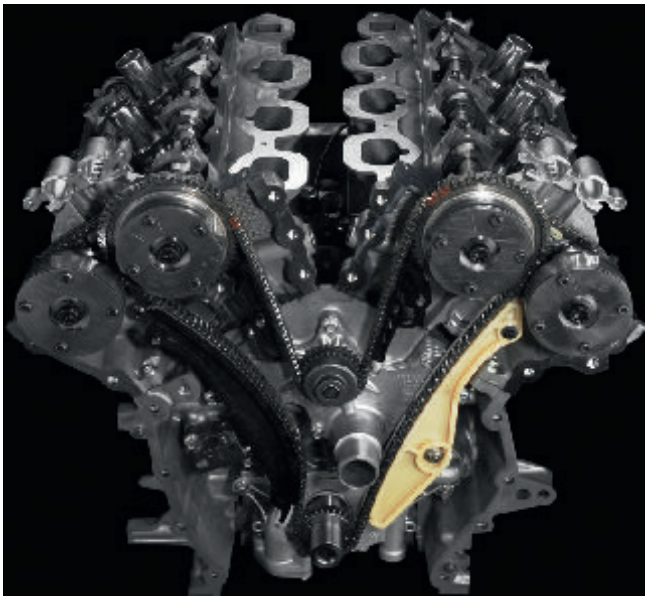

Figure 6.3 V-6 Mustang engine. (Source: Ford Media)

In this chapter I have not created specific assessment and learning activities for every subject, instead I have suggested types of activity and made a long list of subjects or systems that can be the topic of the work. However, doing an assignment after each section of the book is a good way to check progress.

6.2 Assignments

Using the information in this book, the resources on www.automotive-technology.co.uk and other web sources, such as Wikipedia, there are lots of assignments you can carry out.

For example, for the subjects/systems listed in Table 6.1 you could:

- Write a report to explain the operation and important features of *<insert subject or system here>*. Include images diagrams, tables, charts, bullets as needed. Remember that any report should have a beginning, a middle and an end; in other words, an introduction, the main bit, and a summary or conclusion.
- Outline why *<insert subject or system here>* are manufactured from certain materials and in different ways.
- Name and state the purpose of the main components of *<insert subject or system here>.*
- List the key functions of *<insert subject or system here>.*
- State the reasons why *<insert subject or system here>* are important.
- Make a simple sketch to show how *<insert subject or system here>* works.

Your assignments could be 200, 500 or 1000 words long (or more) as appropriate, or as determined by your teacher, instructor or lecturer. Note that Table 6.1 is pretty much the contents page of this book, but I have removed some parts and edited others to make it more appropriate for this section.

Table 6.1 List of assignment activities

1. Overview and introduction
   a. Mehicle categories
      i. Layouts
      ii. Types and sizes
      iii. Body design
      iv. Chassis type and body panels
      v. Main systems
   b. The motor industry
      i. Types of motor vehicle companies
      ii. Company structure
      iii. Role of a franchised dealer
      iv. Reception and booking systems
      v. Parts department
      vi. Estimating costs and times
      vii. Job cards and systems
      viii. Invoicing
      ix. Warranties
      x. Computerized workshop system
   c. Working safely
      i. Introduction
      ii. The key safety regulations and laws in your country
      iii. Personal protective equipment (PPE)
      iv. Identifying and reducing hazards
      v. Moving loads
      vi. Vehicle safety
      vii. Safety procedures
      viii. Fire
      ix. A clean working environment
      x. Signage
      xi. Environmental protection
   d. Basic science, materials, mathematics and mechanics
      i. Units
      ii. Velocity and acceleration
      iii. Friction
      iv. Pressure
      v. Centre of gravity or centre of mass
      vi. Oscillation
      vii. Energy, work and power
      viii. Force and torque
      ix. Mass, weight and force
      x. Volume and density
      xi. Heat and temperature
      xii. Percentages
      xiii. Fractions
      xiv. Ratios
      xv. Areas
      xvi. Volumes
      xvii. Indices
      xviii. Drawings
      xix. Mechanical machines
      xx. Gears
      xxi. Hydraulics
      xxii. Materials and properties

(*Continued*)

Table 6.1 (Continued)

- e. Tools and equipment
  - i. Hand tools
  - ii. Test equipment
  - iii. Workshop equipment
- f. Workshop bench skills
  - i. Fitting and machining
  - ii. Filing
  - iii. Drilling
  - iv. Cutting
  - v. Thread cutting
  - vi. Joining
  - vii. Nuts and bolts
  - viii. Adhesives
  - ix. Soldering
  - x. Brazing
  - xi. Welding
  - xii. Shrinking
  - xiii. Compression fitting
  - xiv. Riveting
  - xv. Gaskets
  - xvi. Sealants
  - xvii. Oil seals
- g. Servicing and inspections
  - i. Rules and regulations
  - ii. Service sheets
  - iii. Road test
  - iv. Effects of incorrect adjustments
  - v. Maintenance and inspections
  - vi. Information sources

2. Engine systems
   - a. Engine mechanical
     - i. Introduction and operating cycles
     - ii. Engine operating details
     - iii. Engine components
   - b. Engine lubrication
     - i. Friction and lubrication
     - ii. Methods of lubrication
     - iii. Lubrication system
     - iv. Filters
     - v. Oil pumps
     - vi. Standards
   - c. Engine cooling
     - i. Introduction
     - ii. System operation
     - iii. Interior heater
   - d. Air supply, exhaust and emissions
     - i. Air pollution and engine combustion
     - ii. Reducing pollution
     - iii. Air supply system
     - iv. Exhaust systems
     - v. Catalyst systems
     - vi. Emission control systems
     - vii. Turbocharging and supercharging
   - e. Fuel systems
     - i. Introduction
     - ii. Petrol fuel injection systems
     - iii. Diesel fuel injection systems
     - iv. Alternative fuels
   - f. Ignition systems
     - i. Ignition overview
     - ii. Electronic ignition
     - iii. Distributorless ignition system (DIS)
     - iv. Coil on plug (COP) direct ignition system
     - v. Spark plugs
   - g. Hybrid cars
     - i. Safety
     - ii. Hybrids overview
3. Electrical systems
   - a. Electrical and electronic principles
     - i. Electrical fundamentals
     - ii. Electrical components and circuits
     - iii. Electronic components
   - b. Engine electrical
     - i. Batteries
     - ii. Starting system
     - iii. Charging system
   - c. Lighting and indicators
     - i. Lighting systems
     - ii. Stoplights and reverse lights
     - iii. Interior lighting
     - iv. Lighting circuits
     - v. Indicators and hazard lights
   - d. Body electrical and electronic systems
     - i. Washers and wipers
     - ii. Horns
     - iii. Obstacle avoidance
     - iv. Cruise control
     - v. Seats, mirrors, sunroofs, locking and windows
     - vi. Screen heating
     - vii. Security systems
     - viii. Safety systems
   - e. Monitoring and instrumentation
     - i. Sensors
     - ii. Gauges
     - iii. Global positioning system (GPS)

(*Continued*)

Table 6.1 (Continued)

- f. Air conditioning
  - i. Air conditioning fundamentals
  - ii. Air conditioning components
- 4. Chassis systems
  - a. Suspension
    - i. Overview of suspension
    - ii. Dampers/shock absorbers
    - iii. Suspension layouts
    - iv. Active suspension
  - b. Steering
    - i. Introduction to steering
    - ii. Steering racks and boxes
    - iii. Steering geometry
    - iv. Power steering
  - c. Brakes
    - i. Disc, drum and parking brakes
    - ii. Hydraulic components
    - iii. Brake servo operation
    - iv. Braking force control
    - v. Anti-lock brake systems
    - vi. Traction control
  - d. Wheels and tyres
    - i. Wheels
    - ii. Tyres
- 5. Transmission systems
  - a. Manual transmission clutch
    - i. Clutch operation
    - ii. Types of clutch
  - b. Manual transmission gearbox
    - i. Gearbox operation
    - ii. Gear change mechanisms
    - iii. Gears and components
  - c. Automatic transmission
    - i. Torque converter
    - ii. Automatic transmission components
    - iii. Constantly variable transmission
    - iv. Direct shift gearbox
  - d. Transmission driveline
    - i. Propshafts and driveshafts
    - ii. Wheel bearings
    - iii. Four-wheel drive
  - e. Final drive and differential
    - i. Final drive
    - ii. Differential

6.3 Tips to help you learn

A good way to learn is to compare one method of doing something with another. For example:

- What are the differences between materials used for F1 and standard road car components?
- How does the operation of an F1 component or system differ from the one used on a road car?

Another good way to learn is to consider the advantages and disadvantages of things. For example:

- What are the advantages and disadvantages of a hybrid vehicle?
- What are the advantages of fuel injection compared to a carburettor?

Also, consider reasons why things have changed and developed in the way they have.

- Why is front-wheel drive now very common on many cars?
- Why did disc brakes replace drum brakes?

Even thinking of these types of questions is a good way to learn, so I will leave the rest to you!

6.4 Practical work

6.4.1 Jobcard, jobsheet, repair order

Figure 6.4 shows an example of a jobcard, jobsheet, repair order (call it what you like!). You can download a copy as a spreadsheet from the website if you wish. One useful aspect in the section for 'Services Requested and Description of Work' is the three-stage cause–concern–correction process (the three C's). This is a good way to think about any practical work, particularly when diagnosing faults. More on this in the Diagnostics book of course, but thinking logically through the problem, i.e. what is it, what caused it and how can it be fixed, is a good way to work. Use this or a similar sheet when you carry out practical tasks.

6.4.2 Practical task list

Remember, before starting any practical work you should have been trained or be supervised. In addition, there are some key things you should always do:

- Fit a vehicle body protection kit.
- Prepare your standard tool kit.
- Get the latest information and/or service manual.
- Comply with personal and environmental safety practices associated with clothing; eye protection; hand tools; power equipment; proper ventilation; and the handling, storage, and disposal of chemicals/materials in accordance with all appropriate safety and environmental regulations.

Table 6.2 gives a list of practical tasks you could carry out.

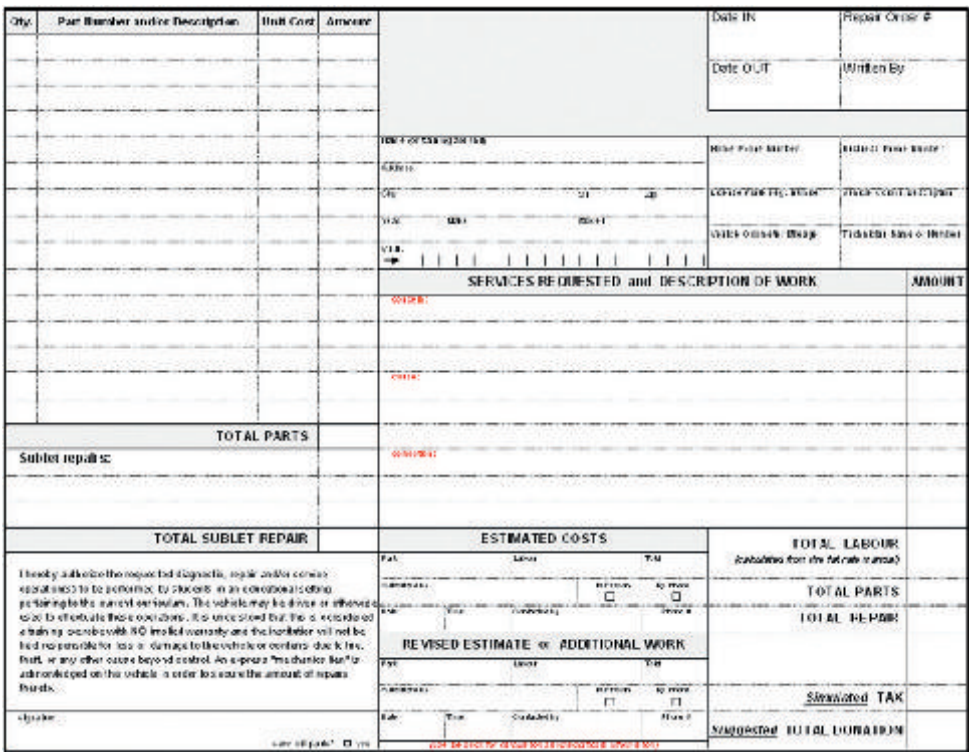

Figure 6.4 Jobcard, jobsheet, repair order

Figure 6.5 Fitting new brake pads. (Source: Bosch Media)

Table 6.2 Practical tasks

1. Engines
   a. Engine mechanical
      i. Adjust valve clearances
      ii. Inspect and replace timing belt
      iii. Carry out exhaust gas analysis using an exhaust gas analyser
      iv. Inspect camshaft and adjust tappets with shims
      v. Inspect chain drive mechanisms
      vi. Remove and reinstall engine
      vii. Inspect and replace sump, covers, gaskets and seals
      viii. Remove and replace pistons and connecting rods; strip and reassemble
      ix. Remove and replace cylinder heads
      x. Remove and replace chain-driven camshaft drives
      xi. Inspect crankshaft condition, journal and bearing dimensions and wear
      xii. Inspect pistons, piston rings and connecting rods and bearings
      xiii. Inspect camshaft and bearings (OHC) and checks on valve timing
      xiv. Perform cylinder power balance tests; determine necessary action
      xv. Perform cylinder compression tests; determine necessary action
      xvi. Perform cylinder leakage tests; determine necessary action
      xvii. Perform engine vacuum tests; determine necessary action
   b. Lubrication
      i. Remove and replace oil pumps and drive mechanisms
      ii. Remove and replace oil filters, oil coolers and turbo chargers
      iii. Carry out oil pressure tests
      iv. Remove and replace oil pressure switch and oil pressure gauge sender units
      v. Inspect oil galleries and drillings in engine components
      vi. Inspect oil sealing devices, gaskets, seals, etc.
      vii. Inspect oil pumps and lubrication components
   c. Cooling
      i. Drain and top up coolant
      ii. Inspect water pump
      iii. Inspect drive belt condition and tension
      iv. Remove and replace drive belts and pulleys
      v. Remove and replace thermostat
      vi. Inspect cooling system, pressure test, check coolant condition and antifreeze
      vii. Remove and replace radiator and electric fan motor and switches
      viii. Remove and replace water pump and engine driven fan
      ix. Remove and replace hoses including radiator, heater and bypass hoses
      x. Drain and top up coolant for winter usage or replace coolant

(*Continued*)

Table 6.2 (Continued)

d. Ignition
   i. Check ignition system components using scanner
   ii. Carry out oscilloscope/engine analyser diagnostic test procedure
   iii. Carry out manifold absolute pressure tests
   iv. Inspect, clean or renew and gap spark plugs
   v. Remove and replace coil, primary and secondary circuit components
   vi. Inspect electronic system primary and secondary circuit components and adjust timing

e. Fuel
   i. Replace and or clean fuel filters
   ii. Remove and replace fuel tanks, evaporative emission control system and fuel lines
   iii. Remove and replace injection components
   iv. Remove and replace fuel injection air supply components
   v. Check fuel system components using digital multimeter and/or oscilloscope
   vi. Inspect electronic injection components
   vii. Inspect fuel system for leaks and condition of pipes and hoses, etc.
   viii. Inspect fuel tanks, evaporative emission control system, and fuel lines
   ix. Carry out vacuum (manifold absolute pressure, MAP) tests
   x. Check fuel system components using fault code readout or scan tool

f. Air supply and exhaust
   i. Remove and replace all parts of catalyst exhaust system
   ii. Inspect turbocharger/supercharger and adjust boost pressure
   iii. Inspect exhaust system including lambda/HEGO sensor/catalytic converter
   iv. Inspect air supply system for leaks and check operation
   v. Check operation of crankcase ventilation (PCV) system
   vi. Remove and replace turbocharger (adjust boost pressure) and intercooler
   vii. Remove and replace EVAP components
   viii. Remove and replace EGR (exhaust gas recirculation) components
   ix. Check operation of EGR (exhaust gas recirculation)
   x. Check operation of catalyst and lambda/HEGO sensor
   xi. Check operation of EVAP (evaporative canister)
   xii. Check emission system components using scanner

2. Electrical

a. Engine electrical
   i. Remove and replace battery, battery cables and securing devices
   ii. Inspect batteries for condition, security and state of charge
   iii. Remove and replace drive belts and pulleys
   iv. Remove and replace alternator
   v. Remove and replace starter motor circuit cables/components
   vi. Remove and replace alternator circuit cables/components
   vii. Carry out alternator and circuit tests for correct charge rates
   viii. Remove and replace pre-engaged starter motor and replace solenoid
   ix. Carry out starter motor and circuit tests

b. Lighting
   i. Check all vehicle lights for correct operation condition and security
   ii. Remove and replace headlight unit
   iii. Check and adjust headlight alignment (beam setting)
   iv. Check stop light operation and adjust switch position
   v. Remove and refit flasher unit

c. Body electrical
   i. Service/check seatbelt operation
   ii. Remove and refit windscreen wiper motor
   iii. Check central door locking and alarm operation
   iv. Check electric window operation and reset position memory
   v. Inspect and measure electric screen heaters
   vi. Remove and refit central door locking actuator

(*Continued*)

Table 6.2 (Continued)

- d. Instruments
  - i. Checking operation of the main instruments and warning lights
  - ii. Remove and refit fuel tank sender unit
  - iii. Remove and refit speedometer cable
  - iv. Check temperature and fuel sender resistances
  - v. Remove and refit temperature sensor
- e. Heating and air conditioning
  - i. Check operation of heating and ventilation system
  - ii. Remove and replace heater unit, strip and rebuild
  - iii. Check operation of air conditioning system
  - iv. Remove and refit air conditioning components
  - v. Check air conditioning system for leaks

3. Chassis
   - a. Suspension
     - i. Remove and refit front suspension strut and spring
     - ii. Remove and refit rear suspension spring
     - iii. Remove, inspect and replace stabilizer bar, bushings, brackets and links
     - iv. Remove, inspect and replace leaf spring, bushes and mountings
     - v. Remove, inspect and replace suspension arm, bushings and ball joint
     - vi. Remove, inspect and replace rear MacPherson strut and spring
     - vii. Check suspension and steering operation
     - viii. Inspect and measure damper/shock absorber operation
     - ix. Measure trim height
   - b. Steering
     - i. Remove, overhaul and refit steering rack
     - ii. Remove, inspect and refit PAS pump
     - iii. Check steering components
     - iv. Measure and adjust tracking (toe-in/toe-out), using optical gauges
     - v. Measure castor, camber and swivel axis/kingpin inclination
   - c. Brakes
     - i. Remove and replace disc brakes and drum brakes
     - ii. Remove, overhaul and refit brake calliper
     - iii. Remove, overhaul and refit brake wheel cylinder
     - iv. Remove and replace brake lines
     - v. Remove and refit brake master cylinder
     - vi. Check vacuum servo unit operation
     - vii. Inspect and measure brake disc thickness and run out
     - viii. Inspect antilock brake system and measure wheel sensors
     - ix. Check anti-lock braking system (ABS) operation
   - d. Wheels and tyres
     - i. Check wheels and tyres for signs of damage and set tyre pressures
     - ii. Measure tyre tread and report on condition
     - iii. Change a tyre
4. Transmission
   - a. Clutch
     - i. Check and adjust clutch freeplay
     - ii. Replace clutch assembly
   - b. Manual gearbox
     - i. Check transmission operation
     - ii. Check gear change operation and adjust linkage
     - iii. Remove and refit gear change mechanism
     - iv. Remove and refit transmission gearbox
     - v. Inspect and measure gearbox components
   - c. Automatic transmission
     - i. Service/adjust throttle valve/kick down cable and manual shift linkages
     - ii. Remove and refit automatic transmission
     - iii. Check/inspect automatic transmission and torque converter
   - d. Driveline
     - i. Check driveline components
     - ii. Measure propshaft/driveshaft run out
     - iii. Remove and replace propshaft and replace universal joint (UJ) and centre bearing
     - iv. Remove and refit wheel bearings
     - v. Remove and refit driveshaft
     - vi. Strip down constant velocity (CV) joint and assess condition
   - e. Final drive
     - i. Remove and refit final drive and differential (FWD & RWD)
     - ii. Inspect and measure differential bevel gears

6.5 Summary

Well, that's it! If you have arrived here, having read all the book, done all the assignments, completed all the practical tasks, used the website: www.automotive-technology.co.uk resources and can remember everything, then well done.

Or did you just start reading the book from the back?!

Index

3D *see* three-dimensional drawings
4WD *see* four-wheel drive
12V batteries: hybrid cars, 253

A

A-bracket suspension, 363
ABS *see* anti-lock brake systems
absolute pressure, 39–40
absorption silencers, 177, 178
acceleration, 39, 196
accident safety, 29
accumulators, 228, 230, 398, 399
ACEA *see* Association des Constructeurs Européens d'Automobiles
Ackermann steering methods, 366, 367, 368, 369, 376
active safety features: definition, 322
active suspension, 364–6
actuators, 185
adaptive cruise control systems, 311–12
additives (viscosity), 148
adhesives, 65–6
advance angle ignition timing, 238–9
advanced ignition, 94–5
Advanced Telemetry Linked Acquisition System (ATLAS), 344
Ah *see* ampere-hour battery ratings
air bag units, 322–5
air conditioning, 337–42
air-coolants, 151, 152
air-cored gauges, 330–1
air filters, 173, 174
air flow controls, 167
air flow meters, 173, 174, 203–4
air-intake ducts, 166
air (mixture strengths), 93–4
air pollution, 168–9
air pump devices, 86
  see also turbocharging
air springs *see* pneumatic springs
air supply systems, 172–6, 207–8
air temperature control valves, 170, 171
air temperature sensors, 205
airtight synthetic rubber tyres, 416
alarms:
  see also security systems
alloy wheels, 410, 411
all-wheel drive (AWD), 477, 478
alternating current (a.c.), 275
alternative fuels, 231–6
  biodiesel, 232–3
  ethanol, 231–2, 236
  hydrogen, 235–6
  liquefied petroleum gas, 234–5
  natural gas, 233, 234
alternators, 7, 287–93
aluminium:
  blocks and liners, 111
  cylinder heads, 123, 127
  radiators, 161–2
American fire extinguishers, 31, 32
American Petroleum Institute (API), 149
ampere-hour (Ah) battery ratings, 278, 280, 281
analogy definition, 447
antifreeze coolants, 151, 152
anti-lock brake systems (ABS), 401–6, 407, 408
anti-roll bars, 355–6
anti-slip regulation (ASR) *see* traction control systems
API *see* American Petroleum Institute
arc welding, 67
areas, 45
armatures, 284, 306
ASCC *see* Australian Safety and Compensation Council
aspiration, 91
  see also naturally aspirated engines
ASR *see* traction control systems
assignments, 490–3
Association des Constructeurs Européens d'Automobiles (ACEA), 150
ATLAS *see* Advanced Telemetry Linked Acquisition System
atmospheric pressure, 90
atoms, basic representation, 259
audible warning devices *see* horns
audits: health and safety, 22
Australian fire extinguishers, 31
Australian Safety and Compensation Council (ASCC), 19
automatic transmission, 311, 445–66, 467
  components, 451–9, 460
  constantly variable transmission, 459–61, 462
  direct shift gearboxes, 461–6, 467
auxiliary air valves, 207–8
AWD *see* all-wheel drive
axial displacement, 122
axial-piston pumps, 222
axles, 48, 55, 362, 363

B

baffle silencers, 177, 178
ball joints, 370, 371
ball and spring detent gearbox mechanisms, 439
ball wheel bearings, 472, 473, 474, 475
bath lubrication, 140
batteries, 250–3, 267, 275–82
BDC *see* bottom dead centre
beads (tyres), 416
beam axle suspension, 354, 355
beam setters, 297
bearings, 112, 113, 119
  crankshafts, 120–3
  Formula 1 engine technology, 256–7
  lubrication, 139
  transmission systems, 471

belts, 135, 136, 324, 326
bench battery chargers, 278, 279, 280, 281
bevel gears, 480, 481
bi-fuel vehicles, 233, 234
big end bearing caps, 119, 120, 121, 139
biodegradable oils, 138–9
biodiesel, 232–3
blade fuses, 265, 266
block diagrams, 46
blocks (engines), 109–14, 154
body design, 3, 4–5
body electrical and electronic systems, 305–25, 326
  cruise control, 310–12
  horns, 308–9
  locking, 312, 316–17
  mirrors, 312, 314, 315
  obstacle avoidance, 309–10
  safety systems, 322–5, 326
  screen heating, 318–19, 320
  seats, 312–14
  security systems, 320–1, 322
  sunroofs, 312, 314, 315, 316
  washers, 305–8
  windows, 312, 317–18, 319
  wipers, 305–8
body panels, 3, 5, 6
bodywork protection, 72, 73
bolts, 63–5
booking systems, 12
boost control systems, 185, 186
boosters *see* servo units
bore diameters, 100
Bosch injection systems, 221, 227
  see also diesel fuel injection...; gasoline direct injection
bottom dead centre (BDC), 81, 84
bottoming taps, 61
bounce-back window features, 317, 318
boundary lubrication, 139
brake fade, 390
brake horsepower, 101
brake lights *see* stoplights
brake systems, 386–409
  anti-lock systems, 401–6, 407, 408
  disc brakes, 386–94
  drum brakes, 386–94
  fluid, 395–6
  force control, 400–1
  Formula 1 technology, 422–3
  hydraulic components, 394–8
  pads, 328, 329, 387–8, 423
  parking brakes, 386–94
  servo operation, 398–400
  shoes, 388, 390–3, 395
  switches, 311
  traction control, 407–9
  vehicle categories, 7
brazing, 66–7
breaker systems, 240
bridge rectifiers, 291
bulbs:
  conventional circuits, 267, 268, 270
  headlights, 293, 295
  indicators, 301
  rear lights, 301–2
  selection, 293, 294
  stoplights, 301–2
bump stops, 354
bypass filtration systems, 145

C

cable-driven speedometers, 331–2
cables (electrical circuits), 267, 268
cable shift gearbox mechanisms, 437, 439
cadence braking, 402
calcium (coolants), 152
callipers, 395, 396, 423
  see also sliding disc brake callipers
cam belts, 163
camber definition, 378
cam covers, 135–6
camshafts, 130–7, 203
CAN *see* controller area networks
capacitors, 273
carbon/carbon dioxide pollution, 168, 169
carbon dioxide extinguishers, 31, 32
carburettors, 189, 191, 192–4, 195–6
car lifts, 55
cast iron:
  blocks and liners, 109–11
  compression rings, 116
  cylinder heads, 123, 124
  definition, 110
  exhaust manifolds, 49, 50
  oil control rings, 116
castor angles, 380, 381
Castrol Magnatec multigrade engine oil, 148
catalyst systems, 179–81
catalytic converters:
  diesel fuel injection systems, 221
  exhaust systems, 177, 178, 179
  gasoline direct injection, 216–17
  pollution reduction, 170, 171
CCA *see* cold cranking amps ratings
cell plate construction, 276
central door locking systems, 321
central point injection (CPI) systems, 194, 197
  see also throttle body injection systems
central processing units (CPU), 199, 200, 201–2
centre of gravity/mass, 40, 41
centrifugal force, 382
CFC *see* chlorofluorocarbon based refrigerants
chalk, 152
charcoal canisters, 182, 183, 184
charcoal filters, 169, 171, 172
charging systems, 287–93
  see also batteries
chasing (thread cutting), 60–1
chassis systems, 347–423
  brakes, 386–409
  Formula 1 technology, 422–3
  steering, 366–86
  suspension, 347–66
  tyres, 409, 416–22
  vehicle categories, 3, 5, 6, 7
  wheels, 409–15
check valves, 400

chlorofluorocarbon (CFC) based refrigerants, 338
choke *see* venturi carburettor types
CI *see* compression ignition
circuits, 260, 261, 264–73
  fuel gauges, 330, 331
  interior lights, 299
  lighting circuits, 299–301
  reverse lights, 298
  seat adjustments, 312–13
  stoplights, 298
  sunroofs, 314, 316
  symbols, 267–8, 269
  temperature gauges, 330, 331
  windows, 318, 319
  wipers, 307–8
clamp fittings, 178, 179
clean combustion *see* complete combustion
cleaning materials, 33, 34
clearance volumes, 100
clear lens headlights, 296–7
closed loop control systems, 310
clutch systems, 285, 425–33, 463, 484–7
CNG *see* compressed natural gas
coded key security systems, 321, 322
coil leads, 245, 246
coil on plug (COP) direct ignition systems, 246–7
coils, 238, 240
coil springs, 348–9, 433
cold cranking amps (CCA) ratings, 278
cold shrinking, 68
cold-start devices, 219
cold starting carburation stages, 195
combustion:
  air pollution, 168–9
  compression ignition, 96–7, 98, 99
  cooling systems, 155
  cylinder heads, 124, 125, 126, 127
  diesel fuel injection systems, 222, 227–8
  fire safety, 30
  four-stroke engines, 81, 82, 84–5
  fuel systems, 190–1, 218–20
  ignition systems, 236, 237, 247–8
  pistons and connecting rods, 115–16, 118
  reaction, 91
  rotary engine, 87, 88
  spark ignition, 92–5
  see also power stroke
commercial API classes, 149
common multipliers, 38
common rail injection, 220, 227–30, 231
commutators, 284
complete combustion, 169, 190
complex reflectors, 296–7
composite materials, 123
compound valve hemispherical (CVH) arrangements, 126, 127
compressed natural gas (CNG), 233
compression fittings, 68
compression ignition (CI), 95–9, 101, 102, 217
compression ratios, 91–2, 100
compression rings, 115–16
compression stroke, 81–8
compressors, 186–7, 338–9, 340
computerized workshop systems, 15–18
concave reflectors, 295
Concept cars, 4
condensers, 339, 340, 341
conduction, 44, 153
conductors, 262–3, 284
cone-shaped diaphragm springs, 432
connecting rods, 114–20, 139–42, 256–7
connectors (electrical circuits), 266, 267
constant dwell electronic ignition systems, 241–2
constant energy electronic ignition systems, 242–3, 244
constantly variable transmission (CVT), 459–61, 462
constant mesh gearboxes, 436, 441–2
constant velocity (CV) joints, 471–2
contact areas (tyres), 418, 419
contact breaker systems, 240
contracts, 14
controller area networks (CAN), 272–3
Control of Substances Hazardous to Health (COSHH), 22
convection, 44, 153
Convertibles, 4
coolant passages, 126, 127
coolants *see* engine cooling
coolant thermistors, 206
cooling system hoses, 166
COP *see* coil on plug direct ignition systems
copper (electrical circuits), 267
core plugs, 112, 113, 154
cornering speeds, 382
corrosion, 50–1, 266–7
COSHH *see* Control of Substances Hazardous to Health
cost estimations, 13
Cosworth Formula 1 engines, 255, 257
countershafts, 441, 442
Coupé, 4
covers (camshafts), 135–6, 137
CPI *see* central point injection systems
CPS *see* crankshaft position sensors
CPU *see* central processing units
cranes, 27, 28
crankcase ventilation systems, 169, 171, 172, 181, 182
crankshaft position sensors (CPS), 244–5, 246
crankshafts, 84–5, 120–2, 123
crescent oil pumps, 145, 146
cross-flow ports, 125
cross-flow radiators, 160, 161
cross-ply tyres, 416, 417, 418
cross-type joints, 467, 470
crown construction (tyres), 418, 419
crown thickness (tyres), 418
crown wheel gear and pinion systems, 481, 482
cruise control, 310–12
cruising carburation stages, 196
cube relays, 265
current:
  charging systems, 288–90
  chemical changes, 276, 277
  circuits, 268, 271
  definition, 260
cutting (workshop skills), 59–62
CVH *see* compound valve hemispherical arrangements
CVT *see* constantly variable transmission
cylinder coatings, 112

cylinder heads, 69, 123–8, 155
cylinder layouts, 101, 103

D

dampers, 348, 353, 354, 356–9
damping clutch springs, 430–1
data bus systems, 271–3
dead-reckoning, 336
deceleration-sensing brake pressure reducers, 400–1
delay phases, 98, 99, 219
delta (Δ) stator windings, 290
density, 43, 44
derived SI units, 37, 38
desiccants, 339
detent gearbox mechanisms, 439
diagonal split brake systems, 397, 398
diaphragm springs, 432
diesel engine, 81, 82
  direct injection, 96, 97, 98, 221–4, 227
  fuel systems, 189, 190, 191, 217–30, 231
  lubrication, 149, 150
  two-stroke, 86
  see also compression ignition
diesel fuel injection systems, 217–30, 231
dies and taps, 60–2
differential transmission systems, 7, 464, 466, 480, 482–5, 487
digital multimeters (DMM), 52, 54
diodes, 273, 274, 290–3
dipsticks, 143
direct acting motors, 385, 386
direct current (d.c.), 275, 284
direct drive gears, 435, 436
direct ignition systems, 246–7
direct injection (DI), 96–8, 217–18, 221–4, 227
  see also diesel fuel injection systems gasoline direct injection
direction indicators *see* indicators
direct shift gearboxes (DSG), 461–6, 467
disc brakes, 7, 386–94, 423
discharged battery cell states, 276, 277–8
DIS (distributorless ignition systems), 237, 244–6
distributorless ignition systems (DIS), 237, 244–6
distributors (ignition systems), 241
divided rims, 410, 412
DMM *see* digital multimeters
DOHC *see* double overhead camshafts
double-acting brake shoes, 395
double-acting master cylinder pistons, 396–7
double offset constant velocity joints, 472
double overhead camshafts (DOHC), 131
doughnut joints, 467, 470
drawings, 46–7
drier systems *see* receiver/drier systems
drillings, 59, 140, 141, 142
drive-by-wire systems, 311
drive chains, 135, 136
drive gears, 135, 136
driven plates, 428, 429, 430
driveshafts, 467–72
drum brakes, 386–94
dry liners, 110, 111
dry sump filter systems, 145
DSG *see* direct shift gearboxes
dual-fuel vehicles, 233, 234
dual-intake systems, 176
dual-mass flywheels, 122, 123
dwell electronic ignition systems, 241–2
dwell maps, 199, 200
dwells definition, 242

E

E85 vehicles, 231, 232, 236
early ignition, 94–5
ECAT *see* electronically controlled automatic transmission
ECM *see* electronic control modules
ECU *see* electronic control units
EDC *see* electronic diesel control
EFi *see* electronic fuel injection systems
EGO *see* exhaust gas oxygen sensors
EGR *see* exhaust gas recirculation systems
EHB *see* electrohydraulic brake systems
electrical systems, 259–345
  air conditioning, 337–42
  body systems, 305–25, 326
  cooling systems, 158, 159
  engine electrical, 275–93
  Formula 1 technology, 342–5
  indicators, 293, 301–5
  lighting, 293–301
  monitoring and instrumentation, 326–36, 337
  power steering, 385–6
  principles, 259–75
  vehicle categories, 7
electrohydraulic brake (EHB) systems, 406, 407, 408
electrohydraulic variable cam control methods, 134
electronically controlled automatic transmission (ECAT), 455–6, 458–9
electronic control modules (ECM) *see* electronic control units
electronic control units (ECUs), 273, 274
  active suspension, 365–6
  automatic transmission, 456, 458–9, 464, 466
  brake systems, 402, 403–5
  data bus systems, 272
  diesel fuel injection systems, 224–5, 226
  gasoline direct injection, 215, 216
  petrol fuel injection, 198, 199, 200, 201–8
  safety systems, 324, 325
  windows, 317–18
electronic diesel control (EDC), 223–5, 228–31, 242
electronic fuel injection (EFi) systems, 194, 197, 198–207
electronic ignition systems, 237, 241–3, 244
electronic spark advance (ESA) ignition systems, 244–5, 246
electronic stability programs (ESP), 406, 407, 408
electrons, 259, 260
emission control systems, 181–4
energy, 40–2
  see also temperature
engine blocks, 109–14, 154
engine breathing, 91
engine capacity, 100
engine cranes, 27, 28
engine electrical, 275–93
  batteries, 275–82
  charging systems, 287–93
  starting systems, 282–7, 288
engine mechanical, 81–137
  components, 109–37
  operating cycles, 81–90
  operating details, 90–108, 109

engines vehicle categories, 6–7
engine systems, 81–258
  air supplies/emissions/exhaust, 168–88
  cooling, 151–67
  design, 102, 103–8, 109
  engine mechanical, 81–137
  Formula 1 engine technology, 255–8
  fuel systems, 189–236
  hybrid cars, 250–5
  ignition systems, 236–49
  liners, 109–14
  lubrication, 137–50
  terminology and methods, 100–2, 103
environmental protection, 33–4, 35
epitrochoid definition, 87
equipment *see* tools
ESA *see* electronic spark advance ignition systems
Escape hybrid E85 vehicles, 236
ESP *see* electronic stability programs
Estate cars, 4
ethanol, 231–2, 236
evaporative emission control systems (EVAP), 171, 172, 182–4
evaporators, 341–2
exhaust extraction, 20, 23, 255, 257
exhaust gas oxygen (EGO) sensors, 181
  see also lambda sensors
exhaust gas recirculation (EGR) systems, 98–9, 184–6, 206–7, 221
exhaust joints, 50–1
exhaust manifolds, 49, 50, 175
exhaust stroke, 81, 83–8
exhaust systems, 176–8, 179
exhaust turbocharging, 185
exhaust valves, 128
expansion boxes, 177, 178
expansion processes, 86, 87
expansion stroke, 86–7
expansion valves, 341, 342
eye protection, 19, 23

F

fans, 164, 165, 167
fan wheels, 186–7
fast charge of batteries, 278–82
fastening *see* joining
FFVs *see* flexible fuel vehicles
FIA technical regulations, 258, 344–5, 423, 487
filament bulbs, 301–2
filing, 58, 59
filters:
  air pollution, 169, 170, 171, 172
  air supply systems, 173, 174
  cooling systems, 166
  diesel fuel injection systems, 222
  lubrication, 143–5
  petrol fuel injection, 209
  pollution reduction, 171, 172
final drive assemblies, 7, 464, 466, 480–2
fingers (clutch systems), 432–3
fire, 29–31, 32, 33
first control cycle smoothing, 405–6
fitting, 57–8
five-cylinder engines, 105, 106
fixed callipers, 395
fixed orifice control valves, 341
fixed value memory *see* read only memory
fixed venturi carburettor types, 191, 192
fixings (wheels), 412, 413
flange connections, 177, 178
flasher units, 302, 303
flat engines, 106, 107
flat post battery terminals, 280, 281
flex-fuel, 231, 232
flexible brake pipes, 389
flexible clutch discs, 430–1
flexible fuel vehicles (FFVs), 231, 232
flexible mountings, 178, 179
float chambers, 193–4
floating callipers, 395, 396
float and needle valves, 193
fluid flywheels, 446–8, 450
fluid level sensors, 328
fluid reservoirs, 394–5
flywheels, 101, 122, 123, 446–8, 450
force, 42, 43
force control (brake systems), 400–1
force-feed lubrication, 140
Ford Focus engines, 6–7
Ford main dealerships, 9
Ford starter systems, 287, 288
Ford steering systems, 369
Formula 1 technology, 255–8
  brake systems, 422–3
  chassis systems, 422–3
  electrical systems, 342–5
  engine systems, 255–8
  gearboxes, 486, 487
  transmission systems, 485–7
four-cylinder engines, 104, 105, 107, 120–1, 227
four-stroke engines, 81–5, 150
four-strokes: engines,
  see also Formula 1 engine technology
four stud wheel fixings, 412, 413
four-wheel drive (4WD), 2, 466, 467, 477–80
fractions, 44–5
franchised dealers, 12
friction, 39, 137–9
frontal impact, 323–4
front-engines:
  front-wheel drives, 1, 2
  rear-drive mounts, 88, 89
  rear-wheel drives, 1
front lights, 293, 294
front/rear split brake systems, 397, 398
front screen heater elements, 319, 320
front-wheel drives:
  engine mounts, 88, 89, 90
  gearboxes, 434, 435, 437, 441–2
  hub and bearing arrangements, 476
fuel systems, 189–236
  alternative fuels, 231–6
  diesel injection systems, 217–30, 231
  droplet size, 214
  electronic injection systems, 199, 200
  evaporative emission control, 182, 183, 184
  gauge circuits, 330, 331
  injection block diagrams, 46
  level sensors, 327, 328

fuel systems (*Continued*)
metering, 81
mixture strengths, 93–4
petrol injection, 194, 197–217
pressure regulators, 210, 211
supplies, 208–11, 212
tank caps, 182, 183
full-flow filter systems, 144
full load carburation stages, 196
fully floating wheel bearings, 473–4
fuses, 265–6, 299, 300, 301

G

garage and car sales businesses, 9
gaskets, 69–70, 123, 124
see also cylinder heads
gasoline *see* petrol
gasoline direct injection (GDi), 197–8, 212–17, 233–4
gas-shielded arc welding, 67
gas welding, 67
gate gear locks, 440
gauges, 329–32, 333
GDi *see* gasoline direct injection
GDS workshop manager *see* workshop systems
gearboxes:
change mechanisms, 437–40
clutch systems, 429
components, 441–5
compression fittings, 68
cruise control systems, 311
direct shift, 461–6, 467
Formula 1 technology, 486, 487
operation, 434–7
switches, 311
vehicle categories, 7
gear oil pumps, 145, 146, 147
gears, 48–9, 286, 434, 480, 481, 483
Ravigneaux planetary, 451–2, 454
worm and steering, 373, 374
GEM *see* general electronic modules
general electronic modules (GEM), 308
generators (reversibility), 260, 261
gerotor oil pumps, 145, 146, 147
global positioning systems (GPS), 332–6, 337
gloves, 19, 23
glow plugs, 219
GPS *see* global positioning systems
gravity *see* centre of gravity
gudgeon pins, 114, 116–18

H

hacksaws, 59–60
Hall effect generators, 202, 203, 242–3
halogen bulbs, 293, 295, 296
handbrake levers, 393–4
hand tools, 51–2, 53
hardened seats, 126, 127
hard water, 152
HASAW *see* Health and Safety at Work etc. Act 1974
Hatchbacks, 4
hazard lights, 301–5
hazards, 24–5, 26, 27
hazard signs, 33, 34
headlights, 293, 295, 296–7
headway sensors, 311–12
health and safety *see* safety
Health and Safety at Work etc. Act 1974 (HASAW), 22
Health and Safety Executive (HSE), 19, 20–1, 22, 23
Health and Safety Information for Employees Regulations (HSIER), 19, 20, 21
heat, 44, 153, 249
see also temperature
heated exhaust gas oxygen (HEGO) sensors, 181
heater matrix, 161–2
heaters, 166–7
heating effect, 260
heat shields, 178, 179
heavy-duty discharged batteries, 277–8
heavy-duty starter motors, 286
HEGO *see* heated exhaust gas oxygen sensors
helical gears, 434
helical springs *see* coil springs
hemispherical roof combustion chamber design, 126
hertz (Hz), 309
HFC *see* hydrofluorocarbon based refrigerants
high-performance spark plugs, 248–9
high-pressure accumulators, 230
high-pressure components, 222, 229
high-pressure fuel systems, 224
high-pressure refrigerants, 338
high-pressure solenoid valves, 224–5
high-voltage battery power switches, 252
high-voltage cables, 253, 254
high-voltage components, 250, 251
high voltage generation, 238
high-voltage magneto ignition systems, 239
Highway Code, 73
homogeneous definition, 215
Honda battery packs, 250, 251
honeycombs of tyres, 417
honeycomb substrates, 180
Hooke-type joints, 467, 469
horizontally opposed cylinders, 104, 106
horns, 308–9
hoses, 166
hot shrinking, 68
HSE *see* Health and Safety Executive
HSIER *see* Health and Safety Information for Employees Regulations
hybrid cars, 236, 250–5, 256, 257
hydragas suspension, 352–3
hydraulic accumulators, 398, 399
hydraulic brake components, 394–8
hydraulic clutch mechanisms, 426–7
hydraulic dampers, 356–7
hydraulic lifters, 132, 133
hydraulic modulators, 404, 405
hydraulic power-assisted steering, 383–5
hydraulic power brakes, 398
hydraulics, 49
hydraulic tappets and components, 132
hydrocarbons, 169
hydrodynamic lubrication, 139
hydrofluorocarbon (HFC) based refrigerants, 337–8
hydrogen:
air pollution, 169
alternative fuels, 235–6
discharged battery cell states, 276, 277

hydrometers, 43, 44, 277, 278, 279
hygroscopic brake fluid, 395–6
hypoid final drive design, 481, 482
Hz *see* hertz

I

ICs *see* integrated circuits
ideal ignition, 94, 95
idle carburation stages, 195
IFS/IRS *see* independent front and rear suspension
ignition lag phases, 219
ignition maps, 199, 201
ignition systems, 236–49
  advance angle timing, 238–9
  coil on plug direct, 246–7
  distributorless, 244–6
  early circuit systems, 240
  electronic, 241–3, 244
  high voltage generation, 238
  overview, 236–41
  spark plugs, 247–9
  traditional types, 239–41
ILSAC *see* International Lubricant Standardization and Approval Committee
IMA *see* hybrid cars
impellers, 446–8
inclined plane effect, 380
incomplete combustion, 92–3, 169, 190, 220
independent front and rear suspension (IFS/IRS), 355
independent garage and car sales businesses, 9
indicator diagrams, 94, 95
indicators, 293, 301–5
indices, 45
indirect injection, 96, 97, 98, 221, 222
induction, 264
induction stroke, 81, 83–8
inductive effect generators, 202, 203
inductive pulse generators, 242, 243, 244
inductive sensors, 53, 55, 202, 245, 246
inductors, 273, 275
inertia motors, 282, 283
inertia starter systems, 285, 286
inertia switches, 229
inert substances, 169
inherent thermal damping, 329–30
initial delay phases, 219
injection:
  advance mechanisms, 226
  lag phases, 219
  wiring harnesses, 202
  see also diesel fuel injection systems gasoline fuel injection systems
injectors, 211, 219, 220, 226, 230, 231
inlet manifolds:
  air supply systems, 173–6
  camshafts, 132, 133, 134
  catalyst systems, 181
  cooling systems, 155, 156
  fuel systems, 192–3, 203, 204, 205
inlet valves, 128
in-line engines, 104–5, 107, 108
inner constant velocity joints, 471
inner tube functions (tyres), 416
input shafts, 429, 441, 463–4, 466
inspections *see* servicing
instrumentation systems, 326–36, 337
insulated conductors, 259
insulating gloves, 252, 253
intake stroke *see* induction stroke
integrated chassis, 5
integrated circuits (ICs), 275
integrated motor assist (IMA) hybrid vehicles *see* hybrid cars
integrated power units (IPU), 250, 251
intercoolers, 185
interior heaters, 166–7
interior lights, 299
intermediate transmission gears, 286
internal combustion engine, 81, 82
International Lubricant Standardization and Approval Committee (ILSAC), 149–50
invoicing, 14–15
iron exhaust manifolds, 49, 50

J

Jaguar, 333, 365
Japanese Automotive Standards Organization (JASO), 150
jobcards, 13–14, 494
joining, 62–7, 467, 470
  see also individual joints; welding
journals (bearings), 120–1

K

keep alive memory (KAM), 199, 201
kerbing, 410, 411
KERS (kinetic energy recovery systems), 255, 487
keyless starter systems, 287, 288
kick down facilities, 453
kinetic energy recovery systems (KERS), 255, 487
kingpins, 370, 371, 379, 380
knocking effect *see* pinking

L

labour charges, 14
ladder chassis, 5
lambda sensors, 170, 171, 201, 206
laminated definition, 349
large goods vehicles (LGV), 3
laser-beam welding, 67
latching relays, 315, 316
late ignition *see* retarded ignition
latent heat, 337, 338
lateral definition, 356
lathes, 57–8
layout circuits, 268, 270
layrub joints, 467, 469
layshafts, 441, 442
lazy locks, 318, 321
LCV *see* light commercial vehicles
lead-acid cell batteries, 275–6
lead (air pollution), 168
leading brake systems, 393, 394
leaf springs, 349–50, 360–1, 362
levers, 48
LGV *see* large goods vehicles
Lifting Operations and Lifting Equipment Regulations 1998 (LOLER), 22
lift motors, 318, 319
light commercial vehicles (LCV), 3

light emitting diodes (LEDs), 298, 301–2, 303, 385–6
lighting, 293–301
light vans, 5
light vehicles (LV), 3, 5
limited slip differential (LSD) transmission, 483–5
Lincoln five-speed gearboxes, 436
linear steering racks, 373–4, 375
line boring, 112
liners, 109–14
liquefied natural gas (LNG), 233
liquefied petroleum gas (LPG), 234–5
liquid coolants *see* water-coolants
little end bearing caps, 119
LNG (liquefied natural gas), 233
load-apportioning valves, 400
load indices, 420, 421
load moving, 25, 27, 28
locking, 312, 316–17
lock-up clutches, 450
Loctite products, 65, 70, 71
LOLER (Lifting Operations and Lifting Equipment Regulations 1998), 22
long inlet tracts, 176
longitudinal definition, 356
lost spark distributorless ignition systems, 244, 245
Lotus T127 Formula 1 cars, 486
low-pressure components, 222, 229
low-pressure fuel systems, 224
low-pressure refrigerants, 338
low pressure servo systems, 399
LPG *see* liquefied petroleum gas
LSD *see* limited slip differential transmission
lubrication, 137–50
  camshafts, 132
  filters, 143–5
  friction, 137–9
  methods, 140
  oil pumps, 145–7
  standards, 147–50
  system, 140–3
  thread cutting, 61
  turbochargers, 187
LV *see* light vehicles

M

machines, 48, 57–8
machining, 57–8
McLaren, 344, 489
MacPherson strut suspension, 354, 359, 360
MAF *see* mass air flow meters
magnetic field sensors, 336
magnetism, 260, 261, 263–4
magneto ignition systems, 239
main beam filaments, 296
maintenance-free batteries, 278, 279
mandatory signs, 33, 34
manifold absolute pressure (MAP), 203, 204, 205
manual brake adjustment, 392
manual transmission, 425–45
markings (tyres), 420
mass, 40, 41, 43, 347–8
mass air flow (MAF) meters, 204
master cylinder pistons, 388, 389, 394–9
MBT *see* minimum spark advance for best torque
mechanical fuel pumps, 191, 192
mechanical machines, 48
metal brake pipes, 389
metal inert gas (MIG) welding, 67
metals, 262, 267
metering devices, 81, 193–4
methane *see* natural gas
metric thread profiles, 64
MFi *see* multipoint fuel injection systems
micrometres (μm), 214
microporous paper elements, 173
microswitches, 316
mid-engine rear-wheel drives, 2, 3
MIG (metal inert gas welding), 67
minimum spark advance for best torque (MBT), 93
Ministry of Transport tests *see* MOT tests
mirrors, 312, 313, 314, 315
modern high-performance spark plugs, 248–9
modern ignition systems, 237–8
modulators, 403, 404, 405
motor brushes, 305–6
motor-driven fans, 164, 165
motor industry, 8–18
  booking systems, 12
  company structure, 10, 11–12
  company types, 9–11
  computerized workshop systems, 15–18
  cost estimations, 13
  franchised dealers, 12
  invoicing, 14–15
  jobcards, 13–14, 494
  parts department, 12–13
  phrases/words, 8
  reception systems, 12
  time estimations, 13
  warranties, 15
'motorists' discount' shops, 10
motor power connections, 250, 251
motor reverse circuits, 312–13
MOT tests, 14, 28, 73
mounting systems, 87–90, 178, 179, 471
mufflers, 177, 178
multicircuit brake systems, 397–8
multifunction switches, 264–5
multigrade engine oil, 148–9
multileaf springs, 349–50
multiple cylinder engines, 106–7
multiplex systems, 271–2
multipoint fuel injection (MFi) systems, 197, 211
multi-V belt configurations, 164
Mustang V-6 engine, 490

N

NASCAR flex-fuel, 231, 232
natural gas, 233, 234
naturally aspirated engines, 90, 192
  see also Formula 1 technology
needle motion sensors, 226
needle valves, 193
negative camber steering, 378
negative castor angles, 380, 381
negative scrub radii (steering), 379
negative temperature coefficients (NTC), 206, 327
neoprene, 70–1

nipped bearing caps, 122
nitrogen oxides (NOx):
  catalyst systems, 180
  compression ignition, 98, 99
  diesel fuel injection systems, 221
  gasoline direct injection, 216–17
  pollution, 169
  spark ignition, 93
noise vibration and harshness, 439
non-linear steering racks, 374–5
non-return valves, 400
NOx *see* nitrogen oxides
nozzle needles, 230
NTC *see* negative temperature coefficients
nuts, 63–5
nylon fan blades, 164, 165
nylon locks, 62, 64

O

OBD *see* on-board diagnostic plugs
obstacle avoidance, 309–10
Occupational Safety and Health Administration (OSHA), 19
octane ratings, 93
OHC *see* overhead camshafts
Ohm's law, 261, 262
OHV *see* overhead valves
oil control rings, 115–16
oil coolers, 142–3
oil lubrication circuits, 132
oil pressure sensors, 329
oil pumps, 145–7
oil seals, 70–1, 120, 121
oils as lubrication, 138, 140–5
oil temperature, 357
oil vapour, 169, 181
oilways, 113–14
on-board diagnostic (OBD) plugs, 207
one-piece track rods, 370
one-touch window modes, 317, 318
one-way clutches, 285
one-way valve diodes, 273, 274
open circuits, 268, 271
optical sensors, 385–6
orthographic drawings, 47
oscillation, 40, 41
oscilloscopes, 52–3, 54, 55
OSHA *see* Occupational Safety and Health Administration
Otto cycle *see* four-stroke engines
outer constant velocity joints, 471
output shafts, 464, 465, 466
overflow throttle valves, 224
overhead camshafts (OHC), 131
overhead valves (OHV), 124–6, 128, 130–1
overretarded ignition, 95
over-square engines, 256
oversteering definition, 383
oxidation catalytic converters, 221
oxygen, 30, 98, 99, 276, 277

P

pads *see* brake pads
Panhard rod suspension, 356, 363, 364
Pa (pascal) units *see* pressure
paper elements, 173
parallel ports, 125
parallel power systems, 253, 254
parking brakes, 386–94
particulates, 220
parts department (motor industry), 12–13
parts invoicing, 14
PAS *see* power steering
pascal (Pa) units *see* pressure
passenger-carrying vehicles (PCV), 3
passive anti-theft systems (PATS), 287, 288
passive safety features, 322, 323
PATS *see* passive anti-theft systems
PCM *see* powertrain control modules
PCR *see* pressure-conscious regulators
PCV *see* passenger-carrying vehicles
PCV systems *see* positive crankcase ventilation systems
PDI *see* predelivery inspections
pent roof combustion chamber design, 126
percentage examples, 44
permanent magnet starter motors, 286
personal protective equipment (PPE), 22, 23–4, 25
petroil mixtures, 138–9
petrol engine, 81, 82
  fuel systems, 189–91
  lubrication, 150
  see also spark ignition
petrol fuel injection systems, 194, 197–217
  air supplies, 207–8
  direct injection, 197, 212–17, 233–4
  electronic injection, 198–207
  fuel supplies, 208–11, 212
petrol octane ratings, 93
petrol tanks, 327, 328
petrol vapour, 182, 184
PFi *see* port fuel injection systems
pick-up pipes, 140, 141
pick-up trucks, 5
PicoScope, 52–3, 54, 55
pictorial drawings, 47
piezo injectors, 230, 231
pig noses *see* flexible mountings
pinion gears, 284, 285
pinion steering, 367
pinking (knocking), 94–5, 124, 125, 219
pistons, 96, 114–20
pivot studs, 132
planetary gear starter motors, 286
planet gears/shafts, 483
plastic inlet manifolds, 173–4, 175
plastic radiators, 161–2
plastic trims (wheels), 410, 411
plies (tyres), 416, 417, 418
plug gaps, 249
plug leads, 245, 246
plug taps, 61
plungers, 140, 141
plunger type gearbox interlocks, 440
pneumatic springs, 256, 351, 352
polarity (battery charging), 281
pollen filters, 166
pollution, 168–72
polymer additives, 148
polyvinyl chloride (PVC), 267
Pontiac six-speed gearboxes, 435

poppet valves, 81, 128
pop rivets, 62, 69
port fuel injection (PFi) systems, 197, 210
positive camber steering, 378
positive castor angles, 380, 381
positive crankcase ventilation (PCV) systems, 171, 172, 181, 182
positive scrub radii (steering), 379
postwork inspections, 78
potentiometers, 204–5
power, 40–2, 101, 262
power connections, 250, 251
power split systems, 253, 254
power steering, 367, 383–6
power stroke, 81, 83, 84–5, 87, 88
power switches, 252
powertrain control modules (PCM), 187, 188, 287, 288
power transistors, 241
power units, 250, 251
practical tasks, 494–8
precombustion, 96–7, 222
precross-flow ports, 125
pre-delivery inspections (PDI), 78
pre-engaged starter systems, 282, 283, 285
pressure, 39–40
  brake systems, 406, 423
  charging devices, 86
  cooling systems, 157–8
  diesel fuel injection, 221–2, 224–5, 229–30
  petrol fuel injection, 208, 210, 211
  see also atmospheric pressure supercharging
pressure-conscious regulators (PCR), 390, 400, 401
pressure plates, 428, 431–2
pressure valves, 140, 141, 158
prework inspections, 78
programmed ignition systems, 237
progression carburation stages, 195
progressive pitch steering racks, 374–5
progressive power-assisted steering, 385
prohibition signs *see* warning signs
propane *see* liquefied petroleum gas
propshafts, 467–72
Provision and Use of Work Equipment Regulations 1998 (PUWER), 22
pulley systems, 163, 164
pulse generators, 242–3
PUWER (Provision and Use of Work Equipment Regulations 1998), 22

Q

Quadralink suspension, 364
'quick-fit' companies, 9

R

R134a refrigerants, 337–8
racks (steering), 367, 369–75
radial flow type superchargers, 187–8
radial lip oil seals, 120, 121
radial tyres, 416, 418, 419
radiation, 44, 153
radiators, 151, 155, 156, 160, 161, 166
ram cylinders, 384–5
ramps, 48
RAM (random access memory), 199, 201
rate of electron flow definition, 260
ratios, 45
Ravigneaux planetary gearsets, 451–2, 454
read only memory (ROM), 199, 200, 201
rear air bag positions, 324, 325
rear drum brakes, 390, 391
rear-engine rear-wheel drives, 2, 3
rear lights, 293, 294, 301–2
rear screen heater elements, 319, 320
rear-wheel drive, 2, 3, 436, 480, 481, 482
receiver/drier systems, 340–1
reception systems, 12
recirculating ball steering boxes, 372–3
rectifiers, 287, 290–1, 292
reed switches, 327
reflectors, 295, 296–7
refrigerants, 337–8, 339–40
regulators, 291–3, 390, 400, 401
relative density, 43
relays:
  control switches, 299
  conventional circuits, 268, 270
  cube relays, 265
  screen heating, 319, 320
  sunroofs, 315, 316
release bearings, 426
remote-control central door locking, 316–17
remote door locking, 316
remote expansion tanks, 161, 162
remote keys, 321, 322
replaceable liners, 111
Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995 (RIDDOR), 22
resistance (electrical systems), 263, 268
resistance welding, 67
resistors, 204, 268, 270, 273
retarded ignition, 94, 95
reverse gear idlers, 441, 442
reverse gear locks, 440
reverse lights, 297–8
reverse shafts, 464, 465
RIDDOR (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995), 22
rigid axle suspension, 362, 363
rims *see* wheels
ring gears, 284, 285
risk management and assessment, 22
  see also hazards
riveting, 62, 69
road tests, 74, 76
Road Traffic Act, 73
rocker covers, 135–6
rocker shafts, 132
rod-operated gearbox shift mechanisms, 438–9
roller cell type fuel pumps, 208, 209
roller wheel bearings, 472, 473, 474, 475
ROM *see* read only memory
Roots blower superchargers, 187, 188
rotary air valves, 207–8
rotary engine, 87, 88
rotary injection pumps, 222, 223–7
rotor oil pumps, 145–6
rotors (charging systems), 287–93
rounded belts, 135
round post battery terminals, 280

rubber doughnut joints, 467, 470
rubber mountings, 178, 179, 471
rubber oil seals, 70–1
rubber stops, 354
rubber suspension, 352, 353
rubber tyres, 416
run flat rim capability, 413, 415
Rzeppa constant velocity joints, 472

S

SAE *see* Society of Automotive Engineers
safety, 18–35, 322–5, 326
  brakes, 396–7
  environmental protection, 33–4, 35
  fire, 29–31, 32, 33
  hazard identification and reduction, 24–5, 26, 27
  hybrid cars, 250–3, 254
  law fundamentals, 20–1, 23
  load moving, 25, 27, 28
  personal protective equipment, 23–4, 25
  procedures, 29
  signage, 33, 34, 35
  United Kingdom, 19, 22
  vehicles, 28
  working environments, 32–3, 34
Safe Work Australia (SWA), 19
Saloon cars, 4
satellites *see* global positioning systems
screen heating, 318–19, 320
screw and nut steering boxes, 370, 372
scrub radii (steering), 379
sealants, 70, 71
sealing rings, 115, 116
seat adjustments, 312–14
seat angles, 129
security systems, 320–1, 322
selector forks, 437
self-adjusting brake devices, 392
semi-automatic sequential gearboxes, 486
semiconductor diodes, 290–2
semiconductor transistors, 262
semi-floating wheel bearings, 473
semi-trailing arm suspension, 263, 360, 361, 362
sensors, 326–9
  anti-lock brake systems, 403–5
  catalyst systems, 181
  cruise control systems, 311–12
  definition, 326
  diesel fuel injection systems, 226
  electric power steering, 385–6
  GPS, 336
  ignition systems, 244–5, 246
  petrol fuel injection systems, 201–6, 212, 214
  PicoScope, 53, 55
  pollution reduction, 170, 171
  power steering, 385–6
series power systems (hybrid cars), 253–4
service API classes, 149
service plugs, 207
servicing, 71–9
  history, 72
  incorrect adjustment effects, 76, 77
  information sources, 78–9
  maintenance and inspections, 76, 78
  road tests, 74, 76
  rules and regulations, 73, 74
  service sheets, 72–5
  terminology, 72
servo units, 389, 398–400
shielded dip filaments, 296
shielded metal-arc welding, 67
shock absorbers, 356–9
shoes *see* brake shoes
short-circuits, 268, 271
short inlet tracts, 176
shrinking, 68
SI *see* spark ignition
siamese ports, 125
side air bag positions, 324, 325
sidewall construction (tyres), 418, 419
sidewall thickness (tyres), 418
sight glasses, 341
signage (safety), 33, 34, 35
silencers, 177, 178
silent drive chains, 479
single-acting brake shoes, 395
single-choke carburettors, 191, 192
single cylinder engines, 103–4
single-leaf springs, 350
single point injection (SPI) systems, 194, 197
  see also throttle body injection systems
single-tube telescopic dampers, 358
SI units (metric system), 37, 38, 39
six-cylinder engines, 106, 107, 108
slave cylinders, 395
sliding disc brake callipers, 391, 393–4, 395, 396
sliding-mesh gearboxes, 436
slip angles, 382–3
slow charge of batteries, 278, 281
Society of Automotive Engineers (SAE), 147–9
soldering, 66
solenoid:
  diesel fuel injection, 224–5, 230
  petrol fuel injection, 207–8
  starter systems, 282, 283, 285, 286
  suspension, 358–9
solid clutch discs, 430, 431
space savers (wheels), 412
spanners, 51, 52
spark advance ignition systems, 238, 244–5
spark ignition (SI), 92–5, 101, 102, 238, 244–5
spark plugs, 247–9
specialist companies, 10
special (post-accident) inspections, 78
specific heat capacity, 44
speedometers, 331–2, 333
speed ratings (tyres), 420, 421
speed ratios, 49
speed-sensitive power steering, 367
speed sensors, 311, 312, 404–5
SPI *see* single point injection systems
splash lubrication, 140
splined joints, 470
split brake systems, 397–8
split rim wheels, 410, 412
spoked wheels, 409
sports utility vehicles (SUV), 5
spot welding: safety, 23, 24

springs, 140, 141, 347–8, 351
SRS *see* supplementary restraint systems
standard differential transmission, 483–4
star stator windings, 290
starting systems (engines), 282–7, 288
stators, 287, 289–93, 450
steel springs, 351
steel substrates, 180
steel valve seats, 123, 124
steel wheels, 409, 410
steering, 366–86
  boxes and racks, 369–75
  geometry, 375–83
stepper motors, 332, 333
stoichiometric ratios, 94
stoplights, 297–8, 301–2
straight cut gears, 434
strainers (lubrication), 140, 141, 143–4
stratified gasoline direct injection modes, 214, 215
stub axle steering, 368, 369
subvalves, 159–60
sulphur, 168–9
sulphuric acid, 276–7
sump filter systems, 145
sump reservoirs, 140, 141
sundries (invoicing), 14
sunroofs, 312, 314, 315, 316
supercharging, 86, 184–8, 211
superimposed tyre layers, 417
supplementary restraint systems (SRS), 324, 326
suspension, 7, 347–66, 368
SUV *see* sports utility vehicles
SWA *see* Safe Work Australia
swept volumes, 100
swirl chambers, 97, 98
switches:
  conventional circuits, 268, 270
  cruise control, 310, 311
  diesel fuel injection systems, 229
  electrical circuits, 264–5
  hazard lights, 303–4
  hybrid cars, 252
  interior lights, 299
  mirrors, 314, 315
  petrol fuel injection, 204–5
  reed switches, 327
  reverse lights, 298
  security systems, 320, 321
  starter systems, 282, 283, 286
  stoplights, 298
  sunroofs, 315, 316
swivel axis inclination, 380
swivels, 370, 371
synchromesh gearbox mechanisms, 442–3
synchronizers, 442–3, 444
synthetic rubber oil seals, 70–1
synthetic rubber tyres, 416

T

tachometers, 332, 333
tandem master cylinder pistons, 396, 397
tanks *see* petrol tanks
tapered roller wheel bearings, 472, 473, 474, 475
taps and dies, 60–2
TBI *see* throttle body injection systems
TCS *see* traction control systems
TDC *see* top dead centre
telecommand definition, 343
telemetry, 343–4, 345
telescopic dampers, 353, 354, 358
temperature, 44, 49, 50, 248
  control valves, 170, 171
  gauge circuits, 330, 331
  sensors, 327, 328
terminal circuits, 268, 270
terminals (electrical circuits), 266, 267
test equipment, 52–3, 55
thermal gauges, 329, 330
thermistors, 206, 327, 328
thermostatic expansion valves, 341, 342
thermostatic viscous hubs, 164–5
thermostats, 155–6, 158, 159–60
thread cutting, 60–2
three-cylinder in-line engines, 104–5
three-dimensional (3D) drawings, 46
three-piece wheel construction, 410, 412
three-quarter floating wheel bearings, 473, 474
three-shaft gearbox systems, 438
three-way catalytic converters, 216
three-way oxidizing catalysts, 180
throttle body air supply systems, 173, 174
throttle body injection (TBI) systems, 194, 197, 207, 210
throttle butterflies, 193
throttle motors, 311
throttle position sensors, 204–5
time clocks, 282
time estimations (motor industry), 13
time periods definition, 40
timer relays, 319, 320
timing belts, 135, 136
TIN *see* tyre identification numbers
tips for learning, 493
toe-in/out steering, 377–8
tools, 51–7
toothed belts, 135, 136, 164
top dead centre (TDC), 81, 84
top-feed fuel injectors, 211, 212
torque, 42
  automatic transmission, 445–50, 463
  definition, 101
  gears, 48
  linear to rotary motion, 120
  spark ignition, 93, 94
  wheels, 413, 414
torsion bars, 351
torsion beam suspension, 363, 364
Toyota Prius, 250
track rods, 369, 370
traction control systems (TCS), 407–9
traditional ignition systems, 239–41
traditional radiators, 160, 161
trailing arm suspension, 360, 361, 363
trailing brake systems, 393, 394
transfer boxes, 477–8, 479
transformers, 238, 264
transistors, 241, 262, 273, 274

transmission fluid, 445
transmission gears, 286
transmission jacks, 56
transmission systems, 425–87
  automatic transmission, 445–66, 467
  clutch systems, 425–33
  differential, 480, 482–5
  driveline, 467–80
  final drive, 480–2
  Formula 1 technology, 485–7
  gearboxes, 434–45
  hybrid cars, 250, 251
  manual transmission, 425–45
  vehicle categories, 7
transmitters, 321
transverse arm suspension, 360
trapezium Ackermann steering methods, 376
trapezoidal belts, 135
triangulation (satellites), 333–4
trickle battery charging *see* slow charge of batteries
trolley jacks, 55
trucks, 5
T-shaped handles: thread cutting, 61
tubeless tyres, 416
tubeless valve bodies, 415
tungsten filament lighting, 293, 295, 296
turbines, 186–7, 446–8, 450
turbocharging, 86, 172, 184–8, 211
twin-choke carburettors, 191, 192
twin-cylinder engines, 104
twin electric fans, 158, 159
twin filament bulbs, 301–2
twin horn systems, 309
twin leading brake shoes, 393
twin overhead camshafts *see* double overhead camshafts
twin roots blower superchargers, 187, 188
twin-tube telescopic dampers, 358
twin, unequal-length wishbone suspension, 359, 360
two-piece track rods, 370
two-shaft gearbox systems, 438
two-stroke engines, 85–7, 150
two-way telemetry, 343
tyre identification numbers (TIN), 420
tyres, 380–2, 409, 416–22

U

UJs *see* universal joints
ultrasonic reversing aids, 309–10
ultrasonic welding, 67–8
understeering, 382–3
unequal-length wishbone suspension, 359, 360
United Kingdom (UK) safety, 19, 22, 31, 32, 33
units of science, 37, 38
universal joints (UJs), 467, 468, 469, 470
unsprung mass, 347–8
USA *see* American fire extinguishers
used vehicle inspections, 78

V

vacuum systems, 158, 175–6, 388, 398–400
VAF *see* vane air flow meters
value added tax *see* VAT
valve gears, 142
valves, 128–30
  air conditioning, 341, 342
  brake systems, 400
  cooling systems, 158
  diesel fuel injection, 224–5
  four-stroke engines, 81, 82, 84–5
  fuel levels, 193
  petrol fuel injection, 207–8, 210, 211
  pollution reduction, 169–70, 171
  seats, 123, 124
  springs, 256
  suspension, 358–9
  timing, 84–5, 132, 133, 134
  wheels, 413, 415
vane air flow (VAF) meters, 204
vane oil pumps, 145, 146–7
vane type pumps, 224
vans, 5
VAPS *see* variable-assistant power steering
variable-assistant power steering (VAPS), 367, 385
variable cam timing, 134
variable valve timing (VVT), 134
variable vane turbochargers, 187, 188
variable venturi carburettor types, 191, 192
VAT (invoicing), 14
V belt configurations, 164
vehicle categories, 1–8
velocity, 39
V engine configurations, 101, 103–9, 130
ventilation (PCV) systems, 171, 172, 181, 182
venturi carburettor types, 191, 192–4
vibration and harshness, 439
viscosity index improvers (VIIs), 148
viscosity (lubrication), 138, 148–9
viscous coupling, 479, 484–5
viscous hubs, 164–5
volume, 43, 44, 45
volumetric efficiency, 90–1
VOSA (Vehicle and Operator Services Agency) regulations, 73
VVT *see* variable valve timing

W

Wankel engine, 87, 88
warm-air control, 175, 176
warning lights, 143, 303–4, 402, 403
warning signs, 33, 34
warranties, 15
washers, 305–8
wasted spark distributorless ignition systems, 244, 245
waste gate actuators, 185
water (battery cells), 276–7
water-coolants, 151, 152, 154, 156–8
water extinguishers, 31, 32
water jackets, 112–13, 126–7, 154, 162–3
water pumps, 162–3, 164
watts, 262
wave springs, 430
wax pellets, 158–9, 160
websites, 489
wedge-shaped combustion chambers, 124, 125
weight, 43
welding, 23, 24, 56, 67–8
well-base (wheels), 410

wet liners, 110, 111
wheel guns, 56
wheels, 48, 409–15
  bearings, 472–6
  sensor signals, 403–5
  speed instability, 406
  speed sensors, 404–5
wide-band oxygen sensors, 212, 214
windings, 284, 285, 288–93
windows, 312, 317–18, 319
wipers, 305–8
wire mesh strainers, 143–4
wiring, 266, 267, 268, 271, 272
wishbone suspension, 354, 359, 360, 361, 362
work, 40–2
working environment safety, 32–3, 34
workshop systems, 54, 56–71
  adhesives, 65–6
  brazing, 66–7
  compression fitting, 68
  cutting, 59–60
  drilling, 59
  equipment, 53–7
  filing, 58, 59
  fitting, 57–8
  gaskets, 69–70
  joining, 62–3
  machining, 57–8
  motor industry, 15–18
  nuts and bolts, 63–5
  oil seals, 70–1
  riveting, 62, 69
  sealants, 70, 71
  shrinking, 68
  soldering, 66
  thread cutting, 60–2
  welding, 67–8
worm and roller steering gears, 373, 374
worm and rolling finger steering gears, 373, 374
worm and sector steering boxes, 373
wrenches, 51, 52

Z

zener diodes, 273, 292–3
zero scrub radii (steering), 379
zirconia type lambda sensors, 206