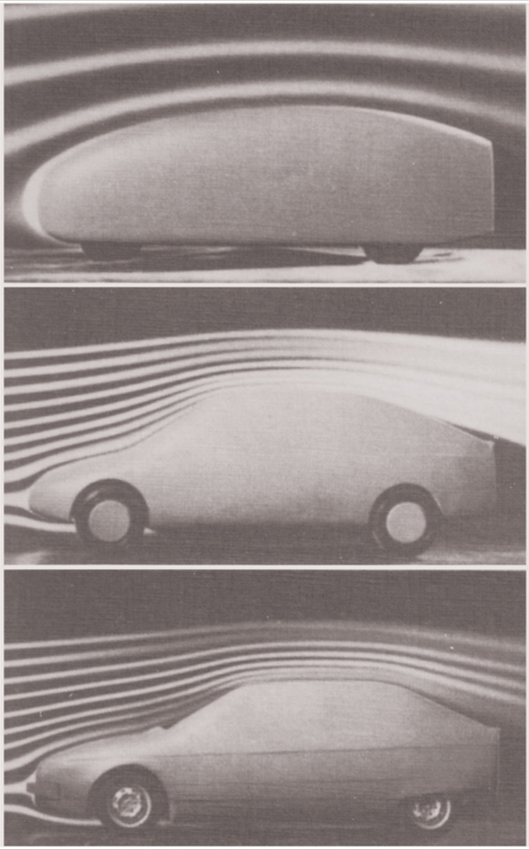
Aerodynamics of Road Vehicles

Edited by Wolf-Heinrich Hucho



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From Fluid Mechanics to Vehicle Engineering

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Butterworth–Heinemann
London Boston Singapore Sydney Toronto Wellington

PART OF REED INTERNATIONAL P.L.C.

English edition first published 1987
Reprinted 1990

Originally published under the title *Aerodynamik des Automobils* by Vogel-Verlag, Würzburg, West Germany.

British Library Cataloguing in Publication Data

Aerodynamics of road vehicles : from fluid
mechanics to vehicle engineering.
1. Motor vehicles — Aerodynamics
I. Hucho, Wolf-Heinrich II. Aerodynamik
des Automobils. *English*
629.04'9 TL245

ISBN 0-408-01422-9

Library of Congress Cataloging-in-Publication Data

Aerodynamik des Automobils. English.
Aerodynamics of road vehicles.

Translation of: Aerodynamik des Automobils.
Bibliography: p.
Includes index.
1. Motor vehicles—Aerodynamics. I. Hucho, Wolf-Heinrich.
TL245.A4713 1986 629.2 86-13693
ISBN 0-408-01422-9

Typeset by Scribe Design, Gillingham, Kent
Printed in Great Britain at the University Press, Cambridge

Preface

The performance, handling and comfort of an automobile are significantly affected by its aerodynamic properties. A low drag is a decisive prerequisite for good fuel economy. Increasing fuel prices and stringent legal regulations ensure that this long-established relationship becomes more widely acknowledged. But the other aspects of vehicle aerodynamics are no less important for the quality of an automobile: side wind stability, wind noise, soiling of the body, the lights and the windows, cooling of the engine, the gear box and the brakes, and finally heating and ventilating of the passenger compartment all depend on the flow field around and through the vehicle.

Vehicle aerodynamics is still an empirical science, if not an art. Whereas other technical disciplines such as aeronautics, naval architecture and turbomachinery are governed by well-established theoretical and experimental methods of fluid mechanics, no consistent design procedures are yet available for road vehicles. The complexity of the flow field around a car, which is characterized by separation, must be blamed for this lack, and this means that the vehicle aerodynamicist must refer to a large amount of detail resulting from earlier development work. His success depends on his ability to transfer these results to his own problem and to combine results originating from many different earlier developments to a consistent solution.

It is the intention of the present book to introduce the vehicle engineer to this approach. His interest is focused on three aspects:

- the fundamental of fluid mechanics as related to vehicle aerodynamics;
- the essential experimental results, presented as ground rules of fluid mechanics and brought to general validity wherever possible;
- design strategies, showing how many existing single results can be combined to provide general solutions.

The aerodynamics of passenger cars, commercial vehicles, sports cars and race cars is dealt with in detail. Not only the external flow field is covered; the problems of the several internal flow systems are treated as well. Because the external and the internal flow fields are interrelated, both have to be considered at the same time. The related test techniques are described in detail, emphasizing the correlation between the wind tunnel, which is the main tool of the vehicle aerodynamicist, and the road, which is the real world for the car in a customer's hands. A chapter on numerical methods concludes the book. Although theoretical models are still of limited evidential value they are more and more used for guiding and supporting, rather than replacing, wind tunnel tests.

The first German edition of this book was originally based on a course given by the authors at the 'Haus der Technik', Essen, Germany, under the aegis of Dr H. Hahn. This English version is a completely revised second edition. It is intended for vehicle engineers in industry and research, at universities and in administrative departments. But it is also aimed at stylists and designers, students and professional writers in the car world. Detailed knowledge of fluid mechanics is not assumed. The chapter on the fundamentals of fluid mechanics provides the reader with the necessary details.

This present English edition would not have come about were it not for the efforts of two true friends of the editor: Mr Gordon Taylor built the bridge to Butterworths and Dr Gino Sovran involved the publication department of the Society of Automotive Engineers (SAE), thus providing a sufficiently broad basis for the project. The editor is deeply indebted to both his friends. He also wishes to express his sincerest thanks to all who have contributed to this book: first of all, of course, to the authors for their readiness to carry the burden of preparing the manuscripts; thanks as well to the secretaries and draughtsladies for typing the manuscripts and for drawing the figures; thanks to the companies of the authors for having given them permission to contribute to the book. The editor expresses his warmest thanks to his wife, Irmgard, for her untiring assistance during the preparation of the extensive material and to his former secretary, Mrs Hildegard Backes, for typing and editing the final manuscript and for continuing to do so even when the editor was in the course of changing his employer. Finally, thanks are owed to the publishers: to Vogel-Verlag, Würzburg, for granting the licence, to Butterworths for good and patient cooperation and the SAE publications department for sharing the project.

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Schwalbach am Taunus, Federal Republic of Germany
December 1986

Contents

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Chapter 1

Introduction to automobile aerodynamics

Wolf-Heinrich Hucho

1.1 Scope

1.1.1 Basic principles

The flow processes to which a moving vehicle is subjected fall into three categories:

- flow of air around the vehicle;
- flow of air through the body;
- flow processes within the machinery.

The first two flow fields are closely related. For example, the flow of air through the engine compartment is directly dependent upon the flow field around the vehicle. Both fields must be considered together. On the other hand, the flow processes within the engine and transmission are not directly connected with the first two, and are not treated here.

The external flow subjects the vehicle to forces and moments which greatly influence the vehicle's performance and directional stability. Until recently vehicle aerodynamics was concerned almost exclusively with these two effects, and has only lately focused on the need to keep the windows and lights free of dirt and accumulated rain water, to reduce wind noise, to

Figure 1.1 Streamlines in the longitudinal midsection of a VW Golf I (Rabbit), photographed for a full-sized vehicle in the large climatic wind tunnel of the Volkswagen AG. The lines of smoke were introduced in the plane of the longitudinal centreline to show the flow pattern with symmetrical oncoming flow. This flow state exists only when there is no side wind

prevent windscreen wipers lifting, and to cool the engine oil sump and brakes, etc.

From the flow pattern shown in Fig. 1.1 some significant flow processes can be discerned, for example flow separation at the rear of the vehicle. Although the streamlines follow the contour of the vehicle over long stretches, even in the area of sharp curves, the air flow separates at the rear edge of the roof, forming a large wake which can be observed (Fig. 1.2) by introducing smoke into the bubble behind the vehicle instead of in the adjacent external flow as in Fig. 1.1.

Figure 1.2 Wake of a VW Golf I, photographed as in Fig. 1.1, smoke introduced into the wake

The aerodynamic drag D, as well as the other force components and moments, increases with the square of the vehicle speed V:

$$D \sim V^2 \tag{1.1}$$

With a medium-size European car, aerodynamic drag accounts for nearly 80 per cent of the total road resistance at 100 km/h (62 mile/h). There is therefore much scope for improving economy by reducing aerodynamic drag. For this reason drag remains the focal point of vehicle aerodynamics, whether the objective is speed or fuel economy.

The complete expression for Eqn 1.1 is:

$$D = c_D A \frac{\rho}{2} V^2 \tag{1.2}$$

where c_D is the non-dimensional drag coefficient; A is the projected frontal area of the vehicle (Fig. 1.3); and ρ is the density of the surrounding air.

The drag D of a vehicle is therefore determined by its frontal area A, and by its shape, the aerodynamic quality of which is described by the drag coefficient c_D. Generally the vehicle size, and hence frontal area, is determined by the design requirements, and efforts to reduce drag are concentrated on reducing the drag coefficient.

The distance between the streamlines ahead of the car compared with those above the vehicle provide an indication of the lift (Fig. 1.1). Closely spaced streamlines mean high velocity and consequently low static pressure (see section 2.3.1). The pressure difference between the upper and lower

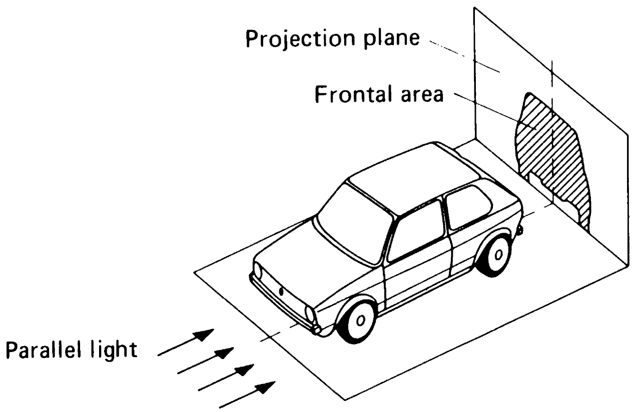


Figure 1.3 Definition of the frontal area A of a vehicle

sides of the vehicle produces a resultant force, at right angles to the direction of motion, which is called lift. As a rule the lift is in the upward direction, i.e. it tends to lift the vehicle and therefore reduces effective wheel loads. It is coupled with a pitching moment, which differentially affects the wheel loads at the front and rear. Below 100 km/h (62 mile/h) lift and pitching moment have only a small effect upon the vehicle, even in a cross-wind. They do change the attitude of the car in relation to the road and therefore slightly affect the aerodynamic drag. The reduction of the wheel loads, however, is small in relation to the static wheel load and the directional stability is hardly affected by lift.

This does not apply to high-speed sports cars, where spoilers are often added to counteract the effects of lift. With racing cars, wings ensure that

Figure 1.4 Negative lift wings on a Formula 1 racing car

the wheel loads increase with speed (Fig. 1.4). How such negative lift wings are tuned in specific cases is described in Chapter 7.

With cross-winds the air flow around the vehicle is asymmetric to the longitudinal centre plane. The shape of the car must be such that the additional forces and moments remain so small that the directional stability is not greatly affected (see Chapter 5). First, the need to react to a cross-wind of varying intensity and direction is inconvenient, as the driver must continually apply steering corrections. Secondly, in very rare cases there is the danger of total loss of control; this can only be countered by suitable aerodynamic design. However, it is also important to prevent drivers from being surprised by side-wind gusts, and being unable to react quickly enough. Better design of roads and their surroundings can help to overcome this problem.

Soiling of the rear of the vehicle can be studied from the wake flow as shown in Fig. 1.2; details are discussed in Chapter 6. Dust or dirty water is whirled up by the wheels, and dust particles and water droplets distributed throughout the entire wake region by turbulent mixing, and deposited on the rear of the vehicle. Since the flow pattern at the rear has a significant influence upon the aerodynamic drag, soiling of the rear cannot be considered in isolation.

Figure 1.1 shows how the external flow field relates to flow processes inside the vehicle. The flow into the radiator (see Chapter 9) is determined by the flow pattern in front of the vehicle. It can be seen that the stagnation point is at the level of the bumper, and that the air flow is oblique to the openings above and below the bumper (not visible in Fig. 1.1). The grill should be designed to direct this air to the radiator, which is generally vertical, while keeping the pressure loss as low as possible.

The flow is attached in the region of the concave space formed by the engine hood and the windscreen. Here there is a pressure build-up, which, as described in Chapter 10, can be utilized for driving air through the heating and ventilation system. On most vehicles the fresh air inlet opening is positioned in the middle of this area. However, at this point the pressure is dependent upon the driving speed, which results in an increase of the fresh air flow as speed increases, making maintenance of steady conditions in the passenger compartment quite difficult. If the inlet openings for the fresh air are moved to points on the body which are at ambient pressure, it is possible to separate the external and internal flow fields, at least while the oncoming flow is symmetrical (no side wind). The fresh air fan, which must be correspondingly larger, then provides a flow which is independent of the driving speed (though only when the exit vents in the body are located in areas of ambient pressure as well).

The most important internal flow fields are the air flow through the radiator and engine compartment, and the heater or ventilation flow through the passenger compartment. Some types of vehicles—such as racing cars—have separate flow ducts for the oil cooler, brake cooling, and the combustion air for the engine (see Chapter 7).

The engine cooling system has the task of removing a heat flux $\dot{Q}$, which is of approximately the same magnitude as the useful engine power P:

$$\dot{Q} \approx P \tag{1.3}$$

As vehicle design has developed, the requirements for cooling air have increased considerably. Since a larger cooling air flow is required for water cooling than for air cooling, these requirements must be related to the type of cooling (see Chapter 9 for details):

1. Engine power has increased continuously over the years, making necessary greater volumes of cooling air.
2. Following the demands of styling and aerodynamics, the front end of cars has become flatter over the years. The openings available for entry of the cooling air have become smaller as a result (Fig. 1.5). Moreover, the earlier large coherent inlet area has been broken up into individual sub-areas.
3. As a result of compact design, less space is available in the engine compartment for the radiator and cooling air duct.
4. In the interests of safety the body has continuously been reinforced at the front end ('hard edge'), so that the flow is impeded by wide bumpers and cross-members.

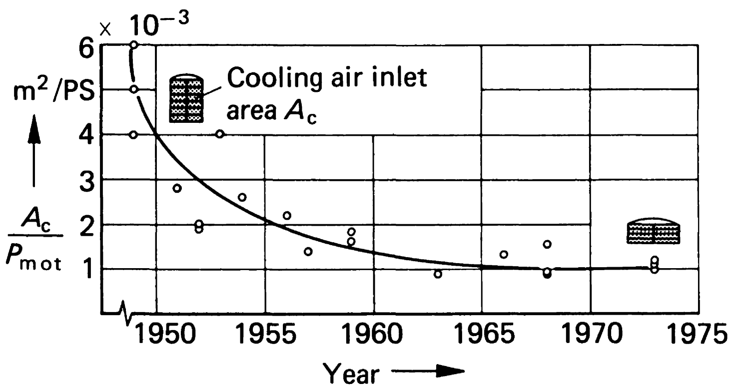


Figure 1.5 Cooling air inlet area in relation to installed engine power, shown as a function of time, after K.-D. Emmenthal

The cooling air must be routed in such a manner that the velocity of the air in front of the radiator is as uniform as possible, thus ensuring optimum radiator efficiency. In addition, the aerodynamic drag of the car is considerably increased as a result of the loss of momentum in the cooling air duct. This increase in drag can be kept small with suitable measures (see section 4.3.2.12). If the ram air flow is not sufficient for cooling, a fan must be added; radiator and fan must be matched to produce an economical system so that the smallest possible amount of power is required to drive the fan.

The air flowing through the passenger compartment must perform three groups of tasks (see Chapter 10):

1. Sufficient ventilation must be assured. All contaminants in the form of gases, vapours and dust must be expelled from the passenger compartment. Simultaneously, this provides for replacement of the oxygen consumed through breathing.
2. A comfortable internal climate must be produced and assured for a wide range of variation in the external conditions. For winter operation

a high-performance heater must be provided. In summer comfort must be ensured by the circulation of fresh air. In extremely hot countries this alone is not sufficient and the air must be cooled with an air conditioner.
3. The internal flow must pass along the windows so that mist evaporates (demisting) and ice, which can form on both sides of the windows, melts (deicing).

Particular requirements are placed on the dynamic characteristic of the flow system in the passenger compartment. For instance, the heater is expected to provide heat quickly after the engine is started. However, during cruise the internal climate should be independent of the vehicle speed, the operating state of the engine and the external climate. The flow should produce as little noise as possible; wind noises must be avoided and the fan noise minimized. The openings in the body, with which the internal flow is coupled with the external flow, must be designed so that water cannot enter even under extreme conditions (e.g. in a car wash).

The objectives of the aerodynamic design work outlined above are influenced by the type of vehicle under consideration. For instance, during the aerodynamic design of a passenger car, the main consideration is drag. On a high-speed minibus or van, reduction of sensitivity to cross-winds may be the primary goal. Various solutions are available depending upon the type of vehicle. On a racing car the objective will be to improve the traction of the tyres, using negative aerodynamic lift regardless of styling; the wings at the front and back have even become characteristic of modern racing cars. On the other hand minimizing the drag of a passenger vehicle must be accomplished with less conspicuous methods which conform to current styles.

1.1.2 Working methods

Parallels exist between the aerodynamics of automobiles and aircraft. The primary objectives are very similar: good driving or flying characteristics (longitudinal dynamics); low aerodynamic drag; balance of forces and moments in both axes perpendicular to the direction of forward motion to ensure good driving or flight stability (transverse stability). Further processing of the measured aerodynamic data in the equations of motion also indicates similarities.

In spite of this, motor vehicle aerodynamics differs in significant respects from aircraft aerodynamics. For example, aircraft aerodynamics are permeated to a great extent by theory.[1.1] The aerodynamic design of an aircraft nowadays derives initially from theoretical, i.e. numerical, considerations, followed by experimental work on small-scale models in wind tunnels and finally in flight tests with a prototype. However, with motor vehicles most of the aerodynamic development work is done experimentally. In principle two different approaches are followed. Until recently, work started with a model (full scale or small scale) designed by the styling department. Aerodynamic development was mainly fine tuning, maintaining the styling as little changed as possible (detail optimization). Nowadays work often starts with a low drag body which is developed into a car in the wind tunnel in conjunction with the stylist (see section 4.4). The smaller dimensions of the motor vehicle offer the advantage of wind tunnel testing of full-scale models or even ready-to-drive prototypes.

There are primarily two reasons why the procedure differs from that of aircraft design. In contrast to an aircraft, the design of a vehicle is not dictated wholly by aerodynamics. Style, performance, handling, safety, comfort and, of course, production engineering are all important considerations. Increased fuel prices have, however, led to greater emphasis upon aerodynamics.

Repeated attempts have been made to apply the results of aircraft aerodynamics to motor vehicles and significant achievements have been made in the solution to individual problems. However, a comprehensive theory of motor vehicle aerodynamics does not yet exist.

The computation of the air flow around aircraft is simplified by the fact that the flow fields around the individual components such as the wing,

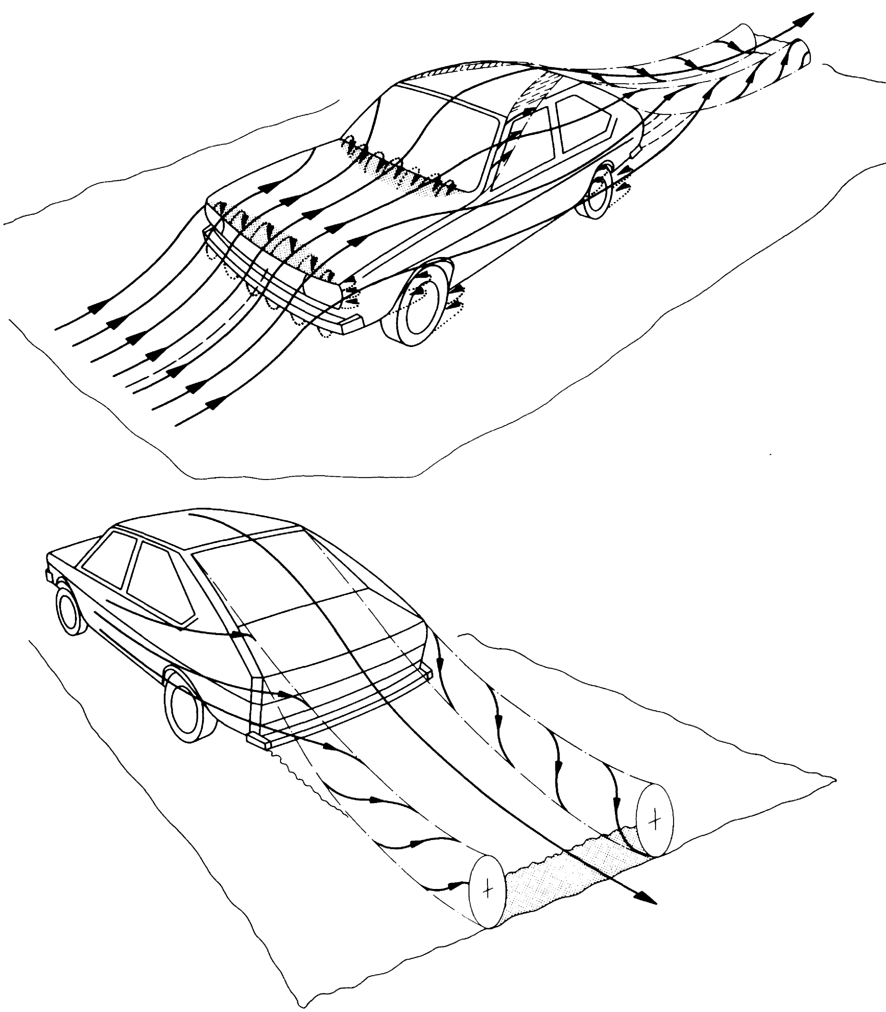


Figure 1.6 Flow around a passenger car (schematic)

fuselage and tail unit can be handled separately. The interaction between the components can also be assessed theoretically. Since the air flow is generally 'attached', the calculation can be accomplished in two steps. First the non-viscous flow field is determined; then the effect of viscosity is calculated from 'boundary layer' theory. The theoretical methods upon which this procedure is based have been developed continuously and have been expanded to include other requirements such as those resulting from higher flying speeds (Mach-number effects).

The flow field around a car cannot be treated in the same way, for two reasons. From Figs 1.1 and 1.2 it is clear that the flow past a car is strongly governed by separation. Figure 1.6 provides further information on the type and location of separation. The effect of viscosity is no longer confined to comparatively small zones close to the surface of the body (boundary layer). Furthermore, with a car it is not possible to distinguish several more or less independent flow fields. The flow field around a car body has to be treated as a whole.

Chapter 13 summarizes the present state of numerical methods in car aerodynamics. These methods may be used to guide the work in the wind tunnel. However, much of the aerodynamic design of a car is to prevent, or to tune, separation. The only way to do this is through experimentation.

1.1.3 Related fields

There are also useful parallels to related fields illustrated in Fig. 1.7, for example in the aerodynamics of buildings:

- flow around bluff bodies
- flow fields governed by separation
- ground influence and ground boundary layer
- interference between buildings
- wind tunnel testing techniques.

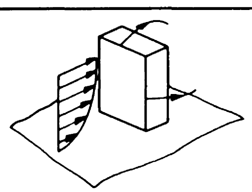
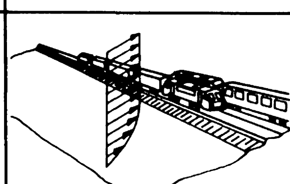
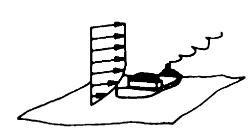
Buildings	Railways	Ships (Superstructure)
		
Total aerodynamic forces Aerodynamic forces on parts Flow field Ventilation	Drag Pressure peaks Cross-wind Flow field Ventilation	Air drag (for gliders and hydro-foil boats) Sideforce Ventilation Stack plume Sail

Figure 1.7 Fields related to automobile aerodynamics

Building aerodynamics addresses a number of similar objectives:

- determination of the effective air forces on the building as a whole
- calculation of the air forces upon parts such as roofs, facades and windows
- influencing the surrounding flow field for protection of pedestrians
- matching of the surrounding flow and the internal flow (climate, chimney draught).

Useful reference material includes Hoerner[1.2] (wind forces on buildings), Ackeret[1.3] (significant problems of building aerodynamics, based on clear examples), Sachs [1.4] (presentation of the current state of knowledge), and construction aerodynamics in condensed form by Houghton and Carruthers.[1.5]

The flow field surrounding a train is very similar to that surrounding a road vehicle. The primary difference results from coupling of individual cars into long trains, which produces a very long body in comparison to its height and width. Special relationships result when trains meet one another, due to the small gap between the tracks, as well as when driving into tunnels and driving through very narrow tunnels. The primary development goals for railway aerodynamics are:

- low aerodynamic drag
- reduction of the pressure peaks when trains meet one another, and when driving into a tunnel
- reduction of the influence of side winds
- matching internal and external flow for purposes of cooling and ventilation.

In contrast to the development of road vehicles, for which the trend to higher driving speeds has virtually vanished with the exception of racing cars, speeds are still being increased in the railway sector. For this reason aerodynamics is becoming increasingly significant in this branch of transportation technology. Some early data on the resistance of trains is given by Hoerner.[1.4] A comprehensive survey on train aerodynamics including many references has been presented by Peters.[1.6] Further information has been provided by Gawthorpe.[1.7] The problems encountered with high-speed trains, particularly in driving through tunnels have been given by Neppert and Sanderson[1.8] and by Steinheuer.[1.9]

The flow field around a ship above the water line is also a focus of increasing attention. The aerodynamic drag of a water-displacing ship is small in comparison to its water resistance, but not so for fast hydroplanes, hydrofoils and hovercraft. The aerodynamics of a surface ship include the lateral force in addition to the resistance, which is of particular concern for ships with high superstructures, such as ferries, when docking. On the other hand, the flow of air around the funnel is a prime concern for passenger ships. The aerodynamics of the sail have many problems in common with wings.

As for trains, naval architects depend upon individual publications, there being no comprehensive work on this subject. Data on the aerodynamic drag are given by Hoerner.[1.2] Of the numerous works on the funnel air flow, those from Thieme[1.10] are worthy of mention. Gould[1.11] considered questions of the lateral forces resulting from wind on ships. His work also includes information on simulation of the water surface and of the air boundary layer over the water surface in a wind tunnel.

There are also parallels in other disciplines on the flow inside the vehicles. The flow of air through the radiator in a car is comparable to the flow of air through the water or oil cooler in an aircraft. In fact much knowledge has been drawn from Küchemann and Weber[1.12] and is utilized in Chapter 9 to describe automobile cooling. The counterpart of the climatization of the passenger compartment is room climatization in buildings (see Chapter 10).

1.2 Historical development

1.2.1 Survey

The history of automobile aerodynamics occupies four chronologically indistinct phases, as illustrated in Fig. 1.8 (see Hucho, Janssen and Emmelmann[1.13]).

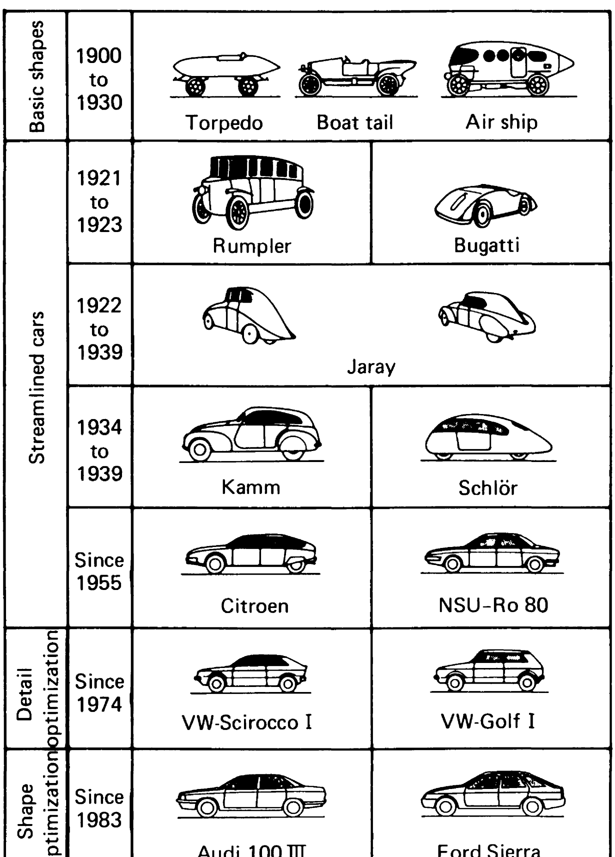


Figure 1.8 The four primary phases of car aerodynamics (updated version, concentrating on passenger cars, of the one in ref. 1.13 by Hucho, Janssen and Emmelmann)

Initial development concentrated exclusively on drag, and the problem of cross-wind sensitivity only arose with increasing driving speeds. Lately attempts have been made, by suitable shaping, to eliminate the deposition of dirt and water on the windows and lights.

The following brief history is based upon available literature. Early numerical data, particularly drag coefficients, must be considered very unreliable. Drag coefficient was sometimes measured on test vehicles through coast-down tests, or by measuring the top speed, both of which can lead to errors (see Chapter 12). Most measured data, however, came from wind tunnel tests on models of varying quality and scale. Nor were the techniques for representation of the roadway uniform, so that, as indicated in Chapter 11, the absolute accuracy of the data is low and the comparability of data from different authors is uncertain.

This brief account of the history of automobile aerodynamics has two aims. The first is to show which work contributed to the development of automobile aerodynamics; the second illustrates how this knowledge was applied to automobile design. Developments up to 1939 are described by Koenig-Fachsenfeld.[1.4] Newer works on the history of automobile aerodynamics, primarily from the American point of view, have been published by Ludvigsen [1.5] and by McDonald.[1.16] The many attempts to apply the growing aerodynamic knowledge to production cars have been illustrated quite recently by Kieselbach,[1.17–1.19] whose books have appeared in German and English.

1.2.2 Basic shapes

In the first phase, dating from the turn of the century, an attempt was made to apply to the automobile streamlined shapes from other disciplines such as naval architecture and airship engineering. They were little suited to the automobile, for instance the 'airship form', or ineffective, for instance the 'boat tail'. Due to the poor roads and low engine power, speeds were still so low that aerodynamic drag only played a subordinate role. Most cars derived from these basic shapes had one error in common: they neglected the fact that the flow past a body of revolution is no longer axially

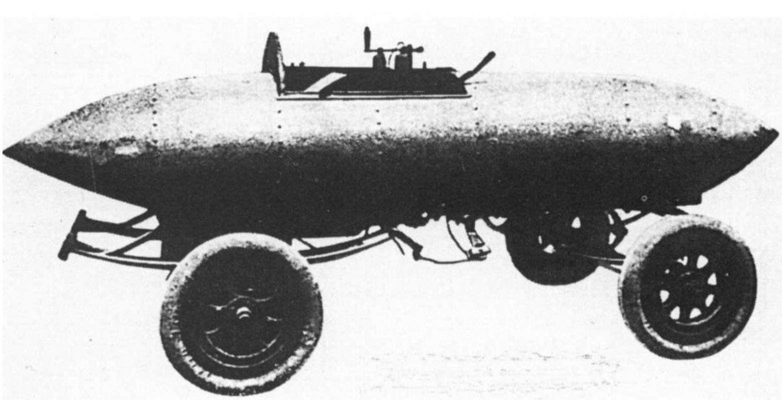


Figure 1.9 Record-breaking car from Camille Jenatzy, 1899

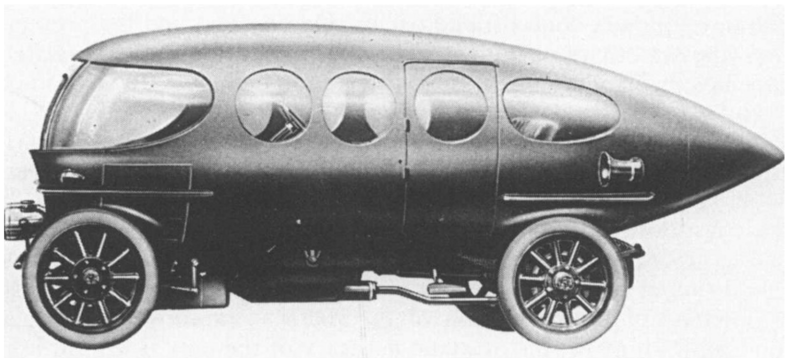


Figure 1.10 Alfa-Romeo of Count Ricotti, 1913 (courtesy Alfa Romeo, Milan)

symmetrical when the body is close to the ground, and when wheels and axles are added. In spite of this, shapes represented great progress toward lower drag in comparison to shapes based on the horse-drawn carriage. Certainly the oldest vehicle developed according to aerodynamic principles was the car built by Camille Jenatzy, who was the first to exceed 100 km/h (62 mile/h) with this electrically driven vehicle on 29 April 1899 (Fig. 1.9); see Frankenberg and Matteuchi.[1.20] With its torpedo shape with a ratio of length to diameter of 4, the body alone was streamlined; the exposed wheels and driver were not 'integrated', which certainly led to a considerable increase in the drag. Jenatzy's record-breaking car was the predecessor of all single-seat race cars, even though the body of the car was still positioned above rather than between the wheels.

Figure 1.10 shows a vehicle with a body in the shape of an airship, an

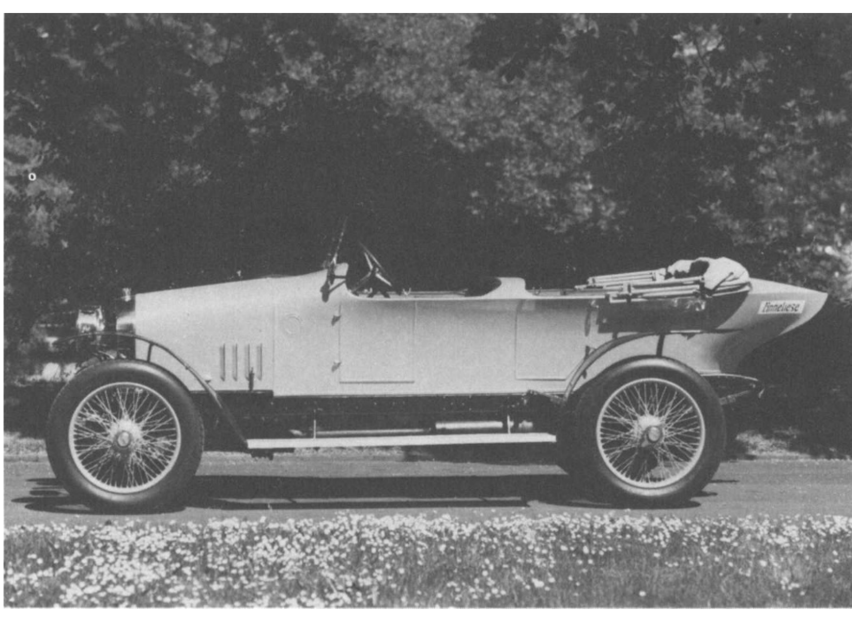


Figure 1.11 Boat-tailed 'Audi-Alpensieger', 1913 (courtesy Deutsches Museum, Munich)

Alfa Romeo from 1913. The length to height ratio for this body is approximately 3. Similar designs existed in which the wheels were partly enclosed by the body (design by O. Bergmann, refs 1.20 and 1.14). The attempt to design a car with an integrated 'ideal' body was repeated several times, but without production success.

In contrast to the shapes shown in Figs 1.9 and 1.10 the so-called 'boat tail' is completely ineffective in terms of aerodynamics (Fig. 1.11). The flow, separating at the front and from the fenders, will not re-attach because of 'boat tailing' the rear end. The boat tail, which was applied in different variants on mass-production limousines and sports cars, is an example of how aerodynamic arguments are often misused to justify stylistic curiosities.

1.2.3 Streamlined shapes

The analysis of the tractive resistance of road vehicles carried out by Riedler[1.21] in 1911 gave vehicle aerodynamics a rational basis. The more Prandtl and Eiffel worked out the nature of aerodynamic drag, the more this knowledge was used to explain the aerodynamic drag of cars; see for instance Aston.[1.22] However, getting away from Newton's 'Impact Theory' was a very slow process.

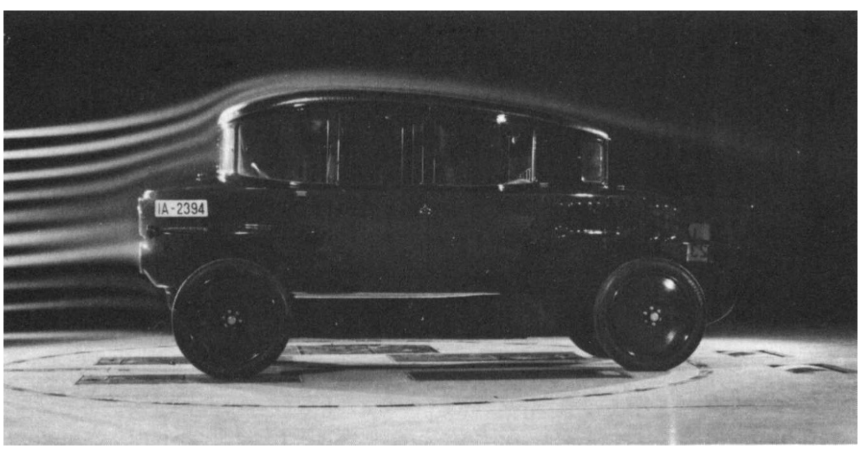


Figure 1.12 Rumpler car, 1924, photographed by R. Buchheim in the large wind tunnel of Volkswagen AG, 1979

After the First World War, the design of streamlined bodies started at a number of locations simultaneously. E. Rumpler, who had become well known through his successful aircraft, the 'Rumpler-Taube', developed several vehicles which he designated 'teardrop cars'. The most famous Rumpler limousine is shown in Fig. 1.12. In order to make use of the narrow space in the rear of the vehicle, Rumpler decided on a rear engine configuration. Viewed from the top, his car has the shape of an aerofoil. But the roof is also well streamlined, thus proving that Rumpler was aware of the three-dimensional character of the flow field (Fig. 1.13). Details are to be found in papers by Heller,[1.23] Eppinger[1.24] and Rumpler himself.[1.25]

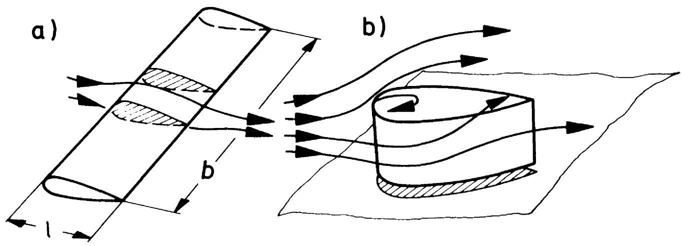


Figure 1.13 (a) Two-dimensional flow around a profile; (b) three-dimensional flow field around a profile section close to ground (schematic)

Measurements performed by Buchheim in the large wind tunnel of Volkswagen AG in 1979, on an original Rumpler car provided by the Deutsches Museum in Munich, gave the following results:

Frontal area $A = 2.57\,\text{m}^2$; drag coefficient $c_D = 0.28$

On the Rumpler car the wheels are uncovered, resulting in an increase in drag, which becomes more significant as the aerodynamic quality of the vehicle body improves; see section 4.3. On the Rumpler car this increase in drag must have been at least 50 per cent, as measurements performed by Klemperer [1.26] as early as 1922 show.

The car entered in the Strassburg Grand Prix by Bugatti in 1923 was developed primarily according to two-dimensional theory (Fig. 1.14).

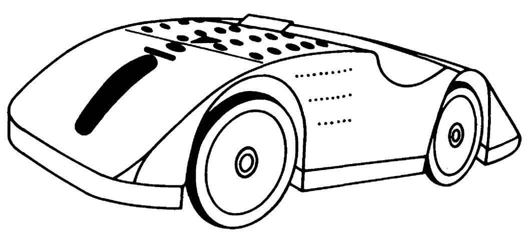


Figure 1.14 Two litre Grand Prix race car from Bugatti, 1923

However, the horizontal profile forming the body pays more attention to the path of the flow in the vicinity of the ground. As on modern championship race cars, the air flow below the car is controlled as much as possible by extending the body downward. The arched shape also facilitates enclosure of the wheels. However, the flow over the tail must have been disturbed considerably by the driver.

The three-dimensional flow around a bluff body in the vicinity of the ground was originally analysed by P. Jaray. In his pioneer work *The Streamlined Car, a New Shape for Automobile Bodies*[1.27] the term 'streamlined car' is used for the first time. A detailed report on the work of Jaray has been published by Bröhl.[1.28] Many sketches, patent-drawings and photos from this unique work clearly demonstrate Jaray's ideas and their application all over the world. Jaray recognized that the flow around a body of revolution, which has a very low drag coefficient in free air, is no longer axially symmetrical when close to the ground. As a result the drag increases, owing to the flow separation occurring at the rear upper side. At the limit, where the ground clearance approaches zero, the optimum shape in terms of drag is a half-body, which forms a complete body of revolution together with its mirror image—produced through reflection from the roadway. This half-body, which had a ratio of length to height of 4, was modified by Jaray so that the mid-section formed a rectangular cross-section with rounded upper corners.

Wind tunnel tests performed by Klemperer[1.26] at Jaray's request showed that the drag of this half-body increased with increasing ground clearance, due to the air flow around the sharp lower edge; by rounding off these edges it was possible to eliminate this increase (Fig. 1.15). Jaray then attempted to approximate the shape of this half-body by assembling individual aerodynamically shaped bodies. The half-body itself, as will be illustrated later, was used again and again by a number of designers.

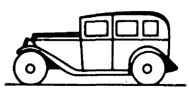
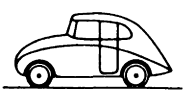
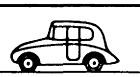
	$A_{1:1}$ [m^2]	c_D
	2.99	0.64
 Large Jaray cars	2.86	0.30
 Small Jaray car	1.87	0.29
 Half-body without wheels	2.99	
	front with sharp edges	0.13
	front edges rounded	0.09
Half-body with wheels		0.15

Figure 1.15 Drag measurements on Jaray cars and half-bodies, carried out by W. Klemperer, 1922, see ref 1.26, on one-tenth scale models; cooling-air duct closed

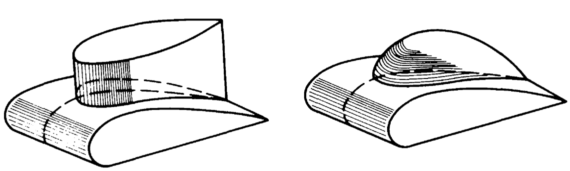


Figure 1.16 'Combination forms' according to P. Jaray (schematic)

Figure 1.16 shows how Jaray laid out his vehicle shapes, using sections from profiles and bodies of revolution. In both examples the basic body is formed by a profile segment. On the first, a second profile is attached vertically, and in the second example half of a body of revolution serves as the upper part. This body, later called the 'combination form', was based upon the consideration that low drag can only be achieved when the separation at the rear is eliminated. With a rear end in the shape of a half-body this can be achieved only with a very long, slender tail. In the combination form, the tapering of the rear end is subdivided into two planes to prevent excessive pressure increase, which could result in separation. Unfortunately Jaray[1.29] published only a 'schematic' pressure distribution for a combination form. Wool-tuft pictures for Jaray cars[1.14] indicate that separation can be prevented only for extremely slender versions of the combination form.

In 1935 Jaray made up a table of types in which he illustrated the large variety of shaping possibilities according to aerodynamic aspects; see for instance ref. 1.14. The characteristic of all of his designs was the relatively sharp horizontal rear edge. Jaray suggested classifying the individual shape parameters by numbers, similar to the system introduced by the National Advisory Committee for Aeronautics (NACA) in the USA for aircraft wing profiles. This approach did not prove particularly practical for road vehicles.

The most important of Klemperer's measurements on models of the first Jaray cars are summarized in Fig. 1.15. Compared to the box body styles of the time, it was possible to halve the drag with the combination form to $c_D = 0.30$, though it took 60 years to exploit this potential with a production car: the Audi 100 III of 1982, with a drag coefficient of 0.30. On the other hand, Klemperer's early measurements clearly show that the drag coefficient of Jaray's combination form of 0.30 is still twice as high as that of the half-body with wheels, 0.15. Chapter 4 shows how modern automobile aerodynamics uses this potential—first published by Jaray and Klemperer in 1922.

As can be seen from Fig. 1.15 the first Jaray models were as high as the box-type cars of the day; the length/height ratio was only 2.1, while this ratio is approximately 3.0 with today's cars. Many prototypes were built to the patents and ideas of Jaray (see Bröhl[1.28] and Kieselbach[1.17,1.18]) by various car manufacturers in Europe and the United States. The prototypes built for Ley, Audi and Dixi (1922 to 1924), and for Chrysler (1927/28), were not readily accepted by the public. Their shape was too

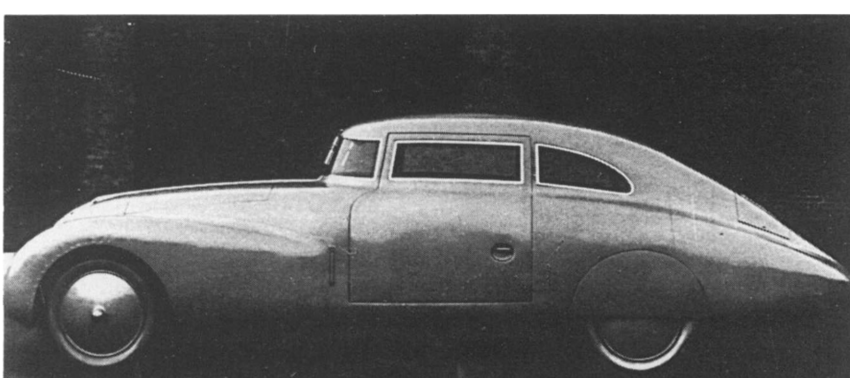


Figure 1.17 The 1.5 litre Adler-Trumpf, 1934/35, designed by E. Kleyer (courtesy Frhr. v. Koenig-Fachsenfeld)

revolutionary, but also Jaray adhered too closely to his basic principles. The prototypes built for the various makes all looked alike.

From 1934, several more attractive Jaray-shape cars were developed, for example the 1934/35 Adler Trumpf sports car (Fig.1.17). The slender shape, with $l/h = 3.3$ and sloping rear end, led to low utility of internal space. As more high-speed highways were constructed cars of streamlined shape became very popular until World War Two ended the era of Jaray cars.

One mass produced Jaray-style car was the Tatra 87 of 1937, designed by H. Ledwinka (Fig. 1.18). With $l/h = 2.9$, this car was less slender than the

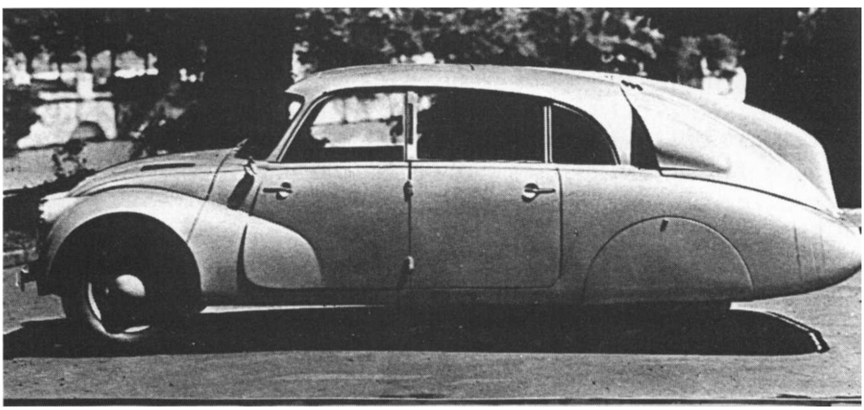


Figure 1.18 The 3 litre 8 cylinder Tatra Type 87, designed by H. Ledwinka

Adler Trumpf, and by placing the engine at the rear end it was possible to locate the passenger compartment further forward, where more space was available. Wind tunnel tests, performed on a one-fifth scale model of the Tatra 87 by Lange in the DVL wind tunnel at Berlin-Adlershof, gave a suspiciously low $c_D = 0.244$.[1.30] A calculated value of $c_D = 0.31$ was deduced from the top speed and the engine power. The actual value of $c_D = 0.36$ was measured by Buchheim in the Volkswagen wind tunnel in 1979 on an original vehicle supplied by the Deutsches Museum, Munich!

The wind tunnel tests on Jaray shapes, which were initiated by Klemperer in 1921/22,[1.26] were continued in 1938 in the Aerodynamische Versuchs-Anstalt (AVA) in Göttingen under the direction of Ludwig Prandtl. A body shape was developed which consisted of a horizontal basic

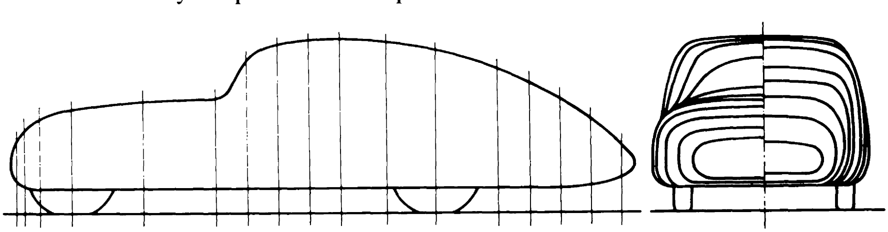


Figure 1.19 Lange car; length l to height h, $l/h = 3.52$; $C_D = 0.14$ to 0.16, completely smooth model

profile upon which a second horizontal profile was added from the windscreen. As with all Jaray shapes, this second profile was also rounded at the front from the top view. The resulting shape is known as the 'Lange car'. A drag coefficient of 0.14 was achieved with the model of this Lange car shown in Fig. 1.19 (see Lange[1.31]). Measurements performed by the author and his co-workers on a one-fifth scale model approximately confirmed this value with 0.16. However, the model lacked details such as running gear, wheel wells or window recesses. Approximately the same low drag coefficient can be achieved with the Lange shape as with half-body shapes (Fig. 1.15), which, however, were more blunt: $l/h = 3$. The Porsche 911 has a shape similar to that of the Lange car.

The relatively large l/h necessary for a Jaray-shape prevented the success of Jaray's idea, though numerous pseudo-Jaray shapes, called fastbacks, were built, such as the 1934 Chrysler Airflow and the Volkswagen Beetle. As will be shown in Chapter 4, this shape, with its steep-sloping rear end, produces two distinct longitudinal vortices. Due to the downwash induced by these trailing vortices, the flow along the longitudinal mid-section of the car remains attached over a long path; however, a high vortex-induced drag is produced so that the total drag is higher than for true Jaray shapes. In comparison to the box-shaped bodies with drag coefficients between 0.6 and 0.8, the pseudo-streamlined cars with drags of 0.4 or 0.5 still represented an improvement.

An approach similar to that of Jaray was pursued in France by Mauboussin[1.32] in 1939. His car, the Mistral, had the shape of an aerofoil in plan—the rear ending in a vertical knife edge. The rear wheels were covered by a horizontal profile, producing an intersection at the rear similar to the Jaray shape. However, the slender taper of the body greatly limited the internal space.

The measurements by Klemperer[1.26] indicated an achievable limit of $c_D = 0.15$ with uncompromising design, which has only recently been bettered (see Chapter 4). However, Jaray's attempt to approach this limit as closely as possible with his combination form led to impractical shapes, and his work provided no indication of the way in which the typical drag of automobiles of the 1920s (around 0.7) could be brought step by step nearer to the goal of 0.15.

However, Lay[1.33] working at Michigan University in the early 1930s started to close this gap. By systematically modifying the shape of the car at the front and the rear, Lay isolated the individual aerodynamic effects (Fig. 1.20). His investigations revealed the strong interaction between the flow fields of the car's fore-body and rear end. The low drag of a long-tail model was maintained only when the flow around the fore-body was well attached. The drag increased significantly when the flow separated at the steep windscreen. On the other hand, if the drag was already high due to the blunt rear end the drag increase from a steep windscreen was only moderate. Unfortunately Lay's model, which could be built up from segments, had parallel side walls and sharp corners, which resulted in a fairly high drag and limited the significance of his findings.

The most important result of Lay's work was that a blunt rear end resulted in only a relatively small increase in drag in comparison to a long tapered rear end. Similar findings were made by Dornier as early as 1920

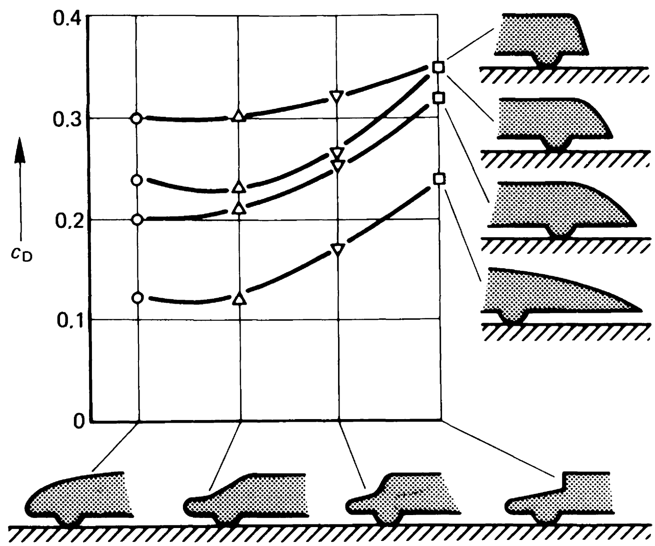


Figure 1.20 Influence of main body parameters on the drag of a car and their interactions, after ref. 1.33

with measurements on aerofoil sections with a cut-off trailing edge (see Hoerner[1.2]).

From 1934, the blunt rear end shape which first occurred in the work of Lay led to the development of the 'Kamm-back', which combined the advantage of greater headroom in the back seat with that of low drag. The Kamm-back, the Lay blunt back and Klemperer's long-tail design are compared in Fig. 1.21. The low drag is achieved because the flow remains

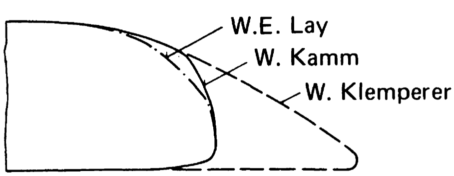


Figure 1.21 Comparison of three different rear end shapes: W. Klemperer's long tail and the blunt rear ends of W.E. Lay and W. Kamm

attached for as long as possible and is then forced to separate by cutting off the rear end at an already much diminished cross-sectional area. This results in a small wake. By tapering the body moderately, the flow is subjected to a pressure increase which ensures that the pressure at the rear of the vehicle, the 'base pressure', is comparatively high, which itself then reduces the overall drag. Kamm proposed this idea in a paper published in 1934,[1.34] but presented no practical design, referring only to the earlier work of Klemperer[1.26] and Lay.[1.33] From patent records (see Kieselbach[1.17]), R.v. Koenig-Fachsenfeld must be credited with the invention of the cut-off rear end, and his published measurements on bus models in 1936[1.35] clearly proved its advantages (see section 1.2.6). Despite this, the cut-off rear end became known as the 'Kamm-back' (sometimes called K-back). Much later (1948) Everling[1.36] claimed that he was the first to recognize the advantage of the cut-off rear end in 1934, when he had designed a bus with a cut-off tail.

Whoever originated this idea, W. Kamm was the first to undertake systematic investigation of rear end design in 1935 at the Research Institute for Motor Vehicles and Vehicle Engines (FKFS) at the Technical University of Stuttgart. In 1938 the first passenger vehicle with a Kamm rear end, the Everling car, was built (Fig. 1.22). Kamm went on to build

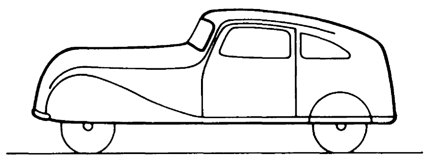


Figure 1.22 First passenger car with K-back, the Everling car, 1938, on a Daimler Benz 170 V chassis

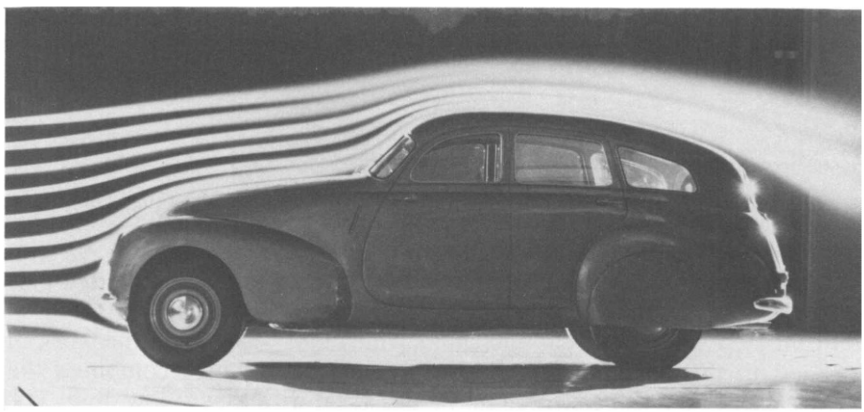


Figure 1.23 Kamm car of 1938/39 in the wind tunnel of Volkswagen AG, 1979 (courtesy Volkswagen AG)

several K-cars, and with the K5 (Fig. 1.23) the shape was developed to the point where mass production would have been possible, but this was thwarted in 1939 by the outbreak of war. The advantage of the Kamm-back, in comparison with other aerodynamic designs, can be clearly seen in Fig. 1.24.

The drag coefficients published for the Everling and Kamm cars indicate a high degree of scatter (Table 1.1), and appear to be too favourable. Dörr, who did the measurements on the Everling car,[1.37] also tested the contemporary Mercedes Benz DB 170 V and devised coast-down test results of $c_D = 0.48$, a figure which seems far too low when it is compared with wind tunnel results published by White[1.38] on similar cars, which averaged $c_D = 0.55$ (bottom right, Table 1.1). Buchheim tested the 1938/39

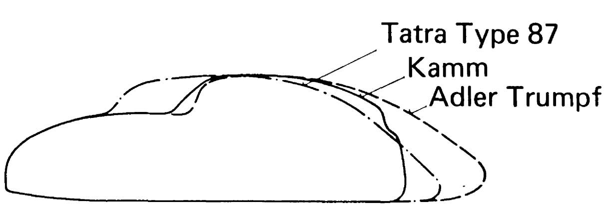
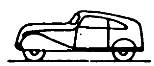
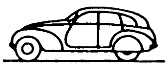
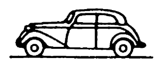


Figure 1.24 The Kamm-back in comparison to two versions of the Jaray-back; the Tatra 87 contour is drawn without the rear fin

Table 1.1 Comparison of published data measured on cars from E. Everling and W. Kamm

Type of measurement	Everling, 1938	Kamm K5, 1939	DB 170 V
	 $A = 2.24\ m^2$	 $A = 2.17\ m^2$	
Model	$c_D = 0.15$		
Expected for full scale car	$c_D = 0.24$		
Coast down	$c_D = 0.31$	$c_D = 0.24$	$c_D = 0.48$
Wind tunnel, full scale		$c_D = 0.37$	$0.52 < c_D < 0.55$ $\overline{c_D} = 0.55$

Kamm car, now on display at Langenburg Castle, in the Volkswagen wind tunnel in 1979 and obtained a drag coefficient $c_D = 0.37$ and a measured frontal area of $2.10\,m^2$, which shows the caution with which one should view the literature!

Although vehicle aerodynamics initially concentrated on the drag in still air conditions (symmetrical oncoming flow), the problems of side wind as well as cooling and ventilation soon became apparent, as noted by Klemperer,[1.26] whose results (Fig. 1.25) showed that drag varied little with

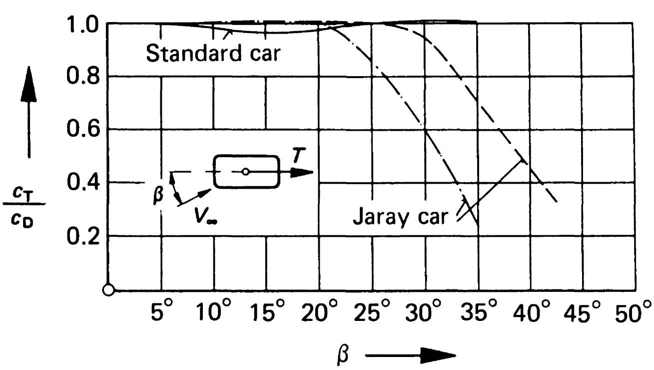


Figure 1.25 Drag variation versus yaw angle, after W. Klemperer[1.26]

increasing yaw angle for 'sharp edged' cars which already had high aerodynamic drag, but decreased sharply—after a slight increase—with streamlined shapes. He stated: 'The body of the vehicle then acts like the sail of a ship sailing hard to windward'. However, he made no measurements of lateral force and yawing moment, the most significant in cross-wind sensitivity. The drag curve for cross-wind will be examined in detail in Chapters 4 and 8, which also show that Fig. 1.25 is too optimistic regarding the effect of the side wind drag. Large angles of yaw, at which Klemperer's 'sail-effect' becomes effective, occur in practice only at low driving speeds, at which drag is insignificant anyway. On the other hand, at small angles of yaw additional resistances occur, which are considerably higher than might be deduced from Fig. 1.25.

Directional stability in cross-winds became increasingly significant with higher driving speeds, when it was realized that vehicles with low drag often possessed poor cross-wind stability (Kamm[1.39]). It was eventually discovered that only vehicles with long, tapering rear ends suffered in this respect, while the yawing of vehicles with truncated rear ends (Kamm back) was not uncommonly high (see Chapter 5).

It was even possible to produce aerodynamically stable yawing moment characteristics by adding tail fins, the effectiveness of which was proved in driving tests by Sawatzki.[1.40] However, fins were used only on record-breaking cars and motor-cycles, and were unsuitable for use on mass-production cars. False fins were sometimes used as styling elements, but even the rather large fin on the Tatra 87 (Fig. 1.18) probably contributed little to stability.

The danger from cross-winds results primarily from gusts, which occur naturally but are also caused by the terrain as well as the presence of vegetation and buildings, as originally reported by Huber.[1.41] However, little thought has been given to reducing cross-winds by proper landscaping, although the barriers and walls constructed to protect the environment from road noise may provide wind protection as well. Special attention has to be paid to gaps in these barriers and walls; see section 5.3.

With the start of systematic work on automobile aerodynamics, the problems of the flow of air through the vehicle were examined. Klemperer[1.26] considered the air flow through the cooling system in his model tests and showed that air flow through the radiator increases vehicle drag. Fiedler and Kamm[1.42] suggested ways of reducing this drag increase. In Kamm's school the flow processes in the radiator were examined in detail. The interaction between the vehicle, radiator and cooling air fan was investigated by Schmitt[1.43] and Eckert.[1.44] The principles for ventilating the passenger compartment were also elaborated by Kamm and his students, who investigated the relation between the external flow field and the volume of air passing through the passenger compartment. Much later (see Chapter 10), the possibility of improving passenger comfort by properly shaping the pattern of the internal flow field was investigated.

As mentioned earlier, true aerodynamically designed 'streamlined shapes' were used only sporadically for mass produced automobiles. The findings of Jaray, Lay, Everling and Kamm were applied, but their potential was not really exploited. Nevertheless, even at a very early date there were attempts to achieve even lower drag following the ideas of Klemperer and his 'half-body shapes'.

As early as 1922 Persu[1.45] built a car in Berlin which was derived from a half-body. The engine was located in the tapering rear end. No test results have been found for this vehicle. From 1930 several American authors worked with half-body cars, but their work was confined to the model stage. The results achieved by Fishleigh,[1.46] Heald,[1.47] Lay[1.33] and Reid[1.48] are summarized in Fig. 1.26. To evaluate the results achieved on the models with varying perfection and different scales, each half-body shape is compared with a contemporary limousine model tested by the same author. With the exception of the extremely long rear end examined by Lay, all half-body models had a drag coefficient approximately one-third of that of the contemporary limousine.

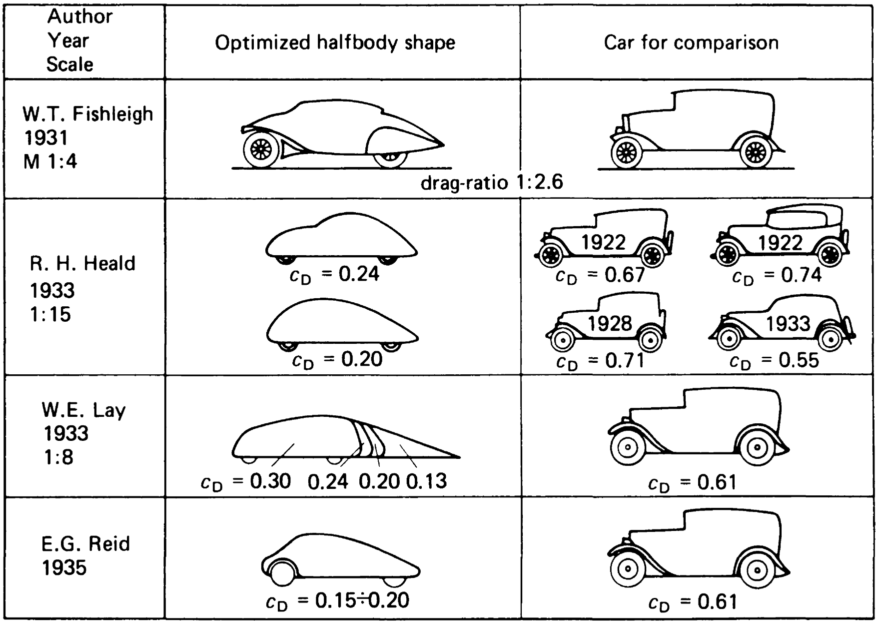


Figure 1.26 Bodies with low aerodynamic drag in comparison to contemporary US passenger cars

The development of a practical car of half-body design superstructure was achieved in 1937 at the Aerodynamische Versuchs-Anstalt (AVA) in Göttingen under Ludwig Prandtl. An analysis of the flow around the Lange car (Fig. 1.19) by Hansen and Schlör[1.49] led to the model shown in Fig. 1.27. The longitudinal mid-section is composed of two 'Göttingen aerofoils' each of which had the same drag coefficient of c_D = 0.125. The

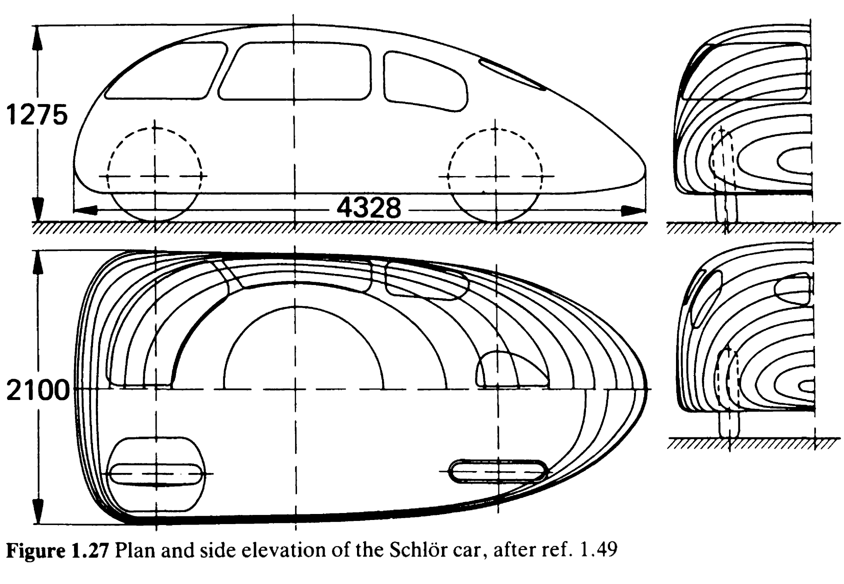


Figure 1.27 Plan and side elevation of the Schlör car, after ref. 1.49

lateral sections were developed from a rotational half-body so that the flow remains attached around a body with the largest possible internal space. The most important test results for this vehicle and scale models are given in Fig. 1.28. The drag coefficient c_D is plotted against the ground clearance e, which is made non-dimensional with the height h of the vehicle. With high ground clearance, the half-body had lower drag than the profile from which it was derived. With decreasing ground clearance, the drag

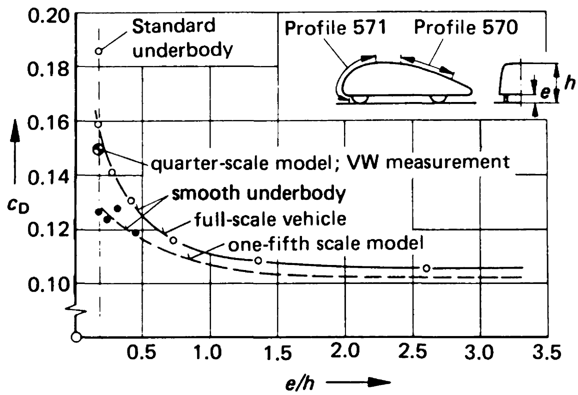


Figure 1.28 Drag coefficient of the Schlör car; measurements on models one-fifth scale (AVA), quarter-scale (VW) and full-scale car (AVA)

increases. The value of $c_D = 0.15$ measured by the author and his co-workers on a quarter-scale model (smooth bottom) with ground clearance suitable for a motor vehicle corresponds quite well with the data obtained by the AVA on the full-scale model with smooth bottom. On the actual vehicle, $c_D = 0.186$ was measured in the large AVA wind tunnel with elliptical nozzle (7 × 4.5 m). This accords well with coast-down tests performed at the Technical University in Hanover in 1939, resulting in $c_D = 0.189$. The Schlör car suffered from an unusually large frontal area of $A = 2.54\,m^2$, resulting primarily from its great width of 2.10 m, needed for

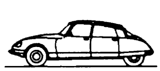
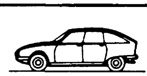
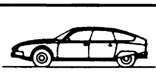
	Model Year	A [m²]	c_D
 ID 19	1956	2.14	0.38
 GS	1970	1.77	0.37
 CX 2000	1974	1.96	0.40
 BX	1982	1.89	0.33 – 0.34

Figure 1.29 Model line-up of Citroen cars from 1956 to 1982

lock-to-lock clearance of the completely covered front wheels. The large frontal area must therefore be considered intrinsic to this design.

The development of half-body designs reached its zenith with the Schlör car, which is impractical for mass produced automobiles.

The development of streamlined automobiles was interrupted by the Second World War. Citroën and Panhard were the only car manufacturers resuming this development after the war, as can be seen from Fig. 1.29. While Jaray's ideas can still be recognized on the ID 19 body (basic body and attached profile) the GS and the CX are more closely related to Kamm's ideas (cut-off rear end). All three models have an extremely low drag coefficient in comparison to their contemporary competitors. The

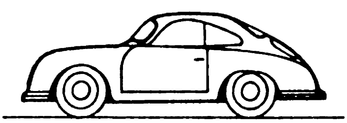
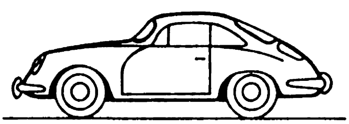
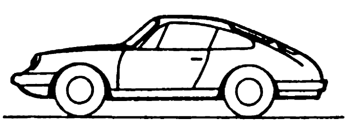
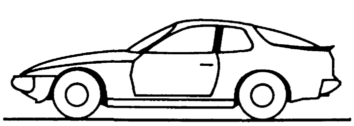
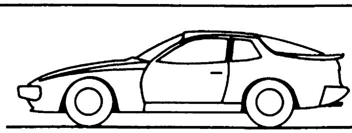
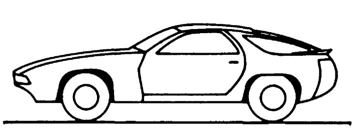
	Model year	A [m^2]	c_D
 356 A	1950	1.61	0.34
 356 B	1959	1.61	0.39-0.40
 911 S	1976	1.77	0.40
 924	1975	1.79	0.33
 944	1981	1.82	0.35
 928 S	1977	1.95	0.38

Figure 1.30 The Porsche car family from 1950 to the present

latest Citroën, the BX, can hardly be recognized as a streamlined car any more.

In the area of sports cars, Porsche, above all, has paid consistent attention to aerodynamic design, as can be recognized from the model series in Fig. 1.30. While the older models 356 A and B can be called Jaray shapes, the 911 is more closely related to the Lange model; see Fig. 1.19. The newer models from Porsche, the 924, 944 and 928, also have a distant relationship to the Lange shape.

In the course of styling a new model, the aerodynamicist is frequently confronted with a question like, 'What happens with drag if one or other detail of the body is changed?' In order to give helpful answers and to convey the basic facts of practical aerodynamics to the stylists, White[1.38] developed a 'Rating Method', based on the many measurements on full-scale cars performed at MIRA up to 1967. He selected nine body parameters crucial to the flow pattern around a car, and thus decisive for its drag; see Fig. 1.31. Each is rated with regard to its aerodynamic quality.

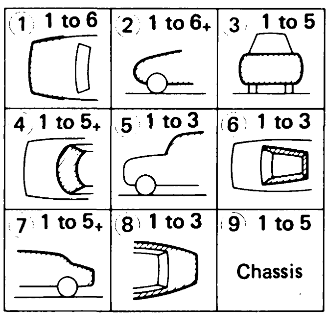


Figure 1.31 Details of the body, which are important for drag, together with their ratings, after ref. 1.38

Good flow quality is awarded low figures; body details likely to spoil the flow quality, for instance large flanges at the A-pillars, are penalized with additional points. The sum of points corresponds to the drag coefficient:

$$c_D = a \sum_{i=1}^{9} P_i \tag{1.4}$$

This linear relation is shown in Fig. 1.32 together with the bandwidth of error, which is stated by White to be ±7 per cent, not including the drag

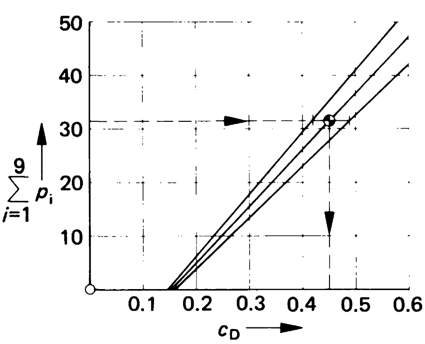


Figure 1.32 Correlation between the sum of rating and drag, after ref. 1.38

due to the cooling air flow. It might be difficult to estimate the cooling air flow drag better than its average value of $\Delta c_{DC} = 0.03$; see Fig. 4.95. This adds another ±5 per cent of error to the drag estimate. In fact, the total error in the drag estimate is ±15 per cent, which covers almost completely the bandwidth of drag coefficients of today's cars. Therefore White's rating method is not appropriate to differentiate today's cars with regard to their drag, not least because low-drag cars, which are coming into production more and more, were not around when White established his rating method. The merit of the method, however, was to identify clearly those areas of a car which have a major influence on drag, and to make them known to people in the car business who have no experience in aerodynamics.

1.2.4 Optimization of body details

Despite the success of modern streamlined cars, aerodynamics has only recently become the dominating design criterion. Previously, ways were found of adapting aerodynamics to practical automotive engineering requirements of styling, packaging, safety, comfort and production. The method of optimizing body details developed by Hucho, Janssen and Emmelmann[1.13] represents one approach. This 'third phase' is characterized in Fig. 1.8 by the Volkswagen Scirocco I and Golf (Rabbit) I. Since this method is treated in detail in section 4.4.1, only the principles will be presented here.

The starting point for aerodynamic development is the stylistic design; modifications to the shape must be made within the styling concept. Details such as radii, curvature, taper, spoilers etc. (Fig. 1.33) are modified in sequence or where required, in combination, step by step, to prevent separation or to control the separation so that the drag is minimized. Practice has shown that in comparison to the initial shape considerable

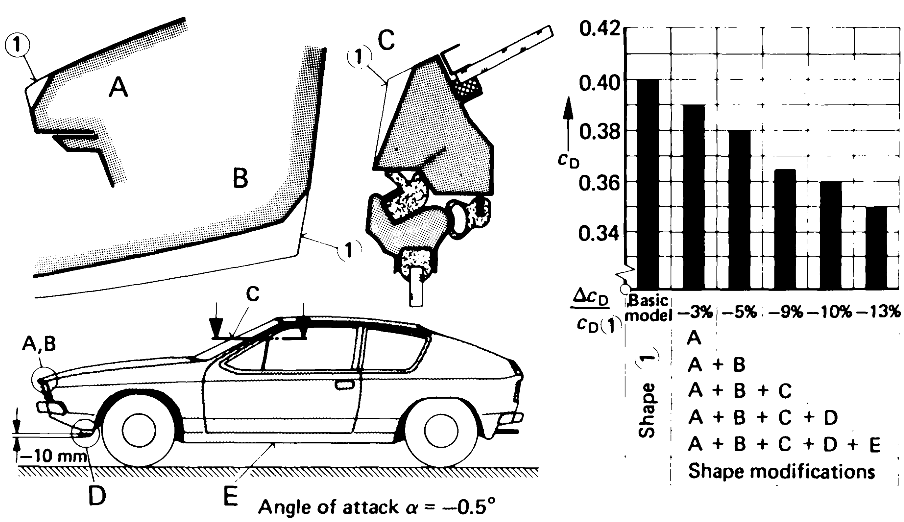


Figure 1.33 Example of development according to the 'optimization of body details'

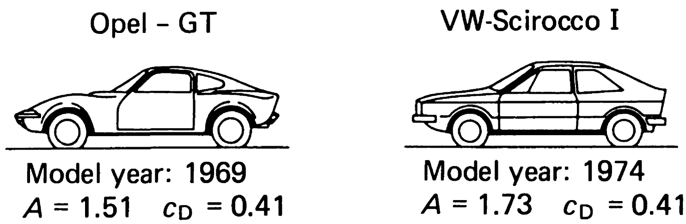


Figure 1.34 Comparison of drag coefficients for Opel-GT, styled by streamlining, and Volkswagen Scirocco I, designed by 'detail optimization'

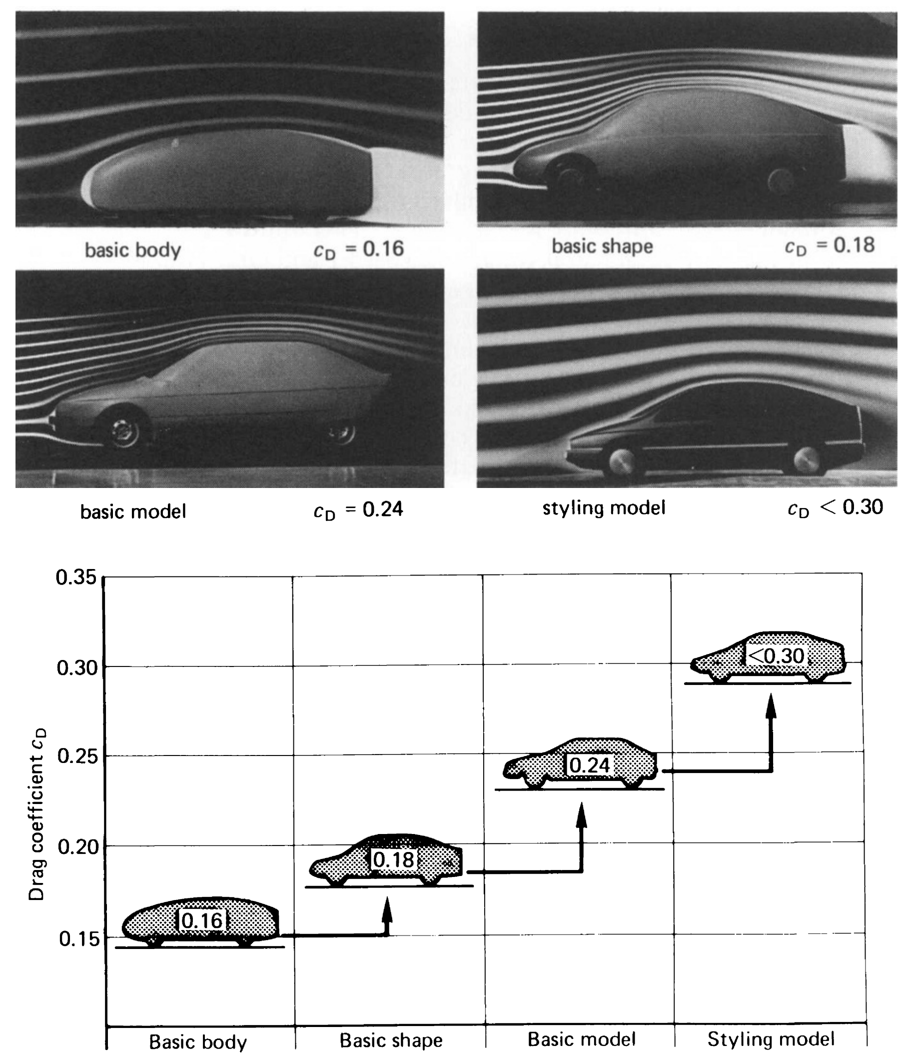


Figure 1.35 Development of a low drag car body, starting from an 'ideal' body, after ref. 1.51

reductions in the drag can be achieved in this manner (Fig. 1.34). Using the technique described, it was possible to reduce the drag coefficient of a VW Scirocco I from 0.50 in the original style model to 0.41. In spite of the emphatic 'hard' styling, it was possible to achieve the same drag coefficient as the Opel GT, which was styled according to the principles of streamlining. However, from many cars developed by detail optimization, it may be concluded that a limit of $c_D = 0.40$ can hardly be bettered.

For car manufacturers who still launch cars with $c_D > 0.45$, this method may serve as a design tool for a good while. To achieve a drag coefficient lower than $c_D = 0.40$ requires more advanced techniques.

One such method is 'interactive shape optimization', which permits significant deviations from the original styling concept; see section 4.4. The other is to start from a body of extremely low drag, and to convert this into a real car with low drag.

1.2.5 Shape development starting from low drag configurations

Unlike the detail optimization method, the aerodynamic development of a car can start from a low-drag body with the same overall dimensions as the final car. This low-drag configuration is converted into a real car step by step, applying the optimization technique for each detail. This method has been elaborated by the author and his co-workers[1.50] and is outlined in Fig. 1.35, after Buchheim et al.[1.51] Details are discussed in section 4.4.2. The Audi 100 III—with a drag coefficient of $c_D = 0.30$—is a striking example of the potential of this method (see bottom of Fig. 1.8). Figure 1.36 shows the two different routes to low-drag cars.

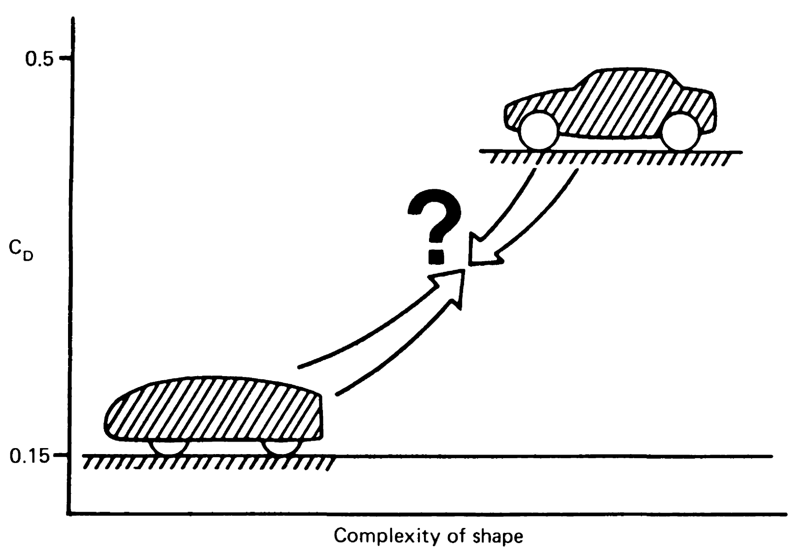


Figure 1.36 Alternative routes to low drag cars, after ref. 1.64

1.2.6 Trucks and buses

The need for high-speed trucks and buses arose with the construction of high-speed road systems in the 1930s. Prior to the construction of the Autobahn, autostrada, motorway and highway, mass transport of goods and people was accomplished by rail. The first buses and trucks were designed like elongated passenger cars. The same aerodynamic design principles were applied: at first the Jaray lines, later the Kamm-back. Kieselbach[1.19] recorded this period with many photographs and design drawings. With the introduction of the 'tram-bus' by Gaubschat in 1936, the shape of buses broke away from cars. With the engine underneath the floor—or later at the rear—more seats could be placed within the same overall length. The front end of the tram-bus was extremely well rounded (Fig. 1.37).

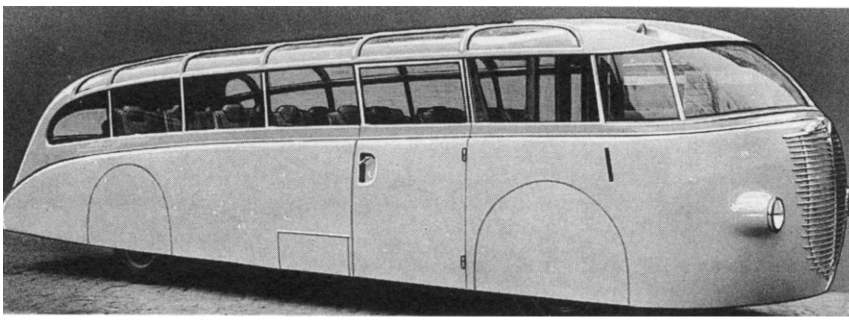


Figure 1.37 The 'Tram-bus' first built by F. Gaubschat on a Büssing chassis, 1936 (courtesy R.J.F. Kieselbach)

By 1930 Pawlowski[1.52] had published data on the influence of leading edge radii on the drag of rectangular bodies. As can be seen from Fig. 1.38, comparatively small radii are sufficient to arrive at minimum drag for box-shaped vehicles. Although this result was confirmed by Lay in 1933 with road tests, and although this finding has been repeated several times (see Chapters 8 and 11), it was not applied for a long time.

In 1936 the Kamm-back was introduced to bus design, based on measurements from Koenig-Fachsenfeld.[1.35] Because it allowed for one more row of seats in comparison to the Jaray back (Fig. 1.39) it was well accepted in practice.

Another milestone in the aerodynamics of commercial vehicles was the front design of the first Volkswagen van by Möller[1.53] in 1951 (Fig. 1.40). The two reasons for the wide recognition given to this work, apart from the drastic drag reduction, were the unique market position long held by this van all over the world, and the reference made by H. Schlichting in his famous book *Boundary Layer Theory*.[1.54] There the result is used to demonstrate the interaction between a body's shape, the flow pattern and the related drag.

However, for the first Volkswagen van no use was made of the earlier work of Pawlowski. The front end of the first VW van was much more rounded than was necessary to achieve an attached flow and the related low drag.

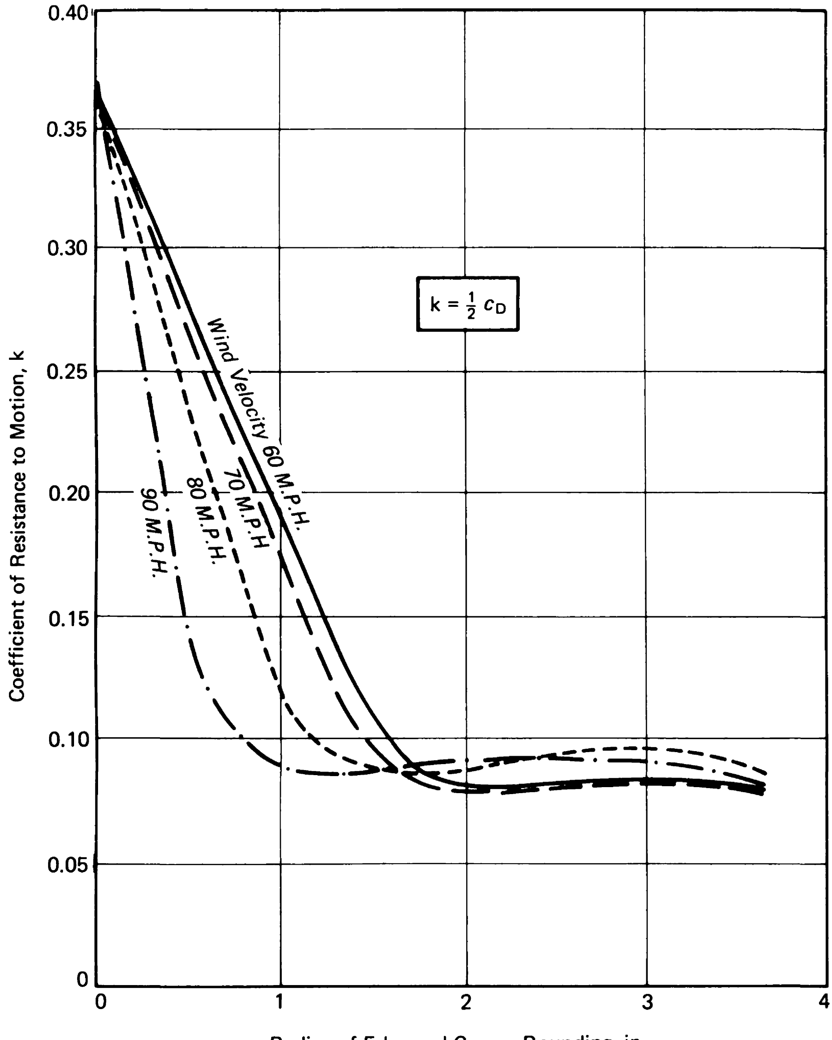


Figure 1.38 Influence of leading edge radii on drag of a rectangular box, after F.W. Palowski,[1.52] 1930

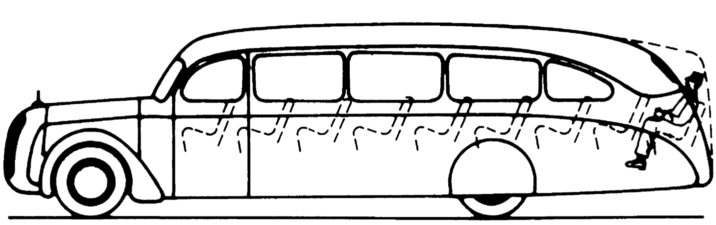


Figure 1.39 Jaray and Kamm backs on a bus

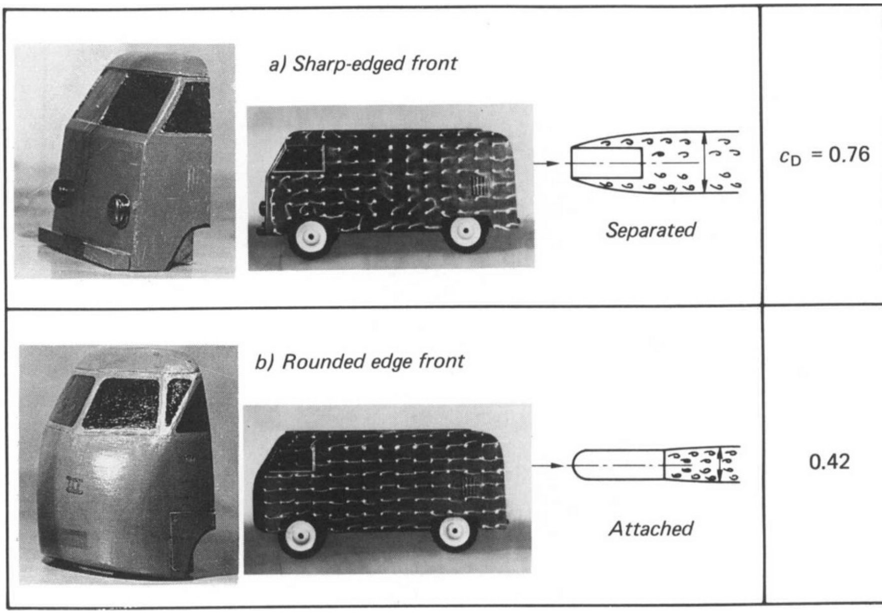


Figure 1.40 Flow around a model of the first Volkswagen van, after E. Möller,[1.53] 1951

The first van—to the knowledge of the author—which was designed according to the ideas of Pawlowski was the Volkswagen LT (Light Truck). The basic work was done on a quarter-scale model in 1969. Owing to the long lead time of this vehicle, these data were not published—together with full-scale measurements—until 1976 (see ref. 1.13, Fig. 29, van B); further details followed in 1978.[1.55] Figure 1.41 clearly shows that a non-dimensional leading-edge radius of 0.045 is sufficient to keep the flow behind the corner attached. The smoke trails taken on a full-scale vehicle (Fig. 1.42) show that only a small radius is needed to prevent separation.

Today leading-edge radii of buses and cabs of trucks, sometimes even those of trailers, are optimized in the same way; see Chapter 8.

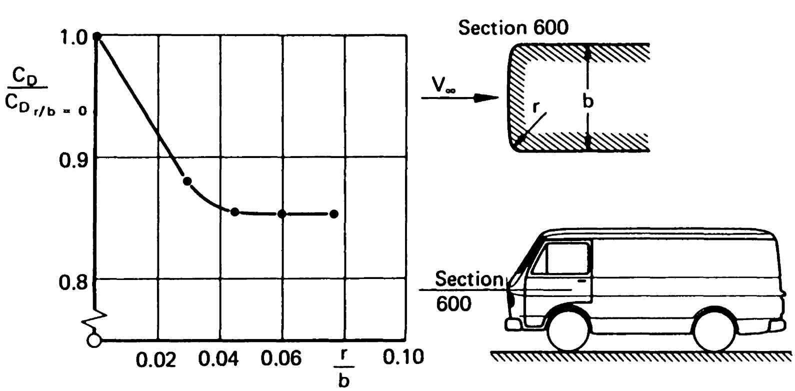


Figure 1.41 Determination of optimum leading edge radius for Volkswagen LT, after ref. 1.55

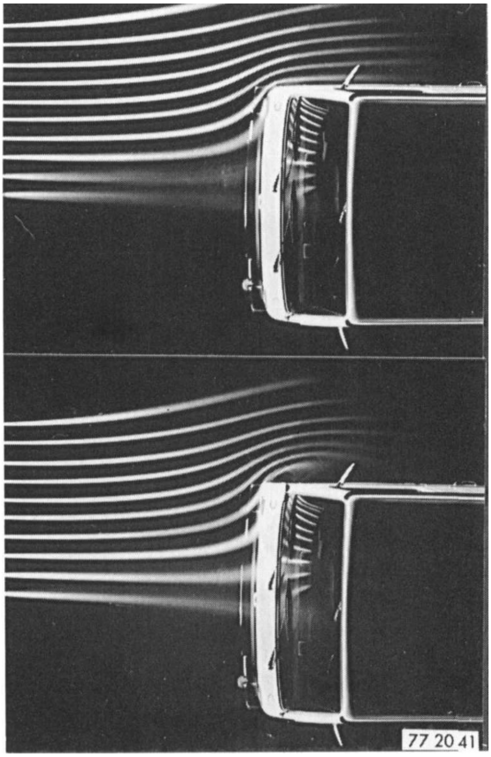


Figure 1.42 Smoke trails, taken from full-scale VW LT. Top: optimum radius, flow attached; bottom: sharp corner, causing separation; after ref. 1.55

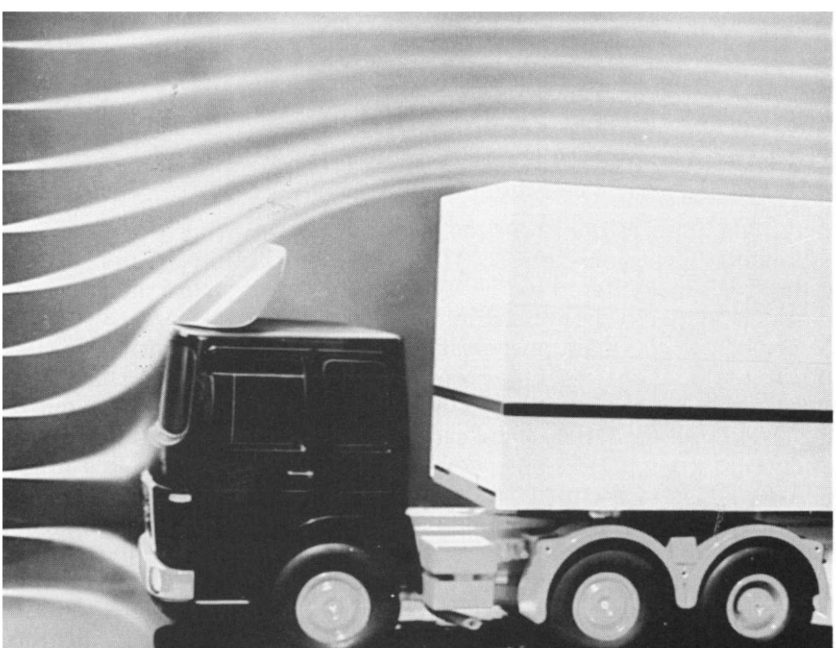


Figure 1.43 Cab-spoiler, providing, if correctly matched, attached flow on top of the trailer; from ref. 1.66

A further step to improve specifically truck aerodynamics was the invention of the cab-spoiler by Saunders.[1.56] The idea of guiding the flow by vanes goes back to the work which Frey[1.57] published as early as 1933. Guide vanes have long been applied to steam locomotives, mainly to keep the smoke away from the driver's cab, but also to reduce drag. Figure 1.43 shows how a guide vane, if properly tuned to cab and trailer, can improve the flow pattern and thus reduce the drag (see Chapter 8). The big advantage of this spoiler, and others, is that it can be attached to trucks already on the road. It also allows for individual matching to various trailer configurations.

1.3 Development trends

1.3.1 Vehicle engineering

The primary dimensions for European passenger cars are established within narrow limits for the individual vehicle classes. The size of the engine and drive train, the space available for the passengers and the volume of the trunk (boot) largely determine the primary dimensions shown in Fig. 1.44.[1.58] Japanese cars come well within the same

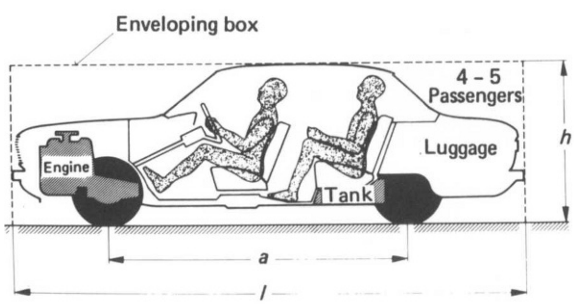


Figure 1.44 Design constraints for a passenger car, according to ref. 1.58

dimensional limits as the European cars. The 'down-sizing' programme of the US auto industry has brought US cars closer to European dimensions. But the free space offered by the 'box dimensions', length l, height h and width w, is ineffectively utilized by the design shape.

Nevertheless, the main proportions of the body shapes vary little (Fig. 1.45). In the smaller class, e.g. Ford Escort, VW Golf I, GM Astra, there are two different shapes: the traditional notchback and the squareback (Fig. 1.45a). On the latter, significant differences in the slant angle of the rear end are present (for more detail see Chapter 4). The middle range, e.g. Audi 80, Ford Sierra, GM Cavalier (Fig. 1.45b), again includes two different types of rear end; in addition to the notchback, the fastback is offered as a sporting alternative. Station wagons are not considered here. The larger passenger cars such as the Mercedes 240 (W 123) or Audi 100 (Fig. 1.45c) are similar in silhouette.[1.59]

If passenger cars are listed according to kerb weight and examined for changes in primary dimensions over the years, one finds that the length, width and wheelbase have remained nearly constant during the last 20

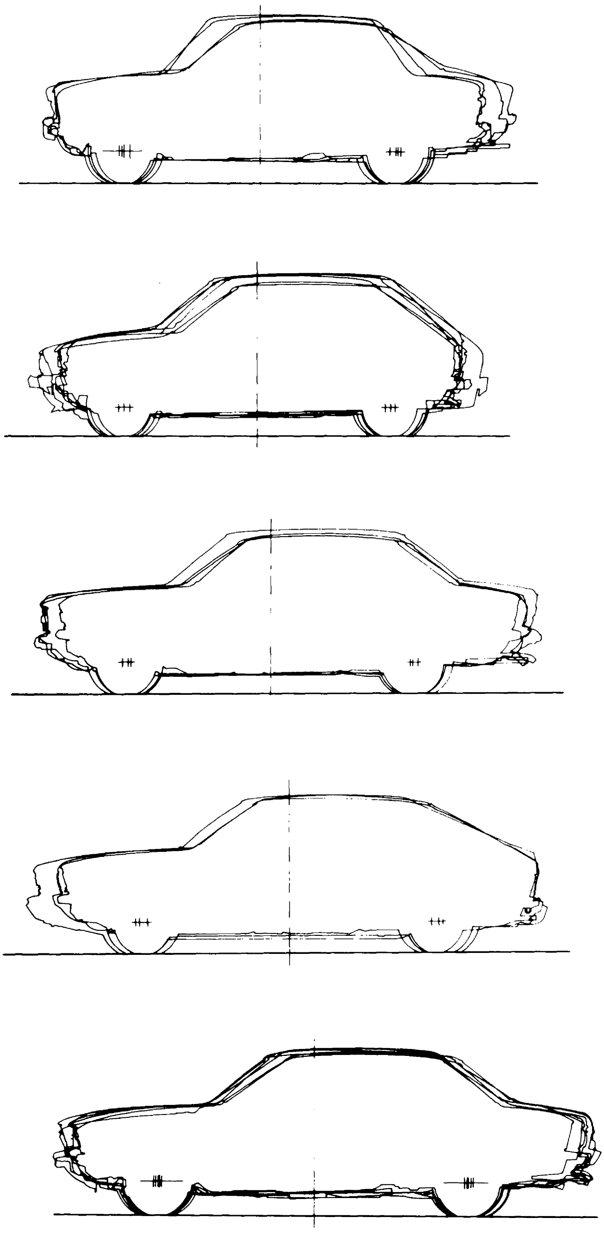


Figure 1.45 Centreline cross-section of European cars, after ref. 1.58: (a) small cars, (b) medium-size cars, (c) 'full-size' cars

years. According to ref. 1.60 (see Fig. 1.46), passenger cars have become continuously lower in height. The vehicles in all weight classes converge to practically the same height dimension; however, the ergonomic limit now seems to have been reached. For very small cars—the minis—the height is

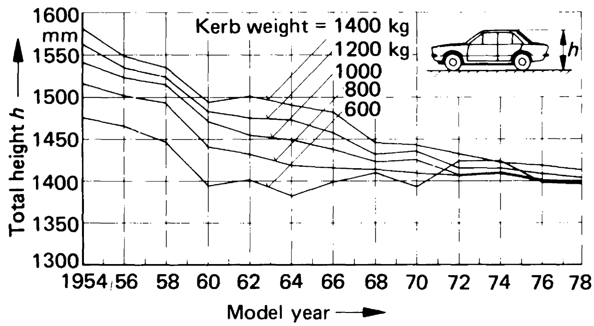


Figure 1.46 Development trend of car height for European cars over the years, after ref. 1.60

increasing again. How height is traded off against length has been demonstrated by Costelli[1.61] for the Fiat Uno car.

In automobile aerodynamics the frontal area A, which was defined in Fig. 1.3, is used to designate the size of a car. Figure 1.47, from Hucho,[1.58] shows that this is in fact a suitable parameter for this purpose. On

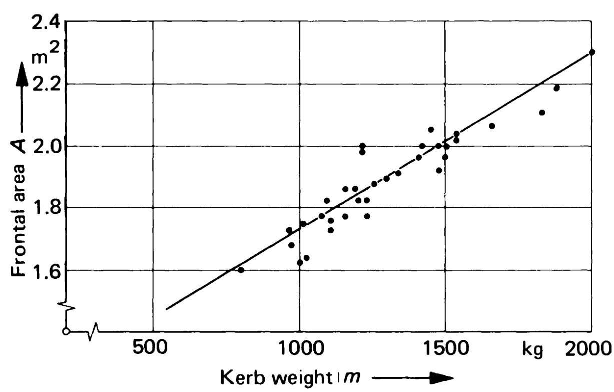
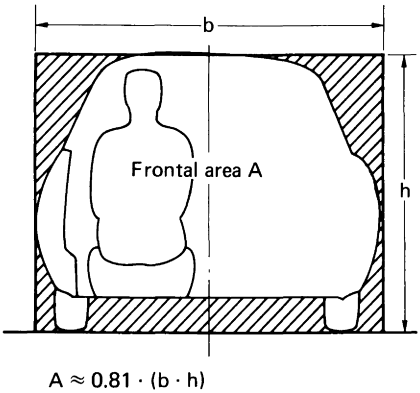


Figure 1.47 Correlation between frontal area A and kerb weight m for European passenger cars, after ref. 1.58

European passenger cars a good correlation exists between the frontal area A and the kerb weight m. In the future the slope of the line A versus m shown in Fig. 1.47 will probably become steeper. While the frontal area A can be assumed to be constant as a comfort dimension for the individual car classes, the kerb weight will be reduced further.

Among the various cars there is little variation in cross-sectional shape. Flegl and Bez[1.62] defined a shape factor f (Fig. 1.48) by which the frontal area can be correlated to the rectangle made up from the car's width and height. The average for f, measured for 85 European cars, is 0.81 with very little scatter. Car designers have cut off from the rectangle what was not needed for the passengers' comfort (see hatched area in Fig. 1.48). Among the different car classes, the frontal area of cars from competing manufacturers is almost identical. This again confirms that the frontal area is well suited to characterize the size of a car for aerodynamic purposes.



Car class	Frontal area A [m²]
Mini	1.8
Medium size	1.9
Upper medium size	2.0
Full size	2.1

Figure 1.48 Frontal area of cars, shape factor *f* for European cars, after ref. 1.62

The weight-to-power ratio for passenger cars has decreased continuously over the last 20 years. In Fig. 1.49 (from ref. 1.60) the kerb weight in relation to the engine power is plotted against time, again with kerb weight as a parameter. The trend to more powerful engines is now beginning to fade, whereas the trend to lighter vehicles, triggered by the energy crisis in the winter of 1973/74, is likely to continue; a further but moderate decrease in the weight-to-power ratio can therefore be expected in the foreseeable future.

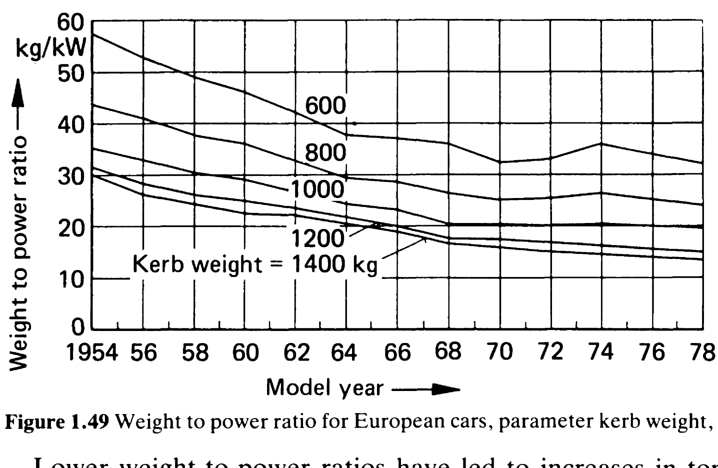


Figure 1.49 Weight to power ratio for European cars, parameter kerb weight, after ref. 1.60

Lower weight-to-power ratios have led to increases in top speeds; see Fig. 1.50 (from ref. 1.60). Despite the fact that there are speed limits in most industrial countries (with the exception of unlimited top speed on the German Autobahn) top speeds are still increasing. The speeds technically obtainable have progressed far beyond the top and average speeds driven in road traffic and even in racing. Figure 1.51 shows the world speed records over the years.[1.20] The dream of driving faster than the speed of sound was achieved in December 1979 in an unofficial record run. However, a relationship between speed records and the practical requirements of automotive engineering is no longer valid (see also section 7.5.2).

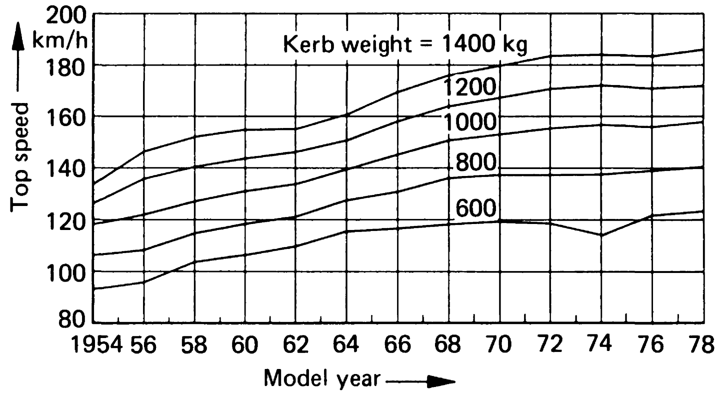


Figure 1.50 Top speed of European cars, parameter kerb weight, after ref. 1.60

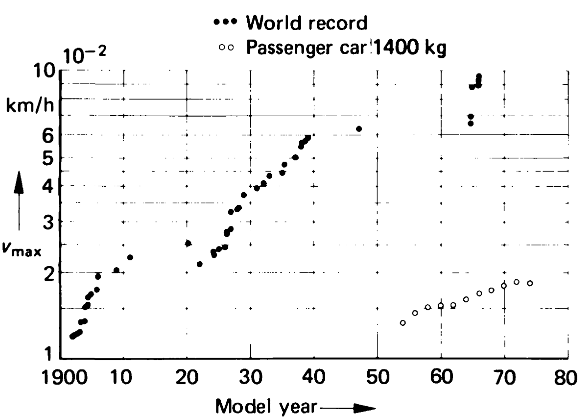


Figure 1.51 Official land speed records compared with top speeds of passenger cars

1.3.2 Automobile aerodynamics

The trend in the aerodynamic development of cars is summarized in the next two diagrams. Figure 1.52[1.13] shows how drag decreased between 1920 and the mid-1970s. Owing to the lack of statistical data only a general tendency can be outlined.

The reduction of the drag coefficient from $c_D \approx 0.8$ for cars in the 1920s to an average value of 0.45 for the cars of the 1960s and 1970s occurred in two stages. In the first, the period between the two World Wars, the cars were stretched and body details were rounded while maintaining significant characteristics such as projecting fenders and headlights. In addition to a lower drag coefficient of approximately 0.55, frontal areas were decreased, resulting in a considerable reduction of the total aerodynamic drag.

The second stage in the reduction of drag was reached with the introduction of the pontoon body with its variants, the notchback, fastback and squareback. By incorporating the fenders and headlights in a closed body shape, it was possible to improve significantly the flow of air around

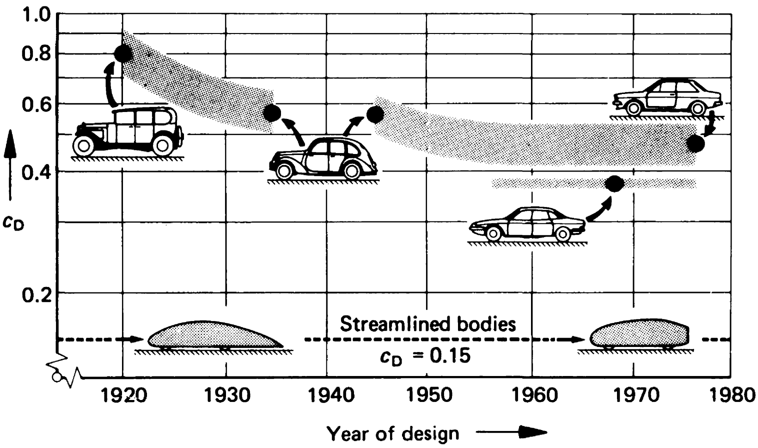


Figure 1.52 Trend in aerodynamic drag coefficient c_D against time, from 1920 to the mid-seventies, after ref. 1.13

the vehicle. Using this design, drag coefficients of 0.4 to 0.5 were achieved, depending upon the detail design. This scatter range has remained unchanged since about 1960. However, it is difficult to determine whether the reduction in drag resulted from the influence of aerodynamics, from styling or from more advanced manufacturing techniques.

The recent past is illustrated in Fig. 1.53. The histograms, from ref. 1.63, comprise the population of current European cars, classified by drag coefficient. The class-width is chosen as $\Delta c_D = 0.01$. From these data, the average drag coefficient has been calculated and plotted against time. These data are comparable in that they are all derived from measurements carried out in the Volkswagen wind tunnel. The average drag coefficient began to drop in 1978. The range of data—the scatter—is still enormous. Even some contemporary cars have drag coefficients worse than 0.50, while the best, the Opel Omega, has $c_D = 0.28$!

With concept cars (see section 4.63) there is still room for further drag reductions. Drag figures of 0.14 (GM Aero 2002) and 0.15 (Ford Probe IV) have been claimed for operational cars. Klemperer's value of 0.15, established in 1922, at last seems attainable. Today a drag coefficient of 0.30 is possible without major and expensive technical compromise. In the long run 0.20 might be achieved with production cars.

Increasing fuel prices will also encourage aerodynamic development of commercial vehicles. Drag coefficients for box vans cover the range of 0.4 to 0.5. A value of 0.40 can be realized without loss of transport space. Today the drag coefficients for heavy trucks lie between 0.6 and 1.0, the wide range being the result of the great variations in shape. Considerable drag reduction can be achieved through the design of the cab and the use of air deflectors. A value of 0.40 is a realistic goal for trucks and buses.

1.3.3 Vehicle aerodynamics and design

The relationship between aerodynamicist and stylist has been delicate in the past but is steadily improving. In early times, most of the aerodynamic

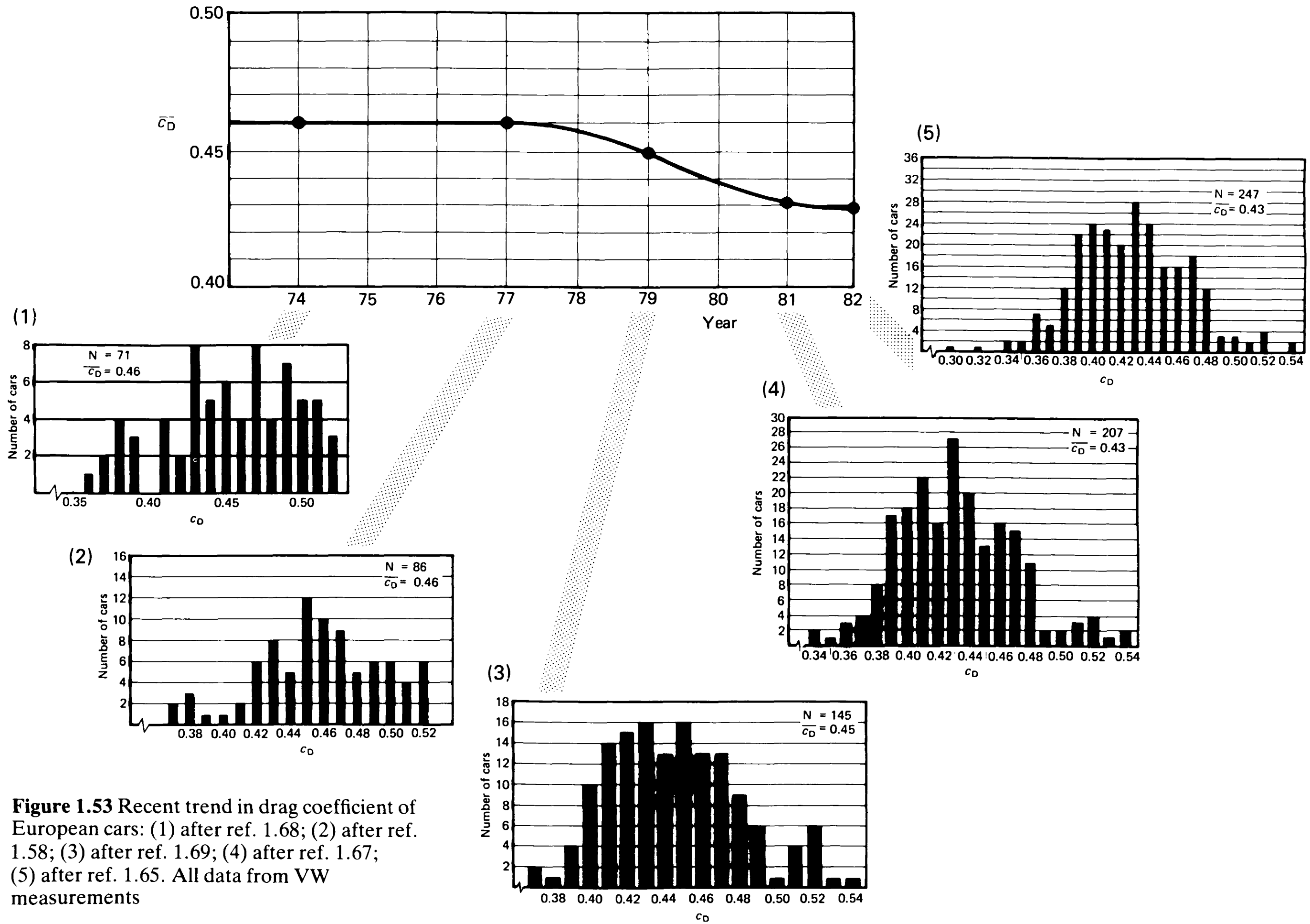


Figure 1.53 Recent trend in drag coefficient of European cars: (1) after ref. 1.68; (2) after ref. 1.58; (3) after ref. 1.69; (4) after ref. 1.67; (5) after ref. 1.65. All data from VW measurements

work was done by experts from outside the car industry, with experience in fluid mechanics on aircraft aerodynamics but with little understanding of the automobile. Most of their suggestions were too advanced for their time and were therefore not considered. The work of Rumpler and of Schlör is typical. And even Jaray, whose ideas were much closer to the automobile, had little success because of his unwillingness to interact with the stylists. All his cars looked alike, which is just what the stylist does not want. On the other hand, stylists used, and sometimes misused, aerodynamic 'devices' as marketing gimmicks. The boat tail, fastback and tailfins are examples.

This situation started to change when the car makers began to carry out aerodynamic development in their own purpose-built wind tunnels. The aerodynamicist, now an employee, became an automobile engineer and had to interact with design. He became aware that the demands of aerodynamics did not ease the task of the stylist, who already had many technical restraints and legal requirements to observe. The stylist, however, discovered that aerodynamics could set trends more logically and reasonably than did fashion, and began to accept this trend as valid for design criteria. The trend of drag coefficient against time shown in Figs 1.52 and 1.53 is a direct record of the cooperation between the two departments.

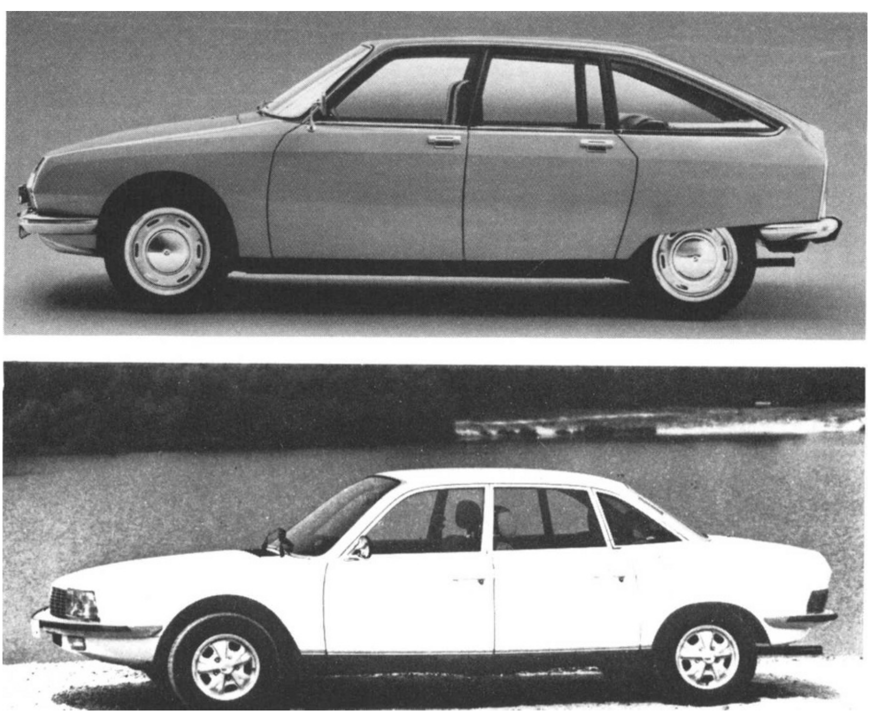


Figure 1.54 Top: Citroen GS, 1970, $c_D = 0.38$ (courtesy Citroën). Bottom: NSU Ro 80, 1976, $c_D = 0.38$. Model launched 1967, $c_D = 0.36$ (courtesy Volkswagen AG)

(a)

(b)

(c)

(d)

Figure 1.55 (a) Audi 100 III, 1982, $c_D = 0.30$ (courtesy Audi AG). (b) Ford Sierra, 1982, $c_D = 0.34$ (courtesy Ford Werke AG). (c) Mercedes Benz 190 ('Baby Benz'), 1982, $c_D = 0.33$ (courtesy Daimler Benz AG). (d) Renault 25, 1984, $c_D = 0.31$ (courtesy Renault)

Now aware of this improved cooperation, the buying public and motoring journalists became increasingly concerned that aerodynamics might lead to uniformity, and make all cars look alike. The following examples prove that this has not been true in the past, is far from being true at present, and need not necessarily be so in the future.

Examples from the past are shown in Fig. 1.54. The Citroën GS of 1970 accompanied the unique Citroën ID 19 and was a contemporary of the NSU Ro80, which was launched in 1967. Of course the good aerodynamics of both cars is apparent.

Four examples from the present are displayed in Fig. 1.55. All four cars, the Audi 100 III, the Ford Sierra, the Mercedes Benz 190 ('Baby-Benz')

Figure 1.56 Possible future low drag car shape: Citroen XENIA, 1981

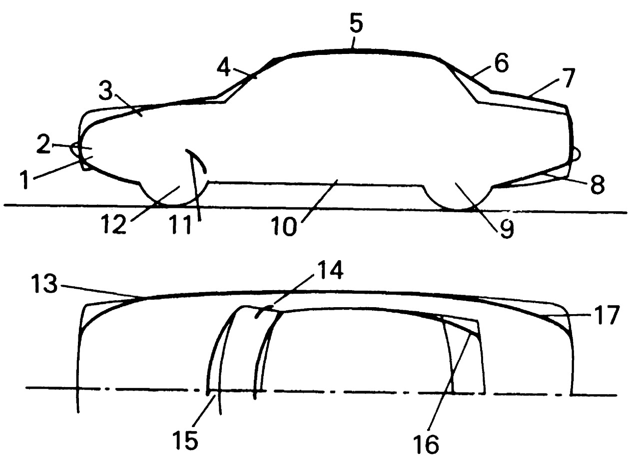


Figure 1.57 Contour comparison of today's 'standard' car, $c_D = 0.43$ and a low drag car, $c_D = 0.30$, after ref. 1.64

1 round front end
2 cooling air duct optimized
3 bonnet slope
4 windscreen slope
5 roof camber
6 rear window slope
7 trunk height
8 rear diffuser
9 covered wheels
10 smooth underside
11 round wheel-well moulding
12 wheel fairing
13 top view tapered
14 A-pillar round
15 windscreen curved
16 C-pillar inswept
17 rear end boat tailed

and the Renault 25, were designed under ambitious aerodynamic guidelines, but they still maintained their marque identities.

What might be expected from the future can be seen in Fig. 1.56. More examples are given in section 4.6.3. Although the drag coefficient will be reduced still further, there is ample room for individuality even for cars with $c_D = 0.15$, which is close to the limit for an 'ideal body' with wheels.

Today's cars are very similar not only in cross-section, as has been demonstrated in Fig. 1.45, but also in many other details such as rectangular head- and tail-lamps. Aerodynamics cannot therefore be blamed. However, future cars will have several common characteristics because of aerodynamics. These are identified in Fig. 1.57, after Hucho.[1.63,1.64] This similarity will be no more pronounced than it is today, for reasons other than aerodynamics. Neither is it expected that only one set of the many ruling parameters will lead to a target drag figure, or that there will be no room for product identity.

1.3.4 Development expenditure

Aerodynamic development of motor vehicles is expensive. Much capital must be invested in testing facilities such as wind tunnels and climatic tunnels. Secondly, considerable costs result from the work itself. Finally, the development time may be lengthened by aerodynamic work. The efforts to improve the aerodynamics of vehicles is witnessed by the large number of wind tunnels constructed specifically for this purpose. Nearly all major manufacturers now have such facilities at their disposal or are currently building them. These wind tunnels are described in greater detail in Chapter 11. Generally, the demands upon the quality of a wind tunnel increase with the expectations placed upon the quality and reliability of the results. Similarly, the development costs increase steeply with the quality of the intended results.

If a drag coefficient of 0.50 is to be achieved, hardly any costs result for the aerodynamic development. If the individual results published in the literature are properly applied, wind tunnel tests can be eliminated completely for such a conservative development goal. If a value of 0.45 is sought, development costs still remain moderate. Several days of testing in a model wind tunnel on a model with a scale of 1:4 or 1:5 will assure that the objective is reached. The development time for the new model is not lengthened. On the other hand, a value of 0.40 is achieved only at high cost. Measurements requiring a number of weeks on painstakingly prepared, full-size models in a large wind tunnel are indispensable. The suggestions for modification of the shape must be clarified in consultation with the stylists, the designers and the production engineers; the development process is affected considerably by this. If a value of 0.30 is set as target, development of the shape must precede the actual development of the vehicle. With the present state of knowledge in automobile aerodynamics, several months must be scheduled for this. This procedure also requires full-size models and a large wind tunnel. The absolute magnitude of the development costs is dependent upon the specific company and cannot be given in generally valid figures. Buchheim et al.[1.65] said that 1000 hours in the wind tunnel were necessary to develop the Audi 100 III. However, this figure includes the work for engine cooling and compartment ventilation as well. Assuming a cost of $1500 per hour, this alone results in $1.5 million wind tunnel cost, not taking into account the cost of the models and of numerical calculations.

The increase in development costs resulting from higher development goals must be counteracted by the availability of greater in-depth knowledge and the application of theoretically sound development procedures. Already today there are methods on hand to predict fairly accurately the characteristics of an engine cooling system or a passenger compartment heating system (see Chapters 9 and 10). Numerical methods, which allow the calculation of the external flow field or parts thereof, are under development. What they can accomplish today and what they are unable to predict is outlined in Chapter 13. In the future, improved predictions can be expected from new calculation procedures. Even so, they will not replace testing, and at most will facilitate test preparation and evaluation, and thus will allow the test expenditure—in terms of costs as well as time—to be kept in check.

1.4 Notation

A	frontal area; Fig. 1.3
A_C	cooling air inlet area; Fig. 1.5
D	aerodynamic drag
P	engine power
Q	heat flux; Eqn 1.3
T	tangential force; Fig. 1.25
V_∞	oncoming flow velocity; Fig. 1.25
V	driving speed
a	wheelbase; Fig. 1.44
c_D	drag coefficient; Eqn 1.2
c_T	tangential force coefficient; Fig. 1.25
e	ground clearance
h	height of vehicle
l	length of vehicle
m	vehicle mass
w	width of vehicle
Λ	aspect ratio
α	angle of attack
β	angle of yaw; Fig. 1.25
ρ	air density

Chapter 2

Some fundamentals of fluid mechanics

Dietrich Hummel

2.1 Properties of incompressible fluids

2.1.1 Density

The density of any material is defined as its mass per unit volume. In fluids this property depends on the pressure p and on the temperature T. The highest speeds achieved by land-vehicles during record attempts (Fig. 1.51) are in the order of the speed of sound, which is for air $a = 340\,\text{m/s} = 1225\,\text{km/h} = 765.6\,\text{mile/h}$. In the flow field of a body exposed to such a free stream the compressibility of the air, i.e. the variation of density due to changes of pressure and temperature, is very important. On the other hand, most vehicles including racing cars are operated at speeds V which are lower than one-third of the speed of sound. For this speed range the variations of pressure and temperature in the flow field vary little from those of the free stream values, and therefore the corresponding density changes can be neglected. Thus the fluid can be regarded as incompressible. In the case of air the density is a constant property, the numerical value of which is, according to US standard atmosphere sea-level conditions ($p = 1\,\text{atm}$, $T = 288\,\text{K}$)

$$\rho = 1.2250\,\text{kg/m}^3 \quad (= \text{N}\,\text{s}^2/\text{m}^4)$$

2.1.2 Viscosity

Viscosity is caused by the molecular friction between the fluid particles; it relates momentum flux to velocity gradient, or applied stress to resulting

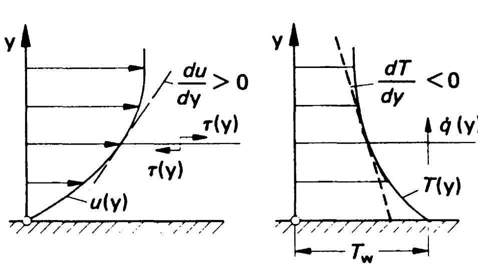


Figure 2.1 Distribution of velocity and temperature in the vicinity of a wall (schematic)