Chapter 6

Operation, safety and comfort

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6.1 Definition of themes

In Chapters 4 and 5 a relationship was established between the flow around a passenger car and the resulting forces and moments. In this context, separations are of interest in as much as they influence the integral force and moment coefficients. This global approach is no longer sufficient within the framework of this chapter.

The aim here is to illustrate that air flow around a vehicle should be developed also on the basis of factors that have nothing at all to do with the mechanics of motion, but which are of crucial importance in terms of operation, safety and comfort of the vehicle. Phenomena such as the accumulation of dirt on the vehicle, cooling of the brakes, the magnitude of forces on individual bodywork components, the fluttering of bodywork components and bolted-on parts and, finally, the occurrence of wind noise are directly connected with air flow around the vehicle. Treatment of these problems requires an exact picture of the character of local flow. Figures 4.3 and 4.4 give a qualitative illustration of the individual fields of flow. Quantitative results are available only by measuring individual local fields.

6.2 The field of flow around a vehicle

6.2.1 Air flow patterns

A distinction can be made between two basic types of flow around a vehicle: there are areas of attached flow as well as of separated flow. Further differentiation can be made between separated flow of quasi-two-dimensional type and of three-dimensional type (see section 4.2). The location of such areas of separation and the determination of their extent is possible by means of relatively simple test techniques. Figures 6.1 and 6.2 give examples of how vehicle air flow can be made visible. In Fig. 6.1 thin woollen threads have been fixed to the vehicle surface at set intervals. The orientation which the threads adopt during air flow gives an indication as to the local direction of flow. Three-dimensional separation behind the A-pillar is clearly visible in this figure.

Figure 6.2 shows an oil flow picture of a test vehicle. A thin emulsion of aluminium oxide, kerosene and petroleum, painted onto the vehicle, is

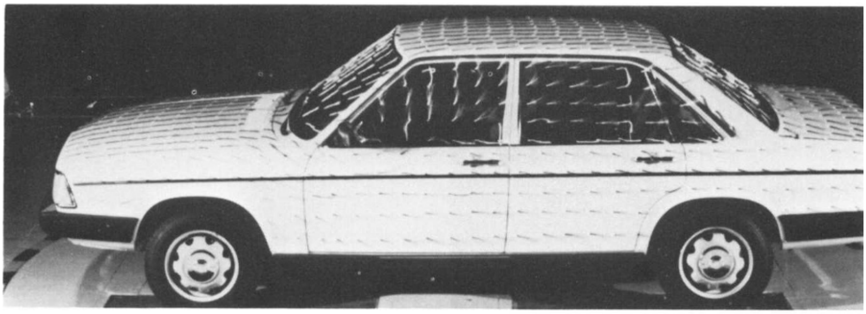

Figure 6.1 Air flow around a vehicle, made visible by using woollen threads, after ref. 6.17

Figure 6.2 Flow pattern of a delivery van with front edge radius $r = 0$ mm, angle of yaw $\beta = 0°$, after ref. 6.6

dried by the air flow in the wind tunnel. The picture thus created is likewise only a limited indication as to local direction of flow, since the influence of gravity upon each particle of the liquid distorts its path. Thus, the lines formed on the surface of a body during this procedure always deviate downwards from the actual lines of flow. On the other hand, the illustration shows two clearly recognizable areas of separation, one behind the A-pillar, the other behind the vertical edge of the front end. Air flow in this illustration was frontal. Both techniques mentioned here give an idea of the course of lines of flow at the vehicle surface. Such investigations cannot give any indication as to air flow within the area surrounding the vehicle, but smoke flow can be of use.

The air flow around the front of a car made visible in Fig. 6.3 (after Hucho and Janssen[6.6]) illustrates an example of separation at the front edge of an engine bonnet. The introduction of smoke into the separated air flow (below in Fig. 6.3) is a particularly effective way of making separated air flow visible. Smoke, injected into a separation bubble, fills this bubble

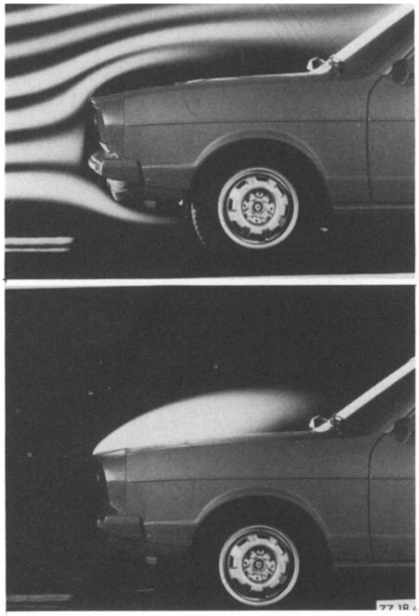

Figure 6.3 Separation bubble made visible by means of smoke, which is injected either as streaks into the undisturbed flow or into the separated flow, after ref. 6.6

completely because of the recirculating flow pattern inside the bubble. Therefore the separation line is clearly identified.

An exact, quantitative description of the flow field is possible only through the measurement of speed and pressure distributions by means of probes. However, during the development of a new car this precise information is hardly heeded. Flow visualization methods are adequate to identify problem areas.

Within the framework of the problems outlined in section 6.1, the following areas of separation occurring on a vehicle are of interest:

- Engine bonnet separation
- Roof separation
- A-pillar eddies
- Longitudinal tail vortices
- Wake.

Separation over the bonnet of a vehicle (see Fig. 6.3) is caused by the front edge being too sharp and, apart from the two side areas of the vehicle, can be regarded as being quasi-two-dimensional. Separation at the front roof edge is essentially identical to engine bonnet separation. The third important area of air flow separation occurs to the rear of the A-pillar, the A-pillar eddy. Eddy separation occurs at this pillar, the roof post between front and side windows, just as it does on angled delta wings. Figure 6.4, after Watanabe et al.,[6.5] shows air flow made visible in this area on a vehicle. This oil flow picture confirms the nature of air flow determined by model tests. A vortex is formed, with a secondary one to the side of the edge. Figure 6.5 is a schematic drawing, also after Watanabe. This type of separation has a three-dimensional character.

There are two forms of air flow separation in the rear region.

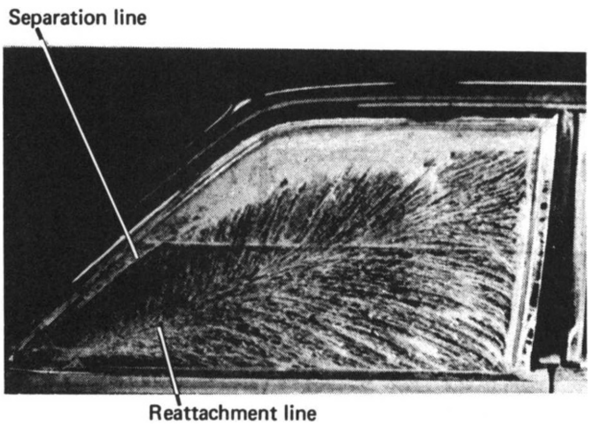

Figure 6.4 Oil flow picture of the three-dimensional A-pillar separation, after ref. 6.5

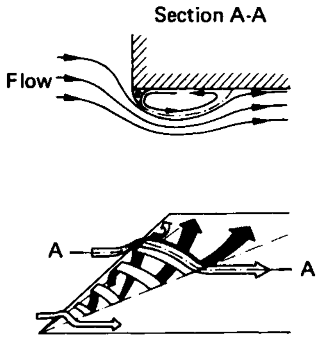

Figure 6.5 Schematic drawing of an A-pillar vortex, after ref. 6.5

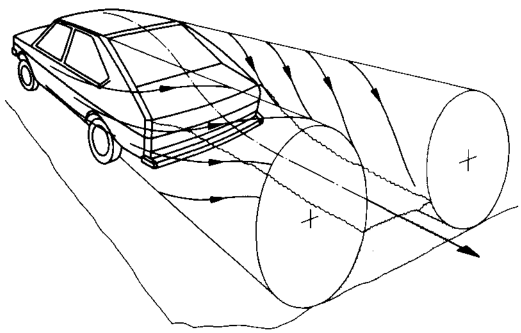

Figure 6.6 Schematic drawing of fully formed trailing vortices on a fastback vehicle, after ref. 6.3

Longitudinal vortices, after Hucho[6.3] and highly simplified in Fig. 6.6, are caused by the static pressure difference between the upper and lower sides of the vehicle (Figure 4.4 corresponds rather more to the actual course of air flow). The pressure difference between the underside of the vehicle and the roof induces on both sides an upward flow which, together with the flow over the roof, forms trailing vortices.

Figure 6.7 Wake made visible behind a VW Golf (longitudinal vortices have not formed)

The second type of air flow separation in the rear area of a vehicle is the wake, which has been made visible in Fig. 6.7 by introducing smoke. Flow over the vehicle can no longer follow the contour, separating from the rear edge of the roof. Flow within the area of separation appears random. However, there is a tendency towards particular flow directions. This will be dealt with further in section 6.4.3. The immediate aim is to examine the influence of the air flow details dealt with here in the context of operation, safety and comfort.

6.2.2 Pressure distribution

When a vehicle is moving, a certain velocity distribution, and thus also pressure distribution, is set up. Figure 6.8 shows a comparison between the pressure distributions measured along the longitudinal centreline of three

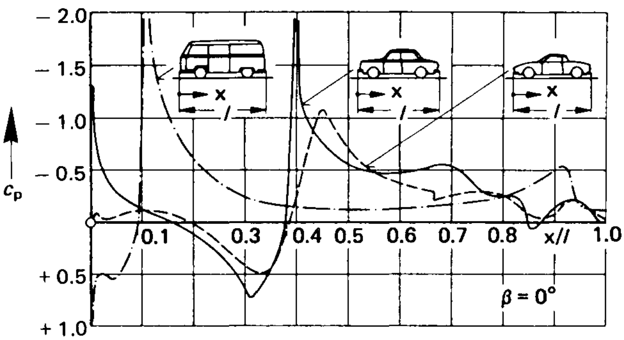

Figure 6.8 Upper body surface pressure distributions of several vehicles

different types of vehicle: a van, a notchback car and a sports car. Pressure is represented in line with Eqn 2.8 as a dimensionless coefficient c_p. Knowledge of local pressure distribution is important for three reasons (see also section 2.3.2):

- Determining areas for air inlets to the passenger compartment
- Determining areas for air outlets from the passenger compartment
- Determining the forces acting upon bodywork components.

Two different concepts may be employed in order to supply air to and remove air from the passenger compartment (see also section 10.4.1):

- Speed-dependent volume flow
- Speed-independent volume flow.

Volume flow can be made independent of vehicle speed by locating air inlets and outlets in areas of equal pressure. There is then no pressure difference, and a constant air flow rate can be generated by means of a continuously operating fan. The extra noise generated, as well as higher production costs for the more powerful fan, have however led to a preference in practice for the second option, involving volume flow which is indeed dependent on vehicle speed, but with which the fresh air fan need not necessarily operate continuously.

Generally speaking, there is little freedom of choice as regards air inlets. In order to guarantee a sufficient supply of air with minimal fan power, the location chosen for the air inlet is in an area where pressure is highest. As shown in Fig. 6.8, there are two possibilities as far as a passenger car is concerned. First, in the front end of the vehicle, i.e. in an area near to the stagnation point where $c_p = 1$. The drawback here is that exhaust gas from a vehicle in front enters the passenger compartment. Furthermore, a long air duct is necessary from the air inlet to the passenger compartment, meaning additional design outlay and thus greater expense. The second possibility is in the region in front of the windshield, the scuttle. The air inlets are generally located in the centre of this region. Static pressure at this point, which must be known in order to be able to design the ventilation system, can vary from vehicle to vehicle. It is influenced by the slope of the windshield, as well as by the nature of air flow on the front bonnet. If air flow separates at the front edge of the bonnet, the pressure depends upon where the air flow reattaches again.

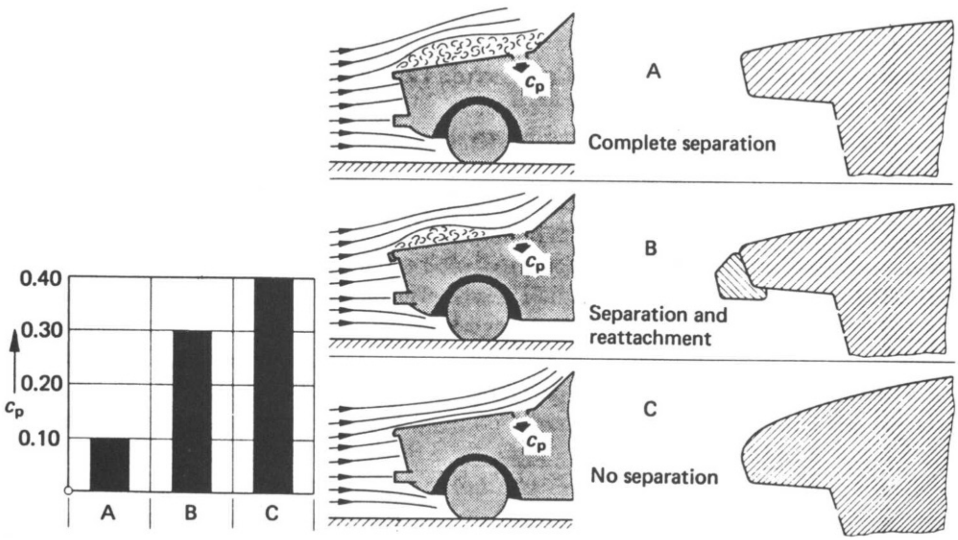

Figure 6.9 The influence of bonnet air flow upon pressure in front of the windscreen, after ref. 6.2

Figure 6.9 shows the influence of the design of the front edge upon pressure just in front of the windshield (after Janssen and Hucho[6.2]). With design A, where flow separation above the hood is complete, only slight pressure of $c_p = +0.1$ is set up. If a vehicle were to be built with this front end contour, it would need to have a continuously operating fan. With contour B, where air flow around the front edge is better, air flow separates at the edge and reattaches to the vehicle surface in front of the air inlet region. The pressure measured with this design rises to $c_p = +0.3$. With a rounded hood edge, such as contour C, air flow does not separate from the hood. Pressure rises to $c_p = +0.4$, thus providing for sufficient ventilation during cruise without an additional fan.

With vans (see Fig. 6.8) the front panel of the vehicle is the only possible position for air inlets. However, it must be placed as high up as possible, in order to prevent exhaust gas from entering the passenger compartment.

There is greater freedom of choice in the location of air outlets. At first sight, it would seem suitable to choose an area where pressure is lowest, i.e. the transitional area between windshield and roof. This solution does indeed generate the maximum pressure difference, and thus maximum air volume flow, though distribution of fresh air and warm air in the passenger compartment would be unsatisfactory (see Chapter 10) since there would be no air circulation through the rear of the passenger compartment. Furthermore, severe noise problems would be introduced, as tests have indicated. Bearing certain production factors in mind, satisfactory passenger compartment flow is most easily attainable if the air outlets are located further towards the rear.

There are various areas of lower pressure to choose from at the rear end. In Fig. 6.10, the results of pressure distribution measurements are given (after Hucho[6.10]), which were conducted with a view to the selection of air outlet locations on notchback vehicles. Measurements were made in four

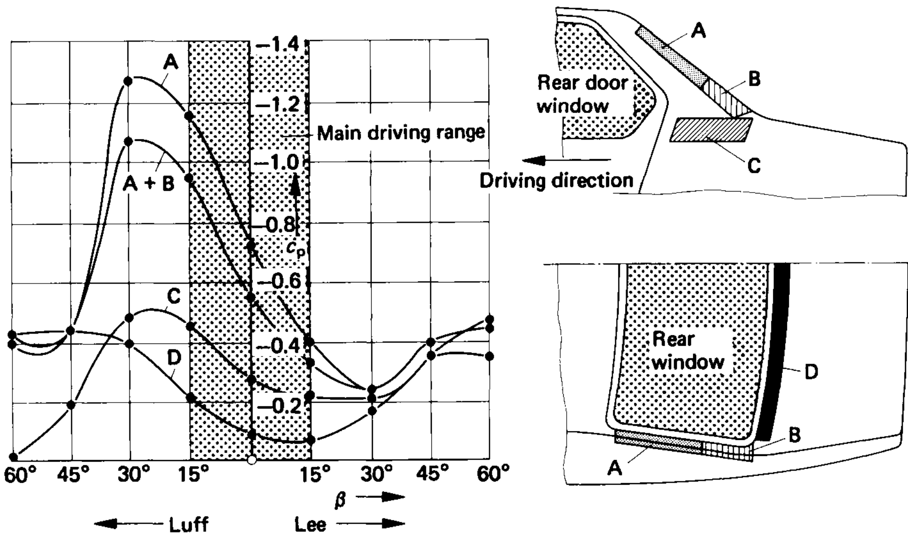

Figure 6.10 Pressure distribution measurements with a view to the selection of air outlet locations on a notchback passenger car, after ref. 6.1

areas of low static pressure potentially suitable in construction terms for the location of air outlets. The values featured are the mean values of the pressure coefficients measured in these areas. It can be clearly seen that there is a considerable rise in pressure in the event of side wind on the lee side. The yaw angle β must be varied within the series of tests, in order to ensure that the air outlets work properly even when cross-winds act upon the moving vehicle.

Pressure conditions at an outlet are determined to a great extent by details of bodywork design. If, for instance, the outlet is located to the rear of the rain gutter on the C-pillar, pressure at this point is mostly dependent upon the geometrical shape of the rain gutter. Results comparable to those in Fig. 6.10 were obtained by Hucho and Janssen[6.16] when developing air outlets for the Volkswagen 1300 (Beetle).

6.3 Forces acting upon bodywork components

The fact that pressure distribution around the vehicle results in air forces and moments has already been dealt with in Chapters 4 and 5. This chapter deals in more detail with the forces acting upon individual bodywork components. These forces can be either steady or non-steady. Using the front side window as an example, Fig. 6.11 shows that these forces can

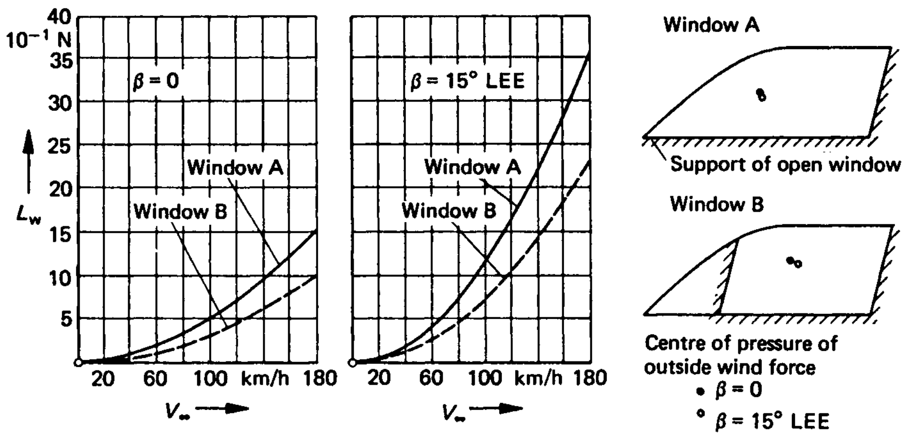

Figure 6.11 The influence of vehicle speed and yaw angle upon the resulting side window force

become quite considerable, necessitating appropriate design measures. The magnitude of the force depends of course upon the area of the window, but also to a considerable extent upon the direction of the oncoming air flow. The resulting force increases on the lee side because of the decreasing static pressure on the outside. This effect can lead to pulling away from the door seal, especially with frameless windows. Through this open gap a high-frequency jet is set up, caused by the pressure difference (see section 6.5.2). This causes great discomfort. A remedy is available in the form of an increase in the resistance of components to distortion, or, adopting the aerodynamic approach, by increasing exterior pressure by reducing local air flow speed.

Forces and moments acting upon movable bodywork components, such as hoods and lids, merit particular attention. Because of the high suction peak on the front edge of the hood (see Fig. 6.8) great forces are generated. If the front compartment is to hold luggage care must be taken to ensure that the lid is tightly sealed even at high speeds. Sloping the lid or increasing the radius of the front edge will reduce the suction peak in the front area of the hood.

Periodic flow, occurring for example in separated regions, leads to non-steady forces upon vehicle components, and can, if they are flexible, lead to so-called fluttering, see also section 2.3.4.2. Such effects have been observed on passenger car front hoods and van roofs. When developing the air flow around bodywork components which have a large surface the danger of such self-excited flutter motion cannot always be reduced by preventing separation. Very often the only measure is to design the related part to be more rigid. The tendency towards long, low vehicles, and thus to only slightly convex bodywork components, as well as to weight-saving construction, will mean that greater attention will have to be paid to the problem of flutter in the future.

This examination of non-steady forces acting upon bodywork components must also include the exterior rear-view mirror. Periodic air flow in the separation area to the rear of the rear-view mirror leads to a non-steady load upon the mirror. Since the very function of the mirror necessitates that it be mechanically movable, sympathetic movement of the component can occur. In order to counter this, the mirror geometry may be modified in such a way that the tendency to vibrate is prevented. The final geometry of the mirror is, however, determined by still further factors (see also section 6.4.2).

6.4 Dirt accumulation on the vehicle

6.4.1 Basic considerations

The accumulation of dirt on the surface of a vehicle is significant in two respects (see also section 8.6): first in terms of safety, i.e. the accumulation of dirt on the headlamps, direction indicators and windows, and secondly, in aesthetic terms, i.e. the problem of the accumulation of dirt over large sections on the vehicle sides, in particular near the sills and door handles. The very title 'Dirt accumulation on the vehicle' represents a whole new factor: air flow around the vehicle is now to be treated as a bearer of dirt (see also section 2.3.4.3). The particles carried by the air could be either liquid (water) or solid (dirt raised from the road surface). When driving, these two types can combine in the form of dirty water. However, for the sake of simplicity, a distinction will be made here between water flow around the vehicle and dry dirt deposits upon a vehicle.

6.4.2 Water flow

Because of the reduction in visibility it causes, the wetting of a vehicle's windows is treated as a problem in its own right during development work. The windscreen, the A-pillar and the side windows to its rear, the exterior rear-view mirror and the rear windows are involved. The development of water flow always takes place with a defined method of water guidance in mind. Water must be diverted and then got rid of before it can accumulate on a window and cause a nuisance.

Various approaches have been proposed as regards the windshield (Götz[6.8]), see also section 8.6.1. Flow guides and 'air curtains' from air sources located beneath and in front of the windshield have not, however, proved viable. As far as the windshield is concerned, further improvements will have to be made to conventional wash/wipe systems.

Water on vehicle side windows not only reduces lateral visibility but also restricts the usefulness of the exterior rear-view mirrors. This can be countered by appropriate design of the A-pillar. However, when developing appropriate A-pillar geometry, the influence of this geometry upon the vehicle's aerodynamic drag (see also section 4.3.2.3) and upon the generation of wind noise (see section 6.5.2) must be borne in mind.

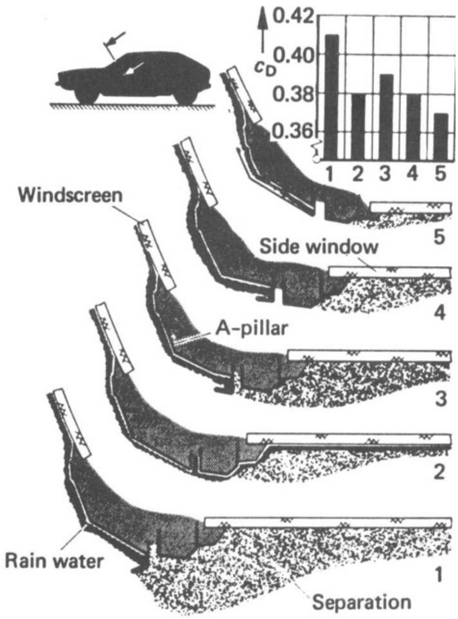

Figure 6.12 The influence of the design of the windscreen pillar upon the drag coefficient c_D, water flow and air flow separation, after ref. 6.2

Figure 6.12, from Janssen and Hucho, [6.2] shows the various stages in the development of an A-pillar. Design 1 could be easily manufactured, but would generate very great aerodynamic drag because of the intensive air flow separation it would bring about. Water flow from the front does not wet the side windows. Versions 2 to 5 represent further developments of this design. Contour 2 brings about a considerable reduction in aerodynamic drag because of the considerably smaller area of separation. However, this alternative is unacceptable since water spills out over the A-pillar and wets the side windows. In design 3, the side windows are indeed dry, but the drag coefficient is greater. In view of the greater outlay involved in the construction of alternative 5, contour 4 with integrated gutter is the most practical of those discussed here.

The exterior rear-view mirrors represent a further cause of water deposits on the side windows. The mirror wake can cause wetting not only of the side windows but also of the mirror surface. No general statements can be made concerning the shaping of the mirror. On the contrary, optimum mirror geometry has to be achieved on the basis of tests carried out during new development. In this context, optimum means that there is as far as possible no contact surface between mirror wake and side window, and that the flow guarantees a clear mirror surface.

Wetting of the rear windows of notchback and fastback vehicles is caused by air flow over the roof. A water trap situated above the rear window can prevent the overflowing water from reaching the window. The water flowing over the roof is intercepted above the rear window and drains away downwards to both sides of the window. Figure 6.13 shows a design solution formulated by Janssen[6.17] for just such a water trap for a fastback vehicle. In this instance, the trap is represented by the gap between roof and tailgate.

The left-hand side of the figure represents an early vehicle development stage, while the right-hand side demonstrates the geometry as used in the

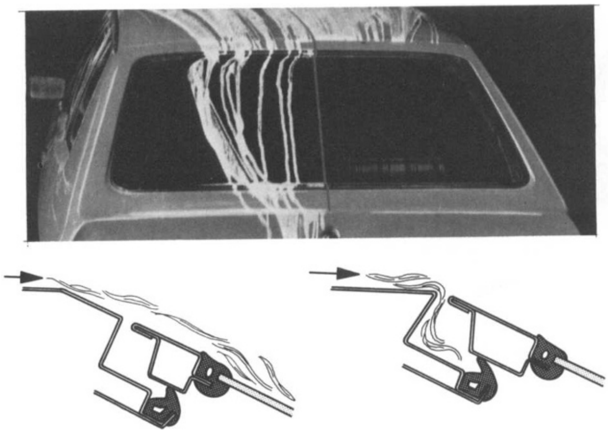

Figure 6.13 Wetting of the rear window and its prevention in the standard vehicle, after ref. 6.17

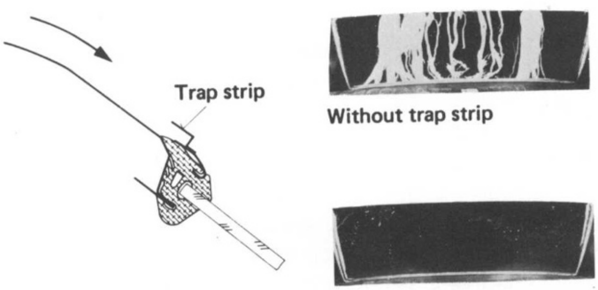

Figure 6.14 Water flow over the rear window of a notchback passenger car; the effect of a water trap strip, after ref. 6.1

production vehicle. In the latter instance, the water is drained to the side between roof and tailgate.

Figure 6.14 (after Hucho[6.1]) shows how water flow is kept away from the rear window of a notchback car. Water flowing over the roof is trapped by a strip integrated into the rubber seal. An experiment is necessary to match the geometry of this strip to the vehicle's contour.

6.4.3 Dirt accumulation

In the last section attention was paid to water flow on and around the vehicle windows. Water lying on the road and rain is seldom likely to be completely clean. Apart from the problems concerning water flow outlined above, there is thus the additional problem of dirt being deposited on the window. This source of dirt will not be dealt with again here, since the prevention of water flow over the windows will also prevent the depositing of dirt on the windows caused by this very water flow.

The shaping of a vehicle has hardly any influence at all upon the accumulation of dirt on the headlamps. There is as yet no aerodynamic alternative to the mechanical cleaning of headlamps.

Dirt on the rear window has two causes. The first, water flow over the vehicle roof, has already been dealt with in detail in section 6.4.2. It is observed on fastback and notchback shapes. Water and dirt on the rear window of squareback vehicles is caused by the accumulation of water droplets and dirt particles within the wake and the depositing of this matter upon the bodywork surface as a result of the swirling movement within this area of separated flow. Figure 6.15 shows the two basic forms of air flow separation already dealt with in Chapter 4. In the upper picture air flow

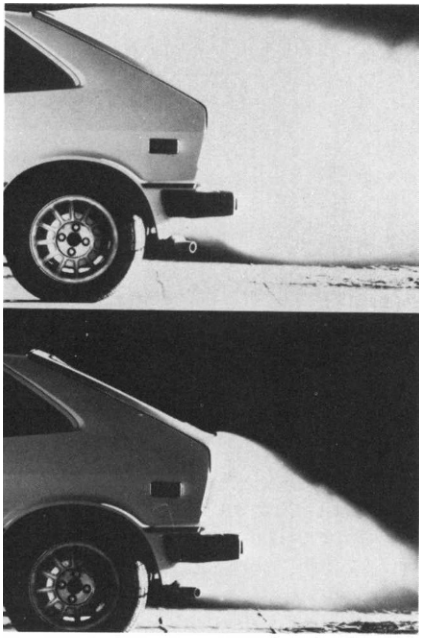

Figure 6.15 Separation patterns in the wake: (a) air flow separates at rear edge (squareback-type); (b) air flow remains attached until beneath the rear window (fastback-type), after ref. 6.3

separates at the rear roof edge. The rear window thus lies within the area of the wake, and is exposed to dirty water borne by air swirling at random. The lower diagram shows attached flow in the rear window area. In terms of a clean rear window, this is preferable, but in section 4.3.2.5 it is shown that attached flow at the rear window is not always desirable in the context of the minimization of aerodynamic drag.

Unless additional measures are taken, air flow separates at the rear roof edge of squareback vehicles. Thus, the rear window lies within the wake area and becomes very dirty. Figure 6.16, from Hucho[6.1] shows how the

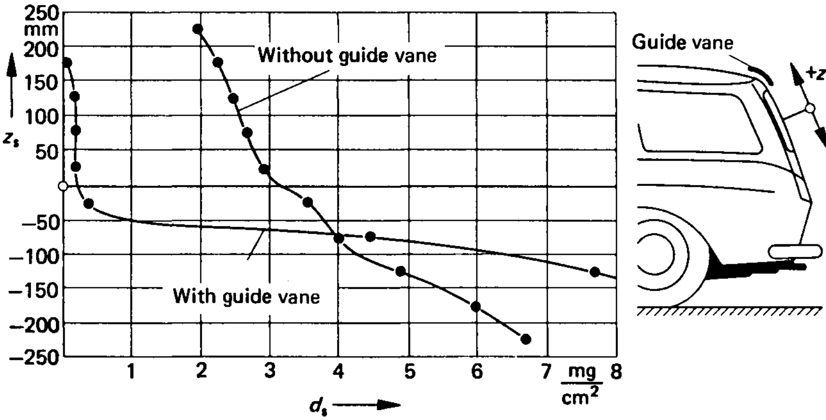

Figure 6.16 The influence of an air guide vane upon the accumulation of dirt on the rear window of a squareback vehicle, after ref. 6.1

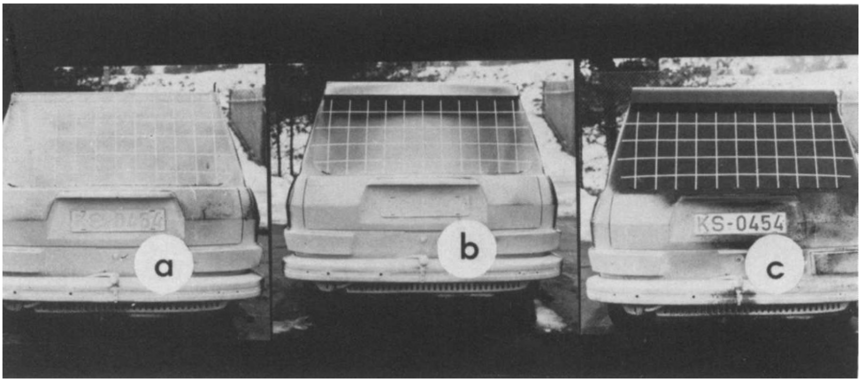

Figure 6.17 Variations to the guide-vane gap; the influence upon the accumulation of dirt on the rear window, after ref. 6.6: (a) without guide vane; (b) gap width 20 mm; (c) gap width 40 mm

rear window can be kept clean by means of a guide vane. The shape and position of such a guide vane must be determined on a vehicle-specific basis. The deflected air ensures that the upper part of the rear window remains almost completely free of dirt, though a considerable increase does take place in the lower third of the window.

In Fig. 6.17, after Hucho and Janssen[6.6] it is clear that this phenomenon can be countered by varying the guide vane gap. If there is sufficient distance between the guide vane and vehicle contour, the air screen remains attached as far as to the lower edge of the rear window. However, the increase in aerodynamic drag brought about by such bolted-on guide vanes disqualifies them from consideration as far as large-scale production is concerned. A guide vane integrated into the vehicle would cause production difficulties and would lead to a considerable increase in costs. However, an integrated guide vane is used in one range of buses, as illustrated in Fig. 8.94.

Vehicle rear lights are highly susceptible to dirt because they lie within the area of the wake. Measurements of dirt thickness which have been carried out (Götz[6.8]) have led to the conclusion that the heaviest accumulation of dirt on rear lights is observed on notchback vehicles, followed by fastback and squareback versions. One possible solution is represented by a flowing air screen between the rear-light level and the surrounding separated flow. The associated drawbacks and difficulties have already been illustrated in the discussion dealing with the squareback vehicle. When developing vehicles nowadays, efforts are made to minimize dirt deposits in this area by designing appropriate shapes for the rear lights. Ribbed rear lights have been shown to represent an effective solution, since the recessed areas are less heavily coated by dirt contained in the swirling air.

Delivery vans are often subject to dirt deposits on their sides. The dirty water swirled up out of the front wheel housing is deposited over large areas of the bodywork. Figure 6.18, from unpublished experiments carried out by E. Rohlf in the Volkswagen AG wind tunnel, shows how careful design can reduce this effect to a level no longer to be regarded as a nuisance. Design modifications to the bodywork are restricted in this case to a front apron and a divider on the edge of the wheel well. Design A gives a steep pressure gradient from the wheel well to the side wall above it. The result is an upward velocity component of the spray water emerging from

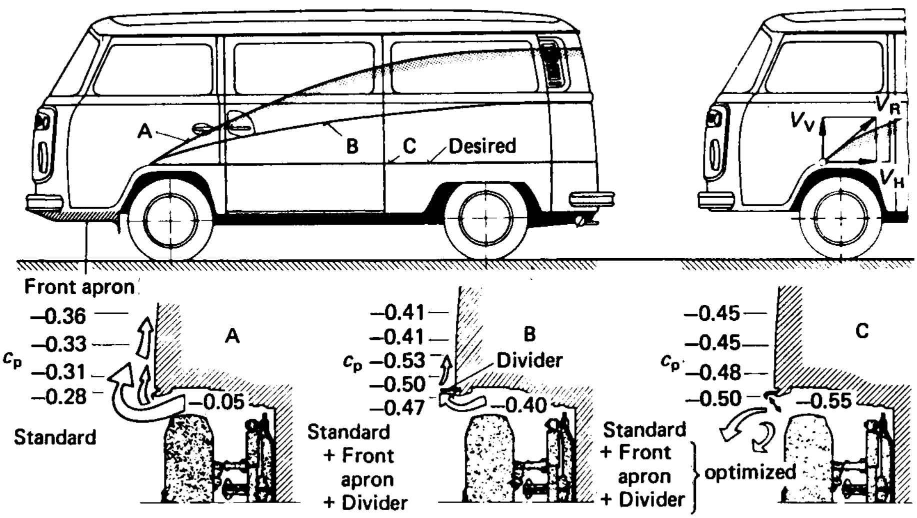

Figure 6.18 The accumulation of dirt on delivery van side walls, after E. Rohlf

the wheel well. Contour B gives rise to a smaller vertical velocity component as a result of a less steep pressure gradient, though dirt still stretches over an area which is often used for advertising purposes on such vehicles. Only design C, with a weak and reversed pressure gradient, can be regarded as satisfactory. As Fig. 6.18 shows, the reversal of the pressure gradient is achieved by reducing pressure in the wheel well. An increase in pressure on the outer skin above the wheel could be achieved only at the cost of major, unacceptable changes in shape.

6.5 Wind noise

6.5.1 The fundamentals of noise generation on vehicles

Wind noise is generated by vehicle air flow. Wind noise must be handled in conjunction with the other sources of vehicle noise. Refer to Günther et al.[6.9] and Zboralski[6.10] for the fundamentals of acoustics.

Vehicle noise is generated essentially by the engine, the tyres and the air stream. The interior noise measurement in a subcompact car can give an idea of the relative magnitude of the three sources. At a vehicle speed of 150 km/h (93.8 mile/h), corresponding to an engine speed of 5500 rpm (the microphone for recording measured data was located on a level corresponding to that of the driver's left ear), the following levels were recorded:

Engine	82.5 dB(A)
Tyres	78.0 dB(A)
Wind	78.5 dB(A)

From these, a total noise level of 85 dB(A) is calculated.

The trend towards deluxe vehicles as well as legislation to protect the environment necessitate efforts to reduce both interior and exterior noise levels.

Future exterior noise legislation will lead primarily to a reduction in engine noise by means of better noise absorption. A desirable spin-off of this will be a reduction in interior engine noise. This will mean that the relatively low tyre- and wind-noise levels will assume greater importance in terms of interior noise.

Vehicle wind noise is assessed using two criteria. The first is the limiting of the wind noise frequency spectrum. When deluxe vehicles are being developed, efforts are made to achieve so-called 'uniform' noise. Uniform here means that the noise frequency band is as far as possible speed-independent, so that the total noise level rises continuously and that there are no frequency peaks.

The second assessment criterion is the sound pressure level mentioned at the beginning of this section, i.e. sound volume. The noise level measured in the passenger compartment is dependent not only upon the noise generated but also on the sound conductance characteristics and resonance characteristics of the vehicle. Important in this respect are, for instance, acoustic insulating mats and acoustic absorption elements, such as are found in today's mass-produced vehicles, and which positively influence the sound conductance behaviour of the bodywork. Such acoustic absorption is beset by major problems in terms of wind noise, since, for reasons of design, there is minimal scope for insulation between those points where wind noise occurs and the passenger compartment. Therefore the only alternative way of reducing wind noise is to reduce the intensity of the noise at the point of its generation, by means of design optimization.

6.5.2 The influence of air flow mechanisms

The various types of air flow illustrated in Figs 4.3 and 4.4, which were discussed in more detail in section 6.2.1, can be distinguished on the basis of the mechanism involved in noise generation, as Stapleford and Carr[6.11] have demonstrated on a simple model, a rectangular cuboid. The following types of air flow are observed:

- Attached flow
- Quasi-two-dimensional separation
- Reattached air flow
- Three-dimensional vortex separation

Figure 6.19, after Stapleford and Carr[6.11] shows these four types of air flow on a cuboid. The Reynolds number of air flow determined by the length of the cuboid was $Re_l = 9.2 \times 10^5$. Attached flow along the entire

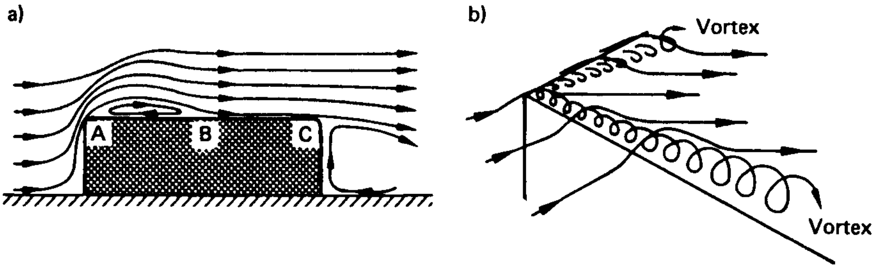

Figure 6.19 Types of air flow generated on a cuboid in order to measure sound levels, after ref. 6.11

length of the cuboid can be generated by means of a rounded edge at contour point A. A sharp edge at this point brings about a separation bubble between A and B with subsequent reattachment of air flow. The fourth form of air flow to be examined can be brought about by oblique air flow over the sharp-edged object. The oil film pictures of the cuboid air flow thus generated are shown in Figs 6.20 to 6.22 (also from ref. 6.11). Within the separation bubble, a distinction can be made between area A with side air flow and area B with clearly reversed flow. Measurements of the sound pressure level were made with microphones flush with the surface.

Table 6.1 gives the maximum sound pressure level measured for each type of air flow, and the frequency range over which this level was measured. The maximum levels measured within the range 500 Hz to 1500 Hz are shown in Fig. 6.23 (after ref. 6.11) in the form of lines of constant sound pressure. This investigation showed that the areas of separated air flow were particularly noise-intensive, as was the reverse flow

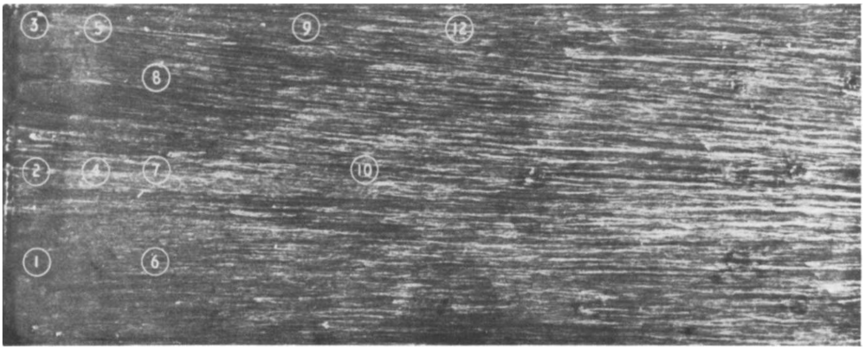

Figure 6.20 Oil film picture of air flow in contact along entire length (front edge is rounded, see also Fig. 6.19), after ref. 6.11

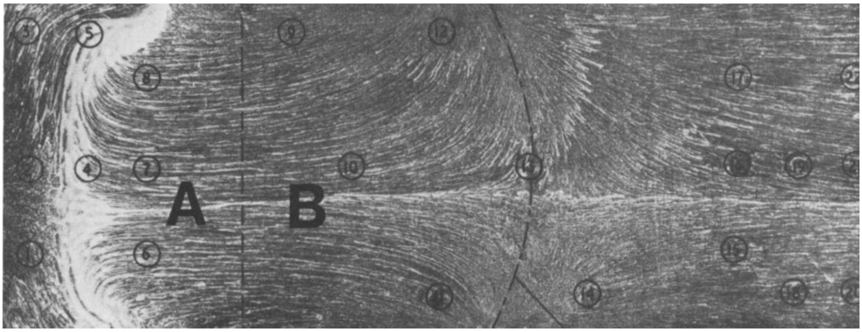

Figure 6.21 Oil film picture of the quasi-two-dimensional separation bubble with reattached air flow (see also Fig. 6.19), after ref. 6.11

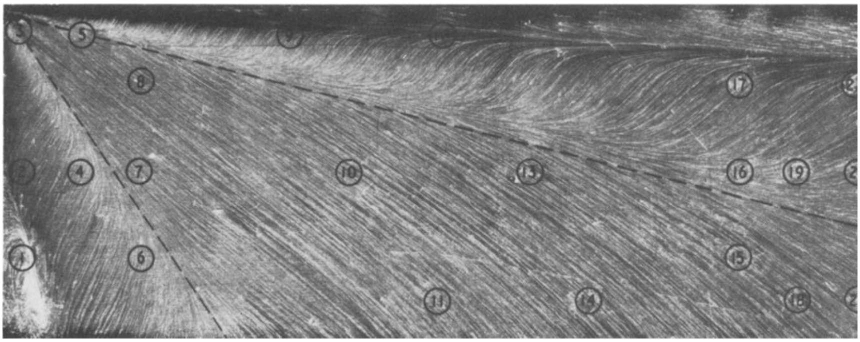

Figure 6.22 Oil film picture of cuboid with air flow under 30°, with formation of two three-dimensional vortices (see also Fig. 6.19), after ref. 6.11

area within the separation bubble and, particularly strikingly, the three-dimensional vortex separation. Both types of air flow together cover a very wide frequency range, in this instance from 200 Hz to about 800 Hz.

The measured values given in Table 6.1 are meant only as a guide, and should not be viewed as anything more. The measurements have shown

Table 6.1 Relation between character of flow, maximum sound pressure level and frequency range (after ref. 6.11)

Character of flow	*Max. sound pressure level* L_{max} (dB(A))	*Frequency range of* L_{max} (Hz)
All attached	111	800 to 1200
Separation bubble A	108	400 to 500
Separation bubble B	115	200 to 500
Reattached	113	300 to 600
Vortex	130	500 to 800

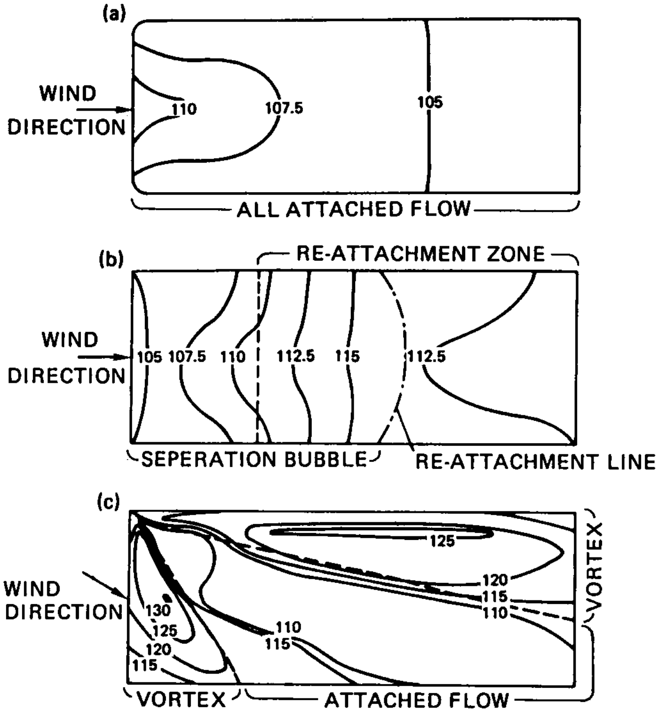

Figure 6.23 Surface sound pressure level in the frequency range 500 Hz to 1500 Hz, after ref. 6.11: (a) attached air flow; (b) two-dimensional separation with reattachment; (c) three-dimensional vortex

that the level measured in the separation area behind the A-pillar on a vehicle of normal size can be more than 30 dB(A) higher than that measured in the centre of the roof, an area of attached air flow. Thus, it is also in the interests of the acoustic engineer to avoid air flow separation as far as possible.

Figure 6.24 shows the sound pressure measurement made by Watanabe et al.[6.5] in the separation bubble of the right-angled step. The frequency at which measurement was made was 1 kHz. The measurement underlines the evidence contained in Fig. 6.23 a and b. In a quasi-two-dimensional separation bubble, maximum noise intensity occurs in the area of

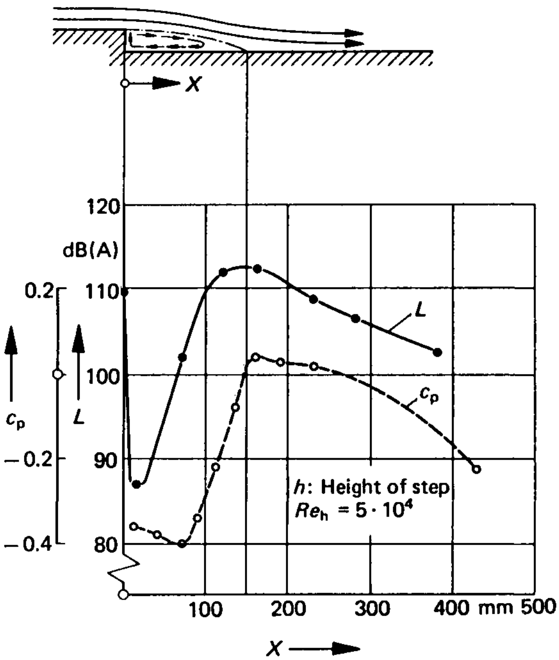

Figure 6.24 Pressure and sound pressure level measurement to the rear of a step, after ref. 6.5

reattachment of air flow. The level measured within attached air flow decreases as length of attached air flow increases.

There are, in addition, two extremely undesirable effects to be dealt with, which occur especially in motor vehicles: first, so-called 'booming' and second, leaking door seals. Booming occurs with open side windows or an open sliding roof. Effects are induced within the air column inside the vehicle by the exterior air flow, causing the passenger compartment to become a resonator. According to Aspinall[6.14] there are two possible types of booming in the instance of an open side window. The first type occurs predominantly at low vehicle speeds (up to 80 km/h, 50 mile/h) on the luff side, and the sound pressure has a periodic character. The second form occurs on the lee side at higher vehicle speeds, and the sound pressure is random in character. In the case of frontal air flow, the periodic type of air flow occurs.

For both types of low-frequency booming, whose frequencies lie beneath 60 Hz, scope was found for reducing wind noise. Deflectors located on the front side of the opening have proved effective in the case of periodic booming. Such ramps avoid unstable pumping effects on the rear edge of the opening and define a clear reattachment point of air flow. Reductions in local sound pressure level from over 120 dB to below 90 dB were recorded on vehicles equipped in this way.

However, this method of air flow guidance is difficult to integrate into vehicle design in the case of the side window. On the other hand, deflectors which are mechanically extended when the sliding roof is opened have gained acceptance in production.

The second type of booming can be reduced by a more sloping windshield. The air volume flow around the A-pillar is thus reduced, i.e. lower air flow speeds are reached at the window opening.

No functional link can be quoted between, on the one hand, the geometry and location of the deflectors, or angle of slope of the windshield and, on the other hand, the sound pressure level and individual frequency spectra. Optimum solutions have been found on a vehicle-specific basis using different shapes, sizes and locations. In wind tunnel experiments, optimization must take place on a vehicle-specific basis.

As has long been known, passengers find the noise caused by leaking door seals most unpleasant. Imperfect seals can be caused by one of two things:

- Unsatisfactory workmanship
- The great suction force on the door (see section 6.3) can lead to local lifting-off of the door from the seal in the area of the window.

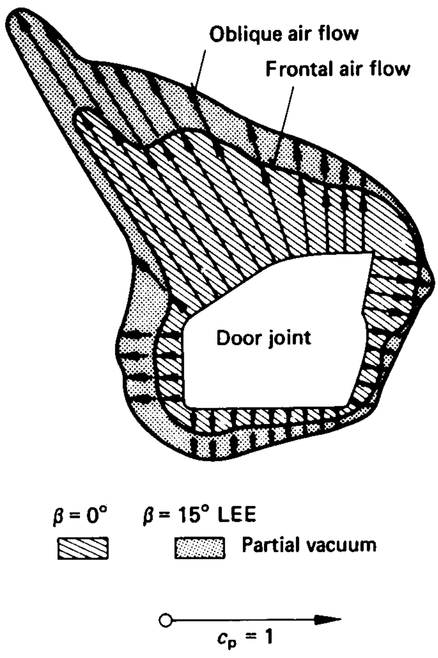

Figure 6.25 Static pressure distribution in the door clearance of a passenger car

Figure 6.25 shows the measured distribution of static pressure in the front door joint of a passenger car. A considerable negative pressure is set up precisely in the area where the door is not supported. The pressure coefficients c_p measured in this area, particularly on the lee side, are among the lowest over the whole vehicle. Similar measurements on a VW 411 have been published by Hucho and Janssen.[6.16] These measurements were used as a basis for the design of the door seals and for the formulation of a tightness test in quality assurance.

A leaking door joint is undesirable for two reasons:

- Damping of the intensive noise from the A-pillar vortex decreases and the open gap acts as a noise path.

• A high-frequency jet air flow is set up from the passenger compartment through the gap because of the great pressure difference. The door clearance becomes an additional source of noise.

If a door seal remains tight under all driving conditions, the door clearance cannot be considered to provide scope for a reduction in wind noise.

6.6 Air flow around individual components

6.6.1 Windshield wipers

Air flow around the windshield wipers should be designed so that the wiper blades remain in contact with the windshield under all circumstances.

Because of the speed of air flow when the vehicle is on the move, a lift force is exerted perpendicular to the windshield. This lift force depends upon many parameters and changes continually during wiper operation. The only fixed parameter is wiper arm geometry. All other variables are of changeable character, such as vehicle speed and yaw angle of vehicle air flow. The movement of the wiper arms also continuously changes the effective flow direction of the windshield wipers, and thus also their lift. The body surface velocity, which contributes to this lift, becomes greater as the wiper approaches the horizontal neutral position, i.e. the wiper arms are most susceptible to lifting off from the windshield near the lower reversal point.

In Fig. 6.26, the turning-over of the wiper blades at the point of reversal in the wiper movement is investigated (Barth[6.15]). According to the

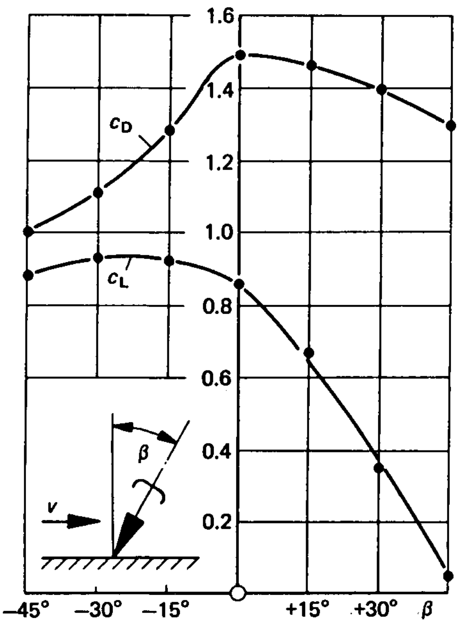

Figure 6.26 Influence of wiping direction upon the aerodynamic drag and lift of a wiper blade, after ref. 6.15

direction of movement, angle β is either positive or negative. During downward movement ($\beta < 0°$) lift is clearly higher than when the wipers are moving upwards ($\beta > 0°$). When $\beta < 0°$ the magnitude of the angle is of hardly any significance. Therefore maximum lift is to be expected during the downward movement, shortly before the lower point of reversal. In order to reduce this lift force, small pressure vanes are used that supplement the spring force.

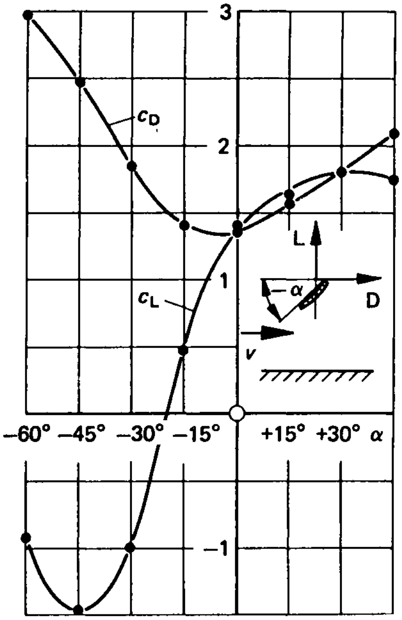

Figure 6.27 Influence of pressure vane angle upon drag and lift of a windscreen wiper configuration, after ref. 6.15

Figure 6.27 (also after Barth[6.15]) shows the influence of the angle of attack of such a vane upon the coefficients of lift c_L and drag c_D. The precondition here is the critical case of air flow perpendicular to the wiper shaft. The angle of attack of $\alpha = -45°$ can be considered optimum in view of the lift. The determination of length, width and profile of such vanes must be based on experiments.

6.6.2 Brakes

An important consideration when undertaking aerodynamic optimization of a vehicle is the necessity to ensure sufficient brake cooling. Results will be given, originating from tests carried out with a view to improving the cooling of disc brakes (Fig. 6.28) from Hucho.[6.1] The aim was to guide as large a flow of air as possible to the disc brakes by means of suitably located air inlets. The left-hand graph shows this air flow volume against the vehicle speed range.

The right-hand graph shows how this cooling air influences the temperature at the disc brake. The related test procedure is outlined in section 12.3.2. The vehicle was originally fitted with an apron at the front end. The temperature curve on the brake caliper over time is that

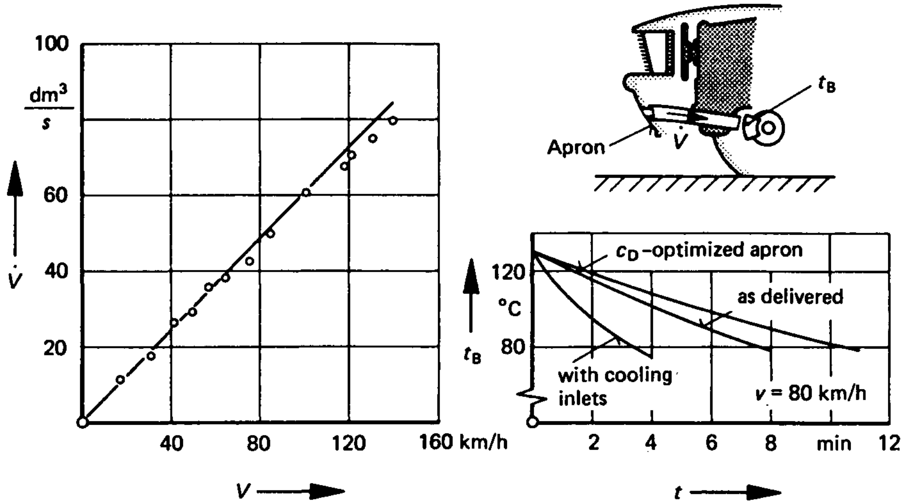

Figure 6.28 Improving brake cooling on a passenger car, after ref. 6.1

identified with 'as delivered' in the figure. To reduce the aerodynamic drag of this vehicle, an aerodynamically optimized apron was developed. The result was, however, an even higher brake temperature. Developing cooling air inlets and the fitting of hoses made it possible to achieve a far more favourable temperature curve, identified on the figure as 'with cooling inlets'. The aerodynamic drag of this model is identical to that of the model with the drag-optimized apron.

6.7 Future prospects

As has been shown in this chapter, the aerodynamics of a motor vehicle cannot simply be identified with the mechanics of vehicle motion. It is rather more a question of a number of problems associated with safety, operation and comfort, which must be solved by aerodynamic means. The solution to the problems outlined here must be formulated in future on a vehicle-specific basis. Tests are an absolute necessity in this context, since the air flow details dealt with in this chapter are dependent upon a whole host of geometrical and aerodynamic parameters. Numerical procedures, which have started to be used in the science of automobile aerodynamics (see Chapter 13), will perhaps make their own contribution in future to the rationalization of test procedures.

6.8 Notation

L, L_{max}	sound pressure level, Table 6.1
L_W	force acting upon side window, Fig. 6.11
Re	Reynolds number
V	vehicle speed
$\dot{V}$	volume air flow, Fig. 6.28

V_∞	oncoming air flow speed
V_V, V_R, V_H	velocity components, Fig. 6.18
c_D	drag coefficient of windshield wiper
c_L	lift coefficient of windshield wiper
c_p	pressure coefficient as per Eqn 2.8
d_S	weight of dirt per unit of area, Fig. 6.16
h	step height, Fig. 6.24
l	vehicle length, Fig. 6.8
t	test duration, Fig. 6.28
t_B	brake temperature, Fig. 6.28
x, y, z	orthogonal coordinates
α	angle of attack of pressure vane, Fig. 6.27
β	angle of yaw
β	angle of inclination of windshield wiper, Fig. 6.26