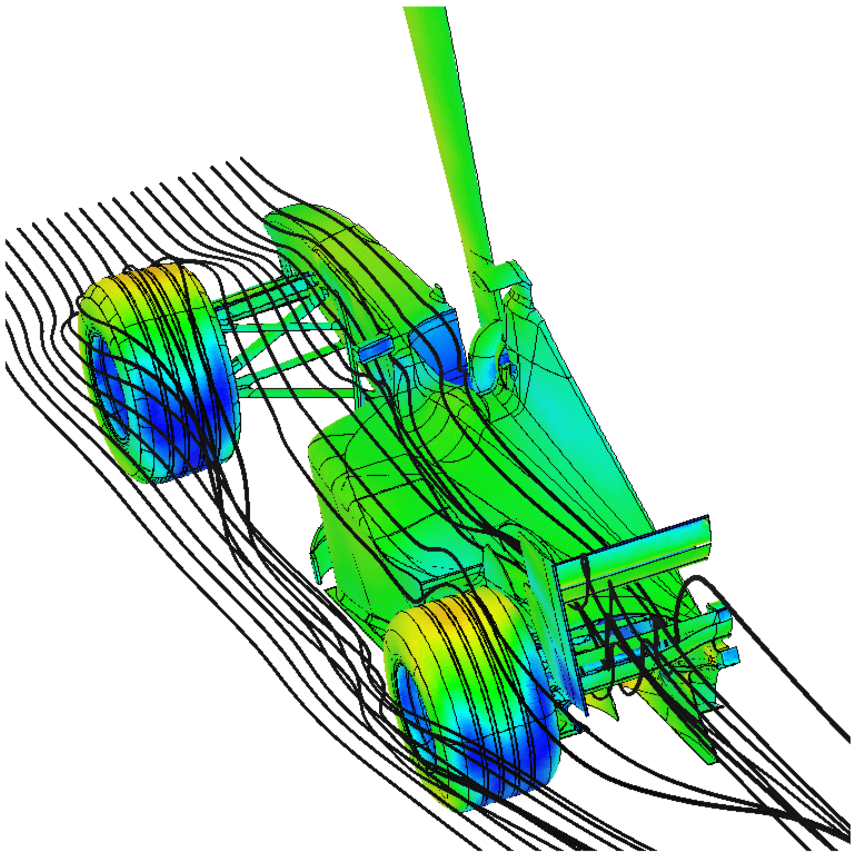
Chalmers University of Technology

Road Vehicle Aerodynamic Design

Underbody influence



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Index

1. Introduction [1.1]

In the 1960s the use of soft rubber compounds and wider tyres, pioneered particularly by Lotus, demonstrated that good road adhesion and hence cornering ability was just as important as raw engine power in producing low lap times. It was found surprising that the friction or slip resistance force could be greater than the contact force between the two surfaces, giving a coefficient of friction greater than 1. The maximum lateral force on a tyre is related to the down load by: $F_y = k \cdot N$ [1.1], where k is the maximum lateral adhesion or cornering coefficient, and is dependant on the tyre-road contact.

Besides on the tyre and the suspension tuning, there is another factor in which is possible to work: the normal force. There are several alternatives to increase the down load:

- increasing the mass of the vehicle: this effectively increase the maximum lateral force that the vehicle can handle, but doesn't improve at all the cornering characteristics, due to the fact that the centripetal forces generated in a turn are given by the following formula: $F_c = m \cdot a_c = m \cdot \frac{v^2}{r}$ [1.2] which, for a given radius and tangential speed, is only dependant on the mass of the vehicle, so the increase in mass means that the centripetal force required increases by an equal amount;

Fig. 1.1: increasing down force by increasing vehicle weight [1.2]

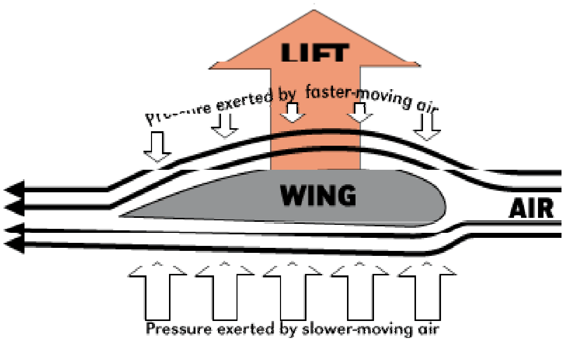

Fig. 1.2: Lift Force

- inverted wings: one or more wing profiles, placed in appropriate points along the vehicle, can create the desired negative lift, but with the penalty of increasing the drag as well;

- ground effect: by the appropriate means, like underbody panels and rear diffusers, the flow under the vehicle can create a low pressure that effectively sucks the vehicle against the road.

Fig. 1.3: Diffuser of the McLaren MP4-5B (1990)

In addition to enhancing the cornering ability, aerodynamic down force allows tyres to transmit a greater thrust force without wheel spin, and hence the acceleration will be increased, specially at high speed, where the aerodynamic effects are more noticeable. With the same criteria, deceleration forces are affected in the same way as thrust forces, so the braking distances can be improved as well. In addition to performance improvements, aerodynamic down force tends to improve the directional stability of the vehicle at high speed.

The Ferrari 360 Modena may not have any large visible spoilers but its underbody has panels shaped to aid its aerodynamic efficiency and to add stability at high speed. Its coefficient of drag is reduced from its predecessor's (the F355) 0,34 C_D to 0,33 C_D and it has a C_L of -0,24, which translates to about 200 kilos of down force at 290 km/h. This is all thanks to its aerodynamics, ground effects, geometry, and 5.400 hours of wind tunnel testing.

2. Ground effect

Ground Effects is the summing of the downforce created by a low pressure area between the underbody and the ground, and the downforce created by the front and rear wings (in the racing and super cars example).

Physics of Ground Effect

The same principles which allow aircraft to fly are also applicable in car racing. The difference being the wing or airfoil shape is mounted upside down producing downforce instead of lift. The air moving under the car moves faster than that above it, creating downforce or negative lift on the car. Airfoils or wings are also used in the front and rear of some car in an effort to generate more downforce.

1) The Bernoulli Effect

A physicist/mathematician called Johann Bernoulli (1667-1748) derived an important relationship that relates the pressure, flow speed and height for flow of an ideal fluid. The Bernoulli effect is expressed by an equation known as Bernoulli's equation. This equation states that, for a given volume of fluid, the total energy is constant. In other words, the pressure of a fluid (liquid or gas) decreases as it flows faster. This is due to the principle of the conservation of energy, which is a fundamental law in physics. This Energy can be described by three components:

- Potential Energy - due to elevation
- Kinetic Energy - due to movement (momentum)
- Pressure Energy - within the fluid

If we have to make measurements at two points (a & b) in the path of the fluid flow we can express this relationship mathematically as: $p_a + \frac{1}{2} \cdot \rho \cdot v_a^2 + \rho \cdot g \cdot h_a = p_b + \frac{1}{2} \cdot \rho \cdot v_b^2 + \rho \cdot g \cdot h_b$ [2.1]

Where
p is the static pressure (at points a & b)
ρ is the density of the fluid
v is the velocity (at points a & b)
g is the gravitational acceleration
h is the height (at points a & b)

Since there is no significant difference in height regarding cars, we can take $h_a = h_b$. And because g and r are also equal the whole term ρ.g.h can be eliminated on both sides of the equation. The term ($\frac{1}{2}$ ρ.v^2) represents dynamic pressure and we will simplify it as q. Thus we have: $p_a + q_a = p_b + q_b$ [2.2]

If an air stream is introduced into a narrowing but otherwise open-ended tube - a Venturi - it is accelerated (increase in v) thus there is an increase in dynamic pressure. So to keep the left hand side of the equation equal to the right hand side (conservation of energy), [illegible] the left side of the equation must decrease. This induced unde[illegible] tube walls, trying to suck those inwards.

2) The Venturi Effect

If a point (a) is taken in the air stream in front of the car and point (b) in the air stream underneath the car, it can be see that the path of the air is narrowing. Again the speed (V) increase thus the static pressure (P) must decrease. There is then a lower pressure under the car than that there is on top of the car, and this pressure difference tends to "suck" the floor of the car and the surface of the track towards each other. Thus it is pulling the car to the ground and we have downforce. This is in fact the nozzle effect (or Venturi ef-

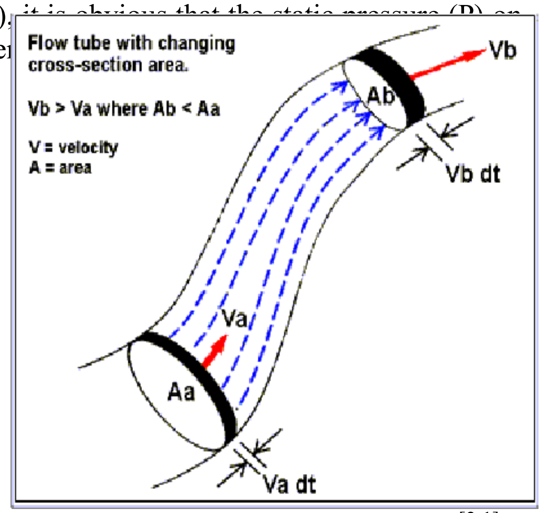

Fig. 2.1: The Venturi Channel [2.1]

fect), when flow in a convergent nozzle accelerates and looses pressure. The downforce produced this way provides a traction-enhancing load without adding mass to the car that needs to be accelerated, decelerated (braking) or resisted in cornering. The object will then be forced toward the faster moving fluid [2.1]

3) The Diffuser

A diffuser is basically an inverted airfoil underneath the car acting as a Venturi channel. Its effect plays a huge role in the balance of the car. In production cars and wings can sometimes be a bad cosmetic feature and only diffusers are used. In some country wings above a certain size is illegal due to the fact that when a pedestrian is hit and he rolls over the car, the wing might kill him.
A diffuser gives the air traveling underneath the car a place to expand and decelerate back to road speed as well as providing wake infill. As the air enters towards the front of the car it accelerates and reduces pressure. There is a second suction peak at the transition of the flat bottom and diffuser. The diffuser then eases this high speed air back to normal velocity and also helps fill in the area behind the race car making the whole underbody a more efficient down force producing device by increasing down force without increasing drag too much.

This configuration is very sensitive to the gap between the underbody and the road is. It can be seen that an augmentation of the gap between the skirt and the road causes a reduction of down force. [2.2]

4) **Underbody Panel**

Since the underbody of the vehicle can play an important role to reduce the drag, introducing a flat panel in the underbody to isolate the drag creator's components (pipes and other parts exposed to the flow) reduces the drag in a considerable percentage. The flat underbody feature is the mean to introduce the Venturi channels in a most efficient way.

It is important to understand that a true flat-bottomed car (one without diffuser) will produce down force on it self. Essentially, the entire flat bottom becomes one large diffuser. It has two suction peaks, one upon entrance, and the second at the trailing edge of the flat under tray. A diffuser simply acts to enhance the underside suction. [2.3]

Another important aerodynamic detail that greatly contributes to the Insight body's low coefficient of drag is the careful management of underbody airflow. The Insight body features a flat underbody design that smoothes airflow under the car, including three plastic resin underbody covers. Areas of the underside that must remain open to the air, such as the exhaust system and the area around the fuel tank, have separate fairings to smooth the airflow around them.

In order to minimize air leakage to the underside, the lower edges of the sides and the rear of the body form a strake that functions as an air dam. At the rear, the floor pan rises at a five-degree -angle toward the rear bumper, creating a gradual increase in underbody area that smoothly feeds underbody air into the low-pressure area at the rear of the vehicle.

Note that high voltage cables that are passed above the underbody covers, and so the covers must be replaced if removed for any reason. [2.4]

3. Underbody Design in Racing Cars

High performance vehicles, like racing cars, serve in many parts of vehicle design as a platform for experimenting with advanced technologies, which might be adapted in production vehicles later on. Albeit in aerodynamic underbody design the priorities set in racing cars are slightly different from those in production vehicles.

The major goal of aerodynamic design for racing cars is not to decrease drag like in passenger cars, but to decrease lift and to create down force in order to improve the road adhesion and thus the handling characteristics of the car, especially by increasing the possible cornering speed. This is because in racing cars fuel consumption and top speed, which are strongly dependent on the drag, are usually not as important as acceleration and handling characteristics, which are more dependent on the down force. This is due to the fact that the created down force contributes to the road adhesion forces, both lateral and longitudinal for accelerating and braking, but not to the cornering force, since it is not dependent on the vehicle mass. That results from the following equations:

- Aerodynamic down force: $F_{down-air} = \frac{1}{2} \cdot \rho \cdot A \cdot c_L \cdot v^2$ [3.1]
- Road adhesion force: $F_{traction} = k \cdot (F_{down-air} + m \cdot g)$ [3.2]

where ρ is the air-density, A the projected frontal area of the car, c_L the lift coefficient, v the vehicle speed, k is the traction coefficient, dependent on the tire properties, $F_{down-air}$ the down force created by aerodynamic means, m the total vehicle mass, g the constant of gravity and r the cornering radius, and equation 1.2, that gives the cornering force equation.

From these equations it can be seen that increasing the total down force simply by increasing the vehicle mass will not increase the maximum possible cornering speed, since the two forces above increase in the same way for increasing vehicle mass and for the maximal cornering speed they will be in equilibrium.

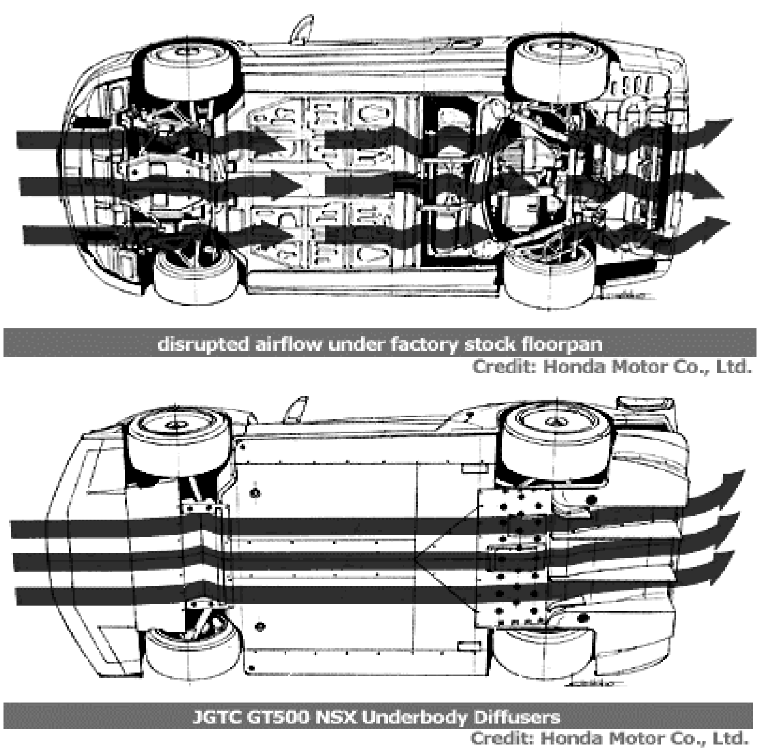

Fig. 3.1: underbody flow for different designs [3.2]

Nevertheless it is also important for racing cars to decrease the drag, as far it can be arranged with the down force requirements. To accomplish the combination of these two goals several devices are used. Figure 3.1 shows schematically the effect of two essential measures for improving the underbody flow of a racing car, a sealed underbody in combination with a rear end diffuser. The picture shows the rough underbody of the factory stock version of a Honda NSX and the corresponding racing version of the car. It can be seen, that the sealed underbody reduces the Eddies caused by the rough vehicle underbody with exposed suspension and exhaust systems. The influence of a sealed underbody will be explained on more detail in Chapter 4.

A device, which is mainly used in racing cars and only rarely seen on production vehicles, is the diffuser at the rear end of the underbody. A principle drawing of a diffuser can be seen in figure 3.2. This component takes advantage of the ground effect, described before. It increases the cross-sectional underbody area towards the rear end and therefore decreasing the speed of the air due to the continuity equation:

- $\rho_1 \cdot A_1 \cdot v_1 = \rho_2 \cdot A_2 \cdot v_2$ [3.3]

As mentioned before, since the air density ρ can be considered as constant for usual car speeds, the air stream velocity has to decrease for increasing area. From the Bernoulli equation it can be seen, that for decreasing speed the pressure has to increase:

- $p + \frac{1}{2} \cdot \rho \cdot v^2 = cons.$ [3.4]

The pressure p at the rear of the vehicle is the atmospheric pressure, respectively slightly below it, because of the drag losses at the vehicle shape. Therefore the pressure under the vehicle has to be beyond atmospheric pressure, what results in a down force in the form of a downward suction.

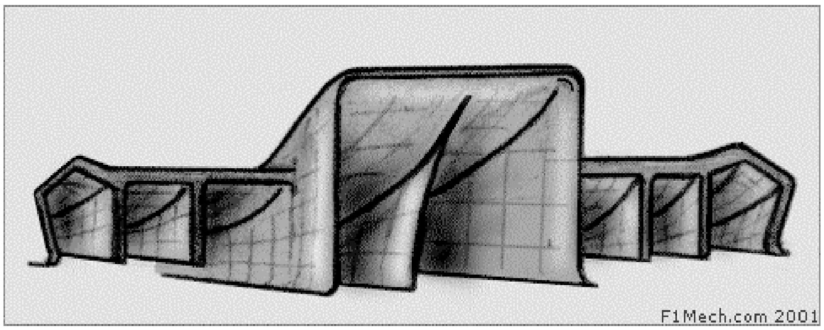

Fig. 3.2: Drawing of a diffuser [3.1]

Note that equation [3.3] is only valid for a constant mass stream of air, which is in reality not the case for the underbody of a vehicle, as there will always be air flowing in from the sides changing the mass flow. Thus the resulting down force will not be as big as could be calculated by the equations above.

Knowing these equations it can easily be seen, that the bigger the cross sectional area ratio between the entrance and the end of the diffuser is, the bigger the suction effect will be. However, racing regulations and underbody design restrict unfortunately the length of the diffuser. Additionally, the longer the diffuser length is, smaller is the area, which is affected by the downward suction. Whereas the angle of the diffuser is restricted by the fact that separation occurs if the angle is too big. Therefore the best way to increase the down force created by underbody and diffuser is to decrease the ground clearance of the car, what has as well the good side effect, that there will not be so much air flowing in from the sides. The ground clearance should, however, not be chosen too small, since for that case not enough or even no air at all will flow below the car body, resulting in a loss of the ground effect and a upward lift force.

Another device to increase down force, mainly used on racing cars which are developed from usual street models and a popular accessory for home-made tuning, is the air dam (at the front and on the sides). It decreases the cross sectional area at the front and the sides of the car, which leads to less air flowing under the vehicle body from the front and the sides and thus higher velocities and lower pressure. Therefore the pressure under the vehicle is lower than atmospheric and approaches further aft the pressure behind the car, which is naturally lower than atmospheric. This produces a down force as well. An example for a front air dam can be seen in picture 3.3.

Fig. 3.3: air dam at BMW 2002[3.3]

4. Street cars

As shown before, well-designed underbody plays an important role for racing cars. It reduces aerodynamic drag and also, what is more important, reduces lift force or even creates down force.

Motor sport is used as a proving ground for the development of technologies that are subsequently applied to road-going vehicles, and it has inspired a great deal of aerodynamic research work. Although the improvements don't have substantial effects in speeds up to about 100 km/h, which is close to the legal highway speed, manufacturers have started to think about underbody modifications and to apply them even to common cars.

The work done on Ferrari 360 Modena underbody is impressive. The floor is shaped very well in order to obtain a suction effect. With use of a diffuser in the rear, the ground effect is enough to provide stability at high speed without help of any visible spoilers. Also the drag coefficient C_D is reduced from 0.34 (F355) to 0.33.

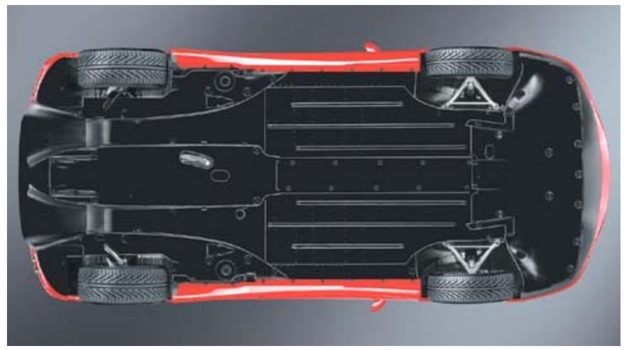

Fig. 4.1. Ferrari 360 Modena [4.3]

The fastest production and road legal car in the world, the McLaren F1, which costs about $1,000,000, also has no visible wings or spoilers. Instead it uses ground effect to maintain stability at its 340 km/h top speed. [4.1]

Another good example is Jaguar XJ220. Ground effects seek to use the airflow around the car to help it handle. The entire car is shaped like an inverted airplane wing. The low nose and chin spoiler on the XJ220 restrict air from passing beneath the car. Whatever air does pass, flows smoothly along the featureless underside. Towards the rear of the car, two cavernous venturi tunnels (visible just in front of the rear wheels) cause the speed of the air to increase and pressure of the air to drop tremendously. The car is sucked into the road by the resulting vacuum effect. Although most of the car is aluminum, the under body panels are made of carbon composites for rugged durability. The close-up of the rear suspension illustrates attention to detail. The lower control arm passes through the venturi tunnel, and is therefor aerodynamically shaped to reduce air resistance. The suspension is vaguely reminiscent of an E-type, although it has both upper and lower control arms. Twin shock absorbers with coil over springs (not visible) are mounted horizontally to the top of the hub carrier, another technique for reducing air resistance. [4.2]

Fig. 4.2. Jaguar XJ220 underbody [4.2]

Looking at more common street cars there are also examples of smoothing the underbody airflow. That is done in order to reduce aerodynamic drag as well as to improve the stability of the car reducing lift forces acting on the car. The underbody, with help of underbody panels covering excrescences which disturb the airflow, is designed to be as smooth as practically possible. Some examples are presented below.

ws main features used in the latest Ford Mondeo to improve the underbody and to reduce
wheel-spoilers, engine compartment panel and rear right panel.

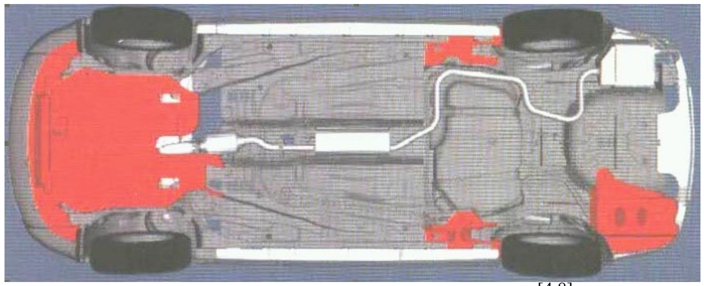

Fig. 4.3. Ford Mondeo underbody [4.8]

How a well designed underbody reduces drag is presented on the picture 4.4. The picture shows Audi A4 with many features stabilizing the airflow. Engineers concentrated very much on the underbody design since there is the biggest potential to improve the C_D value. As the effect of their work "aerofloor" is obtained.

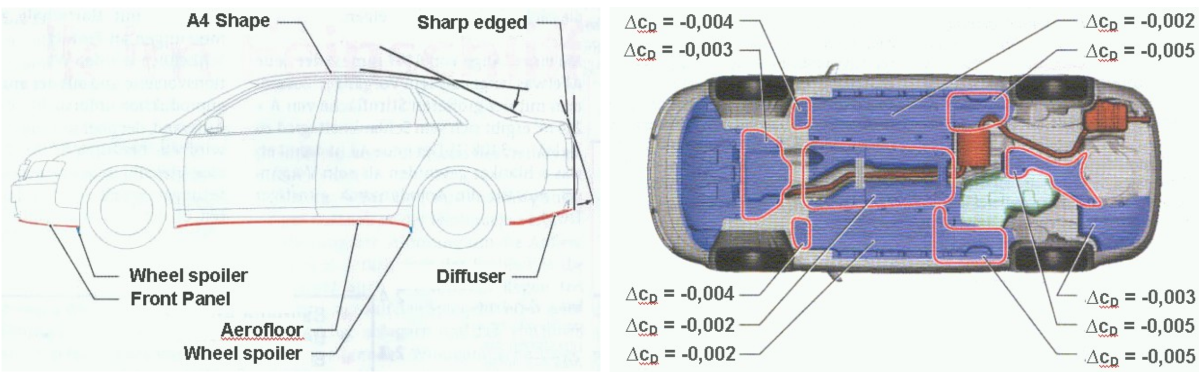

Fig. 4.4. "Aerofloor" of Audi A4 [4.7]

Parts of "aerofloor"	ΔC_D 1:4 scale model	ΔC_D 1:1 model
Front right and left	-0,002	-0,004
Central outer, right and left	-0,004	-0,002
Central inner, right and left	-0,004	-
Central tunnel	-0,007	-0,002
Rear axe	-0,008	-0,005
Rear, right	-	-0,003
Transmission cover	-0,001	-0,003
Sum Δc_D	-0,026	-0,019

Table 4.1. Contribution of Audi A4 underbody improvement to total drag coefficient [4.7]

Three examples below show that in the highest classes there is also a need to gain aerodynamic advantages of a well designed underbody, even though such cars have powerful engines which enable them to achieve high speed and good acceleration without putting much emphasis on a well streamlined body. Nevertheless the improvements of underbody C_D values allow achieving even higher top speed and slightly better acceleration. And lower fuel consumption shouldn't be neglected.

Picture 4.5 presents floor improvements of Audi A8. The exhaust system and the rear axle are integrated very skillfully. Thanks to the fully paneled underbody, it was possible to lower the C_D and to achieve the low rear lift without the "flip" in the luggage compartment's lid. [4.5]

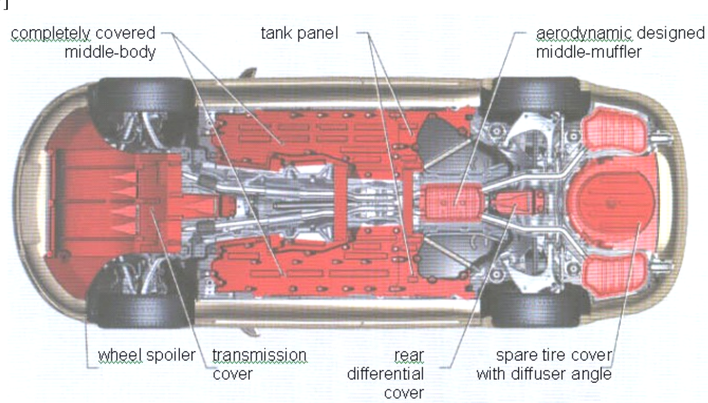

Fig. 4.5. Audi A8 underbody [4.5]

BMW has also improved its top model 7, as well as Mercedes in the current E-class. Pictures 4.6 and 4.7 present effects of underbody refinements.

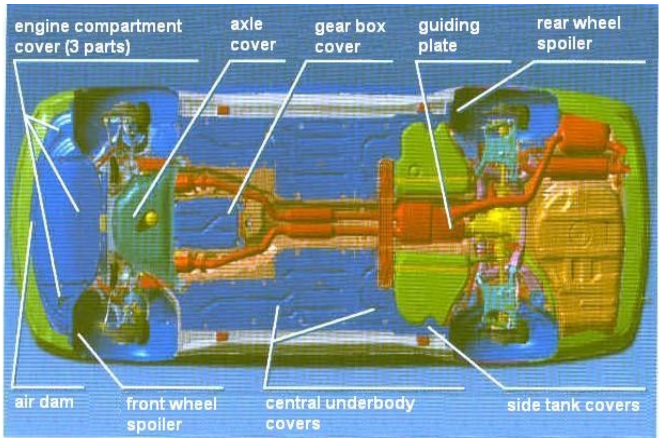

Fig. 4.6. BMW 7 underbody [4.6]

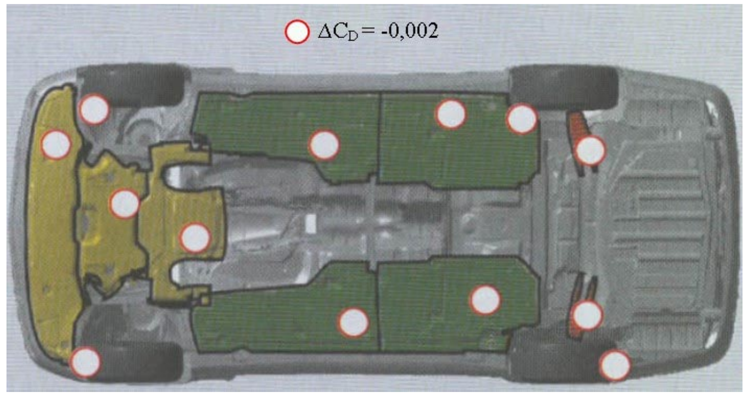

Fig. 4.7. Mercedes E-class underbody [4.4]

5. Problems with the underbody effect and its solutions

When the air is generating a low pressure underneath the car, e.g. using a flat underbody with a diffuser at the rear end, the car is sucked to the ground and down force is generated. There is a certain point where the effect of this down force is situated (like a point where gravity is working on, called the center of gravity). This point is called the CoP (Center of Pressure). The location of this point is very important for the stability and handling of the car especially when a car is braking from high velocity. Then the front of the car is diving a bit (due to the pitching moment) and the underside of the car and the road surface is no longer parallel to each other but in a more wedge shape. That means that the center of pressure is moving in the direction of the front of the car and it makes the rear of the car very light, which can cause the rear wheels locking and the car spinning off the road[5.1]. There are several things that can be done to achieve a more stable condition:

1. prevent a big pitching-angle when braking (prevent moving of CoP)
2. an additional wing might be added to the car
3. create a diffuser that ensures stability at all times (without additional spoilers)

The first point means that one needs a very stiff suspension at high speeds. At regular speeds, though, this kind of stiffness might not be comfortable anymore, so a variable stiffness with speed is required. The second point seems not to be a current trend of a modern street car since a big spoiler might be a bad cosmetic feature. The third point is used nowadays (Ferrari Modena 360) by giving the underbody a certain slope reaching the rear of the car (diffuser) in combination with a special suspension. The underbody of the car looks like an upside-down airfoil that will create the appreciated down force. Unfortunately, this shape includes some dangers as well. Considering an even street surface there should not be any problem in using this shape of underbody. Anyway, most of the streets are quite uneven with bumps and ditches. This means that the ground proximity is reduced and the regular flow under the car can be interrupted. In a very extreme case of a Formula 1 car that means that the underbody can touch the ground and there will be no airflow in the rearward diffuser. The complete contribution of underbody down force will be lost immediately. This can lead to severe crashes, as it was probably one of the reasons why Ayrton Senna died in 1994. However, street cars will not touch the ground but at high speed road unevenness and disturbances generate body motions.

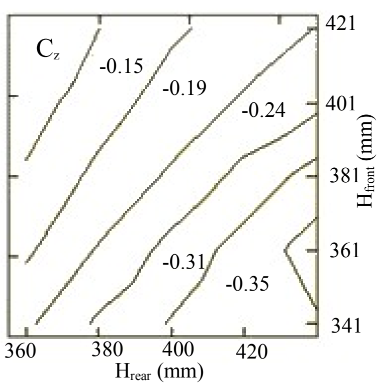

Fig. 5.1: relationship between ground clearance and C_z on a Ferrari Modena 360[5.3]

These motions must be well controlled to provide the desired degree of stability because body motions induce aerodynamic instabilities in the flow field under the vehicle (see figure 1). This instabilities lead to down force losses and variations, which reduce the cars stability. As it can be seen from Figure 5.1 the C_z-value is getting smaller with increased front height and with decreased rear height, respectively.

Ferrari solved this problem in the following way:
The spring stiffness was tailored not only to the sprung mass, but also to the induction of a defined pitch variation of the car at high speed. As speed increases, ground clearance is reduced more in the rear than the front, which produces a positive pitch angle that reduces the total aerodynamic coefficient. Furthermore there is a higher down force at the rear of the car. Finally, effective body-motion control was achieved via a specialized damping control system [5.2].

Despite the fact, that Ferrari found this solution, other companies are going on a more save "path". Currently, in the most expensive street car, the McLaren F1, small spoilers are popping out when the car needs to break down from high speeds. This small spoiler ensures enough down force especially at the rear axle and they are very reliable since there aren´t occurring big flow changes over the roof of the car in contrast to the underbody. Also Porsche relies on the spoiler which is popping out when a speed of more than 80 km/h is reached. In the Porsche case it stays out the whole time and is not only used when braking from high speeds.

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