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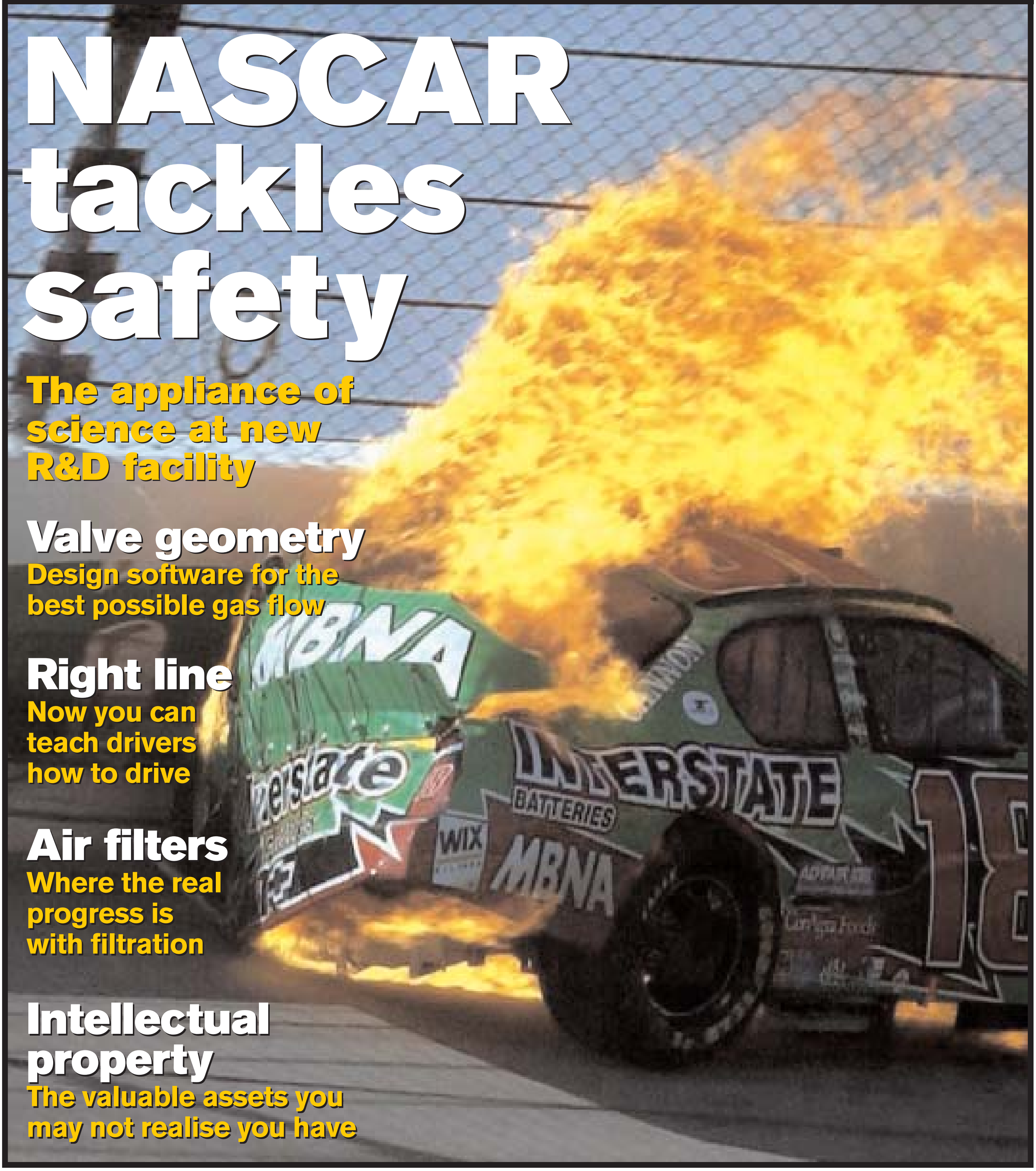

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Underbody downforce

How is downforce generated by a profiled underbody?

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Even racecars governed by strict underfloor design restrictions are designed with a venturi tube principle in mind

Many racecars, even those governed by so-called 'flat bottom' regulations, generate underbody downforce using the principle of the venturi tube. This is often said to work as described mathematically by Bernoulli. But like all models that seek to simply describe how things work, Bernoulli's Equation is based on some over-simplifications. In attempting to explain how downforce is generated by a venturi-shaped underbody, the most significant simplification is that the Bernoulli Model assumes the flow to be inviscid, that is, frictionless and smooth. Clearly this is not the case in the real world.

Now though we have models that can improve our understanding of what really goes on. Computational fluid dynamics, CFD, provides an infinitely clearer picture. And in this first of our regular 'aero-basics' columns with Advantage CFD, its engineers have provided some data and models based on classic Bernoulli theory, and on current CFD modelling methods. The comparisons are interesting...

First, let's define what we're looking at. A venturi tube consists of a converging inlet, a narrow throat, and a diverging diffuser (see Figure 1). In the context of a racecar, an underbody venturi is more like just the upper half of the tube, the car's underside being the only profiled component, while the ground forms the lower side of the 'tube'.

Fluid, in this case air, passing through the venturi tube, enters a

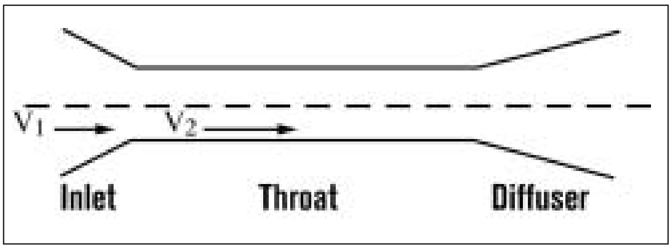

Fig 1: a venturi tube consists of a converging inlet, narrow throat and diverging diffuser

reducing cross sectional area as the inlet converges. Assuming the flow is incompressible, the law of Conservation of Mass requires that the mass flow through the throat is the same as that entering the inlet, vis:

$\rho v_1 A_1 = \rho v_2 A_2$, where ρ = density, A = cross sectional area

Where cross sectional area reduces, the flow velocity must increase. And as my physics teacher used to say, the basis of Bernoulli's Equation is that 'where the flow is fastest, the pressure is least'. As applied to figure 1 this becomes:

$$Ps_1 + \tfrac{1}{2}\rho v_1^2 = Ps_2 + \tfrac{1}{2}\rho v_2^2$$

Strictly speaking, this equation only holds true along a given streamline, or mean flow path, but in essence it says that where the flow accelerates, the dynamic pressure ($\tfrac{1}{2}\rho v^2$) increases, so the local static pressure (Ps) decreases. This is also a manifestation of the principle of Conservation of Energy – as the kinetic energy of the airstream increases with increasing velocity, so its pressure energy decreases, and vice versa.

Produced in association with Advantage CFD.

advantage CFD

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Diffuser angle and downforce

Advantage CFD constructed a spreadsheet-based model that calculated the local static pressures, using Bernoulli's equation, at points along a venturi that represented the profiled underside of an idealised two metre long racecar sidepod. From this, values of total downforce were calculated, and charts of pressure distribution along the venturi profile plotted. Some of the model's geometry could be altered, including inlet angle, ground clearance and diffuser angle, while keeping the length fixed. This month we're going to look at the effect of varying the diffuser angle.

The maximum height of the diffuser remained fixed in this study, so changes to its angle had the effect of changing the diffuser length. In some racing categories technical regulations often define diffuser start points and lengths, but there is some flexibility, to a greater or lesser degree, in other categories.

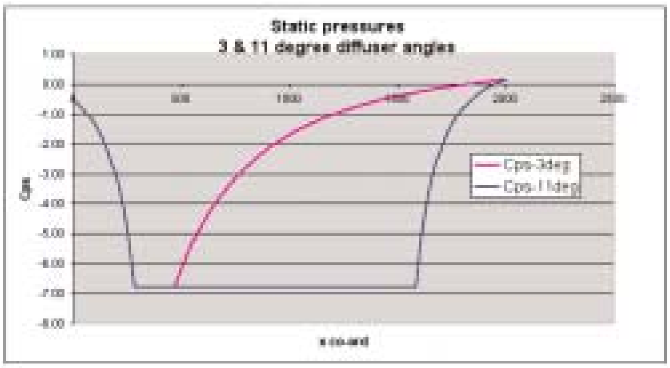

Figure 2: pressure distributions along the underbody – calculated according to Bernoulli

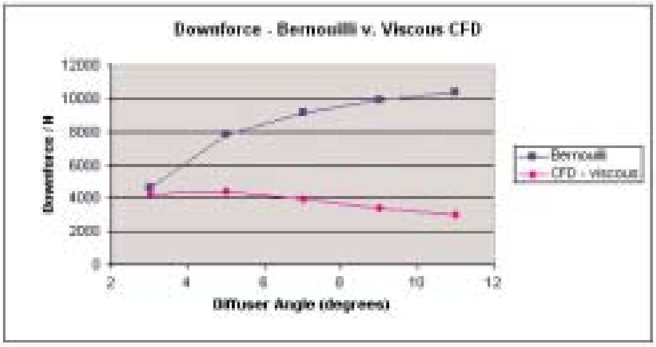

Figure 3: showing all the diffuser angles calculated against Bernoulli downforce values

Figure 2 illustrates the pressure distributions along the underbody, calculated according to Bernoulli's Equation, at the extremes of the diffuser angle range studied here, 3 degrees and 11 degrees. It is clear that the model predicts that low pressure persists for longer where the venturi throat, the flat underbody section, is longer. Thus, more underbody area is maintained at low pressure with the shorter, steeper diffusers, and that produces a greater theoretical downforce value. Figure 3 plots all the diffuser angles calculated versus these Bernoulli downforce values, and shows downforce increasing with increasing diffuser angle in this model. The gains tail off because the lengthening of the venturi throat is not linear with changing angle.

As a means of describing how underbody pressure is reduced and downforce is generated then, Bernoulli's equation provides a starting point. However, it quickly falls down when the airflow in the underbody becomes less than smooth, and when viscous computational fluid dynamics was applied the story was rather different, as figure 3 shows. This model was able to make predictions about what happens in a real fluid, where viscous effects cause boundary layer development. Furthermore, the effects of the adverse pressure gradient in the diffuser, where the airflow is being asked to flow from a low to a high-pressure region (which is not what it prefers to do) are also taken into account.

It is the job of the diffuser to return the underbody airflow back to ambient pressure as it rejoins the airstream at the rear of the car. But if the diffuser angle is too steep, the pressure gradient is also too 'steep' and the result is flow separation. Thus, downforce in our simple model tops out at just 5 degrees when these viscous effects are built in.

Figure 4 shows how substantial the flow separation in our particular model is at 11 degrees, and how the region of high velocity flow in the diffuser is greatly reduced when this much separation has occurred. Figure 5 goes further, and shows the magnitudes and pressure distributions along each of three of our underbody configurations (the black silhouettes represent the CAD models of each underbody).

It can be seen that the pressure differential between inlet and throat, which is what drives the flow through the underbody, is markedly reduced because separation has occurred in the diffuser. This separation has caused a reduction in mass flow through the throat, and the pressure reductions along the throat are thus much smaller in magnitude, leading to less downforce generation.

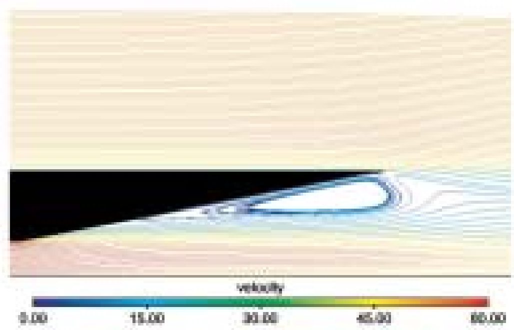

Figure 4: how substantial the flow separation is at 11 degrees

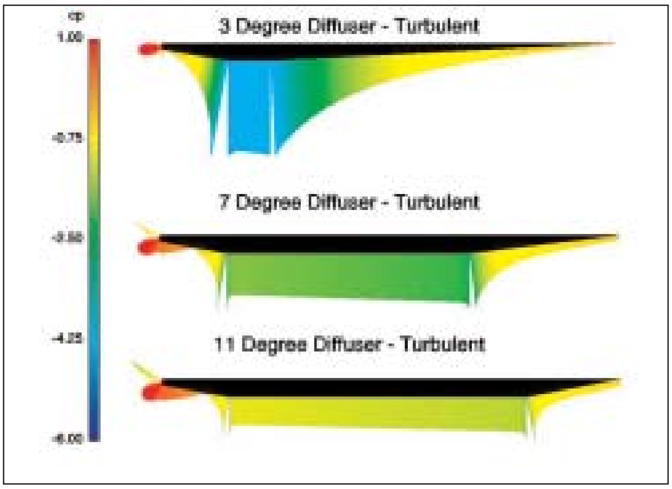

Fig 5: magnitudes and pressure distributions along each of the underbody configurations

Conclusion

Taking both models into account then, the trick to maximising downforce is to have the longest throat section with the shortest, and therefore steepest possible diffuser that maintains attached flow. Of course this 2D CFD study necessarily does not take into account 3D flow effects, such as the sideways spill of air into the low-pressure region that would occur in the real world, and which can permit steeper diffuser angles without separation. And components like wheels and underbody protrusions all serve to complicate the problem, as could the presence of a rear wing, which might beneficially interact by reducing or delaying separation in steeper diffusers. We'll look at the effects of other underbody geometry changes in forthcoming columns.

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