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# RECENT DEVELOPMENTS IN ROAD VEHICLE AERODYNAMICS

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## ABSTRACT

This paper provides an overview of aspects of vehicle aerodynamics including the time averaged and varying forces and pressures for commercial vehicles and passenger cars. The wake flow for a simplified car shape (the Ahmed body) with varying rear slant angles is presented. It is argued that much of the external body shape for cars is dictated by consumer desires, thus is influenced by the stylist rather than the aerodynamicist. Conversely, the internal cooling flows and underbody can be influenced by aerodynamicists, as well as details that influence aerodynamically generated noises and the relative merits of computational versus experimental methods are discussed for these areas.

**Keywords:** Vehicle, Car, Aerodynamic, Review, Ground Simulation, ITS, CFD, EFD

## 1. INTRODUCTION

### 1.1 Background

Understanding and optimisation of the aerodynamic properties of vehicles has occurred over at least the last 100 years. The majority of understanding has occurred via experimental fluid dynamics (EFD) utilising wind tunnels. The first recorded test of a vehicle in a wind tunnel appears to be a train model tested in 1896, as reported in The Engineer [1]. Considerable road vehicle aerodynamic development has taken place in wind tunnels, notably in Germany by Klemperer and Kamm in the 1920-30'ies and the wind tunnel is still used for much development work despite advances in computational fluid mechanics (CFD) in the last few decades.

Advances that document our understanding include the publications by Hoerner that focus on the drag and lift of shapes including trains, cars etc. [2,3] and more recently a range of books dedicated to road vehicle aerodynamics e.g. [4,5] with some more specific texts on racing car aerodynamics e.g. [6]. Probably the largest current source of automotive publication, including vehicle aerodynamics, is the technical paper series of the Society of Automotive Engineers (SAE-Int); many result from the SAE World Congress held annually in Detroit, including a "Special Publication (SP Series), specifically on vehicle aerodynamics. Details can be found via www.sae.org. Additionally there are numerous journals in specific areas of fluid mechanics and fluid/structure interactions.

The advances in EFD have included tunnels with moving ground belts that give a correct simulation of the relative flow and ground movement (at least for the condition of driving through still air) and permit tests on vehicles with rotating wheels.

All road vehicles are significantly influenced by the presence of the ground. However for vehicles with relatively large ground clearances (which include trucks and most passenger cars) it is usual to use a fixed ground plane; often the floor of tunnel test section. Thus the effect of the floor boundary layer is often considered relatively minor and this facilitates testing since the vehicles can be supported from their (stationary) tyre contact patches. As more attention is focused on the underside of cars (an area which permits some aerodynamic optimisation out of the sight of the stylist), more attention is needed on the correct ground simulation and the replication of wheel rotation. When the ground clearance is small and/or the underside flows have a significant influence on force and moments, (e.g. in many racing classes) it is worth expending considerable effort on correct ground simulation. As is commonly known, F1 and CART teams utilise tunnels with complex, moving ground belt systems but generally testing is at about 40% scale. In Europe there are facilities that provide full-size car testing; either with a full width simulation, such as in DNW (the German-Dutch Wind Tunnel), or partial simulation via a central belt system such as the Pininfarina Tunnel in Italy or the IVK/FKFS tunnel in Germany.

Increasingly CFD is utilised for vehicle aerodynamic development. Hucho [7], when reviewing the status of vehicle aerodynamics makes the following points:

- The underside was seen as having the potential to reduce drag, lift and low-frequency noise
- The flow pattern at the rear of the car could be improved
- Simulation of the relative motion could be improved

including the boundary layer of the natural wind and turbulence
- More information was needed about velocities, pressures and stresses, either by CFD or EFD

### 1.2 Consumer Issues

The external shape of a passenger vehicle results from compromises between function and form in the design process. Packaging and styling play crucial roles in the overall product, and customers often desire frequent change and can be followers of fashion. Whilst fuel-efficiency is important, it is far from an overriding concern for many potential purchasers (despite what vehicle aerodynamicists might think!).

Thus although the drag coefficients of cars with the traditional 3-box (sedan) reached a value of about 0.30 in the late seventies (e.g. in 1978 the quoted value for the Audi 100 III was 0.3) and petrol prices continue to rise, the customers' desire for "new" styles/shapes can result in non-optimum forms from the perspective of aerodynamics. This includes an increasing proportion of customers purchasing 4WD and RV's, which not only have drag coefficients that may not be optimum, they also have large frontal areas.

The importance of provision of vehicles with perceived levels of high quality means that there is much attention paid to obtaining low levels of sound and vibration. Globally, one of the largest users of wind-tunnel time is the measurement and reduction of wind noise. This is due mainly to; 1) the inability of computational fluid dynamics (CFD) to provide accurate answers for the fluctuating pressures at frequencies relevant for sound generation; 2) the desire for very low in-cabin sound levels even at high speeds and; 3) the cost of modern sealing systems employed in new cars (which must seal well under all dynamic and thermal driving conditions). This important area is discussed later.

## 2. TIME-AVERAGED FORCES

### 2.1 Commercial Vehicles

Unlike passenger vehicles, many commercial vehicles exhibit two or more bodies in tandem (i.e. a cab and trailers). Unless there is attention paid to minimising flow separations at the front of the vehicle (either by design or with the addition of streamlining devices) a high forebody drag can result. Much work has been done on reducing forebody drag on trucks. This has included large 3-D devices that attach to either the top and rear of the cabin, and/or to the front face of the trailer(s) and by the technique of wake matching where the wake of a correctly sized and placed deflector on the cab roof can be used to reduce the forebody drag of the trailer front. Fundamental work in that area includes work on optimum sizing and placing of a disc in front of the face of a cylinder [8]. However, drag-reductions (and hence predicted fuel-savings) measured in smooth-flow wind-tunnel tests for such deflector-type devices over-predict the savings available under road driving [9]. This effect can be significant and arises from turbulence in the approach flow (described later) – for more details see [10]. It is now clear that the streamlining device that provides the greatest on-road saving is the large 3-D type.

Many attempts have been made to reduce the drag associated with the separation at the rear of trucks, including various degrees of boat tailing by rear corner chamfering, splitters that alter wake dynamics and even a patent for an inflatable boat tail. However few, if any have proven practical for road applications.

A wide range of publications are available of truck aerodynamics, with much understanding being generated from [11]. Whilst there is on-going research in the area, much of the work has been commercialised in the form of add-on devices that attach to either the cab roof or the front face of the container.

### 2.2 Passenger Cars

Modern cars generally exhibit attached flow over the top and side surfaces until the flow separates at the C-Pillars and the rear of the vehicle. Thus much of the drag is due to the lack of pressure recovery resulting from separations which occur at the rear of the vehicle. The A-Pillar region exhibits an unsteady vortical separation in most cars and has been the subject of considerable work by aerodynamicists and acousticians. Here the focus has been on noise reduction rather than drag minimization (and issues such as water management, visibility etc.) and will be discussed later. Thus aerodynamicists have focused on the flow in the rear, with an emphasis on pressure recovery by "boat tailing". Examples include the Camm tail and on commercial vehicles tapering the vertical and top surfaces of trailers discussed above. Clearly for both commercial and passenger vehicles, this can intrude into the volume of the vehicle, and this, coupled with the desire for commercial vehicles to have un-impeded rear access, has precluded much of the drag-reducing possibilities.

### 2.3 Wake Flow

Unlike commercial vehicles, there are considerable degrees of slant on the back of conventional passenger cars and hatchbacks. Whilst the slant can offer some drag savings due to pressure recovery there are deleterious effects associated with large slant angles where strong vortices generated at the C-Pillar generate significant lift and induced drag. Work published after the development of the Volkswagon Golf (aka Rabbit) and Scirocco [12] demonstrated the considerable influence of the vortices on drag and lift, where at rear slant angles close to 30 degrees there is a peak in both the drag and lift forces.

This phenomenon has been studied by many aerodynamicists – both in the public and commercial domains. The shapes of real cars are complex and include corner rounding, complex curvature, joins, gaps etc. In order to provide simplified shapes that capture the complexities of the physics of the flow, "reference models" have been used. These offer the advantages of simplicity of manufacture (or for CFD studies computational shape generation) thus can be used in a variety of testing domains – both physical and simulated. A review of the various simplified reference models is given in [13] where at least 16 different models are identified; many with variable geometry. One of the most investigated shapes, both in EFD and CFD, is the very simple model by Ahmed [14], which represents closely the geometry of an earlier shape by Morel [15] and permits simple variations to the rear slant angle. The sensitivity of drag and lift to the slant angle can be seen in Figure 1.

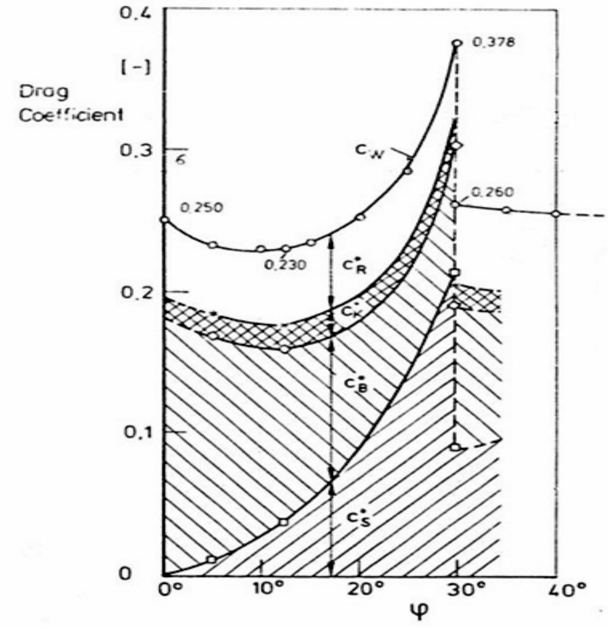

Fig 1. Influence of Rear Slant Angle on Drag Components from [20].

There has been much recent work on understanding the wake of cars e.g. [16, 17, 18] Recent work on furthering the understanding of the wake using the Ahmed body includes the technique of wake mapping. Several methods exist for documenting the flow and an example showing the influence of the rear slant angle on the velocity field can be seen in Figures 2. Here the data were obtained with dynamically-calibrated multi-hole pressure probes, which provide the three orthogonal components of velocity and static pressure at frequencies up to about 1500Hz. Details of this technique can be found in [19]. As the rear slant angle is increased the wake flow exhibits vortices of increasing strength (giving rise to the increasing drag and lift values on the body indicated in Figure 1) until the vortex system breaks down at rear slant angles of over 30 degrees and the drag and lift forces drop rapidly. The implications for the vehicle aerodynamicist are clear. However the geometries of real vehicles are complex and how this complexity, and the lack of an A-Pillar on the Ahmed body, change the flows and forces are on-going areas of work at RMIT and other research institutions.

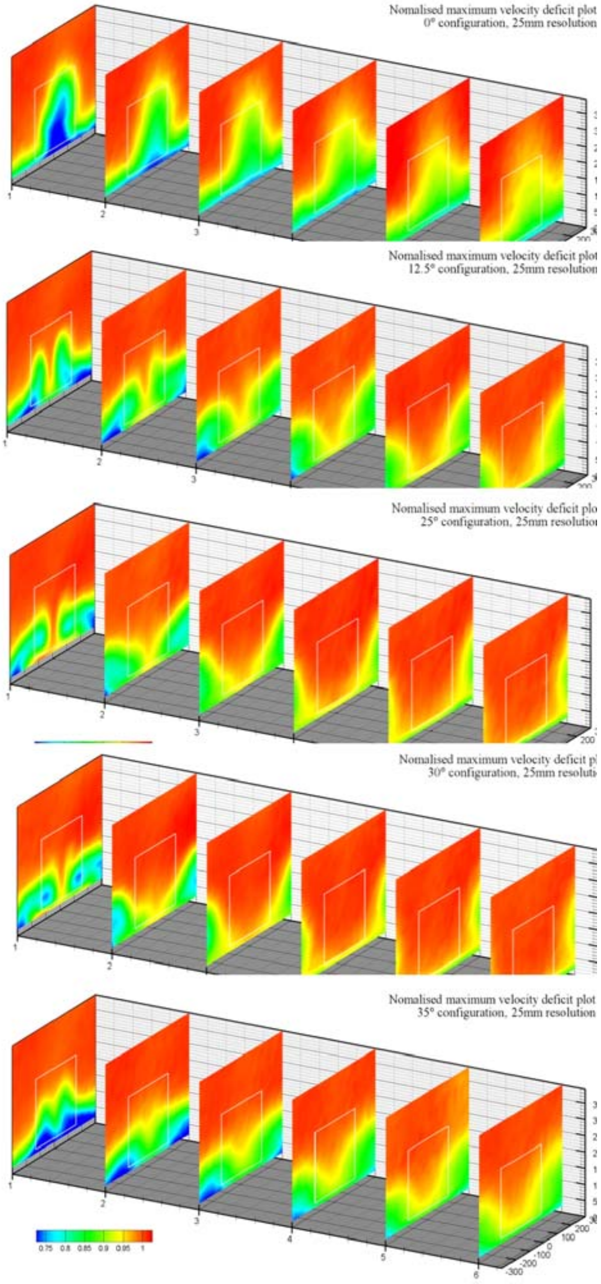

Fig 2. The Wake Velocity Deficit for a 40% Scale Ahmed Body with Varying Degrees of Rear Slant Angle, adapted from [16].

## 2.4 Under-vehicle and internal cooling flows

These areas exhibit potential for further drag reductions and are outside the domain of the stylist. Both regions pose a special challenge for the engineer since cars utilise the regions for heat dissipation (from the engine bay, brakes, etc) and the underside is in close proximity to the moving road surface and the flow can be influenced by the rotating wheels.

Cooling flows will not be discussed in detail here, but the fact that cooling systems are conservatively sized (i.e they are designed to cope with worst-case heat load) and the fact that they can account for up to 10% of the total vehicle drag coefficient, mean that there are avenues for drag reductions by reducing the air through the cooling system to the minimum needed. For much of the time relatively small amounts of air are needed, thus “throttling” the cooling system on the air side can provide reductions in drag coefficient, albeit with added complexity of electro-mechanical systems to close up front grilles as required [20].

Considerable effort is expended by some companies in providing experimental and computational simulations that generate the correct relative motions in the area of the underbody. Examples include the full-size moving grounds in tunnels such as IVK/FKFS and Pininfarina and the complexity that is added to CFD simulations (such as sliding meshes). There are considerable experimental difficulties in obtaining measurements in the areas of the internal cooling flows and the underbody. Problems include access, thermal stratification and the relatively low velocities encountered. Here CFD can, and has, been very useful, with many companies now evaluating cooling systems via CFD, sometimes with experimental inputs from EFD (radiator pressure drops, cooling fan performance curves) – e.g. see Williams [21]. A very useful advantage of CFD is that it enables local forces, pressures etc to be determined, which cannot be readily done with EFD. This has been utilised with identifying drag components of the underbody, including assessing the contributions of wheel spoilers to drag reduction [22].

## 3. TIME VARYING FORCES AND PRESSURES

The perception of quality of a motor vehicle is an important discriminator for the customer. The dynamics of the vehicle are important, both in the macro sense (e.g. unsteady pressures resulting in solid body movements of the vehicle on its suspension) or in the micro sense (e.g. local pressure fluctuations resulting in wind noises and local forces) resulting from the unsteady pressures in and around the vehicle, are important sensory inputs for the driver and passengers. These include the time-varying fluid-dynamic phenomena such as vortex shedding, resulting in fluctuating pressures that give rise to fluctuating forces on components and the entire vehicle body as well as noise. Car companies have significant engineering expertise to assess and minimise noise, vibration and “harshness” (NVH).

### 3.1 Time-Varying Flowfields and Forces

Generally the understanding of fluctuating forces is not as well understood as time-averaged. Whilst the relative flow experienced by the moving vehicle is generally considered smooth and the EFD and CFD inlet conditions generally replicate an unsheared, zero turbulence flow), which is not generally the case on-road. For an isolated moving vehicle, the relative flow experienced is the vehicle speed through still air subtracted from the atmospheric wind speed. The wakes of other vehicles, the (unsteady and sheared) atmospheric wind and the wakes of roadside furniture (subject to the atmospheric wind) further complicate the real driving environment. Measurements of the unsteady nature of the relative flow as experienced by the moving vehicle have been made and are reviewed in [23 and 24] and work is on-going in this area. Most work in this area has been on the transient forces and moments that occur during a passing problem and simulation of the relevant velocities poses challenges – both for CFD and EFD. Car companies employ banks of fans which are used to provide repeatable cross-winds on test tracks, but such methods are limited to understanding the vehicle response (either with or without the driver input) **after** the vehicle has been produced. Simulation methods that have been considered include perturbing the flow upstream of the vehicle via grids or pendulums or active systems, moving the vehicle itself in a smooth stream (such as a rapidly rotating turntable), or combinations of the above. [25] details some of the possible methods. Work on the effects of an approach flow with turbulence utilizing the aero acoustic tunnel based at Monash University in Australia has recently been reported [26]. Also the Pininfarina Tunnel has incorporated active turbulence generation schemes to replicate aspects on the “real” flows found when driving and some significant effects have been found [27].

### 3.2 Noise

The automotive consumer now has a wide choice of potential vehicles and the sound “quality” of the vehicle plays an increasingly important role in vehicle selection. Because of this, vehicle manufacturers now place considerable emphasis on the customer perception of sound. In car companies, the majority of work is performed for in-cabin sound quality and whilst this can extend to the opening and closing noises of components such as switches and doors, the overall sound quality under typical driving conditions is also important. Due to the efforts of the passenger vehicle manufacturers, levels of NVH have been reduced for car mechanical components (engines, drive trains and exhausts for example), such that aerodynamically generated noise and vibration is now very significant. A good overview can be found in George and Callister [28].

The importance of wind noise is such that it is now one of the single largest users of wind-tunnel time and most major car companies have aero-acoustic tunnels, with more planned in the next decade. Such tunnel are characterised by very low-inflow sound levels and semi-reverberant open-jet test sections. The frequencies of interest extend across the range of human hearing (20 to 20,000 Hz) thus there are a wide variety of scales of problem and the physics can involve feedback mechanisms between the acoustic and hydrodynamic fields. CFD is generally not utilised as a tool for prediction and problem solving and many argue that it cannot be used to accurately predict wind noise at the current level of understanding and computational capability.

Details often influence sound quality and level, including noise and vibration from mirrors, aerials, cavities etc. It is now well established that circular and rectangular section cylinders can have their vortex-shedding behavior (and hence noise generating potential) subdued by modifications that include spiral wraps or grinding. Such developments are now commonly adopted in aerials on passenger cars.

Significant differences in transitory nature of the wind noises can be experienced between the relatively smooth flow in most tunnels and the more turbulent flow encountered on-road, with the main difference being revealed by modulation analysis rather than spectra (which average out some low-frequency modulations), see [29] for further details. The area of psychoacoustics is growing in importance for car companies and sound descriptors now include such measures as sones, harshness, roughness and modulation. Since the unsteady nature of the on-road flow field influences these, some sound measurements are now carried out in tunnels with turbulence generation systems as described above.

## 4. FUTURE DEVELOPMENTS AND THE INFLUENCE OF INTELLIGENCE IN VEHICLES

Hybrid vehicles and the influence of renewable energy sources on vehicles can clearly reduce demand on finite resources of fossil fuel. Whilst solar powered vehicles have driven at speeds of well over 100km/h they are clearly not practical for most modes of transportation (see [30] for details of solar energy density, drag coefficients etc). Whatever the source of energy it is useful to minimise its consumption. Intelligent Transport Systems (ITS) offer the possibility to closely couple vehicles, which if there is sufficient velocity defects in the preceding vehicle wake(s) close coupling can offer drag savings from drafting. Whilst the very close coupling of road vehicles can offer significant saving (in the same manner as train aerodynamics) it seems that this may need dedicated vehicles running on dedicated roads. Such possibilities are being investigated in the USA at the Partnership for Advanced Transport Highways (PATH) and also at RMIT. It is interesting to note that such savings can be very vehicle shape specific (as well as spacing specific), with a recent experimental program showing that for the 30 degree Ahmed body shapes in tandem there can be an increase in the trailing vehicle drag for some close spacings [31]. Other on-going work in this area includes the assessment of the drag coefficient reduction of real vehicles at typical inter-vehicle spacings. Such spacings can be found from the increasing use of instrumented motorways and highways).

Since investigating the aerodynamics of several closely-coupled vehicles involves relatively long test sections (with perhaps long moving grounds) the experimental difficulties are considerable. Here CFD can be used to enhance and extend the testing domain. Ongoing work in the area includes considering the best distributions for savings using mixed vehicle shapes and sizes [32].

## 5. CONCLUDING REMARKS

The external body shapes required to minimise both commercial and car vehicles are well known, and for sedan-shaped cars a drag coefficient plateau was reached in the late Seventies. However the majority of modern passenger cars are not of this shape, reflecting a range of consumer requirements and desires (including utility, styling, fashion etc.). These drive the car market to a greater degree than fuel efficiencies and thus aerodynamic optimisation is usually tightly bounded. Thus detail optimization occurs for the external body shape and the remaining areas that can be optimized (in an engineering sense) include the internal cooling flows and the underbody. From noise and sound quality perspectives there are still external areas on the car that can benefit from aerodynamic/aero-acoustic optimization. Future transport systems, where increasingly intelligence is transferred from the driver to the vehicle systems, can permit enhanced transport efficiencies, but these may come from a combination of drag reductions arising from drafting and road throughput with reductions in average inter-vehicle spacing. If the passenger vehicles of the future are influenced more by energy minimization, rather than by consumer desires, greater efficiencies will be generated.

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