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The effect of vehicle spacing on the aerodynamics of a representative car shape

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Abstract

Inter-vehicle spacing on highways is considered and an analysis of spacing is presented, deduced from data from an instrumented highway. Vehicle drag reductions arising from close spacing are discussed and drag and lift data from wind-tunnel tests on two co-linear Ahmed bodies (representative vehicle shapes able to replicate typical car airflow, configured with 30° slant back angles) are given. Inter-body, non-dimensional spacing was varied from 0.1 to 4.0, based on vehicle length. Surprisingly, significant drag increases were found for the rear Ahmed body for spacing of 0.1–1.0, when compared to the drag of the body in isolation. For greater spacing, the drag of the rear body fell below the value of the isolated case, up to the maximum spacing considered. The lift coefficient of the rear body was also found to be very sensitive to spacing. It was concluded that the effect of the strong vortex system arising from the slant back was the cause of the drag and lift changes of the rear vehicle. Since traffic spacing is likely to reduce with the increasing use of intelligent transport systems (ITS), it is argued that more attention should be paid to understanding these effects.

Keywords: Vehicle; Aerodynamic; Interaction; Lift; Drag; Spacing; Ahmed body; Convoy; Platoon

1. Background

Cars are bluff bodies with typical drag coefficients of 0.3–0.4. The majority of aerodynamic drag arises from form drag (also known as pressure drag; Hucho et al., 1998).

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Development work is performed physically (usually via wind-tunnel testing) or, increasingly, via numerical simulation (i.e. CFD). Almost without exception the vehicle testing domain is bounded with real or virtual side boundaries, including a fixed or moving ground representation. The air (real or numerically simulated) into which the test vehicle is positioned is usually smooth with no or low turbulence levels and a uniform velocity through the test domain. Thus the test domain is free from the influences of other vehicles and either simulates the case of no atmospheric wind or includes the simulation of a time-averaged atmospheric wind (via rotating an isolated vehicle at an angle to the flow). Corrections for the mean effects of atmospheric winds (including yaw angle) on moving road vehicles include the ‘‘wind-averaged-drag’’ method, Buckley et al. (1978) or the more comprehensive model suggested by Sovran (1984).

In contrast, road driving is in the influence of turbulent atmospheric winds and traffic wakes. The effects of these influences are to modify the relative wind environment experienced by the moving vehicle to one which has significant temporal and spatial variations. In the last two decades road vehicle aerodynamic research has increasingly been focussed on understanding and simulating parts of this ‘‘real’’ flow environment. Work has drawn on data and methods used in wind engineering where simulation of a correctly scaled model atmospheric boundary layer and the wakes of other close buildings are considered essential.

The effects of upstream bodies on the drag of following bodies can be significant and have been used for drag reductions in a number of ways. These include matching the wake size of a relatively small upstream bluff body (deflector) to shield the front of a downstream bluff body (Roshko and Koenig, 1978), thus minimising the forebody drag of the latter. This wake matching is utilised in some drag-reducing devices fitted to commercial road vehicles. The low drag coefficient experienced by a carriage in a length of train is the result of the upstream carriage shielding the downstream one (as well as the downstream carriage raising the base pressure, except for the last carriage in the train). Early work identifying these effects can be found in Hoerner (1965), with more recent work on goods wagon drag and drag reduction given in Watkins et al. (1992).

Fluctuations at a single point in the on-road relative flow have been measured by prior researchers via vehicle-mounted hot wires (Watkins and Saunders, 1998; Howell, 2000) or at four points in space using multi-hole pressure sensors (Watkins and Melbourne, 2003). In all cases, the intention has been to document the flow field in the absence of traffic. Effects of upstream vehicles include the provision of a complex flow environment for the test vehicle, resulting in modulation of wind noise by the larger scale fluctuations in the atmospheric wind, as well as generating transient forces and moments on vehicles. Limited research to simulate the effects of upstream vehicles has included the positioning of small vehicles upstream of the test vehicle in aero-acoustic wind tunnels and measurements with multi-hole pressure sensors in the immediate wake of driven road vehicles (see Watkins et al., 2001; Saunders and Mansour, 2000). Recently, active turbulence generation systems have been used to more closely simulate the transience in ‘‘real’’ road environments in full-scale automotive wind tunnels (Cogotti, 2004).

2. Aim and scope

Little work is evident on how the reality of road driving in traffic influences the mean drag coefficient of a vehicle. Whilst inter-vehicle spacing is known to have a significant effect on drag, no literature was found regarding the typical inter-vehicle spacing when travelling on highways. Thus the aims of the work presented here are to collect and present initial findings on typical road vehicle spacings and to investigate the changes in aerodynamic forces when travelling under the influence of upstream wakes.

There are many variables in a study of this kind; these include vehicle geometric configuration (e.g. truck or car, including fastback, notchback, etc.), the lateral and longitudinal positioning of vehicles relative to each other and the nature and relative direction of the atmospheric wind. In order to restrict the number of variables, the investigation is limited to a wind-tunnel simulation of a representative car geometry in calm conditions (i.e. no yaw angle) and vehicles that are directly aligned (i.e. co-linear).

3. Considerations of vehicle spacing

The proportion of time spent driving in the influence of other vehicles is increasing. In the early 1980s, the US Federal Highway Administration estimated that more than 60% of peak interstate travel occurred under "congested" conditions. Additionally, the increasing affordability of intelligent transport systems (ITS) (distance sensing, fly-by-wire technologies, etc.) in mass-produced cars makes the possibility of relatively close-coupled convoys practicable. It is well known that the reduced mean velocities when closely following a vehicle (drafting) can significantly reduce the force needed to overcome air drag and is exploited in sports where minimising energy consumption is essential (e.g. cycling).

Very close spacings, and thus low drag coefficients, are possible when vehicles are directly coupled; e.g. trains exhibit a relatively low drag per unit volume arising from close-coupled units. Wind-tunnel tests on relatively bluff goods wagons, Watkins et al. (1992) showed that the wind-averaged drag coefficient reduced by 0.05–0.1 m^{-1} gap spacing for typical practical spacings. To exploit this effect, and to increase the highway capacity (vehicles/lane/hour), the concept of travelling in convoys is currently being explored by the Californian Partners for Advanced Transit and Highways (PATH—see Savas, 2000) and drag reductions of 10–40% have been measured for closely spaced parallelepipeds that resemble trucks (Browand and Hammache, 2004).

Increasingly, major roads are subject to electronic traffic monitoring. In some cases the data are amenable to providing statistical distributions of inter-vehicle spacing, sometimes as a function of speed and vehicle type. Whilst work in this area is ongoing, an initial analysis of the data gives the PDF of vehicle spacing; see Fig. 1. These data are taken from a sample of several thousand vehicles on the M25 orbital motorway around London. Whilst further analysis is intended to provide PDFs of vehicle spacing as a function of speed, time of day, etc., this initial analysis is for all speeds at any time of the day or night and for all lanes. The small peak at a spacing of about 1.0 is thought to arise from very slow moving, or stationary vehicles.[1]

4. Selection of test models

A common trend employed by vehicle aerodynamics researchers is to use reference models to help understand the fundamental flow structures that may be exhibited in road

[1]The M25 is also known by the locals as the largest car park in the world.

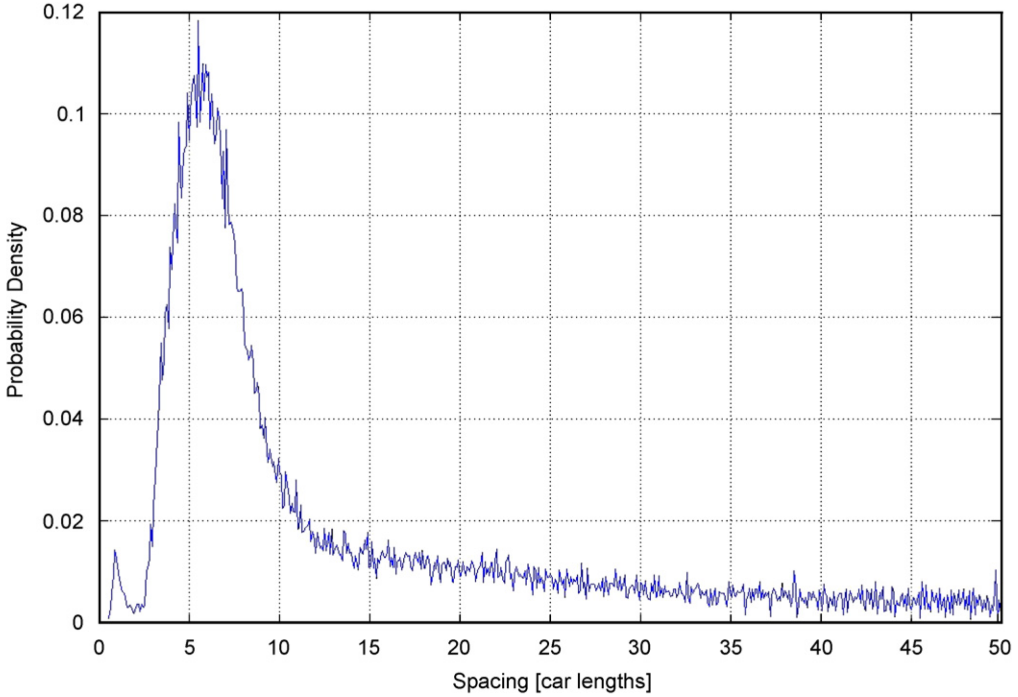


Fig. 1. PDF of traffic spacing from M25.

vehicle wakes. These models are representative of car shapes in that they generate similar critical flow features while maintaining geometric simplicity and allowing simple shape changes. In their review, Le Good and Garry (2004) observed that one of the most common was the Ahmed model, which is used in this study, see Figs. 2 and 3. The models had streamlined fore bodies thus no representation of the *a*-pillars (i.e. the area where the front and side screens meet), and after bodies with backlight angle (representative of a vehicle's *c*-pillar angle, i.e. the slanted back of the vehicle) of 30°. The study is thus concerned with the effect of vehicle after body-generated flow structures, though these are representative of a significant proportion of vehicle aerodynamic flow structure and thus relevant lift/drag data.

Ahmed et al. (1984) observed that for a base slant angle less than or equal to 30°, separating shear layers roll up from the slanted edges of the backlight forming longitudinal vortices. Also, the flow separates from the roof-backlight junction and then reattaches past these separation bubbles before the end of the backlight. Upon leaving the rear of the backlight, the flow again separates from the top and bottom edges and rolls up into two separate re-circulatory flow regions, forming two separation bubbles, one above the other and in opposing directions. Fig. 2 shows the proposed system. Longitudinal and upper recirculation vortices were found to depend on the base slant angle. As the base slant angle reaches 30° (a common angle for modern passenger cars and one which Ahmed termed as "critical"), the separated bubble/region from the roof-backlight junction grows in size forming a dominant horseshoe vortex shape on the backlight. The strength of the

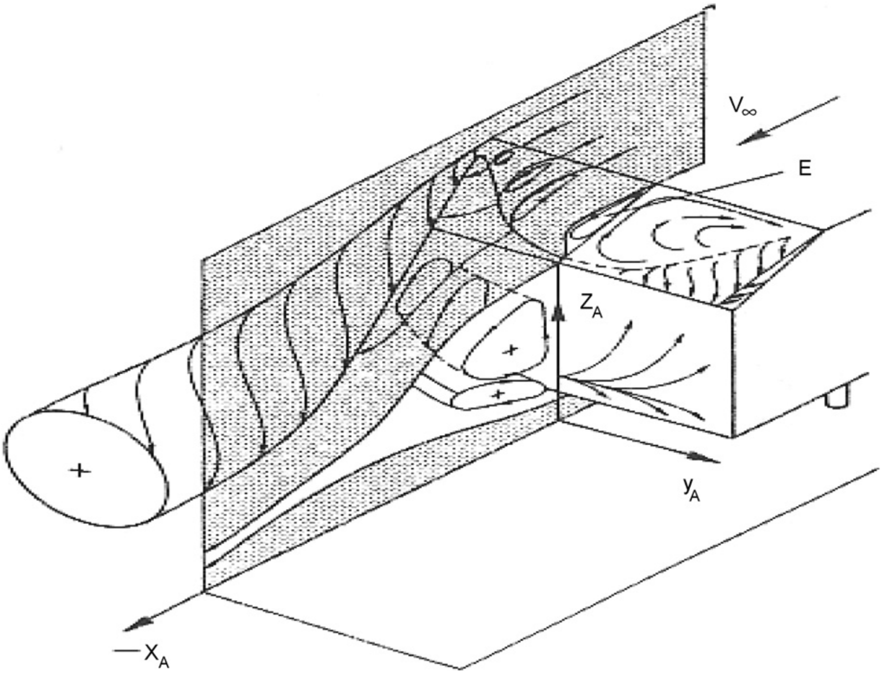


Fig. 2. Proposed vortex system from Ahmed et al. (1984).

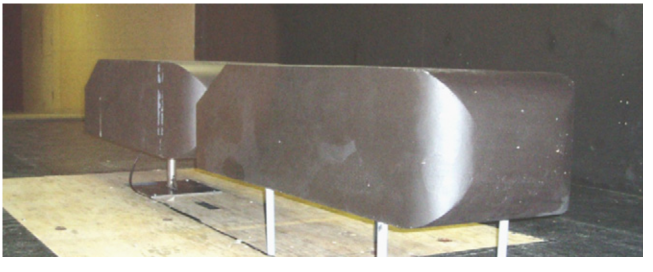


Fig. 3. Sample drafting arrangement.

longitudinal vortices is such that this vehicle shape has a higher lift coefficient than drag coefficient (both based on projected frontal area).

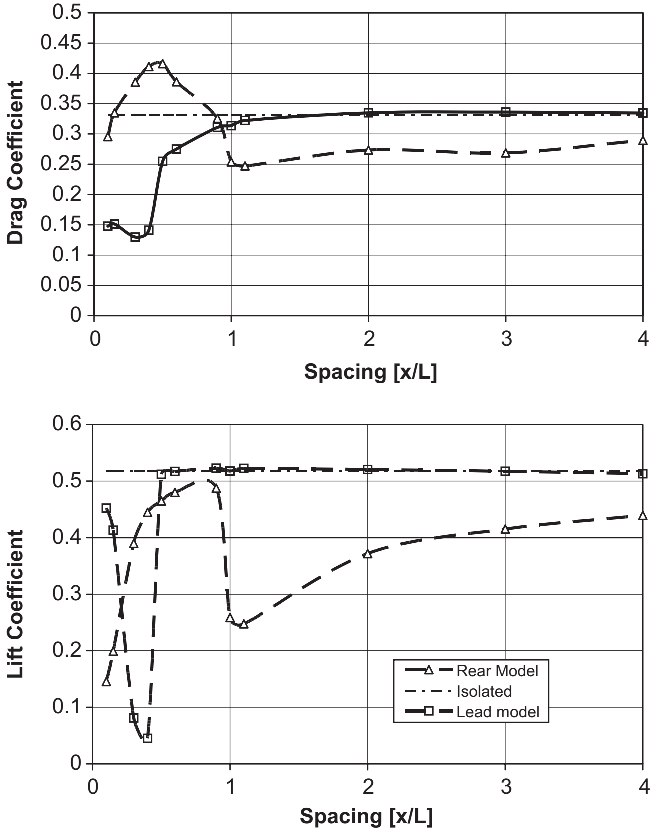
5. Experimental arrangement

Since the effects of varying spacing were of interest, it was necessary to vary the gap between the two Ahmed models. An internal force balance (JR3-160M six-component) was used in the movable model. Fig. 3 shows a sample drafting arrangement used for the two models. The upstream model was fixed (in the location used for routine testing) and the downstream model was located at various spacings from the lead model.

Tests were conducted in the RMIT Industrial Wind Tunnel, a closed-jet and fixed-ground type, having a 2 m high, 3 m wide and 9 m long test section. A 2:1 contraction is situated before the test section and the test speed was 35 m/s corresponding to a test Reynolds number of 2.3×10^6 based on model length. The freestream turbulence intensity was 1.8% and the blockage ratio (less than 2%) was not corrected for in this study.

6. Results and discussion

Figs. 4 and 5 depict time-averaged force coefficients for the front, rear and isolated cases. Fig. 6 shows smoke flow visualisations in the various inter-vehicle gaps where a clear difference can be observed in the wake pattern, as the gap is varied. In the isolated model case, drag and lift coefficients were equal to 0.32 and 0.54, respectively. The value of drag coefficient agrees with typical values from the literature (Ahmed et al., 1984). No lift data were found in the literature. Of interest is the considerable variation in coefficients with vehicle spacing—for the rear vehicle and a spacing of 0.5, the drag has increased by over 30% compared with the vehicle in isolation whereas for spacings of over about 1.0, there are (as expected) drag reductions associated with drafting. For the lead vehicle, significant reductions are possible when in close proximity to the rear vehicle, but for spacings over about 1.0, the drag asymptotes quickly to the drag for the isolated case. Lift coefficients for both vehicles exhibit extremely large variations within the spacing range 0.1–1.0.



Figs. 4 and 5. Lift and drag coefficients.

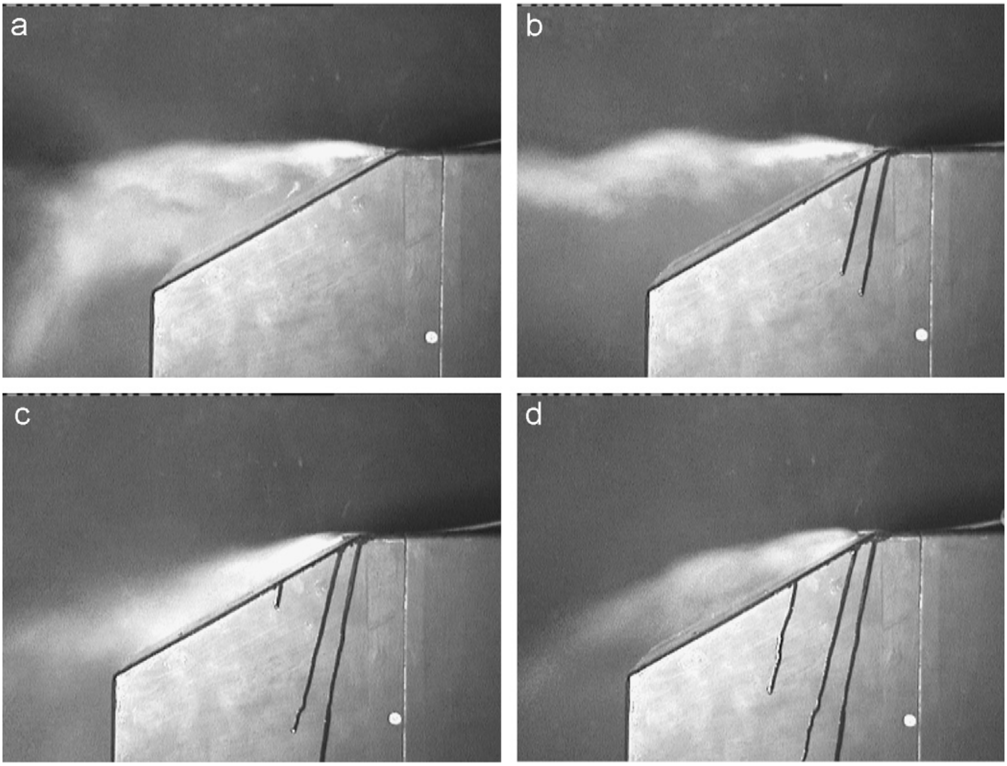


Fig. 6. Smoke flow patterns from the trailing edge of leading model. (a) Spacing = 0.15 of body length, (b) spacing = 0.30 of body length, (c) spacing = 0.50 of body length, and (d) spacing = 1.0 of body length.

7. Discussion and concluding remarks

Despite drafting being generally recognised as a method for reducing drag (and hence fuel consumption), studies on two similar, representative vehicle shapes have demonstrated that, for close spacing, there can be significant drag penalties. Thus the combined drag of a number of isolated vehicles has the potential to be lower than the combined drag of the same number of vehicles in a close-coupled convoy.

Very significant changes in lift were also noted for close spacings and it has been revealed (via surface and off-body visualisation and velocity and flow mapping) that these changes were due to the influence of the rear vortices. Due to the interest in closely spaced vehicles (permitted via ITS) this seems to be an area where our understanding of interaction effects needs to be extended.

The work presented here was for one "critical" geometry (i.e. a slant back angle of 30°); in order to extend understanding to encompass several types of vehicle and driving styles, other slant back angles and spacings are being investigated.

It is relevant to note that all full-size vehicle experimental facilities around the world are severely limited by the length of their test sections and thus work in this area has been generally conducted at model scale. Even at model scale, the length of the test section is usually limited. Where long test sections exist with a fixed ground simulation (which is usually the case), measurements can be compromised from the growth of the boundary layer on the tunnel floor. Similar problems occur when evaluating the aerodynamic aspects of trains—a long test section fitted with moving ground is desirable, but this is experimentally difficult, especially if non-zero yaw angles are to be simulated. For such situations it would appear that CFD simulations will have much to offer.

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