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An experimental characterisation of the wake of a detailed heavy vehicle in cross-wind

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ABSTRACT

The unsteady wakes associated with detailed heavy vehicles with different levels of passive aerodynamic treatment are investigated in a wind tunnel using a 1/3 scale model. Drag coefficient, base pressure and wake total pressure are measured for detailed vehicles at yaw angles up to 15° for six semi-trailer vehicle configurations. Cabin extenders and side-skirts were shown to be more effective at reducing drag under yawed flow conditions, while certain front-end modifications were found to perform best at $\psi = 0^\circ$ when the tractor was more able to shield the trailer from oncoming flow.

Base pressure was shown to reduce with yaw angle, with the low pressure signature of the main lower vortex tilting upwards on the leeward side of the vehicle's base. Total pressure grid measurements showed two different types of wake, those where the stream-wise vortex formed by flow separating off the roof of the trailer is separated from the bulk vehicle wake by a region of high total pressure, and those where the two are indistinguishable. Vehicles without a distinct trailing vortex in this region were found to exhibit stronger horizontal asymmetries in their base pressure profiles.

1. Introduction

Flows over heavy vehicles in cross-winds are important for a number of reasons. Whilst aerodynamic drag is perhaps the most studied because of its direct links to fuel economy and transports costs, cross-wind flows alter vehicle stability, cornering, water/mud spray and wind noise (Weir, 1980; Garry and Cooper, 1986; Hucho, 1987; Cheli et al., 2006; Gaylard and Duncan, 2011). Heavy vehicles can be particularly sensitive to the effects of cross-wind. Having a significantly greater length than width can lead to large side forces, while the sharp edges on the upper sides of the trailer promote separation and the generation of stream-wise vortices, which in turn affect vehicle aerodynamic drag.

The yaw angle (ψ) seen by a vehicle is a function of vehicle speed, wind speed and wind incidence angle. It is suggested in Hucho (1987) that the range of yaw angles needing to be considered is in the region of $\psi = \pm 14^\circ$ based on stationary measurements of wind data as well as the work of Gardell (1980), who based calculations on a vehicle speed of 80 km/h with an 18 km/h crosswind. Scaling this to typical Australian speed limits of 100 km/h reduces the effective yaw range to $\psi = \pm 10^\circ$.

There have been many studies showing the benefits of additional add-on devices, such as side-extenders, boat-tails, and side skirts in lowering aerodynamic drag (Cooper and Leuschen, 2005; Leuschen and Cooper, 2006; Burton et al., 2011; Cooper, 2012; Burton et al., 2013), the latter of which considers the configurations studied herein. It is common practice in wind tunnel testing of a heavy vehicle or add-on device to present forces and moments over a range of yaw angles e.g. (Storms et al., 2004; Cooper and Leuschen, 2005; Landman et al., 2010). Additionally SAE (2012) defines a wind-averaged drag coefficient, which is a weighted average of drag across the set of expected ambient conditions.

Croll et al. (1996) shows that the far wake of the Ground Transportation System (GTS), a simplified heavy vehicle with rounded fore-body corners and length to width ratio similar to heavy vehicles, at $\psi = 10^\circ$ is dominated by a pair of stream-wise, counter-rotating vortices. A number of computational investigations have attempted to match the GTS flow-field at $\psi = 10^\circ$. While none manage to capture the correct near wake (the region of the wake prior to the closure of the dividing streamlines), simulations do show that the stream-wise vortices noted above originate from separation over the upper stream-wise edges of the vehicle (Salari et al., 2004; Maddox et al., 2004).

Van Raemdonck (2012) presented mean base pressure and a PIV velocity field in the half height plane for the simplified GTS model at a yaw angle of 6°. On the leeward side of the vehicle's base, pressure is

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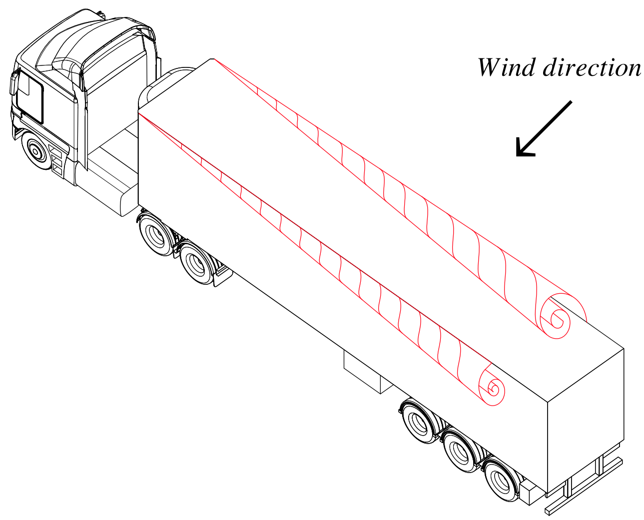

Fig. 1. Development of stream-wise vortices along a heavy vehicle in cross-wind.

reduced relative to the 0° baseline. The velocity field shows that the leeward side, time averaged vortex is enlarged, while the rear stagnation point is shifted towards the windward side of the base. Comparable numerical results show that the RANS simulation employed is unable to replicate this horizontally asymmetric recirculating wake.

Storms et al. (2006) showed base pressure contours as well as tractor-trailer gap PIV for the GCM model at $\psi = 10^\circ$. CFD by Hyams et al. (2011) shows unsteady structures exiting the tractor-trailer gap on the leeward side and convecting downstream towards the wake. Heineck et al. (2004) showed that a dramatic reduction in drag, measured between $\psi = 10^\circ$ and $\psi = 11^\circ$ is related to the core of the main gap vortex moving from the windward to the leeward side, which was accompanied by a significant reduction in both vertical flow and flow through the gap.

When the oncoming flow is angled relative to the vehicle's longitudinal axis, a number of different flow structures will develop. Fig. 1 shows a pair of co-rotating stream-wise vortices separating from the roof trailer. This system is equivalent to that seen on a finite aspect ratio wing with endplates. Due to under-body blockage, the flow field beneath the trailer will be more complex.

Despite the body of knowledge presented above, there still remain questions about the influence of cross-winds on heavy vehicles, particularly relating to the change in aerodynamic response between simplified and detailed vehicles. Wind incidence angle is known to have a non-linear effect on drag as well as other aerodynamic forces and moments. In fact, the effectiveness of individual add-on components may not even be directionally consistent, with some devices providing maximum drag reduction at 0° yaw, while others perform better with increasing wind incidence.

Many wind tunnel and CFD investigations present curves of drag versus yaw angle, both for entire vehicles and as individual component deltas, however considerably less information is available regarding the flow-fields associated with detailed vehicles at yaw. A recent study in a water channel (McArthur et al. (2016)) has provided detailed information into the time varying wake behind simplified and detailed heavy vehicles, however, cross-wind effects were not considered.

Unlike some other ground transport modes, such as high speed trains, a wide variety of heavy vehicle configurations continue to be adopted, primarily because of the large number of often competing requirements, in addition to aerodynamics, that heavy vehicles must fulfil. The aerodynamic challenge faced by the industry is not always one that allows the adoption of a highly streamlined body, rather it is a need to balance requirements including length limits, manoeuvrability, robustness, cost, etc. with aerodynamic performance.

To this end this paper aims to elucidate the effects of cross wind on a number of detailed heavy vehicle configurations by presenting base pressure and wake total pressure measurements behind a 1 : 3 scale heavy vehicle model.

2. Methodology

2.1. Experimental facility

Testing was carried out in the Monash University 1.4 MW wind tunnel. In order to account for the large blockage, a number of modifications were made to the $\frac{3}{4}$ open jet test section. Details of the modifications and results of the subsequent flow validation are presented in McArthur et al. (2013). The velocity profile and distribution were obtained using a four-hole dynamic pressure probe that was traversed in the empty tunnel at a point 3.75 m upstream of the turntable centre, approximately equivalent to the location of the leading edge of the model. The coefficient of variation in mean velocity was ¡ ±0.75% over the area of the model. The displacement thickness increases from 10 mm at the start of test section to 25 mm at 4 m downstream from the centre of the turntable, at the front of the model it is 12 mm, which is 14% of the frontal ground clearance. The mean streamwise turbulence intensity outside of the boundary layer is 1.6%.

The final solid blockage ratio was 10.6%, flow mapping was conducted at a width based Reynolds number ($Re_W = \frac{U_0 \times W}{\mu}$) of 1.4×10^6, corresponding to the maximum rated velocity of the wind tunnel traverse

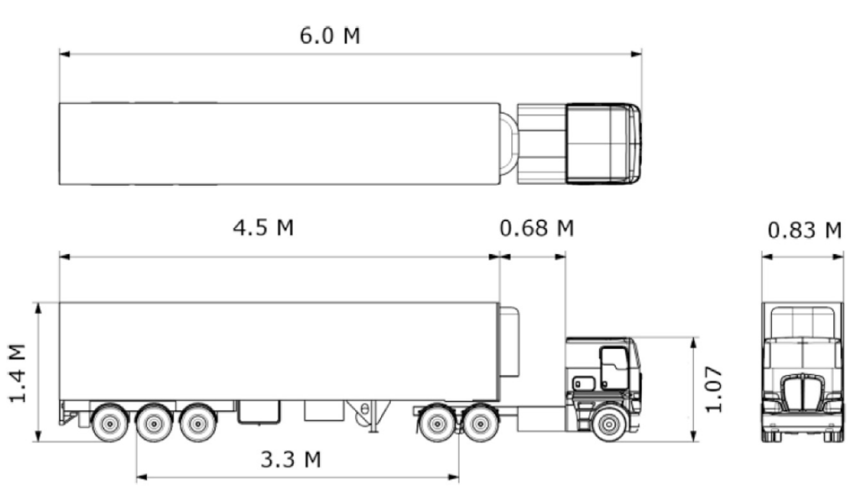

Fig. 2. Scale model key dimensions.