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Comparison of On-Road and Wind-Tunnell Tests for Rigid Truck Aerodynamic Devices

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1. INTRODUCTION

As part of a larger program on the aerodynamic reduction of fuel use by commercial vehicles, a series of tests was conducted on a Rigid (Box Van) Truck with four separate aerodynamic add-on devices. The first stage of the tests involved wind-tunnel studies of a highly-detailed one eighth-scale model in the Industrial Wind Tunnel at the Royal Melbourne Institute of Technology. To gain an insight into the flow field and hence find avenues for drag reduction, the tunnel was used as an initial design tool. Flow visualisation studies were carried out on the unmodified vehicle and then with a series of prototype aerodynamic drag-reducing devices fitted. The devices were then optimised in the tunnel by drag coefficient measurements at a number of yaw angles. Having selected the three most successful practical drag-reducing designs, the devices were fabricated in full scale and a series of road tests were undertaken on them as well as on a commercially-available device.

The Road Tests followed a procedure developed by Buckley (1985) and involved monitoring the relative fuel consumption of two similar vehicles, then fitting one vehicle with an aerodynamic device and measuring the change in fuel consumption. To account for variations in the ambient wind and to allow the results to be processed into coefficient form, a chase car equipped with a propeller-vane anemometer was used. Further details are given by Saunders et al (1985). Having obtained drag coefficient reductions as a function of yaw angle for each device, an initial comparison was made between the road and the model tests. Significant differences were found which generally increased as the yaw angle increased. This is similar to the differences noted by Buckley et al (1978), the general trends of which are shown in Figure 1. A further series of wind-tunnel tests were then made with increased levels of tunnel turbulence.

Other workers have paid much attention to modelling parameters such as Reynolds number, ground simulation and wheel rotation as well as the extraneous influences arising from the walls of the tunnel as summarised by Cooper (1984). However little attention has been paid to the modelling of the unsteady effects arising from the natural wind.

This paper compares results obtained from the road tests with those obtained under a variety of turbulence levels in a later series of wind-tunnel tests.

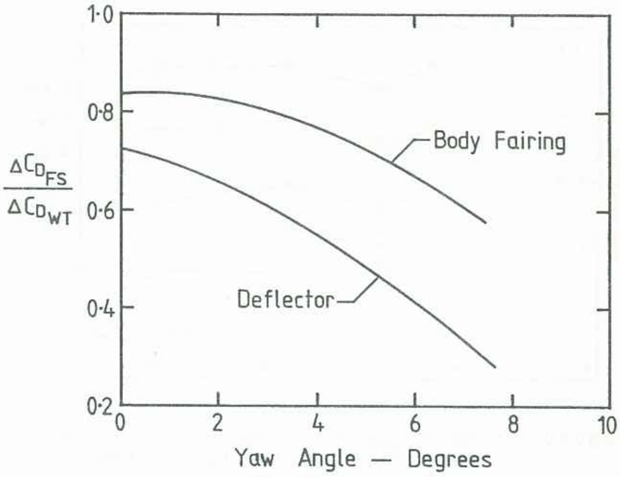

Figure 1: Ratio of full-scale to wind-tunnel measurements of drag reduction as a function of yaw angle. (Adapted from Buckley et al 1978).

2. WIND-TUNNEL INVESTIGATION

2.1 Test Facility

The Industrial Wind Tunnel has a 2:1 contraction ratio leading into a 3m x 2m closed working section. The boundary layer thickness measured at the model leading edge was 40mm. The tunnel speed for all the tests was 22 ms^{-1}.

The one eighth-scale model was a replica of an Isuzu SBR422 cab/chassis fitted with a box container as used by Arnott-Brockhoff-Guest. It was built from dimensions taken from one of the vehicles used in the road tests and incorporated many minor details such as door handles, wiper blades and underbody details. The devices were similarly constructed and hence it was felt that the models duplicated the road test configurations as far as was practically possible.

The model was mounted by a central strut on a six-component strain-gauge force balance and was restrained from excessive pitch motions by a viscous damper. Tests undertaken by Watkins (1986) showed that there was negligible difference when a four point wheel mounting system was used compared to the central strut mounting, or when the radiator area was fully closed or fully open.

2.2 Turbulence Generation and Tunnel Calibration

The tunnel freestream longitudinal rms turbulence intensity was measured at the balance location at half model height and found to be 1.7%. However, the on-road longitudinal rms turbulence intensity has been measured along the test route used for a variety of typical wind conditions by Watkins (1985) and found to range from 1.5% to 4.0% at a road speed of 100 kmh^{-1}. To attempt to reproduce this range of intensities in the tunnel, five different grids were constructed on the turning vanes immediately upstream of the contraction. Velocity and turbulence intensity profiles were measured at the balance position. The mean values of turbulence intensity at half model height are given in Figure 3. It is interesting to note that installation of the finest grid reduced the turbulence intensity from an empty tunnel value of 1.7% down to 1.3% while the next coarser grid gave the same value of turbulence intensity as the empty tunnel. The velocity profiles were obtained from measurements from a total head rake and were referenced to a wall-mounted pitot-static tube. The velocity used in the calculation of drag coefficients was an average over the height of the vehicle. The effect of the tunnel boundary layer was not included.

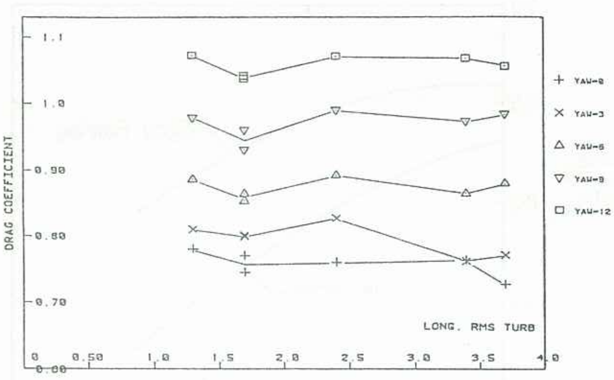

Figure 2: Effects of turbulence intensity baseline vehicle (tunnel tests).

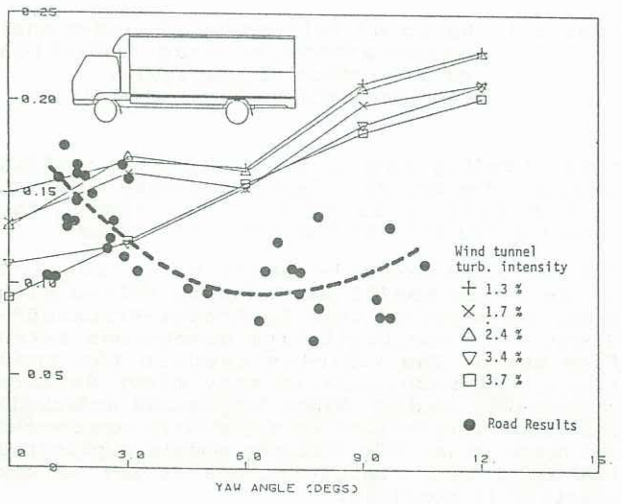

Figure 3: Drag coefficient reduction comparison for Body Fairing.

The longitudinal static pressure gradient was measured along the empty tunnel centreline (in the vicinity of the model) and found to be $-0.008\ m^{-1}$, and varied only slightly with each grid in place. This magnitude of longitudinal pressure gradient will have minor effect on bluff-body drag, so no longitudinal buoyancy corrections were made to the data. To set the model to zero yaw angle, items of asymmetric detail were removed and the model yawed until zero side force was measured. During active runs, the asymmetric details were replaced and the yaw angle was varied from -12 to +12 degrees in 3 degree increments.

2.3 Results

The results for the baseline (unmodified) vehicle are plotted as a function of turbulence intensity in Figure 2, and the results for each of the four devices are shown in Figures 3 to 6. To enable comparisons to be drawn between the tunnel results and the road results (see later), the drag coefficient reductions were averaged at corresponding positive and negative yaw angles, but plotted only for positive yaw angles. For the baseline vehicle it can be seen that although there are slight variations of drag coefficient with intensity, the overall changes are relatively minor. Discussion of the results for each of the devices is left until later.

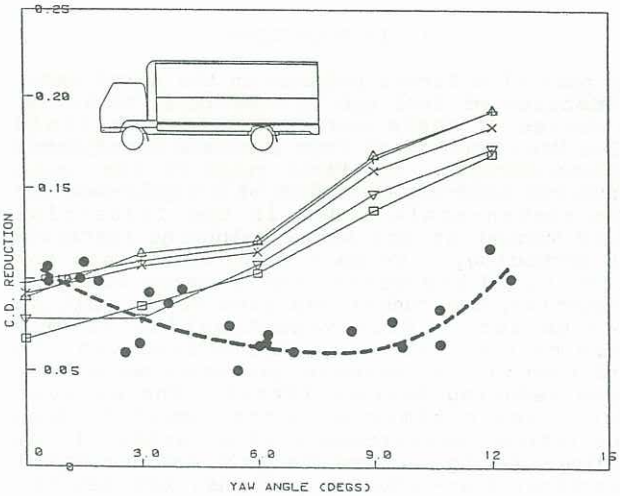

Figure 4: Drag coefficient reduction comparison for the Body Quadrants.

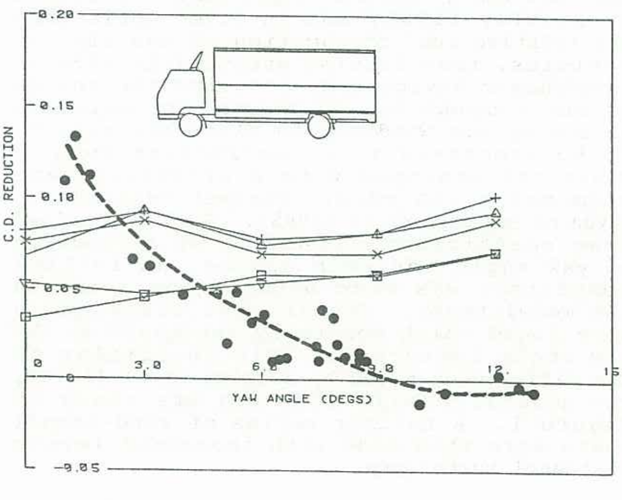

Figure 5: Drag coefficient reduction comparison for Deflector A (commercially available).

3. ON-ROAD TESTS

3.1 Test Procedure

The majority of on-road vehicle testing to date has been under zero or low wind conditions where negligible yaw angles are generated, or on closed loop test circuits when averaged drag reductions or fuel savings are measured (for example, see Rose 1981). However a recent method by Buckley (1985) was used to determine the change in drag coefficient

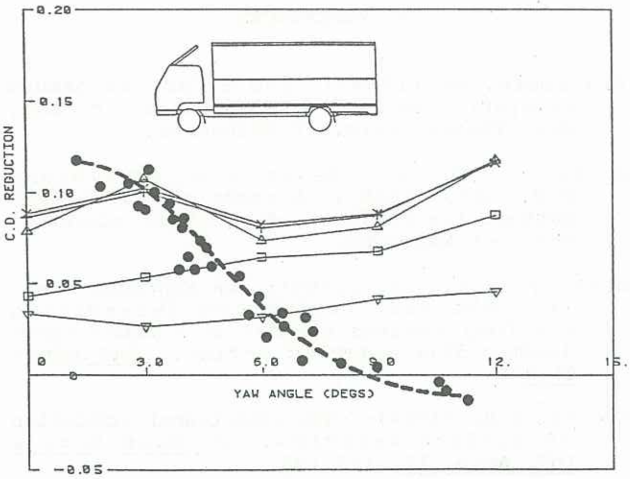

Figure 6: Drag coefficient reduction comparison for Deflector R.

resulting from the fitting of an aerodynamic device. The procedure is based on the SAE (USA) method for evaluating fuel savings SAE (1981), but additionally an instrumented chase car monitors wind speed and yaw angle relative to the moving vehicle. Two geometrically similar trucks were initially driven around the test route under steady-state conditions to measure the ratio of fuel useage for the calculation of a calibration factor. The test vehicle was then fitted with an aerodynamic device and the vehicles driven around the same test route. A gap between the two vehicles of typically 20 seconds was maintained and at no time were they allowed to be closer than 16 seconds. Due to their close proximity they experienced essentially similar environmental influences. Fuel consumption and elapsed time were recorded at 20 km intervals and wind data from the instrumented car and test vehicle engine fuel maps were used to calculate the incremental drag coefficient. All testing was conducted with the trucks unladen and at an essentially constant test speed of 100 kmh^{-1}. The outside traffic lane was used to avoid interference with other slower-moving vehicles and the trucks were run up to speed prior to taking any readings.

Since two vehicles were used, rolling resistance, gravitational and minor losses were essentially similar for both vehicles, although minor inaccuracies can be introduced by changes in transmission efficiency due to the differences in transmitted power between the test and the control vehicle. These are reviewed by Watkins (1986) and are considered to be negligible.

3.2 Results

Figures 3 to 6 show the drag coefficient reductions derived from the road data superimposed on the model-scale results. Each road data point is the drag coefficient reduction plotted as a function of the yaw angle with both variables averaged over a 20 km test segment. To enable fuel saving predictions to be made (see Saunders et al 1985), least squares polynomials were fitted through the data and are shown dotted. Drag coefficient reductions are plotted upwards.

For the deflector-type devices the drag reductions can be seen to reduce markedly with increasing yaw angle and some data at high yaw angles (> 10 degrees) show an increase in total vehicle drag. The solid fairings exhibit an initial reduction in drag saving which then increases when larger yaw angles are encountered. The road data are however rather scattered.

4. DISCUSSION

4.1 Comparison of Results

The results of the four devices tested all exhibit large variations between the tunnel and road tests, with the smallest differences occurring at small yaw angles. For both the Body Fairing and the Body Quadrants road and tunnel data are in reasonable agreement at small yaw angles. Road data for the Body Fairing exhibit considerable scatter at the higher yaw angles. When yaw angles of more than 3 degrees were measured on the road the drag savings fell below the tunnel results, and above 6 degrees the tunnel data substantially overestimated road drag reductions.

For the two deflector devices (Figures 5 and 6), some of the road results gave slightly greater drag reductions at yaw angles below 3 degrees than those found in the tunnel, even with the lowest turbulence level used. However the data points are rather limited in this area. For both deflectors the road drag reductions are smaller than the tunnel results when yaw angles of 4 to 7 degrees are exceeded. For all the devices, the drag reductions differ markedly between road and tunnel tests when tunnel data at any single turbulence level are considered. These differences are clearly larger than any experimental error or possible scatter in the data.

For all devices it appears that the introduction of tunnel turbulence has a derogatory effect on their drag-reducing properties, although in some instances there was no clear trend with increasing turbulence levels. In particular, Deflector R, Figure 6, shows that the drag reduction was at its smallest with 3.4% turbulence intensity rather than at the highest intensity tested of 3.7%. This may be due to a variation in tunnel turbulence scale rather than intensity.

4.2 Modelling Similarity

In any model-scale testing certain modelling criteria should be satisfied. In these tests, geometric similarity was satisfied as closely as was possible, with the exception of rotating wheels. For a commercial vehicle where the drag coefficient is usually high, moving ground and rotating wheel simulation are not generally regarded as necessary, Blackmore (1984).

Corrections for wind-tunnel boundary constraints were not applied due to the extremely small (< 2%) blockage area ratio and the low longitudinal static pressure gradients. It is felt that ignoring these considerations will not affect the following discussion.

To ensure dynamic similarity between flows around geometrically-similar objects, the Reynolds numbers should be the same. In practice it is rare in model-scale tests to achieve a model Reynolds number that corresponds to that of a full-size vehicle operating under highway driving conditions. The SAE (1979) suggests a minimum value of 0.7×10^6 based on vehicle width. This requirement was not met due to structural constraints on the tunnel balance and the test Reynolds number was 0.4×10^6 (approximately one-tenth of the road Reynolds number). Further, it was observed that the flow over the cab roof on the full-scale vehicle without a device fitted was intermittently separated. In the tunnel this was not the case since the flow was always separated from the cab roof. It is difficult to see how the full-scale behavior could be duplicated without resorting to modelling both the correct Reynolds number and turbulence characteristics. However it is interesting to note that at zero yaw angle the drag coefficient reductions in full-scale are close to those found in the model tests and that large deviations consistently occur only at high yaw angles.

Yaw angles are generated on the road by the vector sum of the vehicle's forward motion and the wind speed relative to the ground, and may be expressed by

$$\psi = \tan^{-1} \frac{(V_W/V_T)\sin\Phi}{1 + (V_W/V_T)\cos\Phi}$$

where ψ is the yaw angle, V_W is the wind speed relative to the ground subtending an angle Φ to the vehicle direction and V_T is the vehicle speed relative to the ground. When Φ is either 0 or 180 degrees (the direct headwind or tailwind condition), V_W can assume any value and give a mean yaw angle of zero. Thus a range of turbulence intensities can be experienced. However, for typical highway speeds, high yaw angles can only be generated by high values of V_W, so the range of possible windspeeds is decreased, leading to a smaller possible range of turbulence intensities albeit of higher intensity. Thus data measured on the road at high yaw angles will always have higher turbulence levels asssociated with them, whereas at very low yaw angles there is the possibility of a wider range of turbulence intensities resulting from the wide range of windspeeds.

In addition the turbulence length scale and the mean velocity profile will vary with windspeed and both should strictly be modelled in the wind tunnel. However, this is beyond the scope of this paper. For further details of the vehicle wind environment see Smith (1972) and Watkins (1985).

5. CONCLUSIONS

Comparison between wind tunnel and road tests leads to the following conclusions:

1. There are significant differences between drag reductions measured on accurate scale models in the wind tunnel, and those measured by road tests. The wind-tunnel generally overestimates the drag reductions found on the road, particularly for high yaw angles and for deflector-type devices.

2. When levels of tunnel turbulence intensity are raised, the tunnel results generally lie closer to those measured on the road.

3. The major difference between tunnel and road results was thought to be due to the effects of turbulence, although the model Reynolds number was lower than recommended practice.

4. Full-scale testing with a careful documentation of the wind conditions is recommended for the evaluation of drag-reducing devices for commercial vehicles.

6. ACKNOWLEDGEMENTS

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