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Tri-Axle Tipper Trucks — Some New and Simple Devices as Aerodynamic Means of Saving Fuel — Road and Tunnel Tests

S. WATKINS, J. W. SAUNDERS and K. GIBSON

Department of Mechanical & Production Engineering, Royal Melbourne Institute of Technology, Melbourne, Australia.

ABSTRACT

Wind-tunnel and on-road test results are presented for add-on aerodynamic devices to a Mack R 686 triaxle tipper truck. Tunnel results show the wind-average drag coefficient of the unmodified truck to be about 1.6. The effectiveness of covering a low load with a tarpaulin was shown (7.6% typical predicted fuel saving and 9.7% with trailer fairing added). A trailer fairing and a new tailgate fairing offered a more functional alternative giving a 4.8% fuel saving.

The on-road results again highlighted that the wind tunnel tends to over-predict drag reductions for devices. This appeared to be due to road environment turbulence effects and emphasised the need for road tests to evaluate aerodynamic devices.

INTRODUCTION

Saving 1% of truck fuel distillate by truck aerodynamics saves $10 million of Australia's non-renewable resources (Close, 1981). Many of Australia's trucks consume $50,000 of fuel per year. Savings per truck approaching $5000 are possible. Accordingly, the National Energy Research, Development and Demonstration Program of the Australian Department of Resources and Energy has supported a major program on the reduction of truck aerodynamic drag by a team at the Industrial Aerodynamics Laboratory in the Department of Mechanical and Production Engineering at the Royal Melbourne Institute of Technology (RMIT), (Saunders et al, 1986)

This paper reports a study, principally supported by the Energy Authority of New South Wales and Aztec Transport Services, to reduce the fuel consumption of Mack R 686 tri-axle tipper trucks (Fig 1).

Fig 1: Mack Tipper 'Control' Vehicle

Wind-tunnel measurements have been found to over-estimate drag reductions of various truck attachments on the road, the difference being a function of the type of device and yaw angles involved (Saunders et al, 1985 and the companion paper by Watkins et al). Hence full-scale testing was used to verify the wind-tunnel design work. This paper describes both test methods and compares the results found.

WIND-TUNNEL MODEL & DEVICES TESTED

A 1/10 scale model of the Mack truck and '5 ft' tri-axle Alcan tipper trailer was constructed. Fine-scale detail was incorporated on the model, particularly in areas where there was significant air velocity. The radiator was open, but the detail of the radiator core was not modelled. The dimensions of the model and attachments tested are shown in Fig 2.

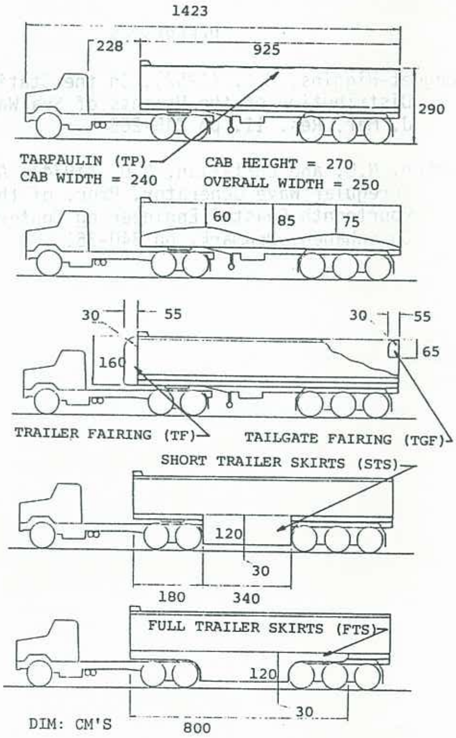

Fig 2: Dimensions of Mack Tipper and Attachments Tested

Model terminology is: BL is the baseline truck configuration without any add-on aerodynamic (AOA) devices attached. Two heights of load were modelled, one representing a dense, low load (LL) which had a fine particle surface roughness simulating gravel and the other, a higher, less dense load (HL) simulating coal. HL was created by elevating LL by 70cm. Tarpaulin (TP) simulated an impervious skin without ropes. Trailer fairing (TF) was a 3-D fairing covering the front face of the trailer and had 30 cm edge radii. Tailgate fairing

(TGF) was a 2-D fairing spanning the width of the tailgate. Short trailer skirts (STS) were flush with the outside of the trailer. Full trailer skirts (FTS) covered additional areas above the wheels. Gates open (GO) simulated the tailgate split vertically in two and opened rearward. A 10 cm step (S) was tested across the bottom of the tailgate. Note that all dimensions are full scale.

Initial studies of the model flow field were made in the 3 m x 2 m cross-section Industrial Wind Tunnel at RMIT. The drag coefficients of promising devices were tested.

The wind-tunnel has been designed principally for vehicle aerodynamics. The longitudinal turbulence intensity was 1.3% with a longitudinal length scale of about 3-6 m. The boundary layer was less than the underbody clearance of the truck. The model was centrally mounted and elevated by the displacement thickness of 5 mm. The blockage ratio of the zero-yaw model was 1.7%

The tests were carried out in accordance with the SAE test procedure J1252 (1979) for wind-tunnel testing of vehicle models, except that instead of mounting the model on a splitter plate, the model was raised above the tunnel floor by the boundary layer displacement thickness and the Reynolds Number based on truck breadth was 300,000. No significant variation in drag coefficient, C_D was found between $1.2 - 4.0 \times 10^6$. (The reference area for C_D calculation was the maximum height of the truck by maximum width.) The basis for the above modelling with respect to full-scale is reviewed in Saunders et al (1985).

ON-ROAD TESTS

Details of the full-scale test procedure and analysis are given by Buckley (1985) and Saunders et al (1985). Essentially, the procedure is a modification of the SAE J1321 Type II truck test procedure (1981) which compares measurements taken from a control truck with a similar following truck which has a device attached. The procedure calculates the drag coefficient reduction produced by an AOA device as a function of yaw angle, by measuring the relative air velocity, yaw angle, truck velocity and the fuel flow-rates.

The route was from the 50-90 km marker on the Hume Highway out of Sydney towards Melbourne. The trucks were driven at maximum legal speed. Fuel and stop-watch readings were taken every 20 km. The vehicles were run empty to accentuate the fuel flow-rate decrement due to any AOA devices. After a 45 min warm-up, the trucks were driven around the test route maintaining a constant 16-20 sec gap between them. A baseline fuel calibration factor between the two trucks without any AOA devices attached was evaluated until it was repeatable to within 1% over the 80 km circuit. The calibration factor was normally checked daily. An AOA device was then attached to the 'test' truck.

An instrumented chase car was run between the two trucks. Mounted on the car was a Gill Anemometer registering the relative air speed and yaw angle at a height of 3.5m. The data was filtered and sampled every 8 sec. The anemometer had previously been calibrated 'in-situ' for both angle and velocity. Voltages corresponding to wind-speed and direction were logged on an on-board micro-computer.

The additional parameters measured were: (a) vehicle weight (measured on a weigh-bridge); (b) fuel specific gravity; (c) fuel tank temperature; (d) ambient temperature; and (e) ambient pressure.

Drag coefficient reductions were obtained from data integrations of 20 km segments. Multiple runs were undertaken to improve the confidence level of the results.

DISCUSSION OF RESULTS

Figs 3-6 show the wind-tunnel results. The joining lines only link similar points rather than representing functional dependence. These curves show the usual rapid increase in drag with yaw angle of truck. The two-body geometry of tractor-trailer trucks accentuates this phenomenon due to the effect of the transverse flow through the 'gap' between the rear of the cabin and the front of the trailer. Table 1 shows the Wind-Average Drag Coefficient (WAD) values. (WAD is a process which integrates the effect of annual-average wind on the C_D as a function of yaw (see SAE J1252).)

Fig 3 shows that the tarpaulin gives substantial drag coefficient reduction (WAD reduction of 20.5%) and highlights the aerodynamic effect of different load heights compared to empty trailers.

Fig 4 shows the effectiveness of the TGF and TF at low yaw angles and trailer skirts at high yaw angles.

Fig 5 shows the substantial drag coefficient reductions available from the best combination of devices. TP+FTS+TF had WAD reduction of 31.5%. This reduction could produce about 15% fuel saving under ideal conditions and typically about 10%, depending on vehicle speed and weight.

Fig 6 shows more functional combinations, omitting the TP and trailer skirts which are not practical for tipper environments. TF+TGF WAD reduction was 9.0%.

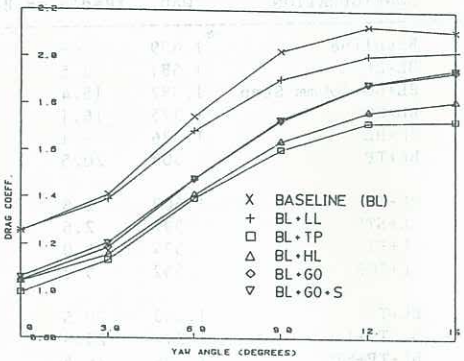

Fig 3: Effect of Changes to Existing Truck in the Wind Tunnel

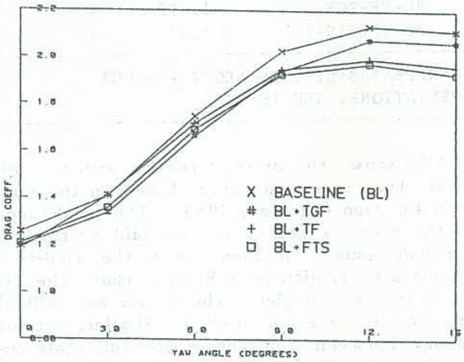

Fig 4: Effect of Individual AOA Devices in the Wind Tunnel

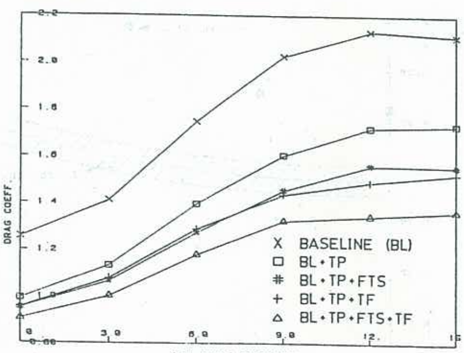

Fig 5: Effect of AOA Packages in the Wind Tunnel

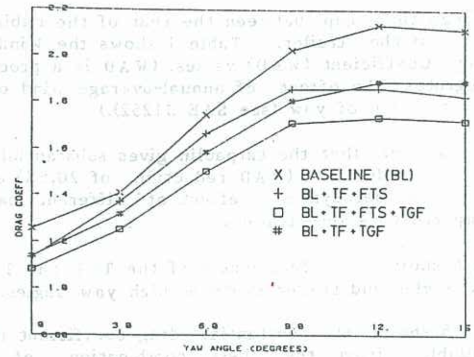

Fig 6: Effect of 'Practical' AOA Packages in the Wind Tunnel

All the WAD & percentage reductions are presented in Table 1

TABLE 1: WIND-AVERAGE DRAG OF DEVICES TESTED

FIG	CONFIGURATION	WAD*	%Red'n on BL
	Baseline	*1.639	---
	BL+LL	1.581	3.5
4.	BL+GO+100mm Step	1.387	15.4
	BL+GO	1.375	16.1
	BL+HL	1.326	19.1
	BL+TP	1.303	20.5
	BL+TF	1.602	2.3
5.	BL+STS	1.597	2.6
	BL+FTS	1.574	4.0
	BL+TGF	1.552	5.3
	BL+TP	1.303	20.5
6.	BL+TP+TF	1.214	25.9
	BL+TP+FTS	1.204	26.5
	BL+TP+TF+FTS	1.122	31.5
	BL+TF+FTS	1.553	5.2
7.	BL+TF+TGF	1.492	9.0
	BL+TF+FTS+TGF	1.415	13.7

* NOTE REPEATABILITY IS ABOUT $\pm$ 0.003
ABBREVIATIONS: SEE TEXT

Figs 7-10 show the on-road results with the uncertainty bands of the regression curves based on the curve being an even function (Buckley, 1985). The wind-tunnel results from the previous graphs are overlaid on these graphs of the on-road results. In Figs 7 & 8, the wind-tunnel drag reductions are significantly higher than the full-scale values at low yaw angles. The values are still higher at larger yaw and are not plotted. Similar, but less severe variations between wind tunnel and full scale were found by Saunders et al (1985), but the companion paper by Watkins et al shows an even more dramatic trend for a rigid truck.

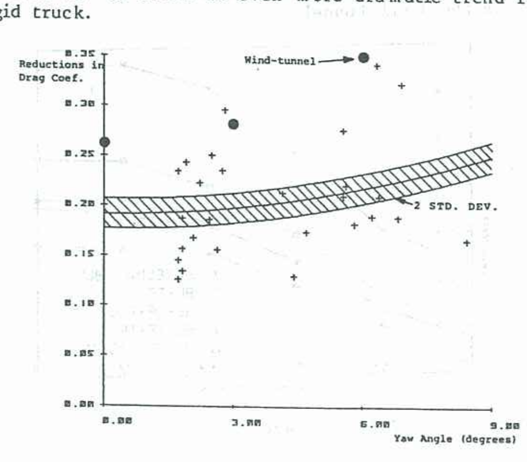

Fig 7: Tarpaulin Only - On-Road with Wind-Tunnel comparison

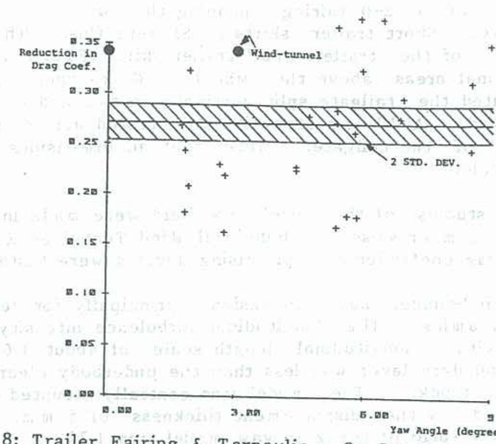

Fig 8: Trailer Fairing & Tarpaulin - On-Road with Wind-Tunnel comparison

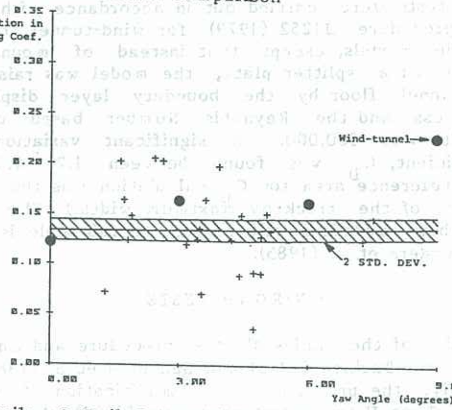

Fig 9: Trailer & Tail Gate Fairing - On-Road with Wind-Tunnel comparison

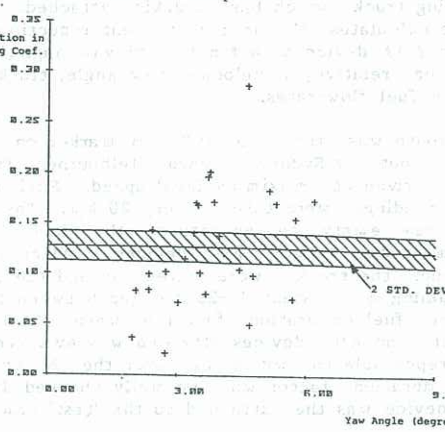

Fig 10: Trailer Fairing with Tail Gate Fairing and Tail Gate Open - On-Road

In the on-road tests, the truck engine is essentially being used as a transducer to calculate the incremental C_D. Under some testing conditions, the effect of the AOA devices is to substantially shift the operating position of the engine on the engine fuel map. The proprietary version of the fuel map must be used. The engines must be well run in and of correct specification. Dynamometer tests are made to perform some checks, but on some hills where there are significant changes in fuel consumption, data used from the fuel map can more easily be in error (Saunders et al, 1985). Further, it is felt that much of the scatter in these tests is due to the large number of cuttings and ravines through which the trucks operate, leading to fluctuations in yaw angle and other local variations in the ambient wind which may not be amenable to a simple averaging process. Both factors made achieving data stationarity difficult.

The wind-tunnel-to-road comparison is reasonable at low yaw angles, but the wind tunnel becomes progressively more optimistic with yaw. Reynolds Number and turbulence simulation are suspected of being the main sources of these errors. An increasing body of evidence suggests that on-road turbulence is the main reason behind the lack of correlation. The wind tunnel only consistently over-predicts the drag savings at higher yaw angles. High yaw angles can only be generated when there is a significant ambient wind, whereas low yaw angles can occur under a variety of wind conditions. Since the comparison is closest at low yaw angles, it is implied that the Reynolds number and other modelling parameters are reasonable (Watkins, 1986). However, at higher yaw angles, it has been suggested that large-scale on-road turbulence is changing the various wakes. (Buckley, 1976; Saunders et al, 1985).

LONG-TERM FUEL SAVING PREDICTIONS

From the on-road aerodynamic drag coefficient reductions, a prediction can be made of the percentage fuel saving for each device. A knowledge of the expected wind environment, the engine fuel map and other mechanical details is also required (Buckley, 1985; Saunders et al, 1985). Table 2 shows an example of the prediction for an Australian mean annual wind speed of 11.2 km/h.

TABLE 2: PREDICTION OF FUEL SAVED WITH TRAILER FAIRING & IMPERVIOUS TARPAULIN FOR VARIOUS GROSS COMBINATION MASS (GCM) TRUCKS WITH VARIATION IN SPEED.

	VEHICLE SPEED (km/h)					
GCM (KG)	60	70	80	90	100	110
14000	8.5	10.1	11.4	12.5	13.4	14.2
18000	8.0	9.5	10.8	11.9	12.9	13.7
22000	7.5	8.9	10.2	11.4	12.4	13.2
26000	7.0	8.4	9.7	10.9	11.9	12.7
30000	6.6	8.0	9.3	10.4	11.4	12.3
34000	6.3	7.6	8.9	10.0	11.0	11.9
38000	6.0	7.3	8.5	9.6	10.6	11.5

With these tables, the truck operator can use an estimate of his average long-term operating conditions to calculate the return period of the investment in AOA devices. The uncertainty in the percentage estimates should be about 2% (Saunders et al, 1985).

The above figures are for a modified truck compared to the basic truck when driven at the same speed. It can be seen that if truck speeds increase or loads decrease, the savings rise due to the predominance of aerodynamics at higher speeds or with lower weights.

If another AOA combination at a GCM of say 26 tonnes and a road speed of 80 km/h has a predicted fuel saving of say 5.0% (compared with 9.7% in Table 2), then all the figures in Table 2 can be multiplied by a ratio of 5.0/9.7 to give a prediction table with an accuracy of about 0.1%. of a correctly calculated version. The predictions in the Conclusions can therefore be used accordingly to generate such tables.

CONCLUSIONS

Based on the limited range of experimental results reported above, and drawing on some previous work, the following conclusions can be drawn:

1. The wind tunnel often significantly over-predicts the drag reductions of add-on aerodynamic devices on trucks. The over-prediction is a function of type of device and the yaw angles involved.

2. Lack of turbulence simulation is suggested to be a significant factor in the discrepancies between wind-tunnel and on-road results.

3. For the development of truck aerodynamic drag reducing devices, the wind tunnel should be used as a first-estimate design tool only. The final estimates of performance should be evaluated by road-test procedures.

4. The results highlight the need for further basic research into the mechanisms governing bluff bodies, particularly two-body flows.

5. The basic tipper-truck configuration is aerodynamically very inefficient with a wind-average drag coefficient of about 1.6. Significant savings are possible with add-on aerodynamic devices. The use of a trailer fairing and of a tarpaulin in reducing the drag of an empty tipper was shown. The alternative of a tailgate fairing was tested. For a representative truck speed of 80 km/h and a total mass of 26 tonnes, the following fuel saving reductions to within 2% accuracy were predicted: (a) tarpaulin over the trailer: 7.6%; (b) tarpaulin with trailer fairing: 9.7%; (c) light porous tarpaulin with trailer fairing: 4.9%; and (d) trailer fairing with tailgate fairing: 4.8%. The predicted savings can be significantly eroded should the drivers use the reduction in drag to gain additional vehicle speed.

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