THE INFLUENCE OF ROADS, TYRES AND AREODYNAMICS ON THE FUEL CONSUMPTION OF COMMERCIAL VEHICLES

Peter Cenek

WORKS CENTRAL LABORATORIES

NZ

Presented to the

Institute of Road Transport Engineers of New Zealand

FOURTH INTERNATIONAL HEAVY VEHICLE SEMINAR

AUCKLAND

3 - 5 March 1992

THE INFLUENCE OF ROADS, TYRES, AND AERODYNAMICS ON THE FUEL CONSUMPTION OF COMMERCIAL VEHICLES

P.D. Cenek
Central Laboratories, Works Consultancy Services Ltd
Lower Hutt, New Zealand

ABSTRACT

Recent research concerning tyre rolling resistance and aerodynamic characteristics of commercial vehicles is reviewed in an attempt to identify those parameters which have the most influence on fuel consumption. It was found that for the majority of New Zealand transport operations, tyre rolling resistance will be a more important consideration than aerodynamic drag apart for light vehicles and vans. Furthermore, rolling resistance will have an even greater influence on fuel consumption as the aerodynamic efficiency of commercial vehicles improves.

Key Words: fuel consumption, rolling resistance, aerodynamic drag, commercial vehicles

INTRODUCTION

For typical New Zealand road transport operations, fuel costs amount to 20-25% of running costs (Ministry of Transport, 1987). Therefore efficient use of fuel is a prerequisite for cost effective operations, despite falling oil prises, and so has been the subject of considerable worldwide research involving both experimental studies utilising instrumented vehicles and surveys of actual operations. This paper is concerned with summarising the principal findings of this research in the context of New Zealand operations, and with identifying remaining opportunities for reducing fuel consumption, particularly with regard to aerodynamic refinements and tyre selections.

First a brief review of the principal factors that affect fuel consumption is given, along with a method for determining whether the fuel consumption of a particular vehicle will be dominated by tyre rolling resistance or aerodynamic drag. This consideration is important when optioning a new vehicle or selecting after-market devices. A discussion of those variables which have the most effect on tyre rolling resistance follows, and alternatives for minimising the aerodynamic drag of the main types of commercial vehicles reviewed. More emphasis has been placed on improving aerodynamic efficiency as there are still too many examples of aerodynamically poor vehicle configurations on New Zealand roads. Accordingly, these are identified and estimates of the corresponding fuel wastage given.

TRACTIVE RESISTANCE AND FUEL CONSUMPTION

It has been shown that the fuel consumption of a vehicle is directly related to the energy necessary for the movement of the vehicle (Watanatada et al, 1987). The different resistances that must be overcome by the energy supplied by the engine are:

- rolling resistance, RR
- air resistance, RA
- gradient or climbing resistance, RG

Energy is also used to overcome transmission losses and the internal friction of the engine.

Assuming:

$$RR = mg \cos \phi \; CR \qquad \ldots (1)$$

$$RA = \tfrac{1}{2} \rho \, C_d A \, (V + V_w)^2 \qquad \ldots (2)$$

$$RG = mg \sin \phi \qquad \ldots (3)$$

where ϕ = road incline angle to the horizontal in radians
mg = vehicle gravitational force (N)
CR = the dimensionless coefficient of rolling resistance
ρ = mass density of air (kg/m^3)
C_d = the dimensionless aerodynamic drag coefficient of the vehicle
A = the projected frontal area of the vehicle (approximately equal to maximum height multiplied by maximum width) (m^2)
V = the vehicle travel speed (m/s)
V_w = the component of wind velocity in the direction opposite to the vehicle travel (m/s)

then the fuel consumption, F (ml/km), at constant speed in still air conditions is:

$$F = P_1 + P_2/V + P_3 V^2 + P_4 \sin \phi \qquad \ldots (4)$$

where P_1 = $b \, mg \cos \phi \; CR/\eta$
P_2/V = idling fuel consumption (ml/km)
P_3 = $(\tfrac{1}{2} b \rho C_d A)/\eta$
P_4 = $b \, mg/\eta$
b = fuel conversion factor (ml/kJ)
η = drive-line efficiency

Equation (4) identifies the variable factors influencing consumption. The first factor is the vehicle's weight. Both rolling and climbing resistance depend on the vehicle's weight. Increase the weight and an increase in fuel consumption results. Up the weight again by the same amount and you get the same percentage rise in consumption as before. Therefore an important ratio is that of payload to vehicle tare weight. Where the vehicle gross weight is limited by law, a low tare means a greater legal payload, and hence greater earning capacity. Excess tare, beyond that actually required to give sufficient structural strength, is expensive "dead iron" that the operator pays for the life of the vehicle.

The second factor is aerodynamic resistance, and this depends on the vehicle's shape, frontal area, and vehicle travel speed. The ease or otherwise with which a shape moves through the air is given a value known as the aerodynamic drag coefficient, C_d. With reference to equation (4), decreasing C_d or frontal area decreases the fuel consumption, decreasing those factors by the same amount again results in the same fall in consumption as before. Therefore fuel consumption is directly proportional to the C_d multiplied by the frontal area of the vehicle, often written as C_dA. What an operator requires is the lowest C_dA for his rigs, which is not simply solved by buying the lowest C_dA tractor, because the tractor must be tuned to the particular load and prevailing wind conditions to ensure that streamline flow occurs. However, by far the most important thing that affects aerodynamic drag is speed. The fuel used to overcome aerodynamic drag is related to the square of the vehicle travel speed. In other words, if speed is increased by a certain amount, then fuel consumption increases too. If the speed is then raised by the same amount again, fuel consumption does not rise simply by as much as before, but by a far larger quantity. Overall, consumption gets worse as speed is raised.

Equation (4) also shows fuel consumption to be directly proportional to:

(a) the rolling resistance coefficient, CR, which in turn is influenced by tyre size and construction, and the road surface; and

(b) the road gradient which is a function of the route topography.

Figure 1 illustrates how the various contributions to fuel consumption vary with road profile and speed for a 38 tonne tractor-semi trailer combination (Hucho, 1987). Figure 2 shows similar resistance components for a bus. Tests up to 100 km/h showed that aerodynamic drag dominates on level road. At the lower average speeds of city traffic, the acceleration component predominates.

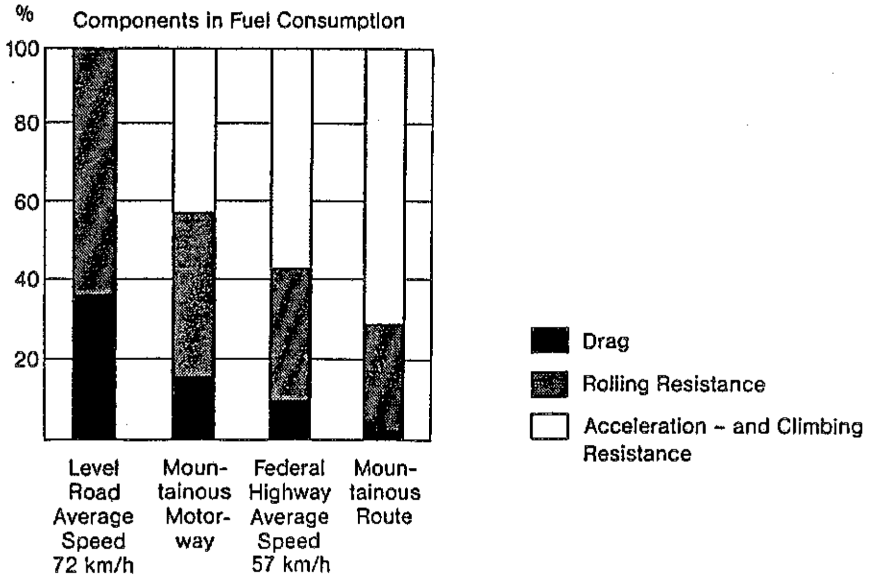

FIGURE 1: Fuel Consumption of a 38 Tonne Tractor-Semi Trailer to Overcome Tractive Resistance Components for Different Route Profiles (after Hucho, 1987)

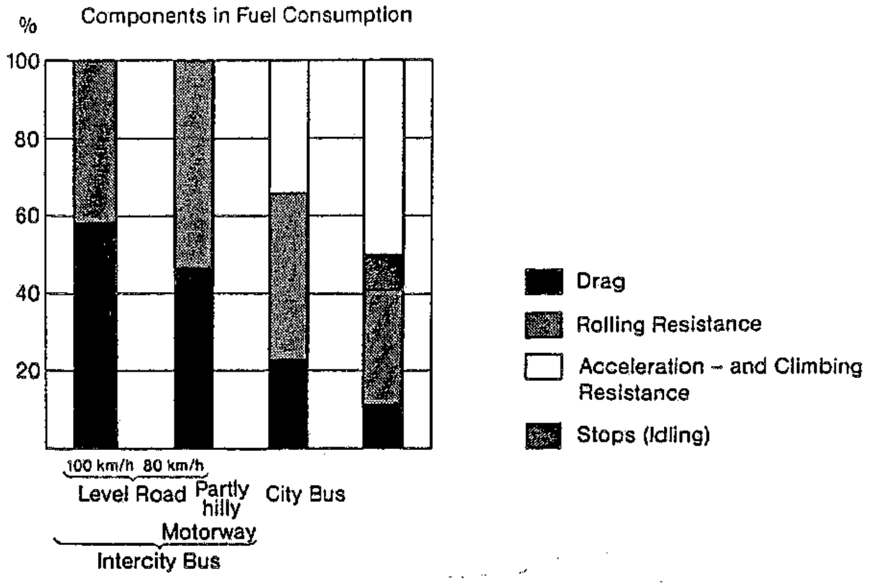

FIGURE 2: **Fuel Consumption to Overcome Components of Tractive Resistance for City and Inter-City Buses (after Hucho, 1987)**

WHAT IS MORE IMPORTANT TO FUEL CONSUMPTION - ROLLING RESISTANCE OR AERODYNAMIC DRAG?

The fuel used in overcoming rolling resistance of commercial vehicles does not vary with speed, and the amount is greater for heavy vehicles than for light ones. Fuel used in fighting aerodynamic drag, however, goes up sharply with speed, and is greater for tall vehicles than for low ones of the same width. Therefore the relative importance of the two factors varies with different vehicles, with their running weights, and with their speed. At constant speed on level road in still air, the "cross-over point" where aerodynamic drag becomes more important than rolling resistance can be calculated from:

$$V_{\text{cross-over}}\ (\text{m/s}) = \sqrt{\frac{mg\ CR}{\frac{1}{2}\rho\ C_d A}} \quad \ldots (5)$$

Equation (5) shows that the cross-over point occurs at low speeds if the vehicle has a particularly large frontal area and low weight. For example, the cross-over is calculated to occur at about 64 km/h for a small, 10 tonne Luton-bodied rigid, and 80 km/h for a 32 tonne artic with a box trailer.

In practice, climbing and accelerating modify the idealised constant speed, level-road relationship of equation (5), as shown in Figure 3 for the main types of commercial vehicles. Figure 3, however, shows that at normal operating speeds, rolling resistance usually exceeds aerodynamic drag apart for light trucks or vans.

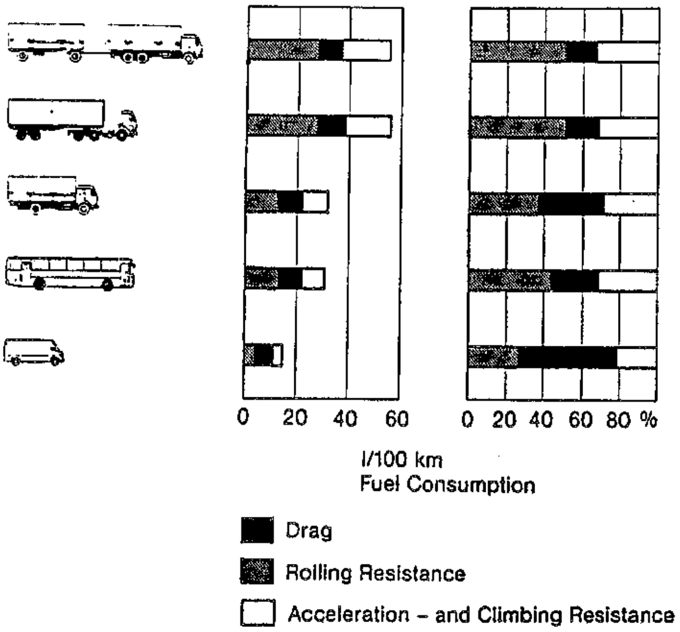

FIGURE 3: **Percentage of Fuel Consumption of Different Vehicles Related to Components of Tractive Resistance (after Hucho, 1987)**

THE ROLLING RESISTANCE OF COMMERCIAL VEHICLE TYRES

Laboratory and on-road based research (Ramshaw and Williams, 1981) have identified the following principal factors which affect the rolling resistance of tyres fitted to commercial vehicles.

(1) Inflation Pressure

The rolling resistance coefficient for both radial ply and cross ply tyres increases proportionally with decrease in inflation pressure at constant load. Tests performed by the Transport and Road Research Laboratory (TRRL) showed that a half laden three-axle artic increased its consumption by 5% when its tyres were under-inflated by 20%. Therefore an easy way for an operator to control fuel costs is to ensure tyres are properly inflated.

(2) Tyre Load

The rolling resistance coefficient of a radial tyre is largely independent of load but increases with increase in load for cross ply tyres. However, for both types of tyre, rolling resistance at normal inflation pressures is proportional to the deflection. Plots of load versus deflection at various fixed inflation pressures usually indicate high rate of deflection which lessen at half of the manufacturer's rated load, any increase in load thereafter producing proportional increase in deflection. This non-linearity partly accounts for the claims of lower rolling resistance for trucks fitted with a lifting axle if the axle is raised on the occasions when the truck is running unloaded or with a light load (i.e. if the axle is lifted the load is approximately doubled on the wheels remaining in contact with the road surface, however if the tyre load is light then, due to the shape of the load/deflection curve, the tyre deflection will be less than twice the original figure).

(3) Slip Angle

The rolling resistance coefficient is greatly affected by slip angle. For example, the TRRL tests showed that an increase in slip angle for conventional aspect ratio (7.00 x 16) tyres to +2° may result in an increase in rolling resistance of 65% for a radial ply tyre and 45% for a cross ply tyre. An increase over the same change of angle for an 18.00 x 19.5 radial ply tyre produced a 90% increase in rolling resistance. The large increases in rolling resistance observed with increasing slip angle indicates the importance of correct tracking of vehicle tyres to minimise power loss and tyre wear. As radial ply tyres have a larger percentage increase in rolling resistance with slip angle than cross ply tyres, on multi-axle vehicles under slewing conditions or axle misalignment they may suffer proportionally larger increases in rolling resistance.

(4) Tyre Size

It was found that the rolling resistance coefficient tends to decrease with increase in rim diameter or tyre width.

(5) Road Roughness and Surface Texture

Experiments reported by Bester (1984), Watanatada et al (1987), and Young (1988) all show the rolling resistance coefficient to increase linearly at a significant rate with increasing road roughness. However, the resulting relationships between the tyre rolling resistance coefficient and road roughness are at considerable variance due to tyre pressure effects not being accounted for and the large experimental scatter resulting from relatively small sample of measurements over limited roughness ranges. Nevertheless, Bester's findings suggest that a 7.2 tonne truck, fitted with cross ply tyres, will use 8.5% more fuel at 80 km/h on a level road having a roughness of 160 NAASRA counts/km than on a road section of 70 NAASRA counts/km (Transit New Zealand's roughness specification for new granular base and chipseal roads). The difference in the corresponding rolling resistance coefficients is about 23%.

Up until now, reported research on the influence of road roughness on tyre rolling resistance of heavy commercial vehicles has been restricted to cross ply tyres. Lu (1983) identified the following two factors as becoming increasingly dominant factors as the road becomes rougher:

(a) additional hysteresis losses in the tyre due to road surface irregularities; and

(b) energy dissipation in the suspension system due to the relative motion between the sprung and unsprung masses.

It is therefore expected that radial tyres will be less affected by road roughness because their construction is better able to absorb road corrugations.

A recent New Zealand study by Cenek and Shaw (1990) showed differences of up to 60% between the rolling resistance of a car tyre on coarse, grade 1 chipseal and asphaltic concrete surfaces found on motorways. A correlation was established between rolling resistance and the surface texture depth of paved roads. Therefore rolling resistance will also vary with tread pattern and inflation pressure due to the degree of penetration of the tyre tread surface with the macrotexture of the road. However, because of the combined effect of harder rubber and higher tyre pressures, the influence of surface texture on the rolling resistance of commercial vehicle tyres is likely to be less than for car tyres.

Studies are to be carried out in New Zealand in the coming year to investigate the effect of local unsealed road types on tyre rolling resistance. Overseas research findings indicate that the rolling resistance coefficient of a dry dirt surface may be approximately 150% more than that of rolled gravel, which in turn is 33% more than asphaltic concrete.

A COMPARISON OF THE ROLLING RESISTANCE OF A "SUPER SINGLE" TYRE AND DUAL TYRES

Results from Ramshaw and Williams can be used to examine the effect of alternative tyres on a vehicle by following the worked example given below.

Considering a vehicle with an axle load of 98.1 kN (10 tonnes), the load on each of four twin 10.00 x 20 tyres would be 24.5 kN (2500 kgf), or if single 18.00 x 19.5 tyres were fitted 49.0 kN (5000 kgf) per tyre. If the dual 10.00 x 20 cross ply or radial ply tyres were inflated to a typical pressure of 700 kN/m^2 (109 lbf/in^2) and 18.00 x 19.5 tyres to 830 kN/m^2 (120 lbf/in^2), and assuming a speed of 60 km/h and tyres fully warmed, then:

> from Figure 4c, total drag on a trailer axle with 18.00 x 19.5 radial ply tyres fitted = 0.0053 x 49 x 2 = 0.52 kN (56 kgf); and
>
> from Figure 4b, total drag on a trailer axle with 10.00 x 20 radial ply tyres fitted = 0.0066 x 24.5 x 4 = 0.65 kN (66 kgf); and also
>
> total drag on a trailer axle with 10.00 x 20 cross ply tyres fitted = 0.0108 x 24.5 = 1.06 kN (108 kgf)

Therefore, replacing twin 10.00 x 20 cross ply tyres with twin 10.00 x 20 radial ply tyres should in theory reduce rolling resistance drag by 39% per axle, and replacing the cross ply tyres by single 18.00 x 19.5 radial ply tyres should produce a reduction of 51% per axle.

These results were confirmed by on-road testing which demonstrated a decrease in fuel consumption of between 2 and 4% between the radial ply and cross ply tyres compared with 6-10% between the "super single" and cross ply tyres.

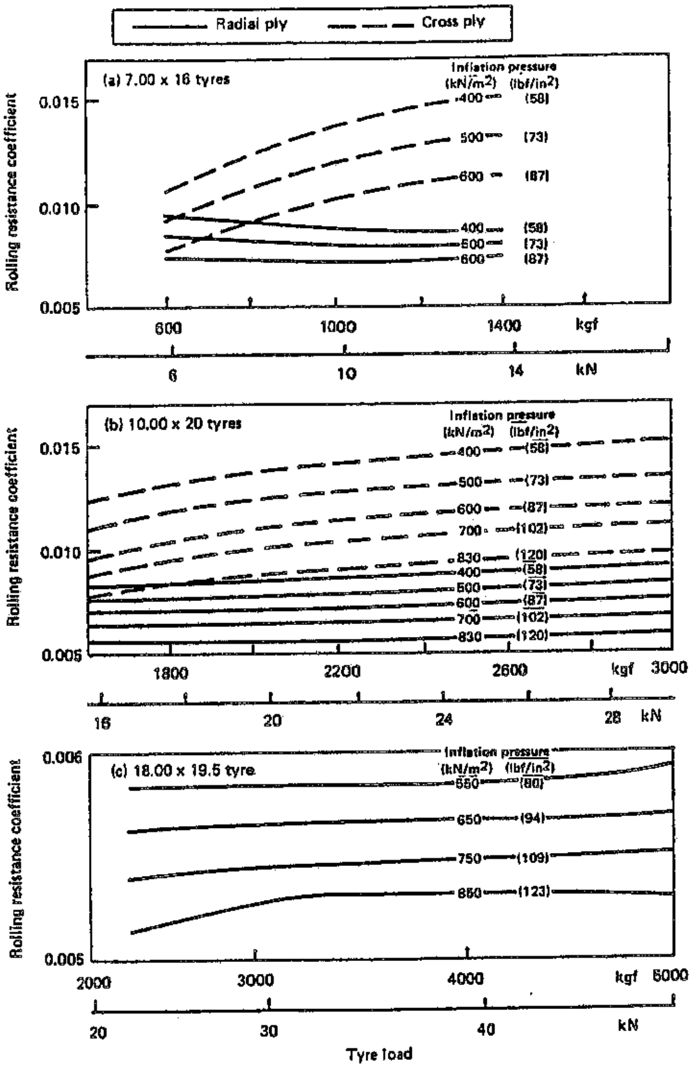

FIGURE 4: **Variation of Rolling Resistance Coefficient with Load on Various Sizes of Radial Ply and Cross Ply Tyres (after Ramshaw and Williams, 1981)**

AERODYNAMIC DRAG OF COMMERCIAL VEHICLES

The effect of aerodynamic drag reduction on fuel consumption in actual operations can best be shown with typical vehicles in typical driving conditions as in Figure 5. Here the fuel savings are based on overall consumption in real conditions such as "very difficult route" or "highway", as opposed to idealised level-road constant-speed driving.

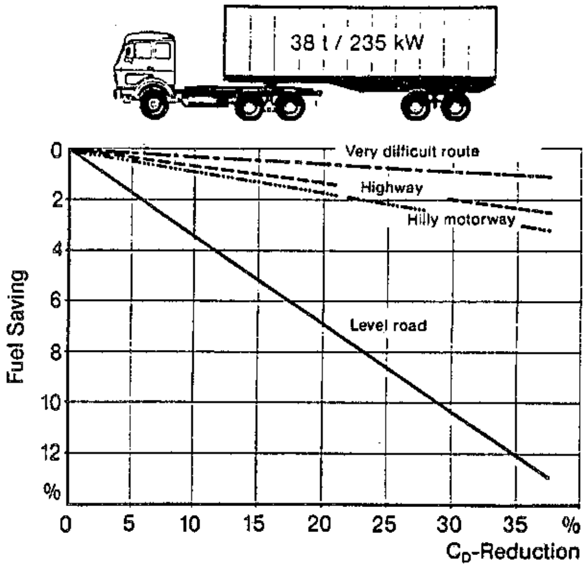

FIGURE 5: **Influence of Drag on Fuel Consumption of a 38 Tonne Semi Trailer (after Hucho, 1987)**

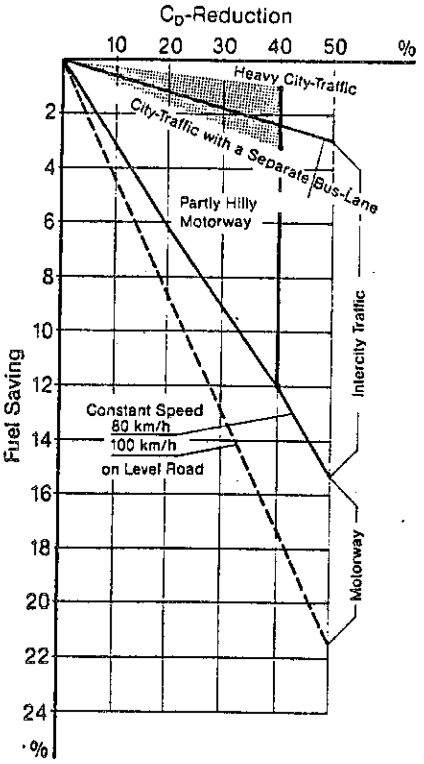

FIGURE 6: **Influence of Drag on Fuel Consumption of Buses (after Hucho, 1987)**

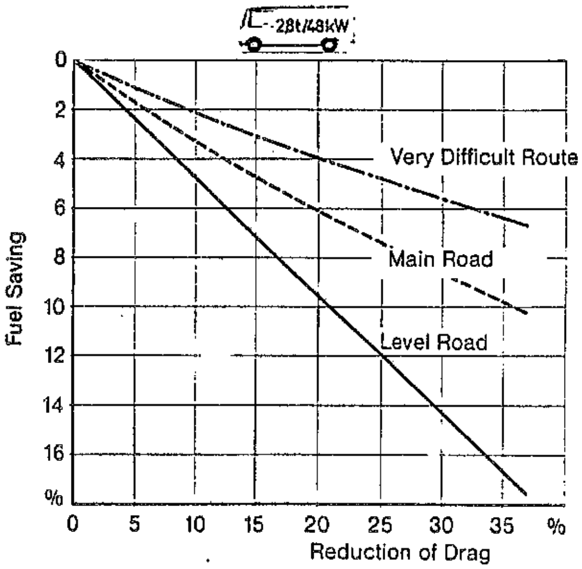

FIGURE 7: **Influence of Drag on Fuel Consumption of a Light Van (after Hucho, 1987)**

The reduction in consumption of the bus, Figure 6, is modest in city traffic though a separate bus lane provides definite fuel economy advantages. Light trucks or vans are less dependent on set routes as shown in Figure 7. Therefore reductions in aerodynamic drag are worthwhile for heavy trucks and buses on motorways, and for light trucks, mini buses and vans even on more "difficult" routes.

With their many different shapes and sizes, commercial vehicles have a wider range of drag coefficients than passenger cars (Figure 8). Buses have drag coefficients (C_d's) about 1½ times those of cars, and tractor-semi trailer units and trucks and trailer units about double. Only light vans, which lend themselves more readily to aerodynamic improvement, have C_d figures close to those of cars.

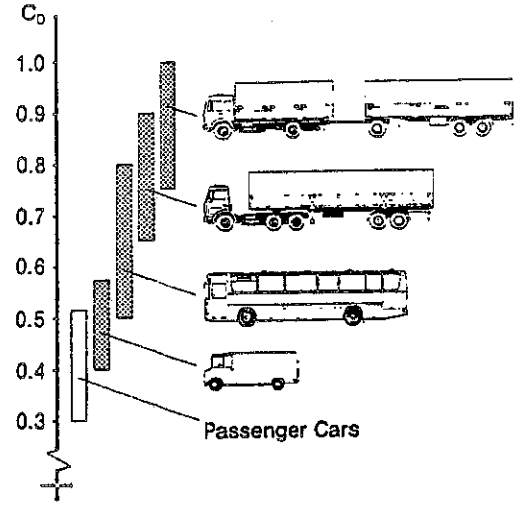

FIGURE 8: **Zero Yaw Aerodynamic Drag Coefficients of Different Commercial Vehicles (after Hucho, 1987)**

The actual aerodynamic drag force on a vehicle depends on the speed and direction of the wind. The vector sum of the wind and vehicle velocity gives the relative wind force. The angle formed between the velocity of travel and the relative wind vector is called the yaw angle, which affects the pressure distributions over the vehicle and the resultant C_d. All commercial vehicle types, with the exception of light vans, show a marked increase in C_d with increasing yaw angle (Figure 9). This can have a considerable effect on fuel consumption as shown in Figure 10.

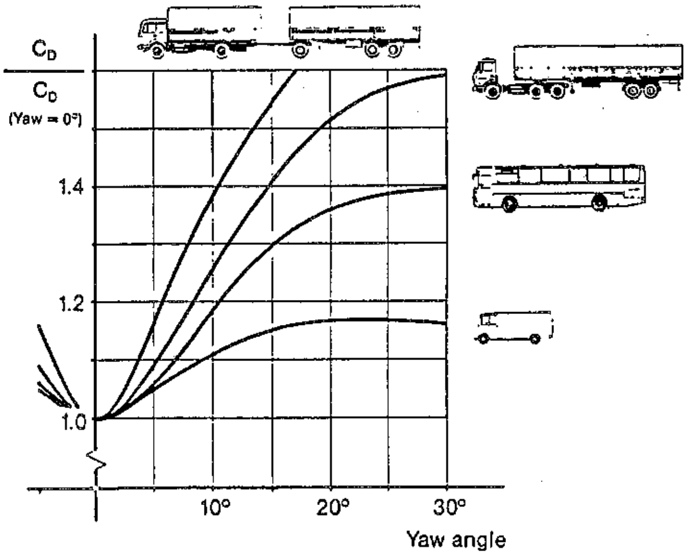

FIGURE 9: **Aerodynamic Drag Versus Yaw of Different Vehicle Types (after Hucho, 1987)**

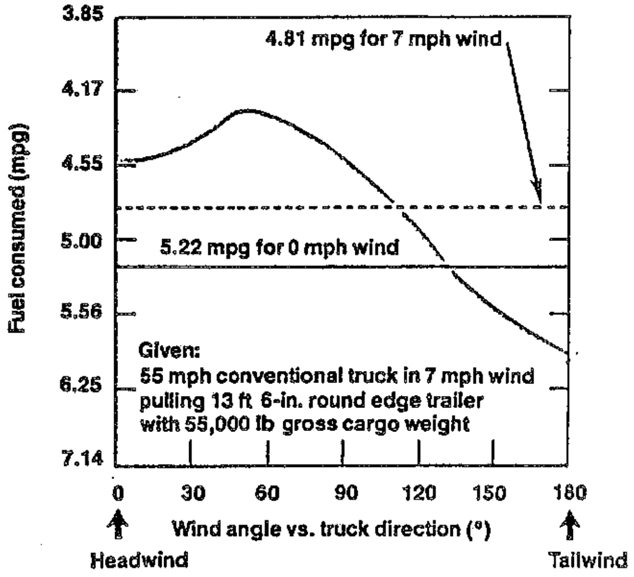

FIGURE 10: **Influence of Wind Direction on Fuel Consumption (after Najlepszy, 1988)**

The constraints on the shape of a commercial vehicle are generally more severe than for cars. Apart from aspects of styling and manufacturing, functional requirements dominate, with the result that designers must deviate as little as possible from the basic cuboid shape. However, to achieve a low aerodynamic drag, the vehicle design must minimise pockets of turbulent air and maximise the areas where the air flow runs smoothly over the body surface.

MINIMISING DRAG OF BUSES AND DELIVERY VANS

The scope for aerodynamic refinement is generally limited to shaping the vehicle front end, and tapering of side panels which is very conducive to smooth air flow. However, because tapering reduces cargo space and has disadvantages for production, it is restricted to short sections of the front and rear ends.

The size of the leading edge radii has a substantial influence on the drag of a bus. From Figure 11, it is evident that a radius of about 150 mm is sufficient to reduce the drag of the bus to such an extent that further appreciable improvement cannot be obtained, even with so-called streamlined front end shapes.

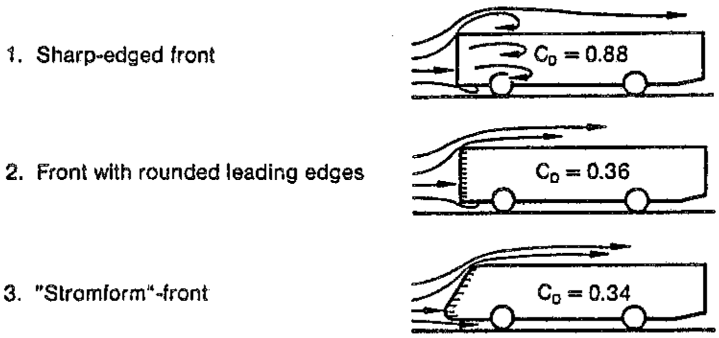

FIGURE 11: Relationship Between Shape of Vehicle Front and Drag Coefficient (after Hucho, 1987)

Figure 12 shows the influence of several important front end design parameters on the C_d of vans. The following are evident:

- Front end taper δ is very effective with steep windshields.
- Raked windshields α are very effective if there is no front end taper. With properly matched taper, windshield rake has only minimal influence.
- Radii on the front edges are also effective up to certain dimensions.

In future, aerodynamic design is likely to influence production vehicles through parameters shown in Figures 11 and 12, consistent with engineering requirements, cab space, entrances, visibility and other safety aspects.

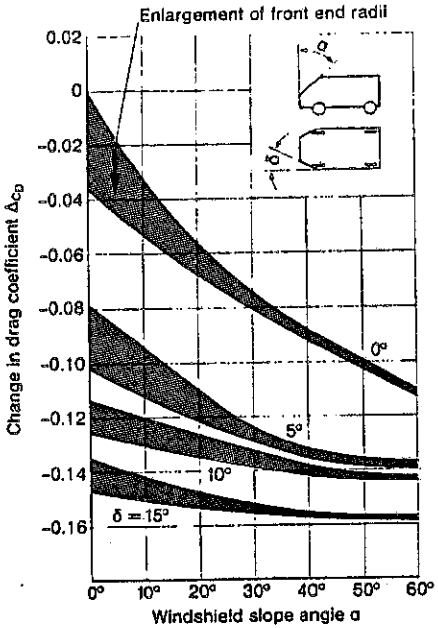

FIGURE 12: **Influence of Front End Shape on C_d (after Hucho, 1987)**

MINIMISING DRAG OF TRUCKS

Numerous wind tunnel studies of high bodied truck and trailer and tractor-trailer units indicate a strong interaction between the cab and body. The gap width, s, measured from the cab rear end to the body front end, and the projecting body height, h, measured above the cab roof, are essential parameters in this relationship.

The effect of varying s and h for three cabs with different shapes but otherwise identical external dimensions are presented in Figure 13.

The results for the sharp-edged cab (C) show:

- A very small influence of gap width s.
- A drag minimum with a projecting body height h = 1.0 m.
- Smaller drag coefficient than for streamlined cabs with projecting body heights h > 1.0 m.

For the streamlined cab (B):

- A broadening of the range of drag coefficients with increasing gap width s, while the band itself also rises with increasing projecting body height h.
- Lower drag compared with sharp-edged cabs for projecting body heights H < 1.0 m.

For the production cab (A):

- A well designed cab is very close to an "ideal" streamlined cab.
- Higher drag than for streamlined cabs with small projecting body heights h < 0.6 m.

The results demonstrate that, in symmetric relative flow, favourable drag coefficients are obtainable even with sharp-edged cabs with a certain body height h. Basically, conditions are favourable where the "flow separation line" from the cab attaches smoothly to the following, generally sharp-edged, body. This situation is changed when yaw is considered. As can be seen from Figure 14, the drag of a sharp-edged cab increases dramatically with yaw. The body, which is shielded by the cab under zero yaw, is now exposed to the oncoming flow. In contrast, trucks with streamlined cabs suffer only slight drag due to yaw.

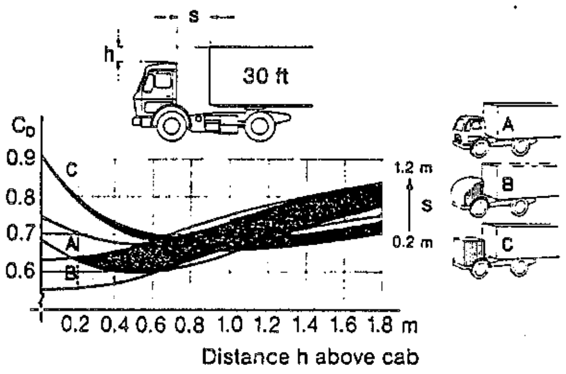

FIGURE 13: Influence of Cab Shape on Aerodynamic Drag Coefficient Taking into Account Different Body Heights, h, and Gap Widths, s (after Hucho, 1987)

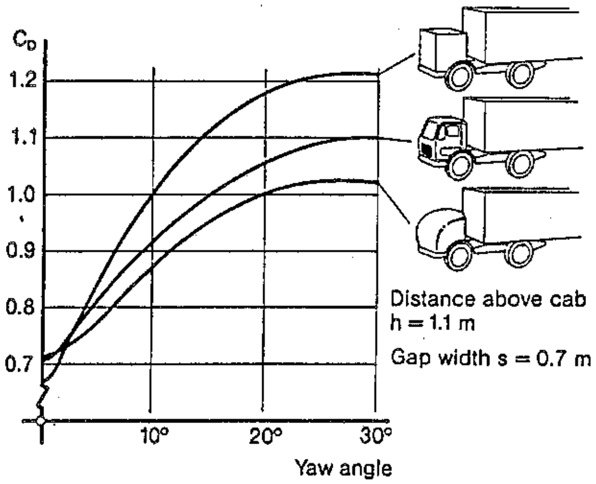

FIGURE 14: Influence of Cab Shape Versus Yaw for a Semi-Trailer Unit (after Hucho, 1987)

Tractors are operated with a variety of different trailers. Therefore low drag of the cab alone does not guarantee low drag for all truck-trailer combinations. For high bodies a whole range of add-on devices for reducing air drag have been developed. Some of those to be seen on the road are compared in Figure 15. For cab mounting, head and side wind deflectors or adjustable air shields have proved to be effective, the latter being easy to fit and cheap. Devices mounted on the body, for instance fin-like vortex stabilisers on the front wall, which by vortex formation reduce the flow of air between cab and body in cross-winds, or half-balloon shaped aerofoils, help to reduce overall drag.

With increasing angle of yaw, appreciably smaller drag coefficients are realised with a bulbous fairing than with an air shield (Figure 16). Also wind deflecting devices are more effective for streamlined cabs than for those with sharp edges.

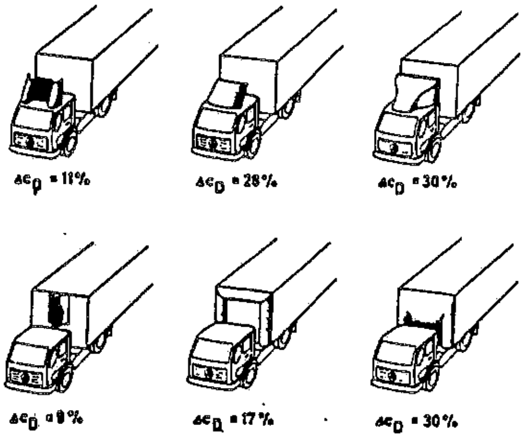

FIGURE 15: Drag Reduction Through Add-On Devices with Head-On Air Flow (after Hucho, 1987)

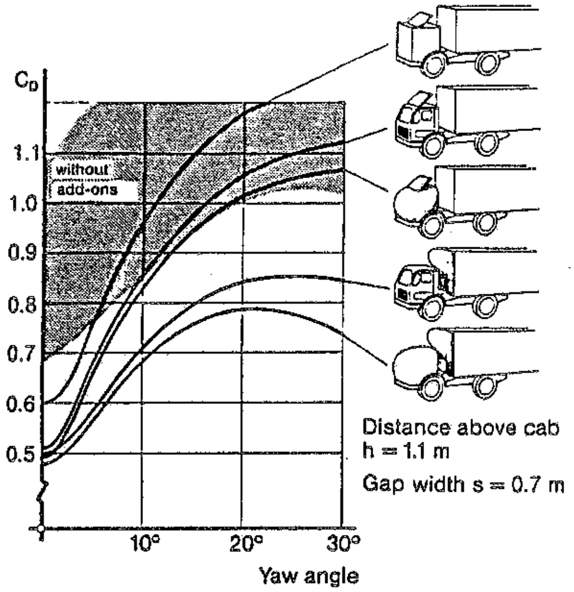

FIGURE 16: Drag Reduction Versus Yaw Through Add-On Devices on a Semi-Trailer Unit (after Hucho, 1987)

Because tractors will often be pulling different trailers, and because of the effects of side winds, the use of properly designed fairings fitted to the front panels of trailers and of rigid bodies is recommended. In terms of cost effectiveness, roof deflectors used in conjunction with vortex controllers (vertical fins fitted to the front panel of a body) are a suitable alternative. However, the fairings must be properly designed. Their function is to smooth the air flow around the trailer or body edges, and to do that the radius of curvature must be at least 150 mm.

Figure 17 shows measures developed to improve the flow pattern in the gap between the tractor and the "full" trailer of a truck-train. The drag of the "ideal", i.e. gapless configuration is approximated by combining the vortex stabiliser with a bulbous fairing.

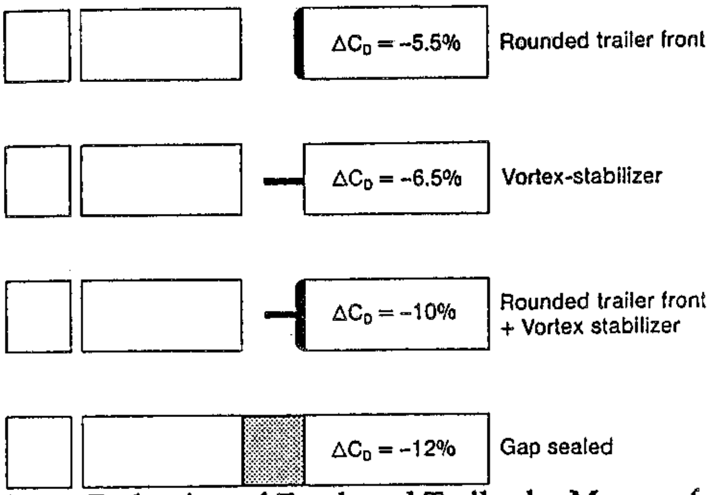

FIGURE 17: Drag Reduction of Truck and Trailer by Means of Add-On Devices on Trailer (after Hucho, 1987)

It is often not functionally practical to have the most aerodynamically ideal trailer configuration. However, its effect on fuel consumption needs to be remembered and possible compromise considered. Figure 18 shows a number of examples of poor aerodynamics and the estimated fuel wastage.

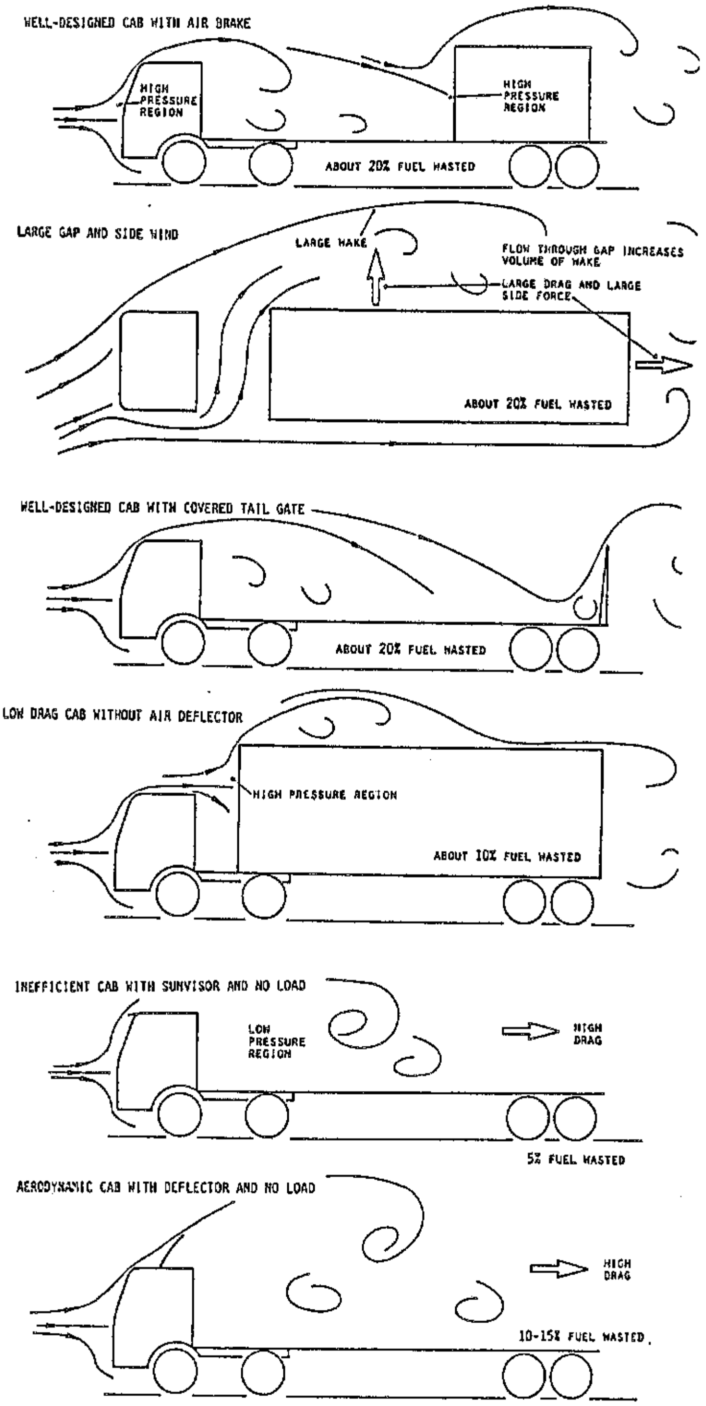

FIGURE 18: Some Examples of Inefficient Aerodynamics and its Effects (after Saunders and Hoffmann, 1982)

CONCLUDING REMARKS

(1) For the majority of New Zealand transportation operations, tyre rolling resistance and vehicle inertia effects are the dominant contributors to fuel consumption. As both are directly dependent on vehicle weight, the payload to tare ratio is an important consideration when selecting a new truck or trailer.

(2) The simplest way to obtain better fuel consumption is to reduce rolling resistance by making sure that tyres are properly inflated and aligned. For every 4% that a vehicle's tyres are under-inflated, fuel consumption goes up by about 1%, whereas an axle misalignment of 1° increases fuel consumption by 3%, and of 2° by 8%. Radial ply tyres are more sensitive to axle misalignment than cross ply tyres.

(3) For low tyre rolling resistance the rim diameter and/or tyre width should be as large as possible. In addition, tyre tread patterns also affect tyre rolling resistance due to the degree of penetration of the tread surface with the macrotexture of the road. Generally ribbed treads roll more easily than block treads.

(4) Smooth, hard, round surfaces provide less rolling resistance than soft, rough surfaces.

(5) The decision about whether to invest in bolt-on aerodynamic aids depends on how each vehicle is used. Large frontal area, low weight, high speed are all factors that increase the chance of saving significant quantities of fuel. As to the devices themselves, body-mounted fairings of good design, or adjustable wide-bladed deflectors used in conjunction with fin-like vortex stabilisers to reduce the flow of air between cab and body, appear to be the most effective in both head-on and yawed wind conditions.

(6) Aerodynamic technology has evolved through the bolt-on stage and is now becoming an integral feature of commercial vehicles. However, as aerodynamic efficiency improves, the cross-over speed where aerodynamic drag becomes more important than rolling resistance will increase if vehicle mass and tyre rolling resistance remains relatively unchanged. As a consequence, rolling resistance will have an even greater influence on fuel consumption in the foreseeable future.

REFERENCES

Bester, C.J. (1984): "Effect of Pavement Type and Condition on the Fuel Consumption of Vehicles", Transportation Road Record 1000, pp 28-32.

Cenek, P.D. and Shaw, P.F. (1990): "Investigation of New Zealand Tyre/Road Interactions", RRU Bulletin 85, Transit New Zealand.

Hucho, W.-H. (1987): "Aerodynamics of Road Vehicles", Butterworths.

Ministry of Transport (1987): "Truck Operating Costs 1987/88", Government Printing Office.

Najlepszy, F. (1988): "Aerodynamic Styling Comes to Big Trucks", Machine Design, Vol. 24, No. 60, March 1988, pp 44-53.

Ramshaw, J. and Williams, T. (1981): "The Rolling Resistance of Commercial Vehicle Tyres", TRRL Supplementary Report 701.

Saunders, J. and Hoffmann, P. (1982): "Local and Overseas Trends in Truck Aerodynamics", Internal Paper, Dept. of Mechanical and Production Engineering, RMIT.

Watanatada, T., Dhareshwar, A.M. and Lima, P.R.S.R. (1987): "Vehicle Speeds and Operating Costs", The World Bank Highway Design and Maintenance Standards Series, John Hopkins University Press.

Young, J. (1988): "The Influence of Road Unevenness on Vehicle Fuel Consumption", TRRL Internal Paper.