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INSTITUT CANADIEN DE RECHERCHES EN GÉNIE FORESTIER

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Wind Tunnel Tests of Devices for Reducing the Aerodynamic Drag of Logging Trucks

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CORRECTIONS:

FERIC Technical Report No. TR-27 (Wind Tunnel Tests of Devices for Reducing the Aerodynamic Drag of Logging Trucks).

FOREWORD (second paragraph, line two)

1. the high accuracy of the results (±0.002)

APPENDIX A, page 23

(line five)

F_{IR} = Inertial Resistance in N (lbf)

(line seven)

URR = Unit Rolling Resistance in N/1000 kg GVW (lbf/1000 lb GVW)

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FOREWORD

Wind tunnel tests of the aerodynamics of trucks hauling different types of log loads, and of several add-on devices suitable for improving the aerodynamics of these trucks, are described in this report. Projections of the fuel savings that air drag reductions would produce are made. A supplementary report will investigate the economic benefits other than fuel savings available from aerodynamic drag reduction.

A wind tunnel simulation approach was chosen because of:

1. the high accuracy of the results (±0.002%)
2. the control over external variables affecting air drag which it offers
3. the low cost involved compared to road testing
4. the little time required for a comprehensive test program
5. the relative ease with which a test program can be undertaken.

The report contains a discussion of the assumptions involved with wind tunnel testing.

The report provides basic information on the aerodynamic characteristics of logging trucks to aid designers of logging trucks and trailers, and to help potential users of these devices evaluate their usefulness in their hauling operations.

All quantitative data within the report are given in "SI" (Système International d'Unités) units with Imperial equivalents appended within parentheses.

FERIC wishes to thank personnel of the Low Speed Aerodynamics Laboratory of the National Research Council of Canada (NRC) for their assistance in conducting the wind tunnel tests and in analysing the data. Appreciation is especially extended to Mr. Kevin R. Cooper of NRC.

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SUMMARY

Concern with energy conservation has led to the development of several add-on devices for improving the aerodynamics of highway trucks. These add-on aerodynamic (AOA) devices, such as deflectors, gap seals and trailer skirts, reduce air drag, which becomes a significant resistance to a truck's motion at speeds above 50 km/h (32 mph). Since less power is required to move the truck at the same speed, fuel savings can be obtained.

Air drag on van-type semi-trailers has been found to be predominantly due to pressure build-ups on the blunt front faces of the tractor and the exposed portion of the trailer. Suction at the rear end, skin friction and parasitic losses are the other contributing factors. The maintenance of smooth air flow around the truck is the key to minimizing air resistance.

Wind tunnel tests using 1:10 scale models of typical logging trucks, trailers and loads were made at the National Research Council of Canada's Low Speed Aerodynamics Laboratory in November, 1977. The aerodynamic drag coefficients (C_D) of the trucks were determined at different angles relative to the wind for a deflector, a gap seal, trailer skirts and combinations of these AOA devices. The drag coefficients were converted to wind averaged drag coefficients ($\overline{C_D}$) which better account for the effects of wind on the truck's aerodynamic behaviour. Estimates of the fuel savings produced by the AOA devices were made.

Some of the main results are that:

- the greatest potential for drag reduction exists with shortwood loads.
- trailer skirts are the only AOA device affecting air drag on both the loaded and unloaded trip.
- a 10-15% reduction in the trailer-produced air drag is available.
- load shaping of the shortwood load can lower the $\overline{C_D}$.
- gap-seals are ineffective on the tree-length loads under the cross-wind conditions for which they are designed.
- there is little difference between the air drag of the conventional and cab-over-engine truck designs.

Use of a deflector on a shortwood truck was found to offer 3.08 ℓ/100 km (1.09 gal/100 miles) fuel savings on the loaded portion of the trip at an average travel speed of 80 km/h (50 mph). This saving would be available only on the loaded trip. On the van trailer, the different combinations of AOA devices offer savings on both the empty and loaded trips.

The effects of the assumptions made during the testing are discussed. The greatest source of variation between real life and wind tunnel simulations is probably caused by the differences in the wind environment at different locations across Canada. Wind averaged drag coefficients ($\overline{C_D}$) have been calculated for different locations and travel directions to better account for localized wind effects.

A correction factor, based on the fact that $\overline{C_D}$ changes at a linear rate of 3% per 15-cm (6-inch) change in the exposed trailer width or height, can be used to determine the drag coefficient for trucks pulling load sizes different from those tested.

There are other benefits from drag reduction in addition to fuel savings which can reduce hauling costs. These include faster travel speeds, reduced engine sizes, larger payloads, and reduced maintenance. Intangible benefits, such as reduced noise levels and driver fatigue, and improved truck handling and safety also exist. Some of these benefits are mutually exclusive.

Suggestions are presented on methods of reducing the aerodynamic drag of logging trucks.

INTRODUCTION

Concern with energy conservation has led to the development of several devices for reducing the aerodynamic drag of trucks. This equipment decreases fuel consumption, since less power is required to overcome the air drag. Great success in applications of these devices on highway trucks has been reported, with fuel savings exceeding 10% claimed in some cases.

However, there are significant differences between intercity line-hauls and wood hauling operations:

- speeds of logging trucks are generally lower
- loads are hauled only in one direction
- log loads are often not box-shaped like a van-trailer
- air flow can occur through the load.

The importance of these differences indicated that tests of the applicability of add-on aerodynamic (AOA) devices to wood hauling operations were needed.

Theory

Aerodynamic drag combines with rolling, grade, curve and acceleration resistances, chassis friction and parasitic loss through fans and pumps to resist the motion of a truck. These forces must be overcome by the truck's engine if the truck is to move (see Figure 1).

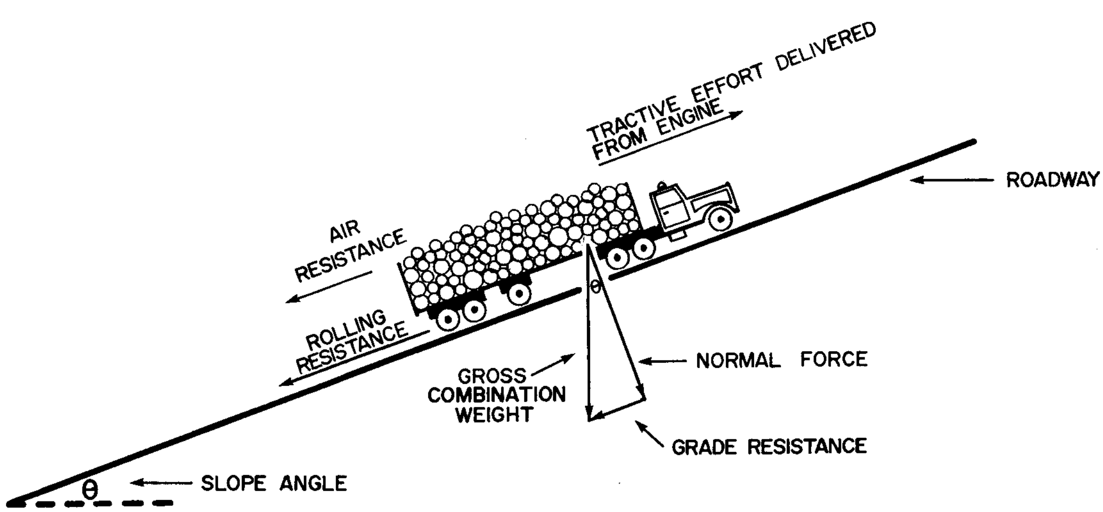

Figure 1. Force Diagram of a Moving Logging Truck

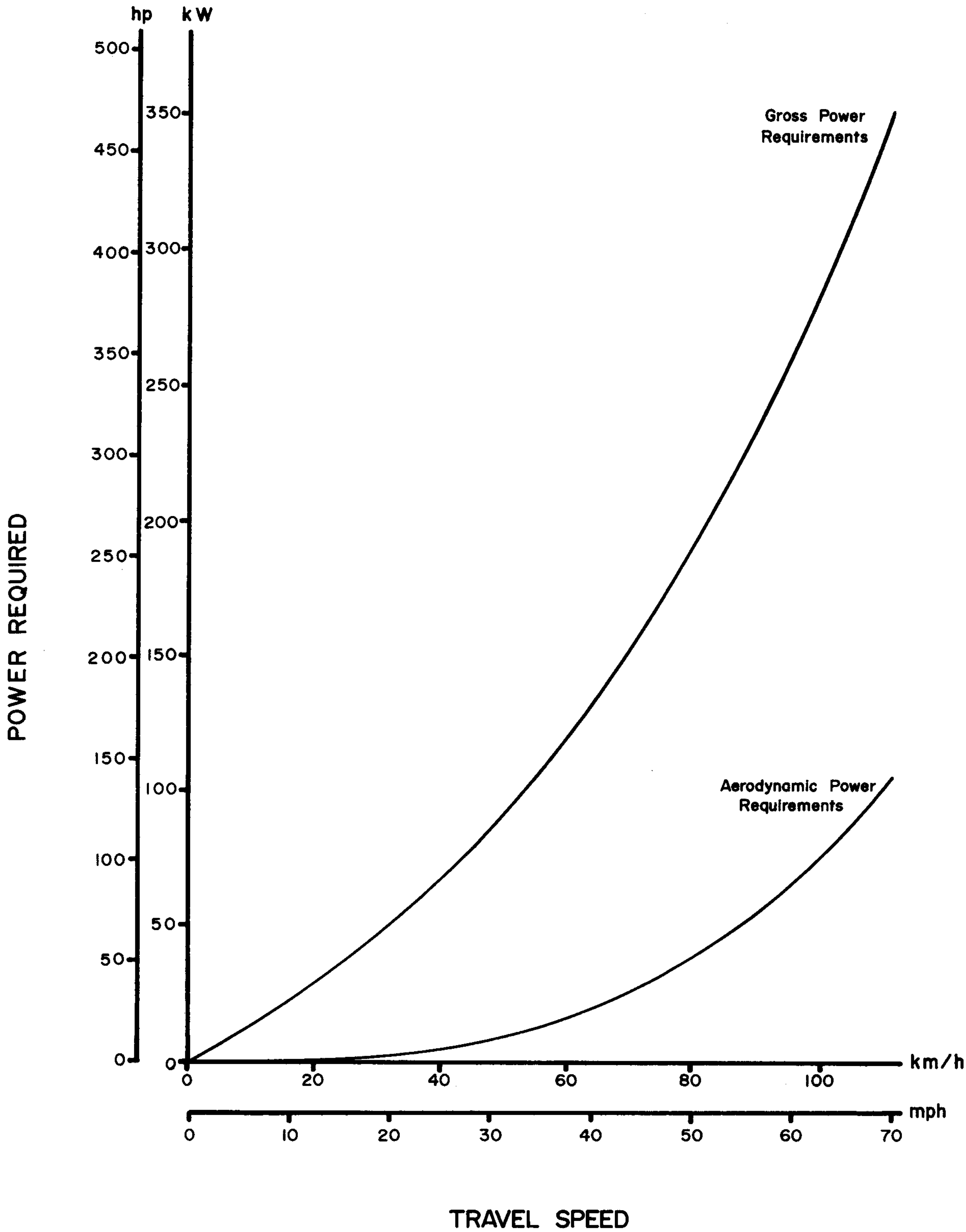

Figure 2. Gross and Aerodynamic Power Requirements of a Loaded Logging Truck on a Level Road.

The resisting forces are influenced by the truck's design and driver, and by characteristics of the road on which the truck is driven. Aerodynamic drag is largely a truck controlled resistance, although the winds, temperature and air pressure of the surrounding environment have some influence. The net power required to overcome aerodynamic drag is calculated with the equation[1]

$$Pa = \frac{\rho \times A \times C_D \times V^3}{93.312} \qquad (1)$$

where:

Pa = power required to overcome air resistance (kW)
ρ = air density (kg/m^3)
C_D = drag coefficient
A = vehicle's frontal area (m^2)
V = resultant air speed approaching the truck (km/h)

The gross and aerodynamic power requirements of a loaded logging truck with 38.5-t (42.5-T) GCW are illustrated in Figure 2. Notice that the power required to overcome aerodynamic drag increases rapidly at travel speeds over 50 km/h (32 mph). Air resistance contributes 20 to 25% of the gross power requirements at travel speeds between 80 and 100 km/h (50 and 62 mph). The fuel consumed to overcome air resistance can be estimated by the equation

$$\mu = \frac{SFC \times DC \times Pa}{\eta \times \sigma \times \psi \times V} = 0.220 \times \frac{Pa}{V} \qquad (2)$$

where:

μ = fuel consumption, ℓ/km
SFC = specific fuel consumption (0.231 kg/kW·hr)
DC = engine's duty cycle (0.65)
η = drive train efficiency (0.87)
σ = fuel density (0.838 kg/ℓ)
ψ = parasitic loss factor (0.935)

The difference in the fuel consumed to overcome air resistance (ℓ/100 km) by an unmodified and a modified truck is given by the equation

$$\Delta\mu = \frac{\rho \times A \times \Delta C_D \times V^2}{4235} \qquad (3)$$

The unit ℓ/100 km is commonly used when describing fuel savings (1 ℓ/100 km = 0.354 gal/100 miles).

The aerodynamic drag of van-type semi-trailer units has been found to be predominantly due to pressure drag. The build-up of pressure from the impact of air on the blunt front faces of the tractor and the exposed part of the trailer accounts for 50% of the unit's air drag. Suction at the rear end causes 25% of the drag. Skin friction as air flows over the truck's surfaces accounts for 10%. The remaining 15% is caused by parasitic losses from air flow over the wheels, axles, mirrors, etc. [2, p. 5]. Reductions in aerodynamic drag of as much as 60% have been demonstrated with extreme streamlining of the tractor-trailer unit.

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[1] An Imperial unit equivalent of this equation is given in Appendix A. Note that 1 kW = 1.34 hp.

Figure 3 illustrates the airflow patterns around a truck. Note how the tractor and trailer block the airflow, the down-flow behind the tractor, the turbulent flow over the load, and the stagnant flow pocket. The deflector maintains smooth flow over the truck.

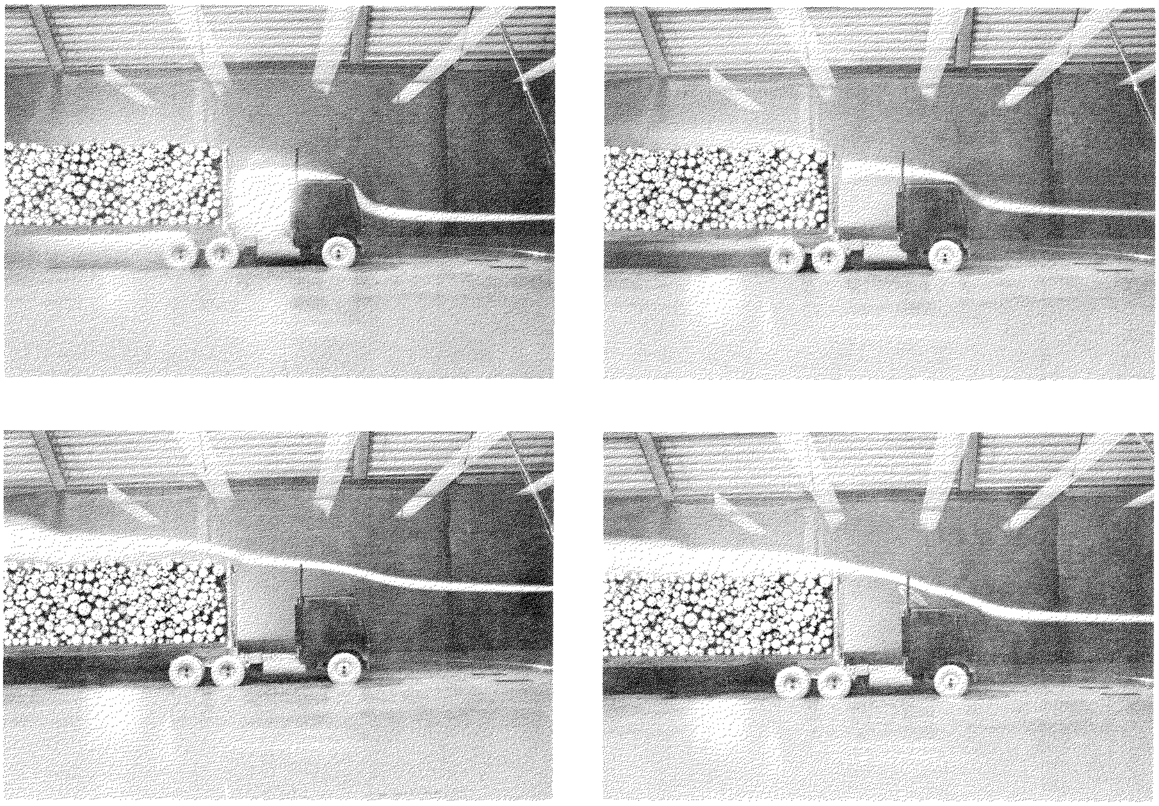


Figure 3. Visualizations of Airflow Patterns Over a Truck.

TYPES OF ADD-ON AERODYNAMIC DEVICES

The reduction of pressure drag by streamlining the truck is the key to minimizing air resistance. Figure 4 illustrates some examples of the AOA equipment which have been developed to maintain smooth airflow.

The cab-mounted deflector is the most common AOA device. It is usually a curved plate of reinforced plastic or fibreglass which deflects the airflow onto the top of the trailer. This decreases the high positive pressure caused by airflow against the exposed vertical face of the trailer. Some deflectors are adjustable for varying load heights, but most are fixed once installed.

The effectiveness of deflectors decreases as the angle between the truck's travel direction and the wind increases [4, pp. 41-42]. Gap seals, which block airflow through the opening between the tractor and trailer, reduce the sensitivity of the truck to crosswinds. As much as one-third of the truck's air drag may arise because of the flow across the gap under crosswind conditions.

Air vanes, fairings on the trailer's front face, and the rounding of trailer corners reduce the pressure on the front face, and prevent flow separation. Trailer skirts improve the truck's aerodynamics under crosswind conditions, and shield the underbody components.

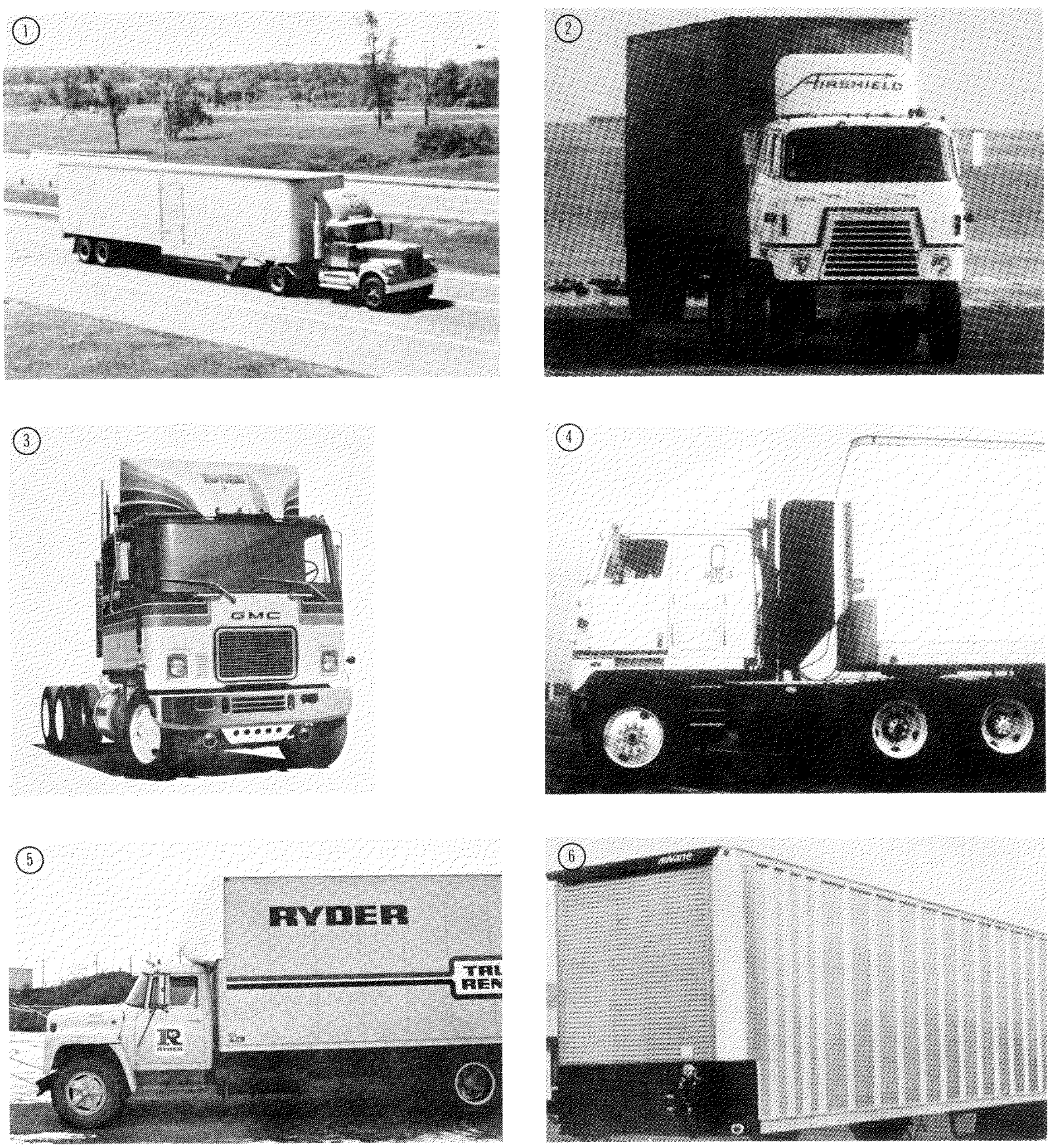


Figure 4. Examples of AOA Equipment: 1) Uniroyal Air Deflector; 2) Airshield Wind Deflector; 3) GMC Dragfoiler; 4) Airshield Roof Fairing and Gap Seal; 5) Nosecone 6) S^3 Airvane.

WIND TUNNEL TEST PROCEDURES

Wind tunnel tests were conducted in the 1.8-m × 2.7-m (6-ft × 9-ft) wind tunnel of the Low Speed Aerodynamics Laboratory, National Research Council of Canada during November, 1977.

A 1:10 scale model of a Kenworth conventional cabbed tractor (cab model N9004) with a logging trailer was used for the tests. The dimensions of the test model are shown in Appendix B. Loads simulating shortwood, sawlogs and tree-lengths were tested. Limited tests of a White Freightliner (cab model WFT8864), and an International Harvester 1600 straight truck were also made. The models and log loads tested are illustrated in Figure 5.

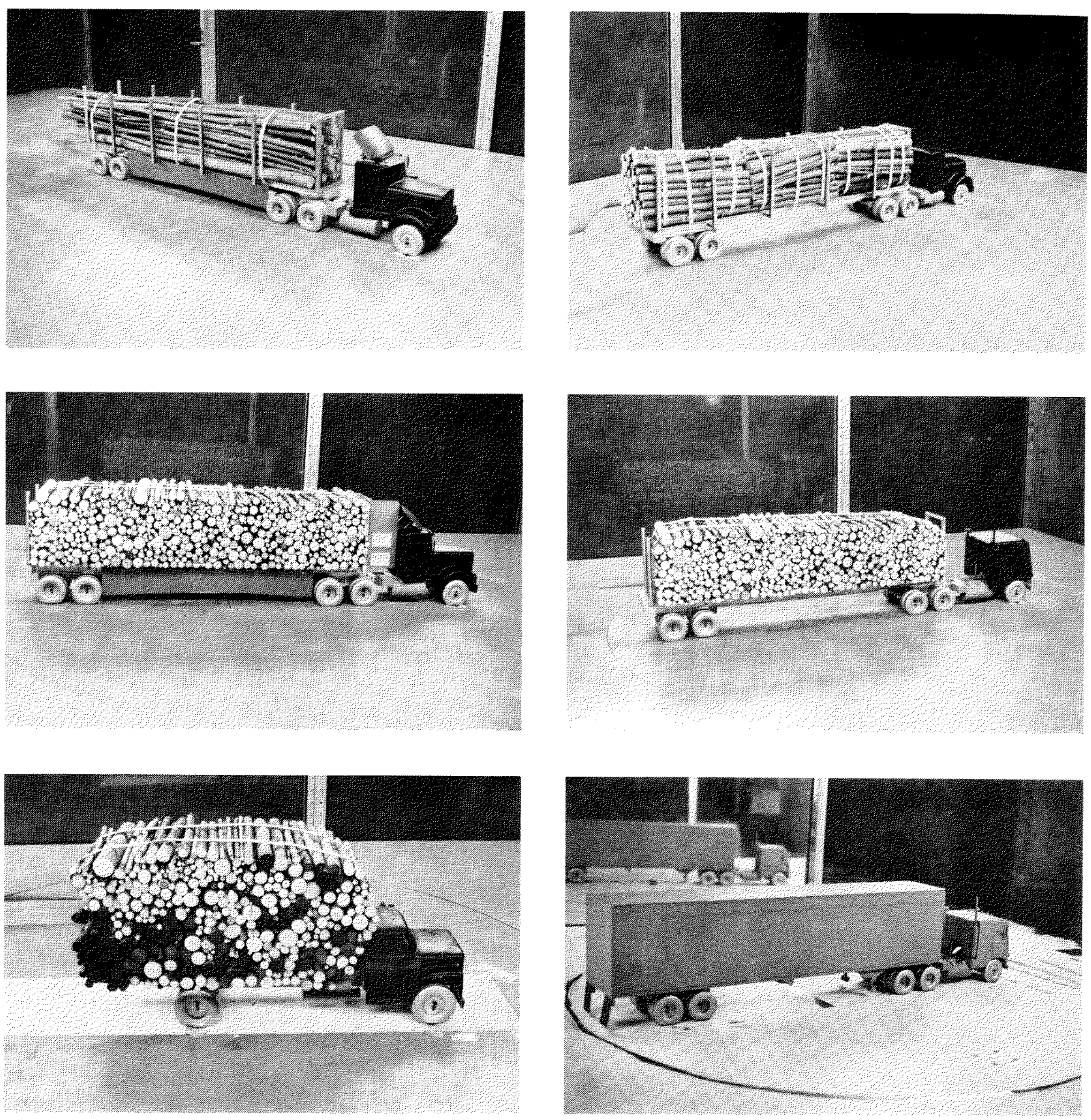


Figure 5. Models and Log Loads Tested in the Wind Tunnel.

The models were mounted on a fixed ground plane located above the boundary layer produced by the tunnel floor (see Figure 6). The model's front and rear tire sets were attached to a mechanical balance located beneath the test section. The balances measured the forces and moments produced when air was blown through the tunnel. The models were rotated between -4 and +20 degrees to simulate crosswind effects.

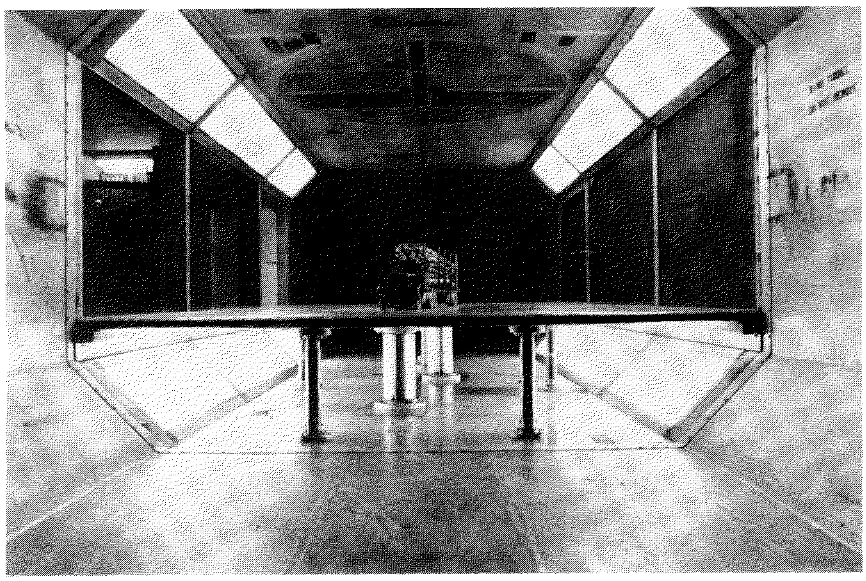


Figure 6. Downstream View of the Tree-Length Model, the Ground Plane and the Turntable. Connections to the weighing devices pass through pipes situated directly under the model.

Test runs were made using a deflector, a gap seal, trailer skirts, and combinations of these AOA devices. Load shaping and assorted fairings (streamlining shapes) were also investigated.

The drag coefficient (C_D), a dimensionless number proportional to the truck's drag, was calculated at each yaw angle in the direction of the longitudinal axis of the truck using the following equation:

$$C_D = \frac{2 \times Da}{\rho \times A \times V^2} \qquad (4)$$

where:

Da = body axis aerodynamic drag force in N
ρ = air density in the test section in kg/m^3
A = reference area in m^2
V = air speed in the test section in m/s

The data were normalized to account for the airflow acceleration caused by the model's presence, using the correction proposed by Maskell [7].

In recognition of the modifications which the average wind speed and its yaw angle induce in a truck's aerodynamics (see Figure 7), the drag coefficients were converted into wind averaged drag coefficients ($\overline{C_D}$) [3, pp. 1750-55; 4, pp. 38-40]. $\overline{C_D}$ values were calculated for the average Canadian wind environment, and for seven representative locations across Canada. Within this report unless otherwise stated, $\overline{C_D}$ values are based on the average Canadian wind speed occuring with equal probability from all directions, and a truck travel speed of 80 km/h (50 mph).

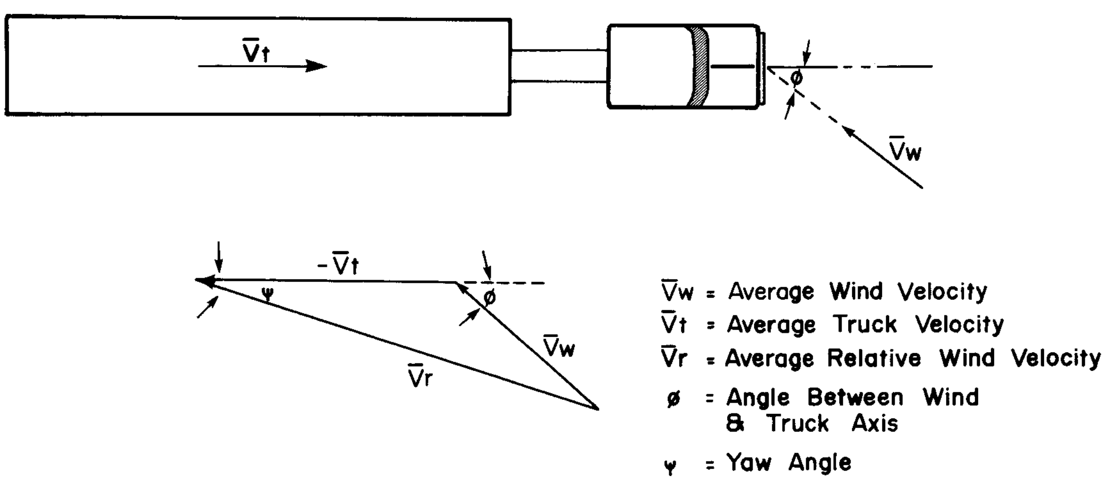


Figure 7. Relative Wind Velocity Vector Diagram.

RESULTS

Wind Averaged Drag Coefficients for Different Loads and Devices

The wind tunnel tests demonstrated that reductions in aerodynamic drag are possible using AOA devices. However, there were considerable differences in the effectiveness when applied to different load types. The greatest reductions in the $\overline{C_D}$ occurred with the shortwood load, and the least with tree-length.

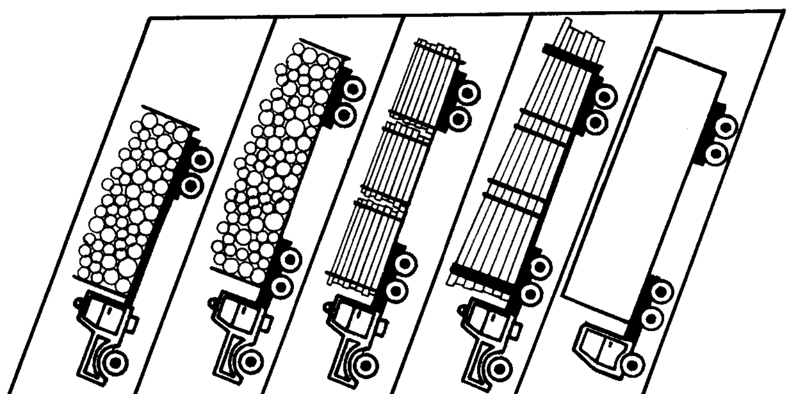
Tables 1 and 2 summarize the $\overline{C_D}$ values of the tested configurations. The chip-van results are based on an earlier test program of van-type trucks (see Figure 5) undertaken by NRC, and were included to give chip haulers an idea of results they might expect from the application of AOA devices.

Large differences between the normal or baseline wind averaged drag coefficients were found. The $\overline{C_D}$ of the semi-trailer with the tree-length load was 14% less than the semi-trailer with the shortwood load. The slightly different frontal area, the tapered shaped and the lower pressure on the front edge which results from airflow through the tree-length load are possible factors in this phenomenon. In addition, the increased surface roughness of the shortwood load produced more turbulent flow, and thus a thicker boundary layer along the load's surface.

A comparison of the $\overline{C_D}$ for the loaded and unloaded baseline conditions in Table 1 and 2 illustrates that the tree-length and sawlog loads contributed only 6% and 11% respectively of the total air drag, whereas the shortwood load contributed 40% of the drag.

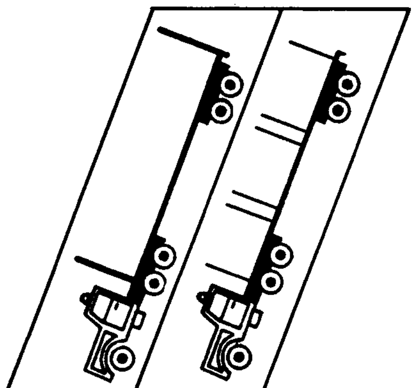
The largest reduction in the $\overline{C_D}$ was 19%, and was produced by using a deflector, gap seal and trailer skirts on a shortwood trailer. A 17% reduction in the $\overline{C_D}$ was obtained using a deflector and skirts on a sawlog trailer. The greatest reduction on the tree-length load was 10% using a deflector and skirts. These reductions in the $\overline{C_D}$ values were less than those shown in tests of the van-trailer where a maximum reduction of 20% was obtained.

TABLE 1. Wind Averaged Drag Coefficients of the Loaded Configurations.



BASELINE	0.89	1.13	1.01	0.97	0.98
DEFLECTOR	0.86	0.97	0.87	0.90	0.86
DEFLECTOR & GAP SEAL	—	0.96	—	0.90	0.82
DEFLECTOR , GAP SEAL & SKIRTS	—	0.92	—	0.87	0.78
DEFLECTOR & SKIRTS	—	0.94	0.84	0.87	0.82
SKIRTS	—	1.10	0.98	0.94	0.93
SKIRTS & GAP SEAL	—	—	—	0.90	—
GAP SEAL	—	—	—	0.92	—

TABLE 2. Wind Averaged Drag Coefficients of the Unloaded Configurations.



BASELINE	0.68	0.91
DEFLECTOR FOLDED	0.69	0.91
DEFLECTOR FOLDED & GAP SEAL	0.70	0.90
DEFLECTOR FOLDED , GAP SEAL & SKIRTS	0.65	0.88
DEFLECTOR FOLDED & SKIRTS	0.65	0.87
SKIRTS	0.64	0.87

The use of AOA equipment created no large reductions in the $\overline{C_D}$ under unloaded conditions (see Table 2). The folded deflector raised the $\overline{C_D}$ by 1.5%. The gap seal had no effect, while the skirts lowered the C_D of the empty truck by 5-6%. Note that drag reduction due to the skirts affects both loaded and empty conditions. The reduction is thus double that of other AOA devices, which influence drag only on the loaded trip.

Trailer Design Effects

There are large differences in the $\overline{C_D}$ for the two empty baseline trailers, although the only physical differences were the removal of the butt screen and the side posts. The C_D of the shortwood trailer was 25% less than that of the sawlog and tree-length trailer.

Further investigations of this result showed that the butt screens commonly used for protecting the cab had no effect on drag. Removal of the side posts was responsible for the 25% reduction in drag. An additional 5% decrease in C_D was achieved by removing the cross-piece joining the front posts.

Yaw Angle Effects

The effects of yaw angle on the baseline configurations of these load types and on a tree-length load with gap seal are shown in Figure 8. Note that the curves are symmetrical around both sides of the zero yaw angle axis. The shortwood truck was the most sensitive to cross-winds, and thus would be slower and more difficult to handle than a similarly equipped tree-length truck.

The gap seal did not prove to be effective under cross-wind conditions for the tree-length load. The tapered shape and the slightly rounded sides which resulted from binding the load probably played a role in this effect. The gap seal worked with the shortwood load.

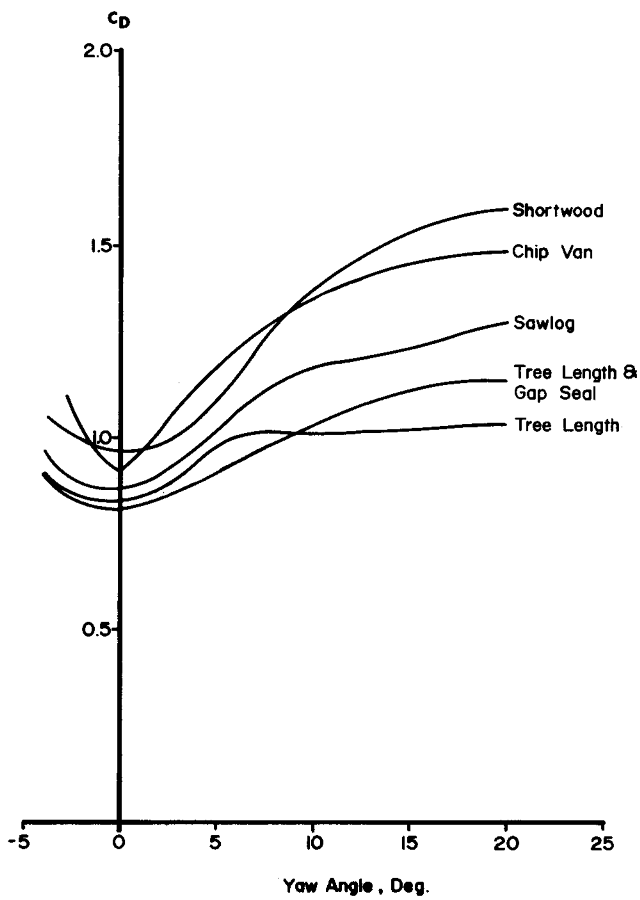


Figure 8. Effects of Yaw Angle on the Drag Coefficient of the Baseline Configurations and a Tree-Length Load with a Gap Seal.

Load Shaping

Shaping the shortwood load by removing about three logs at the load's top front edge (see Figure 9) produced lower wind averaged drag coefficients without the addition of any AOA device. Although not verified, it is likely that a similar rounding of the rear portion of the load's top would have a similar reducing effect. Table 3 illustrates that load shaping has little effect when used in conjunction with the deflector, since similar effects on the airflow patterns are produced by both methods of streamlining.

TABLE 3. Effects of Shaping the Shortwood Load on the $\overline{C_D}$.

	SQUARE FRONT		ROUNDED FRONT	
	$\overline{C_D}$	$\%\Delta\overline{C_D}$	$\overline{C_D}$	$\%\Delta\overline{C_D}$
BASELINE	1.13	—	1.10	3
DEFLECTOR	0.97	14	0.96	13

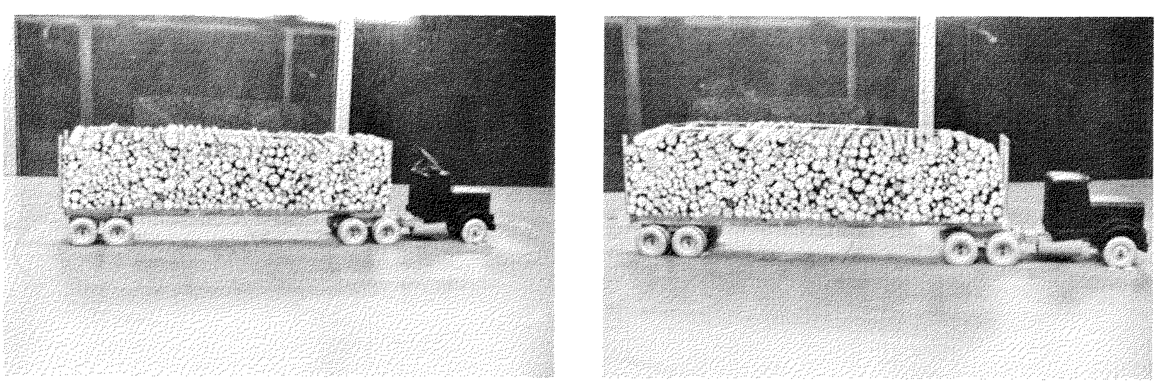


Figure 9. Square and Shaped Shortwood Loads with Deflector.

Conventional Cab Versus Cab-Over-Engine

The $\overline{C_D}$ values of a shortwood truck with a conventional cab (CONV) and a cab-over-engine (COE) are compared in Table 4. Although the COE had a lower $\overline{C_D}$ under the baseline conditions, the deflector was more effective on the CONV cab since the large COE tractor is already doing some of the deflector's work. This suggests that truck manufacturers have paid more attention to the aerodynamic characteristics of COE trucks because of the inherent deficiencies in its bluff design.

The conventional-cabbed truck had a lower $\overline{C_D}$ at travel speeds below 48 km/h (30 mph) than the COE.

TABLE 4. Effects of Cab Type on the $\overline{C_D}$ of a Shortwood Truck.

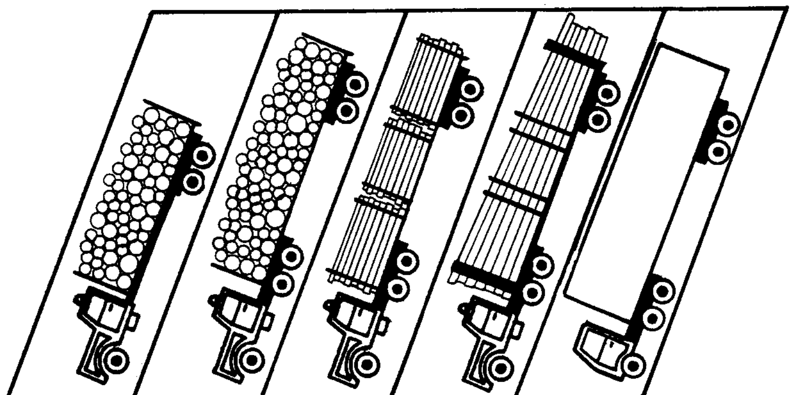
	CONV		COE	
	$\overline{C_D}$	$\%\Delta\overline{C_D}$	$\overline{C_D}$	$\%\Delta\overline{C_D}$
BASELINE	1.13	—	1.11	—
DEFLECTOR	0.97	14	1.02	8

Fuel Savings

Table 5 illustrates the range in fuel savings which could be expected by using the various AOA devices singly and in combination. For example, the use of an air deflector on a shortwood truck would save 3.08 ℓ/100 km (1.09 gal/100 miles) at an average travel speed of 80 km/h (50 mph). This would be equivalent to a 6% saving in fuel consumption, based on a typical fuel consumption rate of 1.84 km/ℓ (5.2 miles/gal). Note that this saving would only be available on the high-speed portion of the loaded trip. Leaving the deflector unfolded when the truck has no load causes an increase in the fuel consumed.

The trailer skirts, and the various combinations of AOA devices on the chip-van trailer would produce savings during both the empty and loaded trips. Since empty travel speeds are usually faster than while loaded, the potential fuel savings are probably larger.

TABLE 5. Fuel Savings in ℓ/100 km (gal/100 miles) Under Loaded Conditions.



DEFLECTOR	0.55 (0.20)	3.08 (1.09)	2.70 (0.95)	1.35 (0.48)	2.33 (0.83)
DEFLECTOR & GAP SEAL	—	3.27 (1.16)	—	1.35 (0.48)	3.11 (1.10)
DEFLECTOR , GAP SEAL & SKIRTS	—	4.04 (1.43)	—	1.93 (0.68)	3.89 (1.38)
DEFLECTOR & SKIRTS	—	3.66 (1.29)	3.27 (1.16)	1.93 (0.68)	3.11 (1.10)
SKIRTS	—	0.58 (0.20)	0.58 (0.20)	0.58 (0.20)	0.97 (0.34)
SKIRTS & GAP SEAL	—	—	—	1.35 (0.48)	—
GAP SEAL	—	—	—	0.96 (0.34)	—

VALIDITY OF ASSUMPTIONS

Wind Tunnel Versus Road Testing

Wind tunnel tests are commonly used to test vehicle aerodynamics, because the effects of external variables during road tests can greatly exceed the effects produced by the drag reduction devices.

For instance, a test may be conducted to find if a 5-percent fuel savings is being produced. However, the external variables can affect fuel savings in the following orders of magnitude under typical road testing conditions[1]:

Wind	15%	Road Conditions	3%
Engine Tune	10%	Tires	3%
Terrain	10%	Temperature	2%
Speed	5%	Warm up	2%
Load	5%	Test Equipment	—
Traffic	5%	Fuel Records	—
Drivers	5%		

Wind tunnel tests are not subject to these uncontrolled variables.

The wind tunnel tests were made at very high speeds [247 km/h (153 mph)] relative to truck speeds, so that the Reynolds numbers[2] of the models were approximately 30% of those of the full-scale trucks. Previous tests have found this proportion to be sufficiently high to represent the full-scale truck. Comparisons of road and wind tunnel test results have demonstrated that both methods agree on the relative effectiveness of the various AOA devices [5, p. 10].

Travel Speed

An average travel speed of 80 km/h (50 mph) was used as a reference point for the wind average drag coefficients in Tables 1 and 2. Although this speed may be slightly fast for wood hauling operations, Figure 10 illustrates that the wind averaged drag coefficient remains fairly constant down to a vehicle speed of about 40 km/h (25 mph).

Note that the $\overline{C_D}$ is quite high at low travel speeds. The values of the $\overline{C_D}$ increase at lower speeds because wind direction variability is greater. Although airflow becomes more turbulent at higher speeds, crosswinds are less frequent at higher wind speeds, so the $\overline{C_D}$ decreases.

However, the higher $\overline{C_D}$ at low travel speeds has little effect on a truck's horsepower requirements because aerodynamic drag is a function of the velocity squared.

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1 These figures were deduced from extensive road testing by the Rudkin-Wiley Corp. of Stratford, Conn., U.S.A., a manufacturer of several AOA devices.

2 A dimensionless number which is significant in modelling any system where viscosity is important in controlling the velocities or flow patterns of the fluid. Since air has a very low viscosity (0.000019 Pa·s versus 0.1 Pa·s for light oil), high wind speeds are required in the wind tunnel to maintain equivalent Reynolds numbers when extrapolating from scale models to full size.

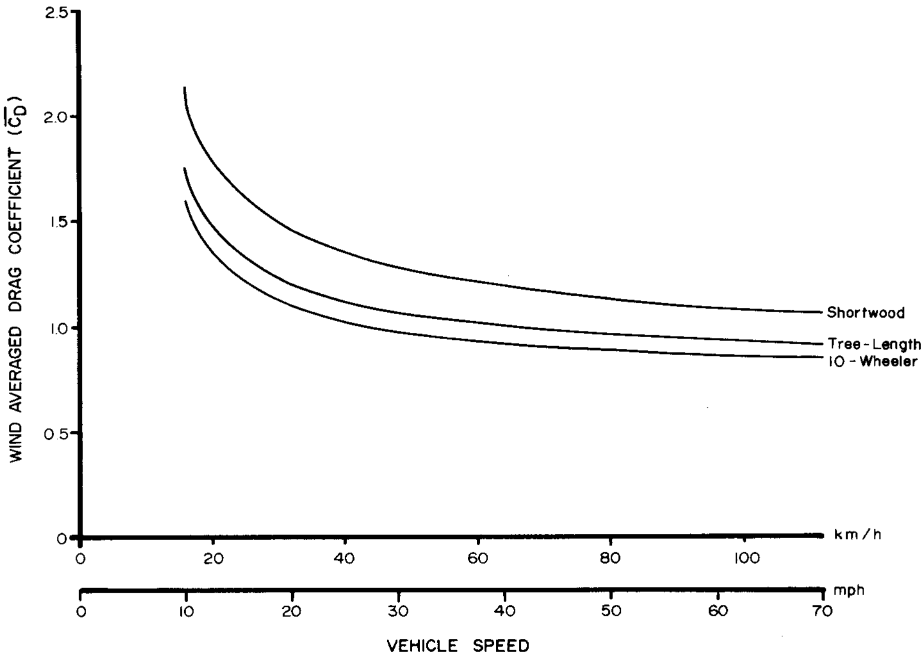

Figure 10. Effects of Travel Speed on the Baseline $\overline{C_D}$.

Smooth Versus Turbulent Flow

Natural winds are turbulent, whereas the wind tunnel produced smooth airflow. Table 6 illustrates the results of an attempt to determine the differences in $\overline{C_D}$ [reference speed of 89 km/h (55 mph)] under smooth and turbulent flow conditions.

TABLE 6. Effects of Turbulence on a Model Tractor-Van Trailer, from Cooper [4, p.45].

CONFIGURATION	SMOOTH FLOW		TURBULENT FLOW		$\Delta\overline{C_{DT}}/\Delta\overline{C_D}$
	$\overline{C_D}$	$\Delta\overline{C_D}$	$\overline{C_{DT}}$	$\Delta\overline{C_{DT}}$	
Baseline	0.99	—	1.01	—	—
Deflector	0.86	0.13	0.90	0.11	0.85
Deflector & Gap Seal	0.82	0.17	0.86	0.15	0.88

The reductions in aerodynamic drag produced by AOA devices are less under turbulent wind conditions. This work suggests that a 12-15% error in the amount of drag reduction indicated by the wind tunnel tests can be attributed to the differences between smooth and turbulent air flows.

Wind Averaged Drag Coefficient

Since $\overline{C_D}$ assumes that the truck is always exposed to the same wind environment, the wind averaged drag coefficient can be biased. Wind speed and directional frequency are not uniform with wind direction, so a different $\overline{C_D}$ exists for each direction of travel. This is a potential source of error in the $\overline{C_D}$ estimate in logging operations where travel routes are often constant or haul roads are located in valleys which tend to concentrate winds and decrease the directional variability. Wind speeds and directions also vary with location and by season.

Figure 11 illustrates the wind velocity probability distribution for several Canadian locations, and the Canadian average based on an average for 30 weather stations. Notice that while the Canadian average wind environment shows nearly uniform probabilities for any wind velocity from all directions, individual stations have distinctly different distributions.

In consideration of these factors, $\overline{C_D}$'s for different travel directions were determined for the average Canadian wind conditions and for 7 locations in Canada. Table 7 compares the wind averaged drag coefficients of a shortwood-loaded truck based on the Canadian average and the Thunder Bay, Ontario wind environments. Note that $\overline{C_D}$ based on the average Canadian wind speed occuring from all directions had as much as 12% error when used as an estimate of the $\overline{C_D}$ on an easterly haul in Thunder Bay, a site with fairly concentric winds.

The magnitude of the potential error from this assumption decreases as travel speeds increase. However since the possible error remains large, $\overline{C_D}$ values were determined for four travel directions at 7 Canadian locations. Appropriate $\overline{C_D}$ values for most areas in Canada can be obtained from FERIC upon request. These $\overline{C_D}$ values are potentially useful when determining truck power requirements and when evaluating the potential benefits of aerodynamic drag reduction.

The effects of this factor mean that air drag may give companies operating from one direction a competitive advantage over other companies in the same area. For example, a trucker with an easterly haul in the Thunder Bay area would have lower hauling costs, because of lower fuel consumption or higher travel speeds, than a trucker hauling in a northerly direction.

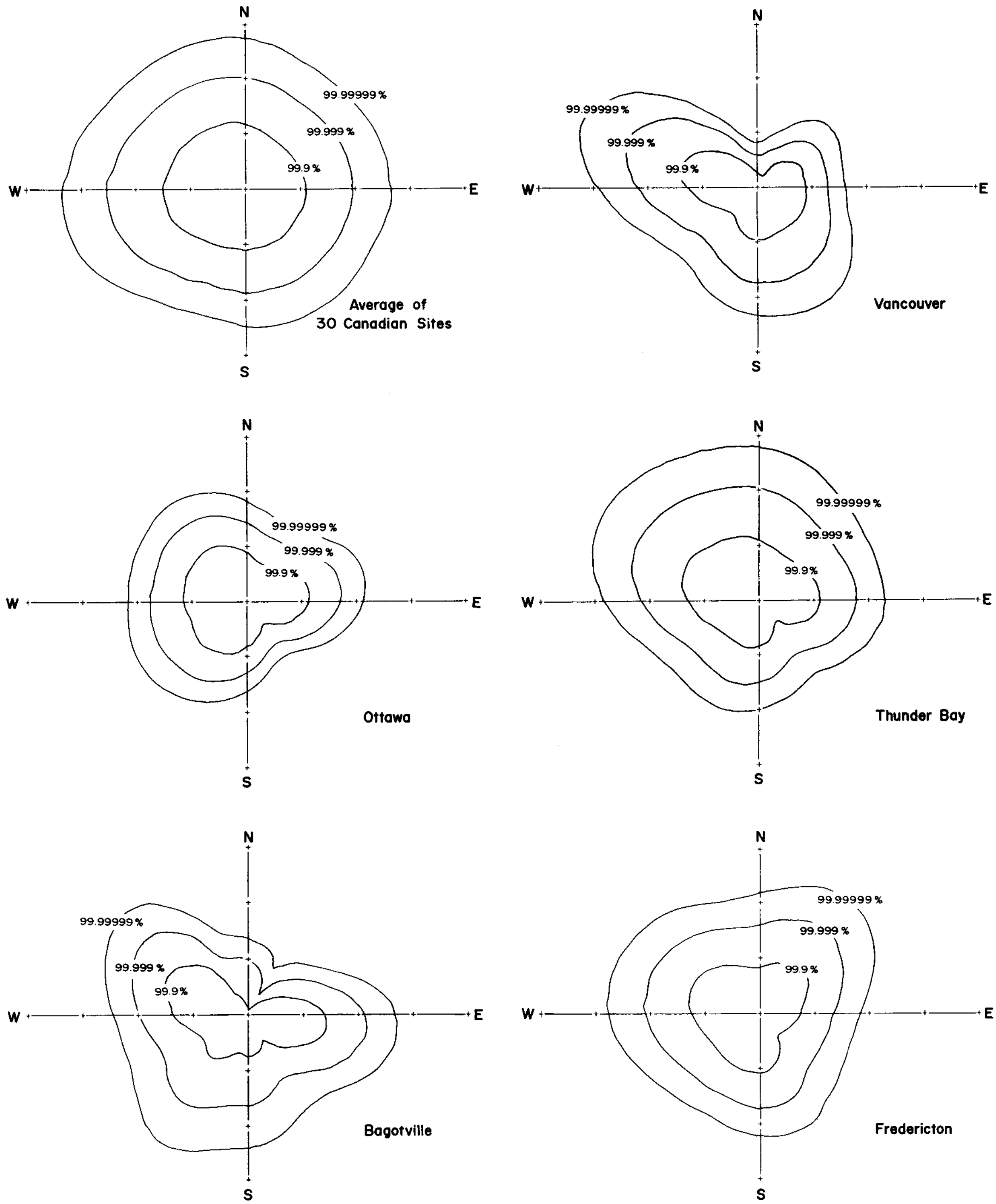

Figure 11. Wind Velocity Probability Distribution for Several Canadian Locations and the Canadian Average.
Wind velocity increments are 16 km/h (10 mph).
The graphs illustrate that, for example, 99.9% of the westerly winds in Canada are less than 24 km/h (15 mph).

TABLE 7. Comparison of the Wind Averaged Drag Coefficients of a Shortwood-Loaded Truck Based on Three Different Assumptions.

TRAVEL SPEED km/h (mph)	$\overline{C_D}$ USING MEAN CANADIAN WIND SPEED OCCURRING EQUALLY FROM ALL DIRECTIONS	$\overline{C_D}$ USING MEAN CANADIAN WIND DISTRIBUTION				$\overline{C_D}$ USING THUNDER BAY WIND DISTRIBUTION			
		TRUCK TRAVEL DIRECTION				TRUCK TRAVEL DIRECTION			
		N	E	S	W	N	E	S	W
56 (35)	1.23	1.19	1.18	1.20	1.17	1.20	1.08	1.14	1.12
64 (40)	1.19	1.16	1.14	1.16	1.14	1.17	1.06	1.12	1.09
72 (45)	1.16	1.13	1.12	1.14	1.11	1.14	1.04	1.09	1.07
80 (50)	1.13	1.11	1.10	1.11	1.09	1.11	1.03	1.07	1.06
89 (55)	1.11	1.09	1.08	1.09	1.07	1.09	1.02	1.06	1.05
97 (60)	1.09	1.09	1.06	1.08	1.06	1.08	1.01	1.05	1.04

GENERAL COMMENTS

Additional information pertaining to the reduction of the aerodynamic drag of logging trucks, and some suggestions on ways to lower air drag are contained in this section.

Effects of Truck Dimension Changes on $\overline{C_D}$

The drag coefficients summarized in this report are based on the model dimensions shown in Appendix B. However, there are significant differences between the truck models and the units sometimes used. Load widths and heights particularly are frequently different depending on highway regulations.

The coefficient of drag changes at a linear rate of 3% per 15-cm (6-inch) change in the exposed trailer width or height [8, p. 1762]. Thus a 0.5-m (20-inch) increase in bunk width to 3 m (10 ft) raises the $\overline{C_D}$ of a tree-length trailer to 1.07. Similarly, a 0.46 m (18-inch) decrease in load height to 3.7 m (12 ft) lowers the $\overline{C_D}$ of a sawlog-loaded truck to 0.92. It should be noted that a change in height or width also affects the frontal area factor.

Benefits

There are in addition to fuel savings a wide range of potential benefits from reducing the aerodynamic drag of logging trucks, all of which can potentially reduce hauling costs. These include

1. Decreased trip times using the same equipment.
2. Reduced capital costs since smaller engines can fulfill the power requirements.
3. Larger payloads.
4. Reduced maintenance since the engine may not rev as high, and less gear shifting is required.

Some of these potential benefits are mutually exclusive, but all can potentially reduce hauling costs.

Several intangible benefits, reduced noise levels and driver fatigue improved truck handling, increased safety of truck operation, and less spray following the truck, can also result from air drag reduction. Less spray in particular may have importance for hauling operations on dirt roads, since fewer "fines" would be lost from the road surface. This might decrease the need for dust reduction measures and lower road maintenance requirements.

Large reductions in chip and sawdust losses have been reported since the application of a deflector to an open-topped chip-van operation in British Columbia. Load heights at the unloading point have increased by 30 cm (1 ft) during the sawdust haul, and greater chip loads were also claimed. Less material is apparently being blown from the vans.

Road Testing Procedures

A simple and accurate operational road test procedure which controls or eliminates the effects of virtually all variables which could affect the test results has been developed by the Society of Automotive Engineers (SAE) [1, pp. 2. C. 43-50]. Copies of these procedures are available upon request from FERIC.

Suggestions When Reducing Aerodynamic Drag

There are several things that can be done to improve the aerodynamics of the haul unit. These include:

1. Mounting mudflaps close behind the wheels. Note that this may require the lengthening of the flaps to maintain their function. Moving the mudflaps to within 12 cm (5 inches) can reduce airdrag by as much as 4%,

2. Minimize the gap between the tractor and trailer within the constraints of safety, weight distribution, manoeuvrability and handling.

3. Collapse deflectors on the return trip if there is no load, except with chip trailers with solid front walls. Use of a deflector when the tractor is pulling no load increases air drag over the unmodified truck. Since most deflectors are not readily adjustable, some modification to allow easy collapsing should be made.

4. Set the deflector at the optimal angle for the load height. Tests have shown that optimal angles exist, and that it is better to have too steep an angle than too shallow [4, p. 79].

5. Using a bug deflector causes flow separation to occur on the hood, increasing air drag.

6. Shaping a shortwood load by rounding the front and rear top can reduce aerodynamic drag.

7. Check to see if additional roof reinforcing is required when installing a deflector. Considerable pressure develops on the deflector, and they have been ripped from cabs causing serious accidents.

8. Watch for fatigue failure caused by vibration. Cracking in the fiberglass or plastic around rivet and bolt holes is usually indicative of this problem. Periodic tightening of all bolts will minimize the vibration.

9. Avoid chip trailers with exterior ribs. These ribs have been demonstrated to increase the drag coefficient by 5-6%. The drag coefficients of chip vans deserve serious consideration, since most chip hauls are at relatively high speeds, and thus the aerodynamic drag is high in both haul directions.

10. Align shortwood loads as well as possible. Protruding log ends probably increase the drag coefficient.

11. Avoid I-beam stakes on all types of trailers. The flanges increase air drag compared to a round section. A pulpwood stick may lack durability and strength, but it has a superior aerodynamic shape.

12. Avoid trailers with fixed solid headracks. Although they do not affect the loaded trip, they can greatly increase the aerodynamic drag and the frontal area when the truck is empty. A heavy screen-like structure can provide the necessary cab protection without increasing the drag.

13. Use chip trailers with rounded front corners. A 25-cm (10-inch) corner radius is sufficient to obtain a large proportion of the potential drag reduction available through large radii. The top longitudinal corner radii have no effect on the air drag. Consideration should also be given to rounding of the rear top and side corners, if interference with the rear door's operation can be minimized.

CONCLUSIONS

Significant reductions in the aerodynamic drag of logging trucks are possible using the various add-on aerodynamic devices presently on the market. Deflectors offer the greatest potential reductions among the tested devices. Trailer skirt and gap seals are relatively ineffective in comparison. However, the skirts produce their drag reduction on both the loaded and unloaded portions of the trip unlike the deflector and gap seal.

The greatest reductions in drag coefficients occur with trucks hauling shortwood and chip-van trailers, with 20% decreases possible under loaded conditions. With sawlog and tree-length loads, reductions in the wind averaged drag coefficients of 17 and 10% respectively occur. Less than a 4% reduction appears possible with tandem straight-trucks.

These reductions in the drag coefficient suggest that on the high-speed portions of the shortwood and chip hauls, maximum fuel savings of 7% are possible. Fuel savings of 6% on sawlog hauls and of less than 4% on tree-length hauls are available.

Considerable room for improvement in trailer design exists. Particularly with stakes and headracks, drag reducing design improvements could be incorporated at little cost, but with sizeable returns over the life of the trailer. A 10-15% decrease in the drag coefficient, which would apply to both the loaded and unloaded trips, appears possible in sawlog and tree-length trailers.

The important consideration when reducing the aerodynamic drag, is that the potential reduction is proportional to the trailer and/or load's exposed front surface area. If there is little difference between the frontal area of the whole unit and that of the truck, the potential for drag reduction is small. However, using AOA devices or other methods to lower the aerodynamic drag coefficient when the height difference is greater than 1 m (3 ft), can produce significant fuel savings on high-speed logging hauls.

APPENDIX A

EQUATIONS FOR CALCULATING RESISTING FORCES

RESISTING FORCE	SYSTEME INTERNATIONAL D'UNITES	IMPERIAL UNITS
ROLLING	$F_{RR} = \frac{[9.81\ URR + 0.537\ V]GVW}{1000}$	$F_{RR} = \frac{[URR + 0.088\ V]GVW}{1000}$
GRADE	$F_{GR} = 9.81\ GVW\ SIN\ \theta$	$F_{GR} = GVW\ SIN\ \theta$
AERODYNAMIC	$F_{AR} = \frac{\rho\ A\ C_D\ V^2}{25.92}$	$F_{AR} = 1.076\ \rho\ A\ C_D\ V^2$
INERTIAL	$F_{IR} = GVW\ \alpha$	$F_{IR} = \frac{GVW\ \dot{\alpha}}{32.2}$

where:

F_{RR} = Rolling Resistance in N (lbf)
F_{GR} = Grade Resistance in N (lbf)
F_{AR} = Aerodynamic Resistance in N (lbf)
F_{IR} = Internal Resistance in N (lbf)
GVW = Gross Vehicle Weight in kg (lb)
URR = Unit Rolling Resistance in kg/1000 kg GVW (lb/1000 lb GVW)
V = Travel Speed in km/h (mph)
θ = Gradient angle in degrees
ρ = Density of Air in kg/m^3 ($slugs/ft^3$)*
A = Vehicle's Frontal Area in m^2 (ft^2)**
C_D = Drag Coefficient
α = Vehicle's Acceleration Rate in m/sec^2 (ft/sec^2)

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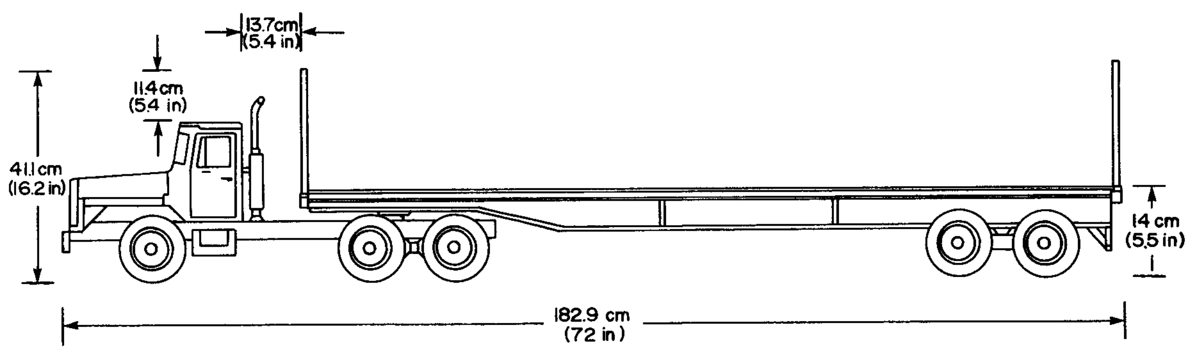
* The density of air is 1.2266 kg/m^3 (0.00238 $slugs/ft^3$) at STP.
** A (m^2) = [Vehicle Height (m) - 0.23] × Vehicle Width (m)
A (ft^2) = [Vehicle Height (ft) - 0.75] × Vehicle Width (ft)

APPENDIX B

DIMENSIONS OF THE 1:10 SCALE TRUCK MODEL



REFERENCES

1. Anon. The DOT/SAE Truck and Bus Fuel Economy Measurement Conference Report. Society of Automotive Engineers, P-59, 1975.

2. Bauer, P.T., Servais, R.A. Criteria for Choosing and Evaluating Aerodynamic Devices for Reducing Fuel Consumption of Trucks. Society of Automotive Engineers, SAE 750701, 1975.

3. Buckley, F.T., Sekscienski, W.S. Comparisons of Effectiveness of Commercially Available Devices for the Reduction of Aerodynamic Drag on Tractor-Trailers. Society of Automotive Engineers, SAE 750704, 1975.

4. Cooper, K.R. A Wind Tunnel Investigation into the Fuel Savings Available from the Aerodynamic Drag Reduction of Trucks. DME/NAE Quarterly Bulletin No. 1976(3), 1976.

5. Davis, W.R., Eryou, N.D., Patry, J.C. Operational Road Tests of Truck Aerodynamic Drag Reduction Devices. Society of Automotive Engineers, SAE 770690, 1977.

6. Lissaman, P.B.S. ed. Reduction of the Aerodynamic Drag of Trucks. Proceedings of the NSF/DOT Conference, Pasadena, Calif., Oct. 1974. National Science Foundation Report NSF-RA-N-74-191, 1974.

7. Maskell, E.C. A Theory of the Blockage Effects on Bluff Bodies and Stalled Winds in a Closed Wind Tunnel. Royal Aircraft Establishment (Great Britain), Report No. AERO-2685, 1963.

8. Mason, W.T. Wind Tunnel Development of the Dragfoiler - A System for Reducing Tractor-Trailer Aerodynamic Drag. Society of Automotive Engineers, SAE 750705, 1975.