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Economics of Aerodynamic Drag Reduction on Logging Trucks: Present and Future

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FOREWORD

In 1978, FERIC undertook a wind tunnel test program to determine the aerodynamics of logging trucks hauling various load types, and to evaluate the effectiveness of several devices being marketed for reducing air drag. This report supplements the earlier report, focusing on the economics of air drag reduction in a logging environment.

The results discussed herein are based on a numerical simulation of logging trucks operating over an actual haul road. This approach was selected since it permitted the evaluation of many different situations, which would have been expensive and difficult, if not impossible, under operating conditions.

Given the present situation vis-à-vis fuel prices and the likelihood of significant increases in the future, a method of quickly evaluating the economics of air drag for future fuel prices has been included in this publication.

FERIC wishes to thank K.R. Cooper of the Low Speed Aerodynamics Laboratory of the National Research Council of Canada (NRC), employees of the Abitibi-Price Paper Co. Ltd., Lakehead Woodlands Division, L.P. Shorr of the Ontario Ministry of Transportation and Communication, and T. Buckley, a former summer student at FERIC, for their contributions to the completion of this project.

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SUMMARY

Earlier results from this project demonstrated that significant reductions in the aerodynamic drag of logging trucks were possible. A numerical simulation model of a truck was used to determine the impact of such air drag reductions on logging hauls.

Two factors limit the impact of drag reduction devices in a logging environment: relatively low travel speeds and drag reductions in only one travel direction.

At the weight-to-power ratios typical of most logging hauls, average loaded travel speeds are relatively low. Depending on the specific haul, the fuel savings may be sufficient to justify purchase of air drag reduction devices at 1979 fuel prices. Even slight decreases in the weight-to-power ratio can lead to faster travel speeds, and greater effectiveness of the drag reduction equipment.

The fuel savings which occur on the loaded trip are equivalent to those found on highway hauls. However since drag reduction occurs in only one travel direction, the overall impact is less. Modifications to the aerodynamic design of trucks and trailers including log stakes and headracks are effective in both travel directions, and would produce considerable savings.

A nomogram is presented in the report for evaluating the savings from aerodynamic drag reductions on logging hauls for present and future fuel prices.

INTRODUCTION

Continuing increases in fuel prices have been a major factor in the rapid escalation of logging haul costs in recent years. Reducing fuel consumption would decrease the effects of this cost spiral. Lowering the aerodynamic drag of trucks is one method of reducing fuel consumption.

A wind tunnel testing program undertaken by FERIC [1] indicated that the drag coefficient of logging trucks could be reduced significantly using various add-on aerodynamic devices. Reductions of from 10 to 20% were found under various load conditions. However, meaningful interpretation of these results was difficult since a 20% drag coefficient reduction does not translate into a 20% fuel saving.

As a result, a continuation of the research project was undertaken to more clearly identify the benefits of aerodynamic drag reduction under logging haul conditions. This work involved development and testing of a numerical simulation model of a truck, and the use of this model to measure the impact of aerodynamic drag modifications on a hauling operation.

TRUCK SIMULATION MODEL

Basic Model

Fuel savings, although a potentially significant benefit by themselves, were not the only reason for interest in air drag reduction. Other potential benefits including lower trip times, reduced capital costs, larger payloads and decreased transmission maintenance, could also reduce hauling costs. Some of these benefits are mutually exclusive.

To quantify all the benefits of air drag reduction in an operational environment, a truck simulator was developed. This simulation model describes the truck-driver-road system using equations for the forces involved in a truck's motion. The vehicle is accelerated, decelerated, shifted and cornered as an experienced driver would negotiate the road. The program logic scans the approaching road segments and simulates human judgement to shift, brake and stop.

The basic equation (1) used in the model is based on Newton's Second Law. The net accelerating force (F_n) is calculated as the difference between the driving and resisting forces.

$$F_n = ma = F_t - (F_r + F_a + F_g + F_c + F_i) \qquad (1)$$

where:
m = vehicle mass
a = acceleration
F_t = thrust force
F_r = rolling resistance force
F_a = aerodynamic drag force
F_g = grade resistance force
F_c = corner resistance force
F_i = inertial resistance force

The detailed operating characteristics of the truck are inputted, including engine power, torque and fuel consumption maps, the road's profile, alignment and surface conditions, the truck's weight and drag coefficient, transmission and rear axle ratios, and shifting parameters. The truck is accelerated in a gear up to some maximum rpm limit, and then shifted into the next gear. Fuel consumption is determined using the engine's fuel map for the rpm level. An idle fuel flow rate is assumed when the truck is coasting.

Figure 1 shows the acceleration performance of a loaded and an empty truck on a flat road. Vehicle weight effects dominate acceleration of the loaded truck. A coasting period of 1.2 seconds during upshifting and a 1.5 second delay interval for downshifting were assumed in the model based on time study results.

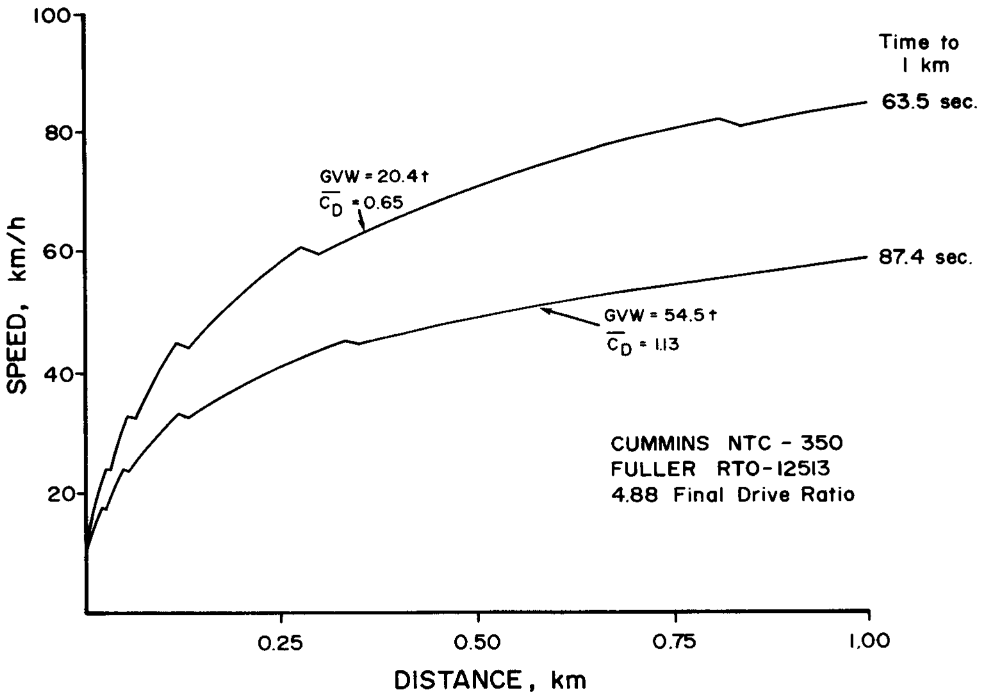


Figure 1. Acceleration Curves for a Loaded and Unloaded Shortwood Truck on a Flat Road.

Validation Tests

Several drivers operating the truck described in Table 1 were timed over 25 short segments of an actual logging road network, a typical combination of bush roads and highways over which loggers haul wood. The computer program was then used to predict the same truck's performance over this road network.

Table 1. Truck Configuration of the Validation Truck

Cab Type	Mack
Load Type	Shortwood
Weight - Loaded	58.1 t
- Empty	24.9 t
Engine	Mack ENDTB-866
Power	279 kW @ 2200 rpm
Transmission	Mack TRTXL-1070
Shift RPM - Upshift	2200
- Downshift	1400
Rear Axle Ratio	5.32
Drag Coefficient - Loaded	1.13
- Empty	0.68

An analysis of the results found that no significant difference in total travel time existed between the observed and simulated results at a 95% confidence level. A breakdown in the measured segments into hill, curve and straight sections found that on the empty trip, the model consistently predicted faster travel times on the corner sections than were observed. However during the observation period, poor road surface conditions were particularly evident on corners, and are probably responsible for the difference between the predicted and observed empty travel times. Table 2 compares the travel times for the main road and total fuel consumption as observed and simulated.

Table 2. Comparison of Observed and Simulated Results for Travel Time over the Main Road, and Total Fuel Consumed.

	TRAVEL TIME (min)			TOTAL FUEL (ℓ)
	UNLOADED	LOADED	TOTAL	
OBSERVED	78.2	112.8	191.0	227.3
SIMULATED	71.4	112.1	183.5	227.0

Evaluation Procedures

To determine the effects of aerodynamic drag reduction on a haul, a series of different trucks were simulated over the road used in the validation tests. The configurations of these trucks are summarized in Table 3.

Table 3. Truck Configurations Used in Vehicle Mission Simulator.

CAB AND LOG LOAD TYPE	WEIGHT (t) EMPTY & LOADED	ENGINE	POWER	TRANSMISSION	UPSHIFT & DOWNSHIFT RPM	REAR AXLE RATIO	$\overline{C_D}$[1] @ 80 km/h	
							BASELINE	MODIFIED
KENWORTH SHORTWOOD (Truck 1)	20.4	CUMMINS NTC-350	261 kW @ 2100 rpm	FULLER RTO-12513	2100 1550	4.88	0.68	0.68[2]
	54.4						1.13	0.97[3]
KENWORTH SHORTWOOD (Truck 2)	20.4	CUMMINS F-350	261 kW @ 1900 rpm	FULLER T955-AL	1900 1300	3.84	0.68	0.68[2]
	54.4						1.13	0.97[3]
KENWORTH SHORTWOOD (Truck 3)	20.4	CUMMINS NTC-400	298 kW @ 2100 rpm	FULLER RTO-12513	2100 1550	4.88	0.68	0.68[2]
	54.4						1.13	0.97[3]
KENWORTH SHORTWOOD (Truck 4)	20.4	CUMMINS NTC-350	261 kW @ 2100 rpm	FULLER RTO-12513	2100 1550	4.88	0.91	0.68[2,4]
	54.4						1.01	0.87[3]

[1] $\overline{C_D}$ = wind averaged drag coefficient.
[2] Deflector folded on empty trip.
[3] Deflector operational.
[4] Vertical stakes removed for return trip.

RESULTS

The effects of air drag reduction on Truck 1's performance are shown in Table 4. Travel time was not greatly affected by the drag reduction. The 14% reduction in the drag coefficient produced some fuel savings which are economically marginal.

Table 4. Results for Trucks 1, 2 and 3 Simulated Over the Road Network.

		TRUCK 1		TRUCK 2		TRUCK 3	
		Unmodified	Deflector	Unmodified	Deflector	Unmodified	Deflector
Time (min)	EMPTY	88	88	89	89	84	84
	LOADED	133	131	138	135	122	120
	TOTAL	221	219	227	224	206	204
	SAVING	—	2	—	3	—	2
Fuel (ℓ)	EMPTY	78.2	78.2	74.1	74.1	75.5	75.5
	LOADED	131.4	129.6	125.5	123.2	131.8	129.6
	TOTAL	209.6	207.8	199.6	197.3	207.3	204.1
	SAVING	—	1.8	—	2.3	—	3.2

The power available to accelerate Truck 1 is one factor limiting the effectiveness of the deflector. Over the road network the available power produced an average loaded travel speed of 55 km/h. At this speed, aerodynamic drag represents only about 20% of total power requirements.

Table 4 also shows the results for Trucks 2 and 3 to demonstrate the effects of different engines on truck and deflector performance. The engines of Trucks 1 and 2 have equal power, but different torque curves. Truck 2's engine, a so-called "fuel saver" features a high torque-rise, and is coupled to a six speed transmission, Truck 3 has 37 kW more power than Truck 1, lowering the weight-to-power ratio, but the same transmission.

A comparison of the results in Table 4 shows that the fuel consumption of Truck 2 is 5% better than Truck 1, but its total trip time is 3% longer. The larger engine in Truck 3 produces some fuel savings, a 15 minute reduction in total trip time, and fewer gear shifts than Truck 1. The decrease in the weight-to-power ratio increased average travel speed by about 3 km/h on the loaded trip. This in turn led to improved deflector performance, particularly with regards to its effects on the number of gear shifts.

The results suggest that over-specifying engine size for a given application is desireable. The fuel savings arise because the motor operates more frequently at rpm levels at which it is most efficient. This in turn should produce longer engine life. The additional power could also prove useful under adverse conditions such as steep grades and on poor quality roads.

The decrease in gear shifting with the larger engine occured primarily on the full trip when transmission loads were greatest. Lower maintenance costs should result, since transmission and clutch life should increase. The additional capital costs of the larger engine are probably offset by the cost savings which arise from the 6% reduction in total trip time. Fuel savings with the deflector on Truck 3, assuming a diesel fuel cost of $0.18/ℓ, are about $0.60/trip or 1.6¢/m^3 when compared with Truck 3 unmodified. This would be sufficient to warrant the deflector's purchase.

The second limiting factor is the deflector's ineffectiveness on the empty portion of the trip. Over the loaded portion of the trip, the device is active and produces savings comparable to those found with intercity haul units. However, this effect only exists on half the travel distance, so total fuel savings place the economics of air drag reduction in a marginal situation at the travel speeds found on many logging hauls.

A possible solution to this effect would be to modify the drag coefficient in both travel directions. Tractor or trailer design modifications would be one way of meeting this objective. The wind tunnel tests showed that the log stakes on sawlog and tree-length trailers were a major contributor to the aerodynamic drag. Redesign or removing the stakes during the trip's empty portion would permit air drag modifications in both travel directions. Table 5 shows the results of such a change on a tree-length haul unit.

Table 5. Effects of Air Drag Reduction in Both Travel Directions on Truck 4's Performance.

		Unmodified	Deflector & Posts
Time (min)	EMPTY	90	88
	LOADED	132	130
	TOTAL	222	218
	SAVING	—	4
Fuel (ℓ)	EMPTY	84.1	78.2
	LOADED	130.1	128.2
	TOTAL	214.2	206.4
	SAVING	—	7.8

With drag reduction in both travel directions, savings in time, fuel and the number of gear shifts are significant. Fuel savings are $1.40/trip, of which a dollar per trip results from air drag reduction on the empty trip. The lower trip times represent a 2% saving. The reduction in gear shifting occurs largely during the empty trip when loads on the transmission are minimal, so no improvement in transmission and clutch life is likely. It should be noted that no improvement in the drag coefficient other than with the deflector was assumed for the loaded trip although drag reduction through post redesign would in fact occur in both travel directions.

DISCUSSION

Evaluating The Savings From Air Drag Reduction

Obviously from the previous results, the savings from air drag reduction on a single trip basis are quite small. However even with small savings, a sizeable financial benefit can be realized if enough trips are made.

To assist readers to make decisions about the applicability of air drag reduction devices to their operations, a nomogram (see Figure 2) has been prepared based on the following equations:

$$AS = \frac{\Delta\mu \text{ x } FP \text{ x } AATD}{100} \qquad (2)$$

where: AS = annual savings ($)
$\Delta\mu$ = fuel savings resulting from drag reduction (ℓ/100 km)
FP = fuel price (\$/ℓ)
AATD = annual affected travel distance (km)

and

$$\Delta\mu = \frac{\rho \text{ x } A \text{ x } \Delta C_D \text{ x } V}{4235} \qquad (3)$$

$$= \frac{1.2266 \text{ x } A \text{ x } (C_{Dum} - C_{Dm}) \text{ x } V}{4235} \qquad (4)$$

where: ρ = air density (kg/m^3)
A = frontal area (m^2)
= [load height (m) - 0.23] x load width (m)
C_{Dum} = drag coefficient of the unmodified truck
C_{Dm} = drag coefficient of the modified truck
V = average travel speed (km/h)

This approach treats fuel costs as the only significant savings arising from air drag reduction. In practice, other benefits do occur but they proved difficult to quantify. For example, the difference between good and poor drivers probably involve more gear shifts and transmission wear than air drag reduction would save. As such, the other benefits could be treated as "bonuses", and an economic analysis of air drag reduction concentrate on the fuel savings produced.

Fuel savings predicted for air drag reduction by the simulation model are greater than those which the equation (2) estimates. It is a small conservative error however, and thus can be disregarded. In addition, the simulation model predicted slightly lower fuel consumption than was actually observed.

Using the Nomogram

Before using the nomogram, the following information is required:

1. Load Width - this distance must include the log stakes if they are mounted along the sides of the load.
2. Load Height - this is the distance from ground level to the top of the load.
3. Change in $\overline{C_D}$ - the change in the wind averaged drag coefficient can be found using the data summarized in the Appendix.
4. Average Travel Speed - this is the speed on the affected portion of the trip. Consideration should be given to using the speed on good quality roads since the average speed for the complete loaded trip can be significantly reduced by low speeds near the landing.
5. Fuel Price - present or expected fuel cost.
6. Affected Travel Distance - this is the loaded travel distance in most situations except chip hauls. This distance must correspond to that used in determining the average travel speed. For example, if the travel speed on high quality roads is used, the distance is that travelled on those roads.

To illustrate the use of the nomogram, the following example has been worked in Figure 2.

Example: Trucks on a shortwood haul have loads about 2.6 m wide with a top 4.1 m above ground level. Use of a deflector with this type of load would reduce the air drag coefficient by 0.16 (1.13-0.97). The average loaded travel speed for the haul is 70 km/h. With fuel costing $0.18/ℓ, how much will using a deflector save, if the trucks travel 100,000 km/year loaded?

The nomogram predicts annual savings of about $420 per truck. Since the deflector and the equipment for raising and lowering it cost about $350, the device has a payback period of less than a year.

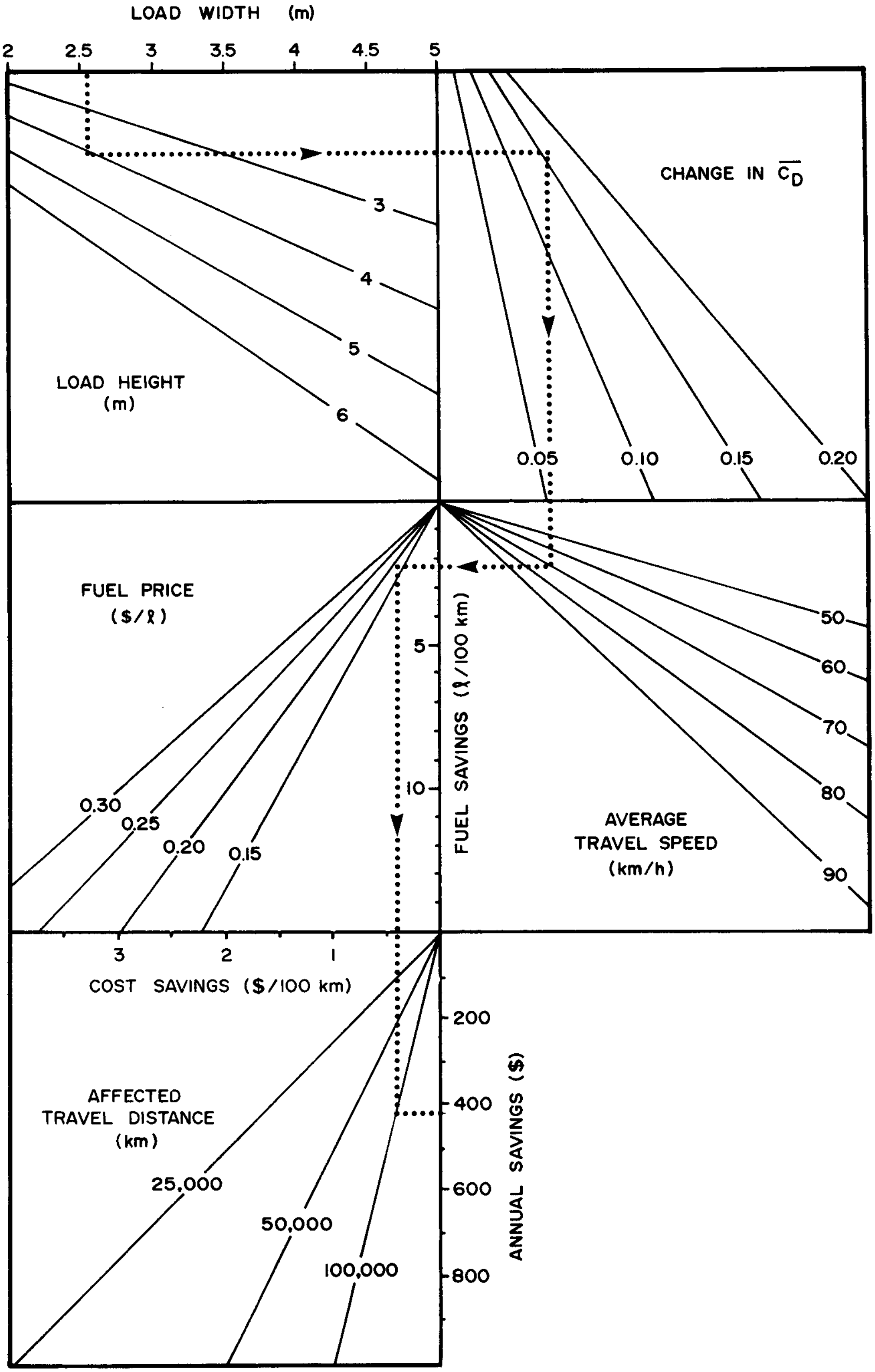


Figure 2. Nomogram for Calculating the Annual Savings Resulting From Air Drag Reduction. The workings of the example are shown on the figure.

CONCLUSIONS

At present fuel prices, the economics of aerodynamic drag reduction require that the hauling operation be at relatively high speed (above 70 km/h), and that the device produce a sizeable reduction in the drag coefficient. Thus, immediate benefits are most likely on long-distance hauls of shortwood, saw-logs and chips. Every increase in fuel price makes the application of air drag reduction devices more attractive in these operations.

If aerodynamic drag reduction occurs over the complete trip, substantial fuel savings occur over the life of the equipment. Aerodynamic design improvements in both trucks and trailers would be the easiest means of obtaining these savings. However, in general the design changes in highway trucks have not been carried through into the off-highway trucks used on most logging operations. Similarly there have been few aerodynamic modifications to trailer design.

Aerodynamic drag reduction will never produce a major cost reduction. The potential savings on a volume basis are quite small. However, multiplied by the total volume produced, sizeable savings result. Air drag reduction is one of the few options available which allow a company to at least partially lessen its exposure to rising fuel prices.

REFERENCES

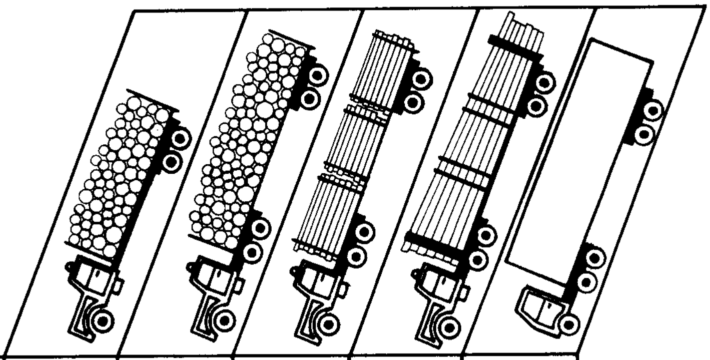
1. Garner, G.J. 1978. Wind Tunnel Tests of Devices for Reducing the Aerodynamic Drag of Logging Trucks. Forest Engineering Research Institute of Canada. Tech. Rep. No. TR-27.

2. Garner, G.J., and K.R. Cooper. 1978. Reducing the Aerodynamic Drag of Logging Trucks. American Society of Agricultural Engineers, ASAE Paper No. 78-1574.

APPENDIX

To help determine the reduction in drag coefficient resulting from the use of various aerodynamic devices, the table which follows has been reproduced from the earlier report [1, p. 9]. The change in drag coefficient is found by subtracting the drag coefficient of the modified truck from the baseline value.

Table 1A. Wind Averaged Drag Coefficients of Loaded Logging Trucks.



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	—