Logging Truck Vehicle Performance Prediction for Efficient Resource Transportation System Planning: Computer Modelling Approach

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ABSTRACT

Transportation systems, characterized by extremely heavy logging trucks running on low standard roads, are critical to Canadian woodlands operations. Because predicting logging vehicle performance is essential to planning efficient forest road transportation systems, a Heavy Vehicle Performance Model (HVPM) was developed which takes into account the characteristics of forest road transportation system components in order to predict vehicle performance parameters such as speed and fuel consumption.

Two independent field test data sets were used to verify the HVPM. Verification results showed that the average speed predicted by the HVPM was as much as 17 percent lower than the average observed speed, while predicted fuel consumption was as much as 20 percent higher than the field observations.

Implementation of the HVPM is presented by showing how it is used to solve three forest road transportation problems: a practical application is given in a case study comparing the performance of two specified trucks on two proposed road alignments, the selection of truck components using vehicle performance predictions from the HVPM is illustrated, and the HVPM is used to predict truck performance on different classes of roads.

Keywords: *forest roads, transportation systems, costs, computer model, heavy truck performance, speed, productivity, fuel consumption.*

INTRODUCTION

The forest sector, which produces about 17 percent of Canada's total annual value of exports, is the most significant industrial sector to the country [8]. It contributes as much to the country's *balance* of trade as the next four sectors (mining, energy, agriculture, fishing), *combined.* Road transportation plays an important role in the industry's operations. Seventy-five percent of the movement of raw forest products (in tonne • km) from road side to mill gate is accomplished by road [3].

Total forest road transportation costs can be divided into two parts [4]:

- forest road construction and maintenance costs
- logging truck operating and maintenance costs

To design an efficient forest road transportation system to minimize total cost, the two parts of the cost must be estimated, and the trade-offs between them carefully assessed.

While forest road construction and maintenance costs can be estimated from data provided by previous forest road projects under the same or similar conditions, it is difficult to predict accurately specific logging truck operating and maintenance costs. Vehicle operating and maintenance costs are related to road design characteristics [6, 19]. Forest roads in Canada are characterized by greater surface roughness, lower traffic volume and steeper gradients than public roads. These factors produce more resistance to truck movement than encountered on public roads [9, 13, 16] and consequently increase logging truck operating costs. In addition, the trucks used on *private* logging roads are usually far heavier (circa 100 to 200 tonnes) than weight regulations allow for public roads (circa 40 to 50 tonnes).

If there was a tool available which considered the characteristics of forest road transportation systems and could predict logging truck performance parameters such as vehicle speed, power and fuel consumption, these parameters could in turn be used to estimate logging truck operating and maintenance costs as they are affected by the characteristics of the road. The objective of the project was therefore to develop a heavy truck performance prediction model that could be used by designers of forest road transportation systems.

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Table 1. Vehicle performance prediction models.

Empirical Models	Reference	Mechanistic Models	Reference
Highway Design and Maintenance Standard (HDM-III)	[18]	ICES-ROADS	[17]
New Zealand Vehicle Operating Costs Model (NZVOC)	[1]	Vehicle Mission Simulations (VMS)	[11]
Australian Road Research Board model	[1]	Truck and Bus Energy Simulation Algorithm Mission (TABESAM)	[10]
		Truck Simulation (TRUCKSIM)	[12, 13]
		Hill Climbing Model (HILLCLIM)	[4]

DEVELOPMENT OF THE HEAVY VEHICLE PERFORMANCE MODEL (HVPM)

Evaluation of Existing Models

Many computer modelling approaches have been used in vehicle performance prediction. Existing performance models may be divided into two classes [7] (Table 1):

- those based on an empirical approach
- those based on a mechanistic approach

An examination of these existing models (Table 1) showed that all but two were developed for conditions other than those existing in forest road transportation systems. The empirical models were developed for predicting global vehicle performance in large road transportation networks [18], rather than for specific forest road segments. The existing mechanistic models, with two exceptions (TRUCKSIM and HILLCLIM), are focused on solving problems under public highway transportation conditions. The coefficients used in these models are not necessarily characteristic of forest road transportation; for example, VMS does not cater very well to low standard pavement structures [9]. Moreover, the existing mechanistic models are either not readily available to woodland managers, or not easily implemented due to hardware requirements. A spreadsheet model HILLCLIM, which *is* readily implemented, can only predict truck speed. Thus, the need for a Heavy Vehicle Performance Model (HVPM) was identified.

Development of the HVPM

Computer models can provide solutions quickly and with more consistent results than other methods, but the results from the computer models are seldom completely accurate. This is particularly true when computer modelling is applied to simulate road transportation system performance which depends on road, truck, driver and environmental characteristics and their interactions [13]. To simulate a road transportation operation, a sophisticated vehicle performance model could be developed which accommodates many variables in a road-truck-driver-environment transportation system. However, such a sophisticated model would have limited practical usage due to the extensive inputs required and it would be very expensive and time-consuming to run [7].

An alternative is to develop a simplified model which is just comprehensive enough to adequately simulate the behaviour of a forest road transportation system but does not require extensive input. There is a link between the sophistication of the model and the accuracy of the results. In this second approach, some accuracy is sacrificed in order to permit the reduced complexity of the model. Once such a model is satisfactorily verified, it can be readily implemented because of the reduced input data requirement.

The HVPM was developed using the second approach, and its design is outlined in this paper. Assumptions made in the design of the HVPM were:

- environmental conditions such as wind, rainfall and temperature have no effect on the predictions
- drive train efficiency has a constant value during the travel of the vehicle over a road segment
- vehicle performance is not affected by competing traffic or traffic signals: free flow is assumed
- full engine power is produced any time the vehicle is not in a decelerating mode

The program was written in the C language, and a compiled version runs efficiently on IBM 286 model microcomputers and compatibles, preferably having co-processors. Typical runs for road lengths of a few kilometres take less than 30 seconds to complete.

Computer models *must* be verified against real data to be useful [5]. This paper also gives details of the verification of the HVPM.

Design of the HVPM

The design of the HVPM was based on a mechanistic approach and depends on the theoretical basis of vehicle motion. The HVPM is designed to simulate the behaviour of a specific vehicle being driven along an actual or proposed road. It considers road design characteristics and the specifications of the vehicle and predicts the effects of these road characteristics on the performance of the vehicle.

The main control logic in the HVPM considers vehicle operating *modes* (Figure 1). Nine vehicle operating modes can be identified, they being the product of the three possible vehicle operating *states* (i.e., accelerating, cruising and decelerating) and the three *speed conditions* (i.e., current speed *under* the speed limit V_{limit}, current speed *at* V_{limit} and current speed *over* V_{limit}), as shown in Figure 1. The speed limit V_{limit} is arbitrarily imposed to consider constraints such as safe speed for the given geometric design, or fuel economy.

The *target operating mode* is the cruising / at-speed-limit mode. Therefore, no matter in which mode the model vehicle starts the segment currently under consideration, it is assumed that the vehicle will progress through a number of modes towards the target mode, the cruising / at-limit mode. An instruction in each cell indicates the corrective action which should be taken by the model to cause the model vehicle to progress from the current mode towards the target mode.

The two widened black lines in Figure 1 represent barriers to operating mode changes not possible for constant V_{limit} and constant resistance to motion F_r. The remaining possible operating mode paths are represented by the two arrows. For example, if initial conditions place the model vehicle in the cruising / under-limit mode, corrective action such as progressive shifting of gears is needed to increase the vehicle speed up to V_{limit}. Relationships between vehicle operating modes under *variable* V_{limit} and F_r result in more complicated operating mode change paths (see [7] for a full treatment of the concept).

Vehicle motion is controlled by the power supplied by the engine at any time, and by the resistances encountered at any time. The tractive effort must always balance all the resistances, including those associated with the translational inertia of the vehicle and the rotational inertia in the drive train components [7]:

$$\begin{aligned} T_e i_g i_r \eta / r = {} & \left(\Sigma R_{ri} + \Sigma R_{rd}\right) + \left[\left(\Sigma m_i + \Sigma I_i / r^2\right) \right. \\ & \left. + \left(\Sigma m_d + \Sigma I_d / r^2\right) + m_b\right] a \\ & + \left(I_e i_g^2 i_r^2 \eta / r^2\right) a + F_a + F_g + F_c \end{aligned}$$

$$T_e i_g i_r \eta / r = R_r + m_e a + F_a + F_g + F_c$$

where:

T_e = engine torque [N•m]
i_e, i_r = transmission and rear axle gear ratios, respectively [unitless]
η = assumed drive train efficiency [unitless]
r = tire rolling radius on driven wheel [m]
R_{ri}, R_{rd} = rolling resistance at an idling wheel and a driven wheel, respectively [N]
m_i, m_d, m_b = mass of an idling wheel, a driven wheel, and the vehicle body, respectively [kg]

Table 2. Input files.

Coefficients File	Road File	Driver File
vehicle specifications:	road characteristics:	driver technique:
resistance coefficients, initial values, engine information, gear ratios	distance, speed limit, gradient, radius	engine speed range, tolerable deceleration rate

I_i, I_d, I_e = mass moment of inertia of an idling wheel, driven wheel, and the rotating engine parts, respectively [N•m•s^2]
a = translational acceleration [m/s^2]
F_a = air resistance [N]
F_g = grade resistance [N]
F_c = curve resistance [N]
R_r = total rolling resistance [N]
m_e = derived "effective" mass [kg]

Equation 1 expresses the relationship between the tractive force and all resistances. In the HVPM, expressions were written to describe each of the resistances, as a function of the current conditions. The balance between tractive force, resistances, and acceleration (or deceleration) is continuously updated, by iterating through Equation 1 repeatedly, at a frequency of about 1 second in real time [7]. Upon each iteration, decisions (i.e., to shift up or down, to coast, or to apply brakes) are made according to the control logic outlined above. See reference [7] for a full treatment.

Input and Output of the HVPM

Data input is accomplished through three separate files (Table 2).

The program generates two output files:
- a detailed output which provides the predicted performance parameters by time interval
- a summary report on performance parameters

VERIFICATION OF THE HVPM

Maine, USA, Study

A pilot study was carried out to observe the performance of 150-tonne truck trains on a section of main forest road in Maine, USA [4]. The 4.8 km gravel test road section was nearly straight. Its longitudinal profile is given in Figure 2(a), and the truck specifications are provided in Table 3.

Table 3. Vehicle specifications, Maine, USA, study.

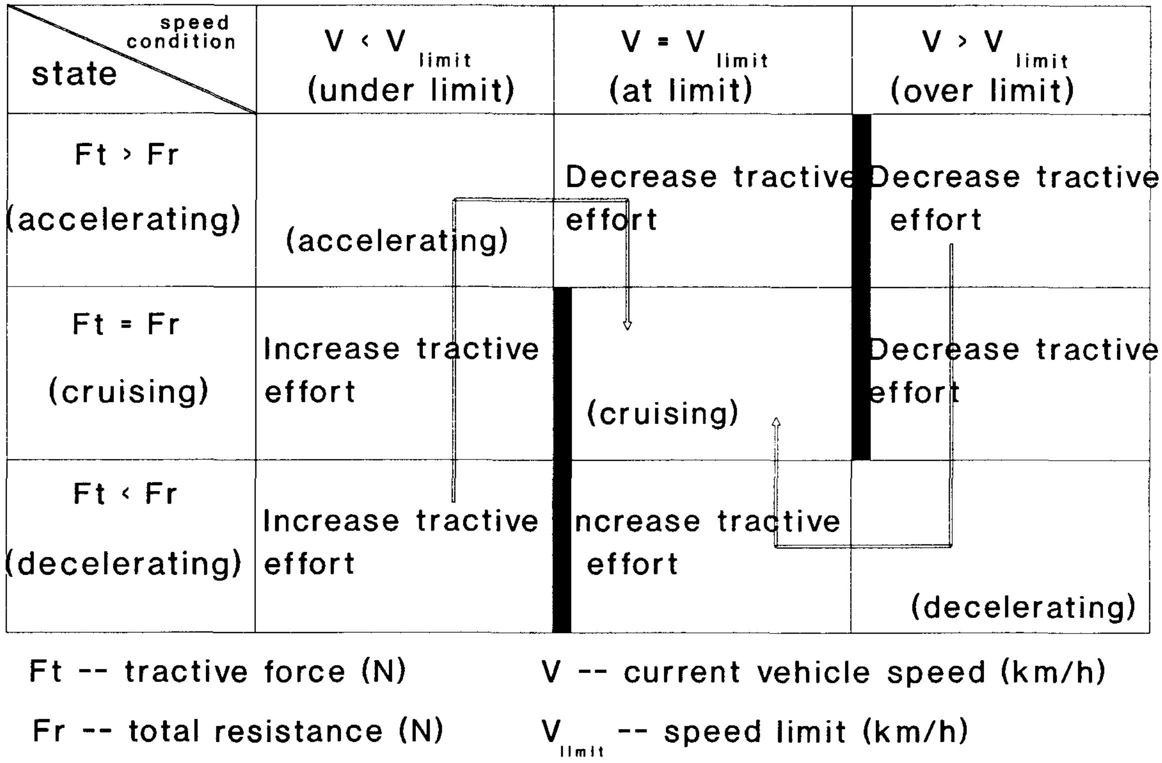
	Specifications
configuration	3-S3-F5
engine	Caterpillar 3406
power	300 kW
transmission	Fuller RTO-14608LL (10 speed)
rear axle	Rockwell (9:1)
gross vehicle mass	150 tonnes
mass/power	500 g/W

During the tests, speeds were simply manually recorded by observing speedometer readings at set intervals along the test road and verbally backing up the readings on audio tape. The comparison of the recorded and predicted speeds is shown in Figure 2(b), where there is no more than about 8 km/h difference. This was considered acceptable, given that the observed speeds indicated by the speedometer were no more accurate.

Newfoundland, Canada, Study

A field project carried out in collaboration with the Forest Engineering Research Institute of Canada (FERIC) at a site in Newfoundland, Canada, provided carefully measured and very detailed truck performance data [5, 7] obtained using a fully-instrumented test truck. The specifications of the truck are shown in Table 4.

The selected test road was a gravel-surfaced main haul road 2.5 km long, with a total rise of 110 m and the vertical profile shown in Figure 3(a). Plots of



state \ speed condition	$V < V_{limit}$ (under limit)	$V = V_{limit}$ (at limit)	$V > V_{limit}$ (over limit)
Ft > Fr (accelerating)	(accelerating)	Decrease tractive effort	Decrease tractive effort
Ft = Fr (cruising)	Increase tractive effort	(cruising)	Decrease tractive effort
Ft < Fr (decelerating)	Increase tractive effort	Increase tractive effort	(decelerating)

Ft -- tractive force (N)

Fr -- total resistance (N)

V -- current vehicle speed (km/h)

V_{limit} -- speed limit (km/h)

Figure 1. HVPM program control logic: vehicle operating *modes*, operating *states*, and speed *conditions*.

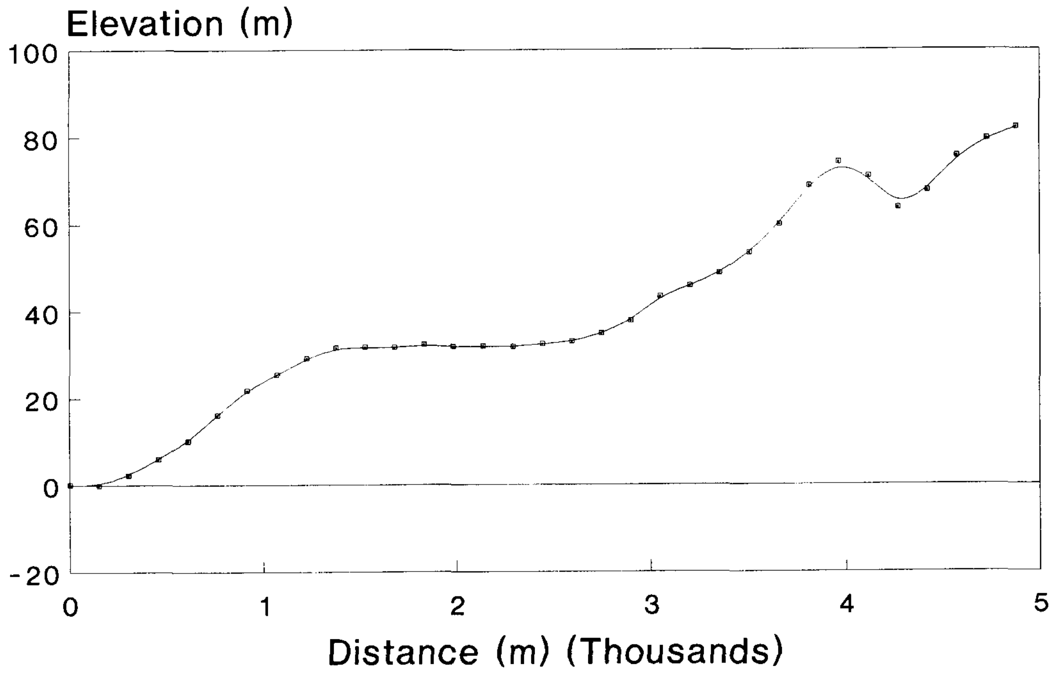


Figure 2(a). Maine, U.S.A., study: vertical road profile.

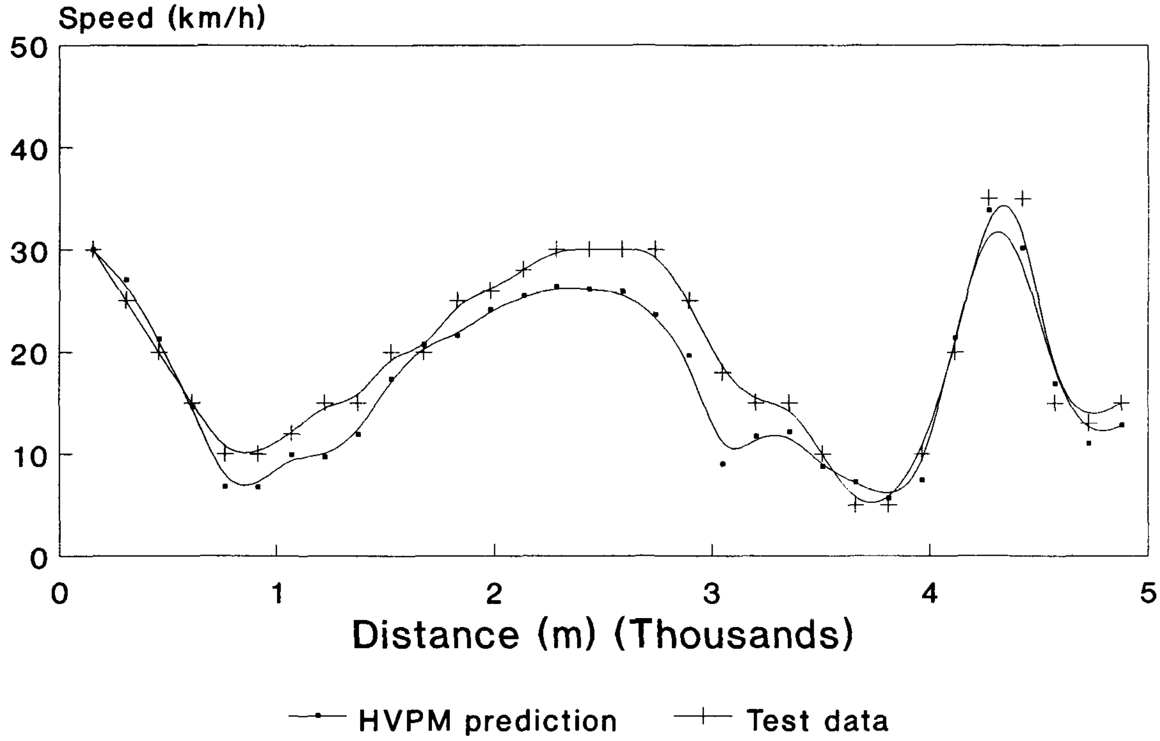


Figure 2(b). Maine, U.S.A., study: observed and predicted vehicle speeds.

truck performance comparisons show good agreement, although there are some differences. The predicted speeds are within 10 km/hr of the observed speeds (Figure 3(b)). The predicted engine speed (Figure 3(c)) follows the pattern observed in the real truck, although it is apparent that the driver generally decided to shift up sooner and shift down later than the HVPM did. It must be remembered that the driver is able to use discretion and to anticipate approaching conditions, whereas the HVPM cannot. A summary of verification results are listed in Table 5.

Table 4. Vehicle specifications, Newfoundland, Canada, study.

	Specifications
configuration	3-S3
engine	Caterpillar 3406
power	300 kW
transmission	Fuller RTO-14608LL (10 speed)
rear axle ratio	4.78:1
gross vehicle mass	48 tonnes
mass/power	160 g/W

IMPLEMENTATION OF THE HVPM

Truck Performance Predictions on Two Proposed Roads—A Case Study

A case study was conducted where a forest operation needed a new haul road, for which alignments along a lake and along a ridge (Figure 4 [5,7,15]) seemed feasible. The proposed alignments had common end points, but different lengths. In addition, two different types of company-owned logging trucks were to be considered. The specifications of the two truck types are shown in Table 6. It is noteworthy that their characteristics, particularly rated power and gross mass/power ratio, were not very different.

The question to be answered by using the HVPM was, which of the two proposed routes should be followed, based on truck performance? The HVPM was run for the four possible combinations of trucks

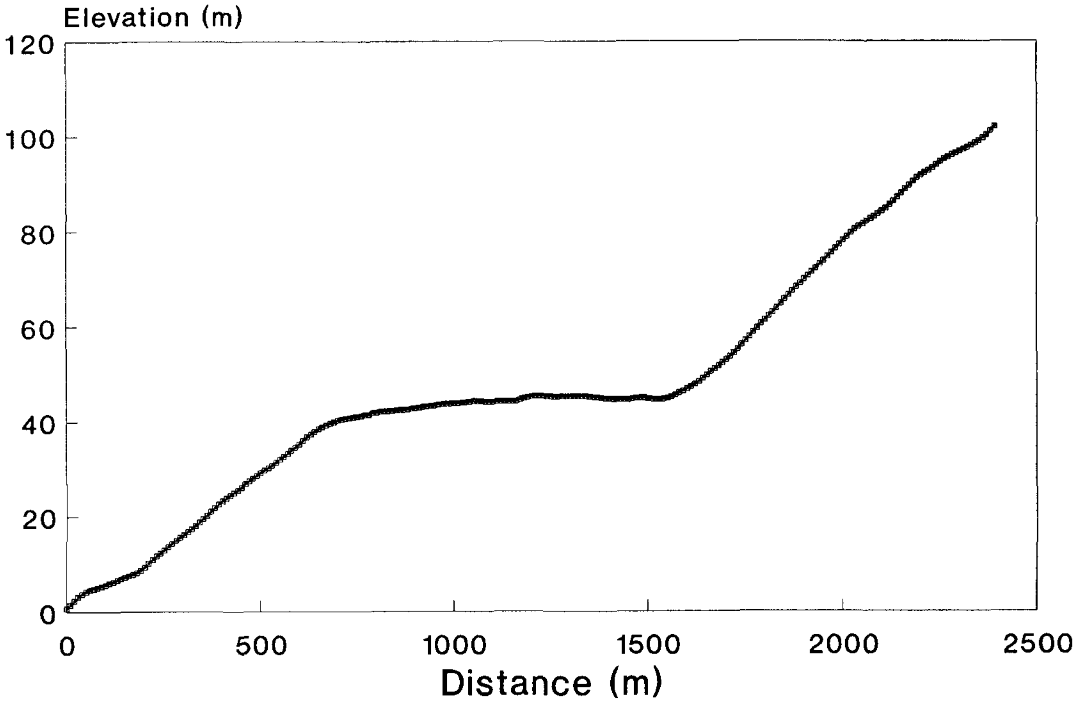


Figure 3(a). Newfoundland, Canada, study: vertical road profile.

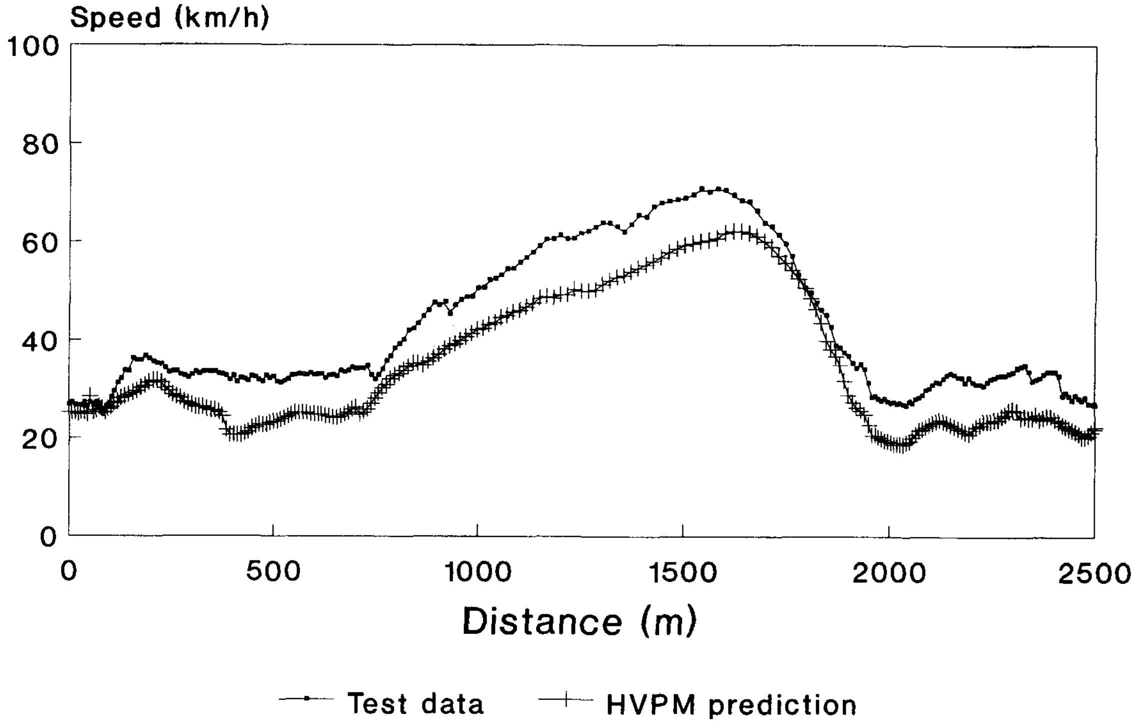


Figure 3(b). Newfoundland, Canada, study: observed and predicted vehicle speeds.

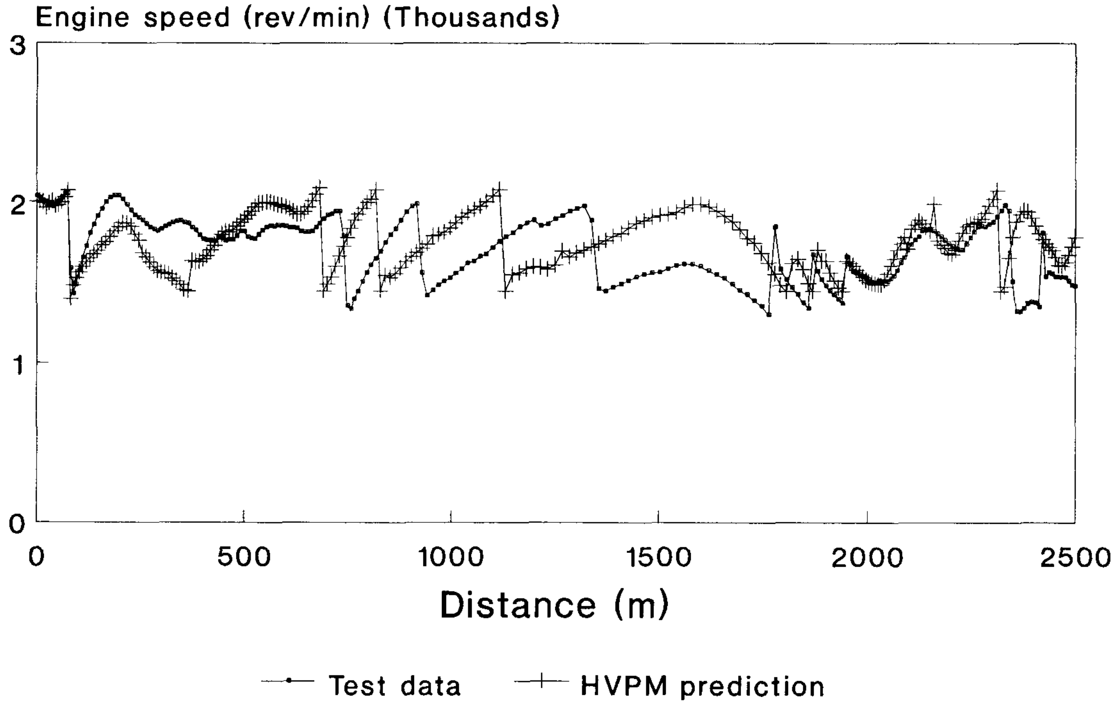


Figure 3(c). Newfoundland, Canada, study: observed and predicted engine speeds.

Table 5. Comparison, Newfoundland, Canada, study

	Observed (a)	**Predicted by HVPM (b)**	**% Difference (b-a)/a**
average speed (km/hr)	37.5	31.3	-17
average engine speed (rev/min)	1740	1710	-2
total fuel consumption	4.6	5.5	+20

Table 6. Vehicle specifications, Quebec, Canada, case study.

	Truck 1	**Truck 2**
engine	Mack RD822SX	Cummins KTA-1150C
power	375 kW	390 kW
transmission	Mack T-2090	Fuller RTO-14608LL
auxiliary transmission	AT-1202	AT-1202
rear axle ratio	3.43:1	3.43:1
planetary	2.80:1	2.80:1
gross vehicle mass	125 tonnes	125 tonnes
gross mass/power	330 g/W	320 g/W
tare mass	45 tonnes	45 tonnes

Figure 4. Quebec, Canada, study: proposed road alignments.

and alignments, with the results shown in Table 7. Because of the unequal lengths of two proposed haul roads, new and more appropriate measures of performance were introduced: productivity was measured in terms of the number of payload tonnes to be delivered each hour, including the unloaded back haul time needed for each cycle, and fuel consumption was measured in terms of the number of litres of fuel required to deliver each payload tonne, including the fuel consumed on the unloaded back haul.

The difference column shows that there was little choice between the two trucks, because they were specified so closely. However, considerable differences appear between the predicted truck performance on the two proposed road alignments. Selecting the shorter, flatter lake side road would result in at least a 28 percent greater productivity and at least a 17 percent reduction in fuel consumption per trip, than selecting the ridge road, with the definitions of productivity and fuel consumption adopted above.

The implicit savings in truck operating cost for vehicles using the lake side alignment will be compared to the increased cost of constructing a road on the lake side alignment, in order to determine the most economical overall transportation system. Construction costs are expected to be higher along the lake side alignment because of the increased requirement for culverts and bridges.

Truck Component Selection

To specify logging trucks, HVPM can be a useful tool to predict drive train component effects on performance. A hypothetical problem was designed to compare performance differences for trucks equipped with two different engines. The performance comparison (Table 8) was made by using the truck specifications in Table 3 and running HVPM for the road profile observed in the Maine study (Figure 2(a)).

The predicted results are shown in Table 8. Truck 4 (375 kW) had an increase in productivity of 16 percent over Truck 3 (300 kW) but fuel consumption also increased by 11 percent. To select one of the engines, the decision might be made by using the predictions to assess overall truck operating costs.

Truck Performance Predictions on Different Roads

Poor roads increase vehicle operating and maintenance costs [2, 19]. A preliminary study of the problem was conducted by using the HVPM to predict truck performance on different classes of roads.

McNally [14] suggested that a static rolling resistance coefficient (SRR) could relate rolling resistance to road conditions. The values in Table 9 were assumed as inputs to the HVPM. The FERIC truck data (Table 4) was selected. It was assumed that such a truck ran on an infinitely long, flat, straight road segment with no speed restrictions. Steady state speeds of each class road were determined by running the HVPM. The predetermined steady state speeds were then selected to be initial speeds and predicted truck performance on the different road classes (loaded trips) based on the steady state speed condition was determined (Table 10).

Table 7. Comparison, Quebec, Canada, case study.

	Truck 1 (a)	Truck 2 (b)	% Difference (b-a)/a
Ridge Road (13.8)			
round trip time (hr)	0.68	0.63	-7
productivity (t/hr)	118	127	+8
round trip fuel consumption (/trip)	40.9	40.4	-1
Lake Road (11.8 km)			
round trip time (hr)	0.50	0.49	-2
productivity (t/hr)	160	163	+2
round trip fuel consumption (/trip)	32.6	33.6	+3
Productivity: (Lake-Ridge)/Ridge	+36%	+17%	
Fuel Consumption: (Lake-Ridge)/Ridge	-20%	-17%	

Table 8. Comparison, predicted performance using two different engines.

	Truck 3 (a)	Truck 4 (b)	% Difference (b-a)/a
engine	Caterpillar	Mack E9 500	
power (kW)	300	375	+25
mass/power (g/W)	500	400	-20
distance (km)	4.7	4.7	
average speed (km/hr)	21	26	+24
total fuel ( )	13.6	14.9	+10
productivity (t/hr)	500	579	+16
efficiency (t•km/)	1.7	1.5	-11

Table 9. Assumed unit rolling resistances.

Road	Typical Road Description	Unit Rolling Resistance (kN/kN GCW)
1	rigid pavement	0.009
2	flexible pavement	0.013
3	granular surface: smooth, well compacted	0.018
4	granular surface: poor, rough, heavy washboarding	0.025
5	granular surface: rough, damp, soft	0.040

Table 10. Comparison, predictions for different road surfaces.

Road	Steady State Speed (km/hr)	Total Fuel ( )	Fuel Consumption (/100 km)
1	99	1.5	75
2	84	1.6	80
3	76	1.9	95
4	56	2.2	110
5	42	3.4	170

The steady state speed on Road 5 was about 42 percent of the steady state speed on Road 1, while the fuel consumption was 2.3 times that of Road 1. It should be noted that the predicted results are affected only by the rolling resistance caused by different road surface characteristics: effects due to drivers, road alignments, and traffic have been eliminated.

Decisions on appropriate road standards could be based on the results of such trials.

SUMMARY

A Heavy Vehicle Performance Model (HVPM) was developed which considers the characteristics of forest road transportation systems, and predicts vehicle performance as measured by speed and fuel consumption. Verification of the HVPM showed that the HVPM predictions were close to the observed field data, although there were some differences. The average speed predicted by the HVPM was typically as much as 17 percent lower than the average speed observed, while predicted fuel consumption was typically as much as 20 percent higher than observed. These differences are not felt to be unreasonable, particularly if the model is used in a comparative fashion.

A practical application of the HVPM was given in a case study conducted for a forest operation to compare the performance of two specified trucks on two proposed road alignments. A second example illustrated the selection of truck components using vehicle performance predictions from the HVPM. Finally, a third application example demonstrated how the HVPM could be used to predict the effects of road standards on truck performance.

The HVPM is a tool which designers could well use to assist in determining overall forest road transportation system costs and planning more efficient forest road transportation systems.

RECOMMENDATIONS

Recommended further studies:

- determining how to integrate the vehicle performance model with geographic information systems (GIS) and forest construction cost prediction models to facilitate the planning of forest transportation systems
- developing generalized relationships between unpaved road design characteristics (such as road structural stiffness, roughness) and rolling resistance, to lead to more reliable vehicle performance predictions

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