Review of the HDM-III User Cost Model for Suitability to Canadian Heavy Vehicles

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Operating expenses of the Canadian heavy-vehicle fleet exceed several times the expenditures on the public road system, but sound aids that recognize the importance of user costs in road investment decisions are lacking. A state-of-the-art model of user costs was developed after a study in Brazil by the World Bank. The current version of the Highway Design and Maintenance Standards Model, HDM-III, is evaluated for relevance to the Canadian heavy-vehicle operating conditions, and the results of preliminary calibrations for five typical vehicles are presented. The model is relevant to studying road infrastructure issues. It is also easy to operate and calibrate, but the cost-roughness slope and the effect of road texture, a roadworks decision variable in Canada, remain to be validated. The model will become more useful once the effects of congested traffic conditions on operating speeds are incorporated. Maintenance and depreciation costs need closer examination because they are interrelated and complicated by the inclusion of factory warranty costs in the purchase price. Maintenance cost formulas themselves need reevaluation because they were developed for a low labor-cost environment. If the present HDM-III "adjusted utilization method" is retained, it should be modified to account for the fact that time savings on a haul do not necessarily translate into additional trips. Relationships for cargo delay and damage due to road conditions also need improvement.

Trucking makes a major contribution to the economy. Not counting the smaller operations, Canadian for-hire and private carriers spend well over $20 billion annually in operating costs and engage more than 120,000 straight trucks, 49,000 tractors, and 110,000 trailers (*1*). Trucks move about two-thirds of the commerce between Canada and the United States at a cost of $2.5 to $3 billion, an amount that could double in less than 10 years with free trade. Deregulation will have growth effects similar to those observed between 1978 and 1987 in the United States (*2*).

Most of the heavy vehicle travel takes place on paved surfaces that account for 40 percent of the total 840 000 km of road in Canada. Robust economic arguments are needed to support increased road agency funding levels and proposed changes in heavy vehicle size and weight regulation. An accurate assessment of trucking costs is important because they have significant multiplier effects in the national economy. Canadian road users' contribution to the economy is an order of magnitude higher than the present public spending on construction, maintenance, and reconstruction of all rural and urban roads (*3*).

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Highway user cost and benefit analyses in Canada rely on outdated data. There is a recognized need to establish user cost parameters for the Canadian vehicle fleet and develop a methodology for road deterioration relationships (*3*). Trucking industry models, such as those of Trimac (*4*) or IBI Group (*5*), are unable to relate the costs to road surface condition or geometry and are less useful for studying road infrastructure issues. The applicability of the HDM-III model of road user costs to Canadian heavy vehicles is discussed in this paper.

HDM-III MODEL

Following a large-scale study in Brazil in 1975 to 1981, the World Bank developed the Highway Design and Maintenance Standards Model. The present version of the model, HDM-III, can aid feasibility studies of individual projects as well as policy studies for highway networks (*6*). The model is generic and can be calibrated to suit local conditions if they differ from those covered by the model's data base. The research represents the largest effort to date to develop a model capturing the relationships between costs of construction, maintenance, and utilization of roads. The model is based on the following premises deduced from earlier studies:

- User costs are related to highway construction and maintenance standards through the effect of road geometry and pavement surface condition.
- Pavement deterioration depends on the original construction, maintenance, and reconstruction, as well as traffic loading and uncontrollable environmental effects.
- Surface roughness is the principal road-related factor affecting user costs in free-flow traffic that can be related to all major pavement performance variables.
- Interrelationships are structured to describe known mechanistic and economic phenomena and can be suitably calibrated using the observed data.

User Cost Components

User costs depend on a region's economy, vehicle technology, driver behavior, and fleet-operating decisions. In order to facilitate future calibrations of the model to different local conditions, the World Bank's goal was to employ generic principles. The goal was reached for vehicle speed and fuel consumption models. Tire consumption and vehicle maintenance modeling experienced difficulties in gathering controlled experimental data. Generic economic causes of interactions between vehicle maintenance, depreciation, and interest costs were fully appreciated only after HDM-III was examined for conditions different than in the Brazilian study.

Operating cost relationships were developed for automobiles, light vehicles, two- and three-axle trucks, an articulated truck, and a bus. Vehicle speed, fuel, and tire consumption models were derived from a force-balance equation. The other user cost components are: oil; maintenance parts and labor; depreciation as the loss of vehicle market value; interest on undepreciated capital tied up in the vehicle assets; and driver, occupant, and cargo delay costs. Administration overhead costs can be calculated either as a lump sum per vehicle prorated over the annual distance travelled or as a percentage of running costs. This cost category could include other fixed costs such as terminal, registration, insurance, and license costs.

A sum of the vehicle operating costs (VOC) and delay costs weighted by each vehicle percentage in the traffic mix is the total cost on a road section or network link. This total cost is used in the HDM-III highway investment model and in the evaluation of alternative individual projects.

A stand-alone VOC prediction model is available for an IBM PC or compatible microcomputer running on an MS-DOS 2.0 or higher version. The program fits a curve to the total user cost expressed as an exponential function of surface roughness. Road geometry features are fixed parameters in the program.

Assumptions and Limitations

The HDM-III user cost submodel assumes that roads consist of homogeneous sections of sufficient length for a vehicle to attain a steady-state speed for a given road geometry and surface condition. The speed is a function of engine power, road gradient, horizontal curvature, surface roughness, and driver behavior.

The submodel in its original form cannot include the costs resulting from congested traffic conditions and start-stop operations. Until a suitable revision is made, these costs can be included in the HDM-III highway investment model by a generalized procedure. Other user costs such as construction-related traffic delays, accidents, and environmental pollution can also be entered from separate estimates.

A significant amount of work will be required to adapt and calibrate the HDM-III user cost submodel so as to accurately reflect the heavy-vehicle conditions in all Canadian provinces. Preliminary calibrations have already been accomplished within two Canadian projects (*3,7*). The assumptions and limitations of HDM-III user cost model will now be discussed from the point of view of application to heavy vehicles in Canada.

COMPARISON OF BRAZIL STUDY AND CANADIAN HEAVY-VEHICLE OPERATING CONDITIONS

Vehicle Technology

The Brazilian vehicle fleet was supplied by the domestic automotive industry, ranked among the world's top ten. Brazilian truck designs in the 1970s featured engine efficiency and body design for payload maximization within gross vehicle weight and axle load limits, but were not as efficient as their European counterparts. By 1980, a range of engines was available that could run on a variety of gasoline, gasohol, and diesel fuels. Vehicle owners could match truck specifications to the type of service they wished to provide.

Data for typical Canadian and Brazilian heavy vehicles are compared in Table 1. The most widely used interurban truck in Brazil was a three-axle rigid vehicle with a nondriven trailing axle, grossing between 18 to 22 tonnes and powered by a 147-hp (SAE) engine. This should be compared with a 1986 five-axle unit grossing 37.5 (Saskatchewan) to 49 tonnes (Quebec) and equipped with a 300- to 350-hp engine. The new Canadian heavy-vehicle weight regulations allow a gross combination weight (GCW) of 46.5 tonnes for five-axle combinations and 63.5 tonnes for Roads and Transportation Association of Canada (RTAC) B-trains that are eight-axle configurations. Canadian two- and three-axle trucks are used mainly in urban service. The three-axle tractor body design in Brazil was cab-over-engine, but conventional design was favored in North America for some time because of its lower maintenance cost and better fuel economy. Five-axle combinations were lighter and not as numerous as in Canada, and larger combinations were unusual. Intercity buses were also lighter in Brazil.

An extensive use of lighter materials in the body and mechanical components of both the truck and trailers has led to increased payload capacity per axle. In a quest for lighter equipment, North American truck operators have considered sacrificing vehicle durability and truck life. Advances in truck combinations technology have produced units of seven and more axles that did not exist in Brazil. Recent regulatory changes allowing higher gross vehicle weights are certain to increase truck productivity.

Modern tractors are powered by energy-efficient power plants with semiautomatic transmissions. Aerodynamic design is considered an important feature of equipment operated on long hauls. The vehicles are increasingly being equipped with radial tires that augment fuel efficiency by up to 30 percent compared with bias-ply tires. "Electronic" engines that can be programmed for a specified horsepower, torque, and speed for a given haul are already available.

The bus supply in Brazil ranged from integral and platform, rear-engine vehicles with air suspension and air-conditioning for long-distance operations on paved roads to traditional front-engine, ladder-type chassis versions for use on unpaved routes. All buses crossing state boundaries or traveling routes longer than 300 km within a state had to be fitted with a tachograph. Rules governing speed limits and driving hours were strictly enforced for both buses and trucks.

Fleet Operation

Computer applications in trucking management have created an unprecedented potential for productivity improvements that were technically impossible for operators participating in the Brazilian study. Computerized dispatching and routing systems can help the dispatcher's judgment in optimizing the company's pick up and delivery operations. Maintenance, parts inventory, fuel, and tire control software, when used intelligently, reduce fleet operating costs and increase service reli-

TABLE 1 DIFFERENCES IN VEHICLE TYPE AND UTILIZATION

VEHICLE	CANADIAN PRAIRIE PROVINCES, 1986	BRAZIL, 1976
2-Axle Truck(1)	International(2)	Mercedes Benz 1113
GVW, kg	14,600	15,000
Curb weight, kg	5,700	5,400
Max. rated engine power, hp (SAE)	166	147
Max. rated engine speed, rpm	2,400	2,800
Typical annual km	32,000(3)/5,000(4)	101,000
Typical annual hours driven	1,000/200	2,040
Type of service	Urban/Farms	Intercity
3-Axle Truck(1)	International(2)	Mercedes Benz 1133
GVW, kg	21,500	18,500
Curb weight, kg	11,000	6,600
Max. rated engine power, hp (SAE)	180	147
Max. rated engine speed, rpm	2,700	2,800
Typical annual km	32,000	101,000
Typical annual hours driven	1,000	2,040
Type of service	Urban	Intercity
5-Axle Truck(1)	Kenworth W900(2)	Scania 110/39
GVW, kg	37,500	22,000
Curb weight, kg	14,500	14,700
Max. rated engine power, hp (SAE)	350	285
Max. rated engine speed, rpm	2,150	2,200
Typical annual km	140,000(4)	?
Typical annual hours driven	1,600(4)	?
Type of service	Intercity	Intercity
7-Axle Combination(1)	Western Star(2)	(6)
GVW, kg	53,500	
Curb weight, kg	16,000	
Max. rated engine power, hp (SAE)	400	
Max. rated engine speed, rpm	2,100	
Typical annual km	140,000(4)	
Typical annual hours driven	1,600(4)	
Type of service	Intercity	
Bus	M.C.I.(7)	Mercedes Benz 0362(8)
GVW, kg	17,200	11,500
Curb weight, kg	12,900	8,100
Max. rated engine power, hp (SAE)	300	149
Max. rated engine speed, rpm	2,100	2,800
Typical annual km	> 100,000?	?
Typical annual hours driven	1,600?	2,400
Type of service	Intercity	Intercity

NOTES: Brazil data from *reference (8)*
(1) Trimac (1986) data for general merchandise cargo;
(2) Vehicle dealer automotive data on most popular makes;
(3) Estimate using 33 km/h average running speed in urban service;
(4) Lea Associates 1987 survey and "1985 Travel on Saskatchewan Highways";
(5) Trimac (1986) data for bulk cargo;
(6) Equivalents to 7-axle combinations did not exist in the Brazil study;
(7) Motor Coach Industries (M.C.I.), 3-axle bus;
(8) 2-axle bus.

ability. Less-than-truckload freight can be consolidated and empty truck runs eliminated by using computerized matching service for the interchange of information between shippers and carriers.

Electronic data interchange between shippers, carriers, and consignees eliminates paperwork, speeds up deliveries, and enables manufacturers and distributors to synchronize the flow of goods. This is possible owing to high-technology developments such as on-board computers in trucks, driver-dispatcher communication systems, and satellite tracking of vehicles. These systems are now becoming a reality among larger motor carriers, who will be able to fill the transport function in the just-in-time, cost-reducing method of materials and goods management in manufacture and distribution.

Rolling Resistance

The largest contribution to vehicle rolling resistance arises from the hysteresis of tire materials caused by deflection on road surface macrotexture. In the Brazilian study, rolling resistance was regressed through controlled experiments on longitudinal road roughness, which was considered the primary variable. Surface texture, tire, and suspension characteristics were ignored. Road-surface texture characteristics are definitely a location-specific variable, depending on materials, methods of construction, and the weathering effects of climate (*9*). Tire properties have changed considerably relative to the bias-ply technology prevailing in Brazil.

Neither load conditions nor pavement texture was found to be a significant determinant of test truck rolling resistance, but tire pressure was found to be highly significant (*10*). Between a flush seal, hot mixes, and a chip seal, the macrotexture varies by almost eight times, whereas microtexture varies by almost two times (*11*). Rolling resistance is 25 percent higher on deeply textured asphalt than on medium texture asphalt, and almost 70 percent higher than on smooth concrete (*12*).

The HDM-III relationships relating to rolling resistance would need revision in Canada. Coast-down experiments are recommended using vehicles of contemporary suspension and tire designs on a range of typical Canadian road surfaces in order to verify the Brazilian rolling resistance relationships. This verification is important, considering that the force-balance equation underlies fuel and tire consumption and time-related user cost estimation. It is also important to quantify the effect of the pavement deflection bowl. It has been observed in Canada that loaded trucks need to gear down in order to climb a gradient created in front of the wheels on thin pavements.

Vehicle Speeds

The HDM-III VOC model has been developed for steady-state speeds encountered under free-flow traffic conditions. Speed change and stop-and-go cycles along the roadway are not modeled in the present version, but at least one compatible model for these traffic conditions exists (*12*) and could be included in a future version of HDM. The new version would be much more useful in Canada for both highways and urban roads.

In the Brazilian study, vehicle loads were estimated visually and payloads recorded in broad weight classes. Truck payload has an important influence on speeds, and visual observations are not accurate estimates of loads carried. One study (*7*) encountered some complications in calibrating the speed relationships, possibly for this reason.

For lack of other measures, the HDM-III roughness-related speed function was adopted from the standard Mays-meter-equipped Chevrolet Opala car. Its average rectified velocity of suspension motion was used as a surrogate for that of the heavier vehicles. This assumption may not be suitable for trucks, especially those hauling high-value cargo susceptible to damage by vibrations and shocks.

Fuel Consumption

The Brazilian study found that fuel consumption could be predicted by using a constant nominal engine speed rather than the actual one. Adjustment factors have been introduced to allow corrections for changes in vehicle technology and for experimental driving conditions. The HDM-III default factors are specific to the Brazilian study. They were obtained by correlating experimental data with actual road-user fuel consumption. Specific vehicle and engine technology imposed by the trucks in Brazil does not permit extrapolation to modern Canadian trucks, and corrections will be required.

HDM-III fuel consumption relationships are based on an inadequate approach to representing pavement texture in the rolling resistance equations. Pavement texture causes energy losses in the tires that are responsible for an additional resistance compared with driving on a surface without texture. A Swedish model (*13*) predicts a 40 percent increase in fuel consumption for heavy vehicles traveling on deeply textured surfaces compared with smooth roads. For free-flow traffic, an Australian model (*12*) found a reasonable agreement with HDM-III fuel consumption predictions for straight trucks and combinations. A Canadian study (*7*) found calibration of HDM-III fuel consumption to be one of the easiest adaptation tasks.

The omission of texture, an important decision variable in highway management in developed countries, has caused some controversy. Zaniewski (*14*) could not find any dependence of fuel consumption on road roughness, possibly because the Serviceability Index does not capture pavement texture characteristics, according to Claffey (*15*). The other factor important in increasing fuel consumption is a higher wheel slippage in Canada because of the presence of slush, snow, and ice on road surfaces in winter. Winter fuels were not used in the Brazil tests.

The Scania test tractor in Brazil had a high fuel consumption when running loaded on grades compared with a similar European version. Investigations have revealed that the vehicle was fitted with a low-speed differential that may be partly responsible for the differences. This was not realized when the fuel data were collected and analyzed. The fuel study results for this vehicle type should be used with caution (T. Watanatada, World Bank, unpublished data, 1987).

Tires

Tire data are difficult to collect because tires are moved between vehicles and axles. Tire life varies even under identical operating conditions according to load carried, position on the vehicle, speed of operation, and driver behavior. Tire utilization also depends on a company's standards of maintenance for tires and vehicles, and on recapping policy.

Tire technology and manufacture continue to change rapidly. Research into tire costs for road vehicles is required to measure the benefits of new tread and carcass materials, recapping techniques, new tire types, and central tire inflation equipment on large articulated vehicles. Steel-braced radial tires were not available in Brazil during the periods in which user surveys were performed, and these tend to give different tire costs per kilometer.

The limitation of the rolling resistance coefficient with regard to capturing pavement texture properties also applies to the tire consumption relationships. A survey of bus companies has found that angular stones in the pavement caused accelerated tire wear (*10*). The HDM-III relationship for tire consumption of trucks and buses is intended for use with roads of moderate horizontal alignment and a well-designed superelevation. These conditions are met on Canadian arterials and collectors, where most of the truck transportation takes place.

Maintenance Costs

HDM-III maintenance cost relationships will most likely be difficult to transfer to Canada. Maintenance expenditures are sensitive to price and wage levels and the trade-offs of depreciation and interest charges, all of which are linked to the size, strength, and structure of the local economy and to the type of transport service offered by the operator. For example, an operator providing service of high reliability at peak periods in a competitive economy will set high levels of inspection and conduct preventive maintenance. These costs will be balanced by keeping reserve vehicles to a minimum.

Despite these transferability problems, close agreement was found between the cost-roughness slope in Brazilian and South African data on bus parts consumption (*10*). Maintenance parts and labor costs, and their trade-off with depreciation and interest charges, are likely to prove highly resistant to a mechanistic approach. Economics, not technology, is the key factor in predicting these components. Calibration of the maintenance cost relationships of HDM-III for Saskatchewan (*7*) met some difficulty because of their mathematical structure.

Depreciation and Interest

In the Brazilian study, no data were collected to estimate the relationships between depreciation and interest costs and road characteristics. HDM-III considers speed, utilization, and service life to be interdependent. A number of relationships are provided for calculating utilization and service life, but only "the adjusted utilization method" is recommended for Canada. It assumes that each vehicle operates on a fixed route throughout a given year and that the annual hours available for driving are constant and independent of vehicle speed and route characteristics. Vehicle operators maximize vehicle productivity by making as many trips as possible within the availability constraints.

HDM-III has two methods for calculating the average annual depreciation and interest. The constant-vehicle-life method uses a straight-line depreciation for a specified vehicle life, which is assumed to be a constant regardless of any calculated vehicle speed. The average annual interest is calculated on the average vehicle price over its lifetime. In the varying-vehicle-life method, vehicle life decreases (or increases) somewhat as vehicle speed increases (or decreases). This means that the service life, lifetime kilometerage, and depreciation charges change less proportionately than speed. This method was found unsuitable for low vehicle utilization levels in New Zealand (*16*).

Occupant and Cargo Delay Costs

In the HDM model, the cost of crew labor and cargo-holding cost are considered to be variable rather than fixed costs. This means that the time spent on loading, unloading, and layovers is not charged against this cost category.

The cargo-holding cost per 1,000 vehicle-km is defined as the product of vehicle hours spent by cargo in transit and the user-specified cargo-holding cost per vehicle-hour delayed. In general, the cargo-holding cost is small, but for cargo of high value the cost will be significant. For example, a $1 million cargo delayed 2.5 hr because of a reduction of truck running speed from 100 km/hr to 80 km/hr will give rise to a delay cost of 2.9 cents/km.

CALIBRATION OF HDM-III FOR CANADIAN HEAVY VEHICLES

Uncalibrated HDM-III

Trimac Consulting Services Ltd. carries out a survey of Canadian truck operating costs every 2 years (*4*). Trimac's assumptions on truck characteristics and unit costs are representative of the industry, and were fed into the Highway User Benefit Assessment Model (HUBAM) used by Transport Canada and into the uncalibrated HDM-III. Figure 1 compares the results of Trimac, HUBAM, and uncalibrated HDM-III analyses for three trucks. HUBAM does not analyze vehicles larger than five axles.

Costs are fairly close for the two-axle truck, provided that driver costs are adjusted and interest charges in HUBAM are taken into account. Trimac's driver cost is high because it reflects an urban pick-up and delivery service at an average 32 km/hr, whereas HDM-III and HUBAM assume intercity haul at free-flow speeds. Fuel and oil costs in HUBAM are overestimated, as is maintenance cost in HDM-III.

Total costs for a five-axle Trimac truck are similar to HUBAM, but HDM-III is much too high because maintenance and tire costs are about four times higher than the corresponding figures. The HDM-III results for a seven-axle truck suffer from a similar deficiency, although the other cost components seem comparable to Trimac's industry rates.

Figure 2 compares the VOC changes on rougher roads relative to a smooth road with a Riding Comfort Index (RCI) value of 8. HDM-III provides much larger benefits than HUBAM for any improvement project, particularly for trucks. This must result from the overprediction of truck maintenance costs and the strong influence of road roughness on these costs. RTAC and Saskatchewan data shown in Figure 2 indicate disagreement in Canada on this crucial relationship underlying all highway feasibility, maintenance, and rehabilitation decisions. The most likely relationships would be between the HDM-III and HUBAM curves.

Figure 3 emphasizes the need for an accurate calibration of vehicle speed in HDM-III. The HUBAM speeds are highest because HDM-III speeds are determined by an 80-km/hr limit in force during the study in Brazil. Neither model is realistic about the gap between automobile and truck free-flow speeds on present highways. Trimac speeds of five- and seven-axle trucks are not comparable because they are trip averages including stops and urban driving at each end of an intercity haul.

Calibrated Relationships

Typical Canadian trucks and a bus operating in the prairie provinces were chosen for trial calibrations of the HDM-III model. Vehicle operating characteristics, utilization, auto-

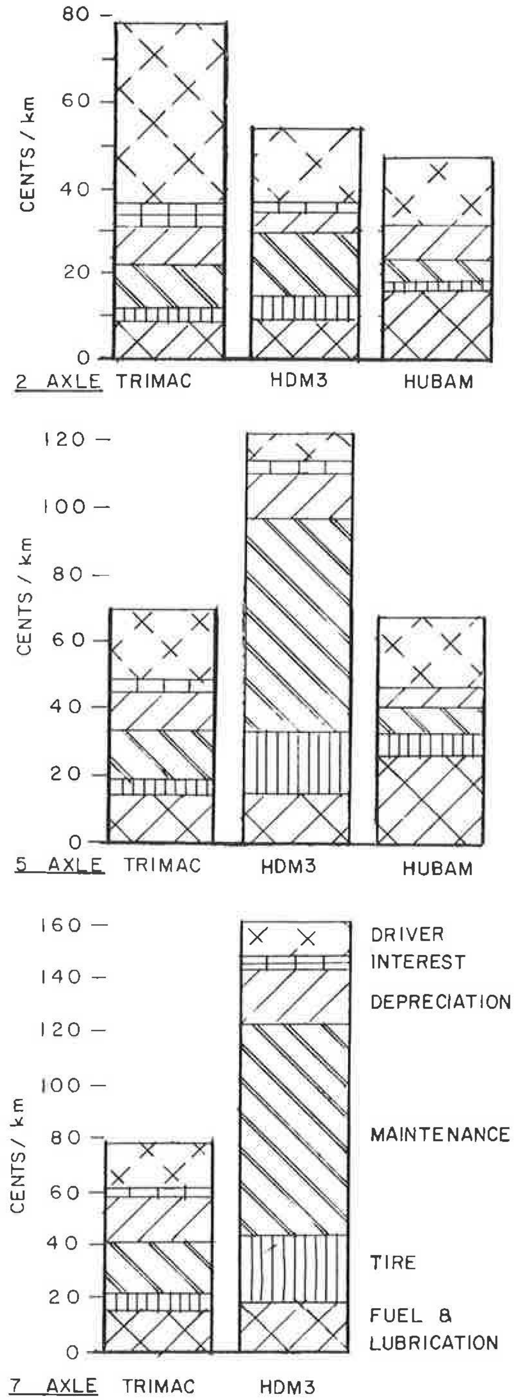

FIGURE 1 Comparison of Trimac's VOC data with predictions by uncalibrated HDM-III and HUBAM.

motive data, and unit costs were obtained in surveys and interviews of the trucking industry, vehicle dealers, and manufacturers. Trimac data (*4*), found reliable compared with the survey data, were used as the benchmark to calibrate HDM-III for smoother road conditions. For rougher roads, data are not readily available and the slope of the VOC-roughness relationship was adopted from the Brazilian study.

Figure 4 shows the total VOC in cents per kilometer as a function of roughness expressed in RCI units. The seven-axle truck has the steepest slope and the three-axle bus the gentlest slope. The two-axle truck has the lowest VOC and the seven-axle truck the highest VOC, but the three-axle truck is more expensive to operate in cents/km than the five-axle.

The breakdown into VOC components is shown in Figure 5 for the seven-axle truck. Crew cost is significant, but depreciation and interest are greater. The largest cost increase with roughness occurs in the maintenance and depreciation components, while fuel cost does not change much with roughness. Fuel cost drops at lower RCI values because of reduced speeds on rough roads, but crew time increases then.

For a three-axle bus, tires cost less because there are fewer of them and the load is lighter. Maintenance is also less because there are fewer components to break down compared to a seven-axle truck.

Figure 6 summarizes the change in total VOC when roughness decreases from RCI 8 to 4. This type of data can be used in road investment decisions to estimate extra user costs due to road deterioration or determine user cost savings from road improvements. The two-axle truck experiences the highest, and the bus the lowest, marginal rates of increase with RCI. When a delay of 20 passengers is added, the marginal rate of the bus halves, indicating a high sensitivity to the number of passengers.

Sensitivity Analyses

The VOC of trucks is about three times more sensitive to rolling resistance than the VOC of cars, regardless of roughness. Cost increments due to deep-textured versus medium-textured asphalt surface would be similar to increments resulting from an RCI drop from 8 to 6.5. A 20 percent decrease in truck utilization leads to a comparable effect. A 10 percent increase in payloads from better productivity, or from higher truck GVW or volume, can lead to 7 to 9 percent reductions in unit trucking costs.

CONCLUSIONS

The HDM-III user cost model is a robust tool for road transportation decisions based on economics, road engineering, and vehicle operation and management principles. Adaptations will be required to make the model an accurate simulator of heavy-vehicle operations because they were not represented in the HDM-III database. The model is relatively easy to adapt, owing to the mechanistic form of most of the relationships, and it will become more useful once the ongoing research into modeling congested traffic flows is incorporated.

Maintenance and depreciation costs need closer examination because they are interrelated and were developed for a low labor cost environment. If retained, the "adjusted utilization method" should be modified to reflect the fact that time savings on a haul do not necessarily translate into additional trips. Relationships for cargo delay and damage due to road conditions need improvement because these costs are more important in developed countries than developing ones, for which HDM was conceived.

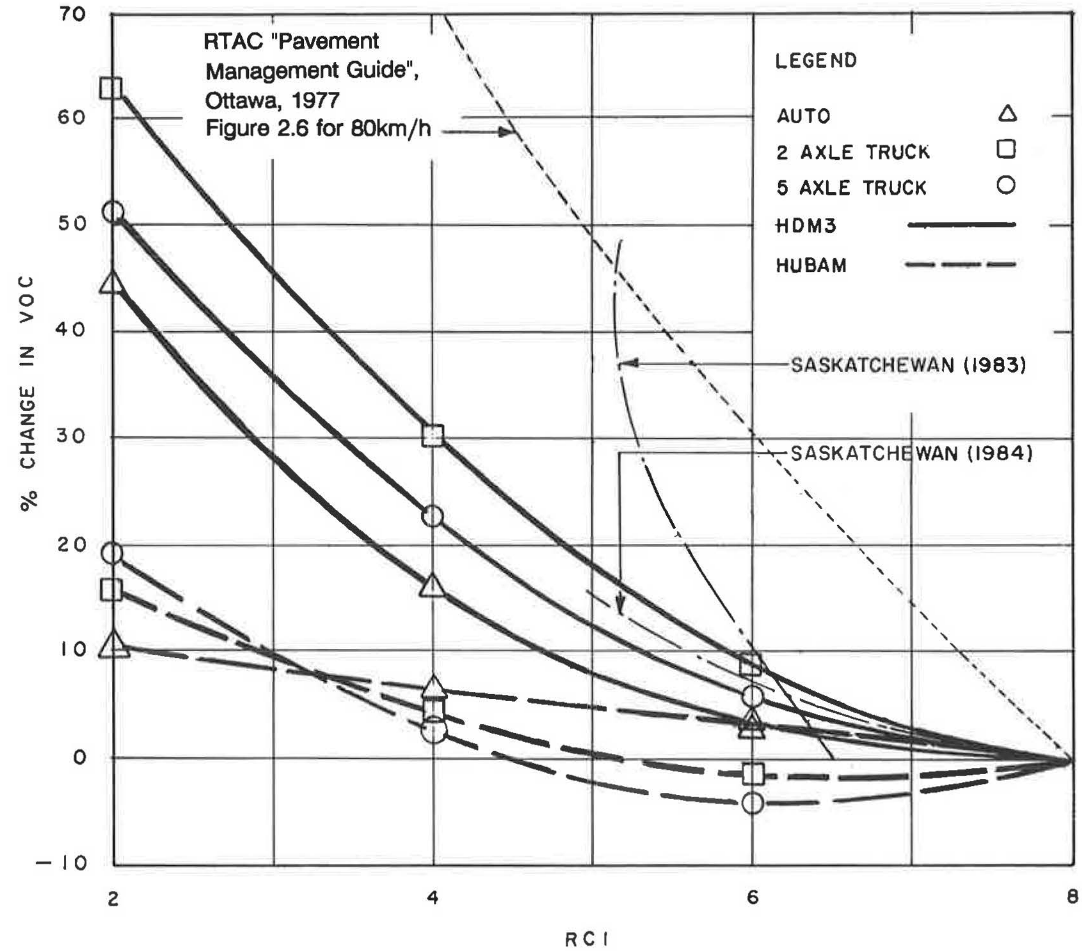

FIGURE 2 Percent change in VOC relative to RCI = 8.

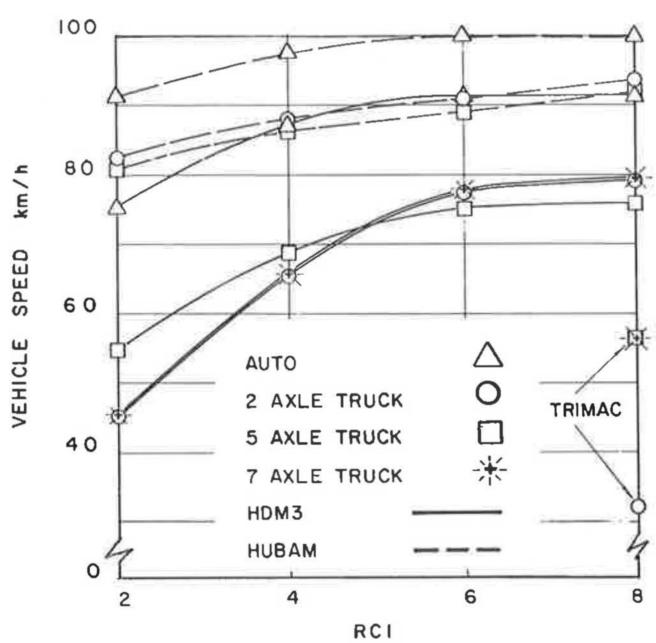

FIGURE 3 Predicted vehicle speeds for free flow conditions.

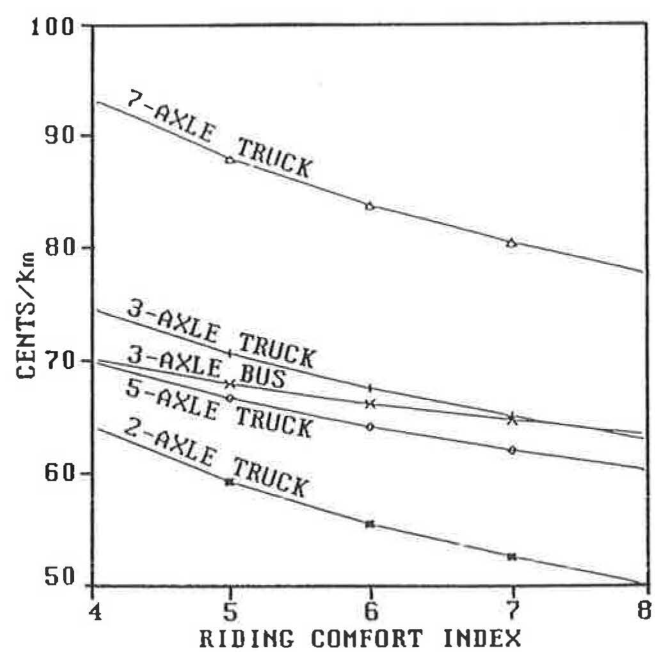

FIGURE 4 Total VOC of heavy vehicles.

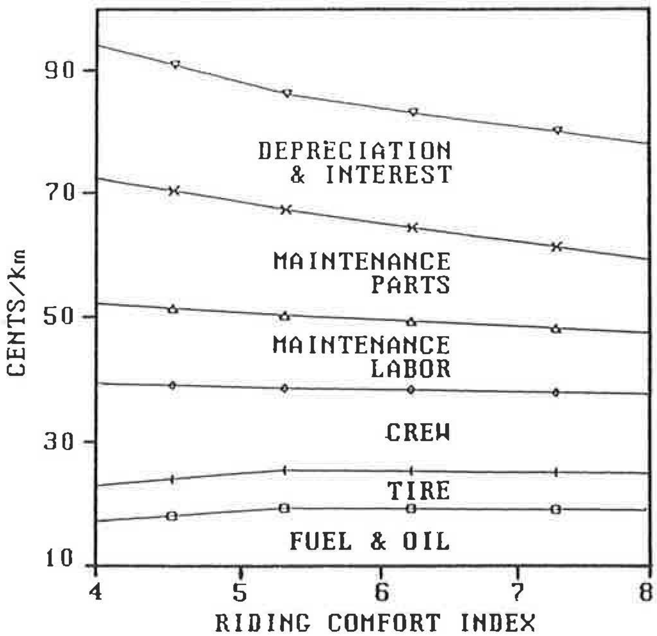

FIGURE 5 Seven-axle truck VOC components.

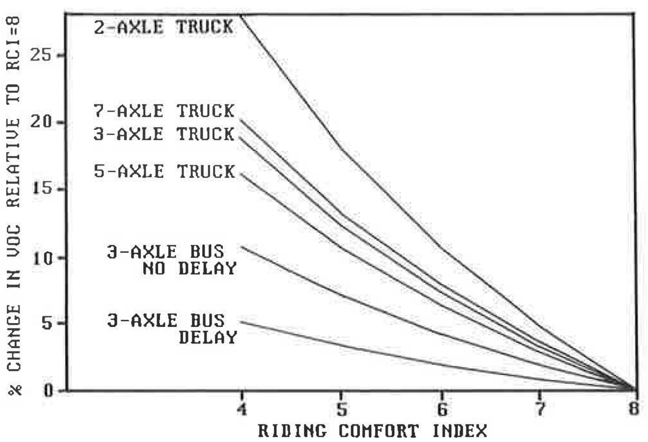

FIGURE 6 Relative change in VOC of heavy vehicles.

Trucking cost data from rough routes are urgently needed for planning. This data would enable verification of the slope of the cost-roughness functions critical in planning and programming road maintenance and rehabilitation. The HDM-III assumptions on road surface texture should also be checked in full-scale experiments using representative trucks and tires, so that the rolling resistance base of speed, fuel, tire, and time-related trucking costs in HDM-III can be regarded with confidence. A similar conclusion has been reached by an independent, in-depth research (*12*). A concerted effort would be desirable among the Canadian road infrastructure administrators, the trucking industry, and the research community to carry out the adaptations and calibrations.

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