

Relevance of HDM3 Road User Cost Model to Canadian Heavy Vehicles

Peter Bein, Manager Research and Development
John B. Cox, President
Merv F. Clark, Senior Maintenance Adviser

N.D. Lea International Ltd.
1455 West Georgia Street
Vancouver, British Columbia V6G 2T3
Telephone: (604) 685-9381, Fax: (604) 683-8655

Symposium on Heavy Vehicle Weights and Dimensions

Kelowna, British Columbia, Canada
June 18-22, 1989

ABSTRACT

Operating expenses of the Canadian heavy vehicle fleet exceed several times the expenditures on the public road system, but sound aids recognizing the importance of user costs in road investment decisions are lacking. A state-of-the-art model of user costs, HDM3, is evaluated for relevance to the Canadian heavy vehicle operating conditions, and results of preliminary calibrations for six typical vehicles are presented.

The HDM3 model is highly relevant to studying road infrastructure issues. It is also easy to operate and to 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 into a forthcoming version.

The cost components in need of closer examination are maintenance and depreciation, which are inter-related and further complicated by the manufacturer's practice to include factory warranty costs into the purchase price. Maintenance cost formulas themselves need re-evaluation because they were developed for a low labour-cost environment.

The HDM3 relationships for calculating truck utilization should be revised. If the present "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, unless tractors are run 24 hours a day and loading/unloading is not a time constraint.

Relationships for cargo delay and damage due to road conditions need improvement because these costs are relatively more important in developed countries than in developing ones, for which HDM was originally conceived.

1. INTRODUCTION

Trucking makes a major contribution to the economy. Even by conservative estimates (1) which ignore smaller operations, Canadian for-hire and private carriers spend well over \$20 billion annually in operating costs and engage over 120,000 straight trucks, 49,000 tractors and 110,000 trailers. Trucking accounts for about two-thirds of the commerce moving between Canada and the U.S.A. Presently a \$2.5 to \$3 billion industry, it 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 U.S.A. where the average length of haul increased 12%, ton-km per tractor 18%, and tractor travel increased 22% (2).

Canada has over 840,000 km of road, but most of the heavy vehicle and automobile travel takes place on paved or hard surfaces, which account for about 40% of the total length of the road system. Maintaining the quality of the system and keeping road transportation costs to a minimum are rational objectives based on sound economic justification. Robust economic arguments are needed for increased road agency funding levels as well as for proposed changes in heavy vehicle size and weight regulation. An accurate consideration of road use costs in the funding allocation decisions is important and mandatory.

Particularly important is an accurate assessment of trucking costs because they have significant multiplier effects in the national economy. Canadian road users' contribution to the national economy is an order of magnitude higher than the present public spending on construction, maintenance and reconstruction of all rural and urban roads.

Highway cost and benefit analyses in Canada which incorporate user costs must rely on outdated or incomplete vehicle operating cost (VOC) data. The pavement deterioration models which must be used in such a life-cycle economic analysis are only reasonably well developed for a limited number of areas in Canada. There is a recognized need to develop user-cost parameters for the Canadian vehicle fleet and to 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.

This paper discusses the applicability of a state-of-the-art model of road-user costs, HDM3, to Canadian transportation conditions and presents calibrated results for some typical heavy vehicles.

2. HDM3 MODEL

2.1 Background

A large-scale project was carried out in Brazil between 1975 and 1981 to develop VOC and pavement deterioration models for economic evaluations of alternative highway investment strategies (6). Extensive analyses of the data by the World Bank produced generic models which can be calibrated to local conditions different from those covered by the database. These models were incorporated into a life-cycle investment model called the Highway Design and Maintenance Standards Model (HDM), which can aid individual project feasibility studies as well as transport network policy studies. The present version of the model is HDM3 (7, 8, 9, 10).

The research represents the largest effort to date to develop a model capturing the interrelationships between costs of highway construction, maintenance and utilization of roads. Quantification of the interrelationships between road costs was based on the following premises which were deduced from earlier studies:

- . VOC and other 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.
- . The principal pavement decision factor affecting user costs in free-flow traffic is surface roughness, which can be related to all major variables affecting pavement performance through pavement deterioration relationships.
- . The interrelationships can be generalized from mechanistic and economic causes and then can be reapplied with a suitable calibration to any conditions which obey these causes.

2.2 Vehicle Operating Cost and Other User Cost Relationships

Recognizing that VOC depend on a region's economy, vehicle technology, driver behaviour and fleet operating decisions, the World Bank's goal was to employ generic principles in order to facilitate future calibrations to different local conditions. The goal was accomplished only for vehicle speed and fuel consumption models. Tire consumption and vehicle maintenance modeling ran into some difficulties of gathering controlled experimental data. Genetic economic causes of interactions between vehicle maintenance, depreciation and interest costs were fully appreciated only after HDM3 had been examined for conditions significantly deviating from the Brazilian ones.

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 for these vehicles were derived from a force-balance equation. The other VOC and user-cost components are: oil; maintenance parts and labour; 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 cost 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.

Model operation is simple. For each of the generic vehicle types, automotive data is input into the model, together with vehicle utilization and unit costs of consumables, wages, crew time and cargo delay, new vehicle cost, and interest rate on undepreciated capital. The VOC submodel first calculates unit physical quantities per vehicle-km and then multiplies them by the unit costs. The sum of these products is the total cost per km travel over a road section with homogeneous geometric and roughness characteristics.

A road is subdivided into homogeneous sections (or an average is used for representative links in network studies) and the cost calculation is repeated for all representative vehicle types. A sum of the 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 HDM3 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 micro-computer running on an MS-DOS 2.0 or later version. The program fits a curve to the total user cost, which is expressed as an exponential function of surface roughness. Road geometry features are fixed parameters in the program.

2.3 Assumptions and Limitations

The HDM3 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 behaviour.

The submodel in its original form cannot include congested traffic conditions and start-stop operations. However, work is under way to include the effects of traffic conditions based on a robust mechanistic model which is compatible with HDM3 (20). In the meantime, these costs can be included in the HDM3 highways 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 HDM3 user-cost submodel so as to accurately reflect the Canadian heavy-vehicle conditions. This work will be much easier, however, than starting from where the HDM work first began. Canada would greatly benefit from the current efforts to include congested traffic conditions into HDM.

Preliminary calibrations have been already accomplished within two Canadian projects (11, 12). This work has confirmed an independent finding by others (13) that an economic rather than a mechanistic approach would be more appropriate in HDM3 to model maintenance, depreciation and interest costs. Other limitations identified in HDM3 include: understatement of the effect of pavement surface texture on tire rolling resistance; analytical weakness of speed relationships for laden trucks on rough surfaces; restrictive database excluding energy-efficient engine technology, heavy truck combinations and modern radial tires; and vehicle utilization analysis employed in vehicle depreciation relationships.

The assumptions and limitations of HDM3 VOC model will now be discussed from the point of view of application to heavy-vehicle operation in Canada.

3. COMPARISON OF BRAZIL STUDY AND CANADIAN HEAVY-VEHICLE OPERATING CONDITIONS

3.1 Vehicle Technology and Fleet Operation

The Brazilian vehicle fleet was supplied by the domestic automotive industry, which figured among the world's top ten vehicle manufacturers. Mercedes Benz made over 30 basic medium to large truck models. Another Brazilian manufacturer was using 1960's Fiat designs, but the Scania trucks were more technically advanced and offered turbo-charged and intercooled engines for line haul use. However, these models were

not as efficient as their European counterparts, and the prediction of fuel consumption for this vehicle class needs correction.

The Brazilian truck designs in the 1970s featured engine efficiency and body design for payload maximization within gross vehicle weight and axle load limits. By 1980, a range of engines was available which 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.

Table 1 compares typical representatives of the Canadian heavy-vehicle fleet with those from the Brazil study. The most widely used inter-urban truck in Brazil was a three-axle rigid vehicle with a non-driven trailing axle, grossing between 18 to 22 tonnes and powered by a 147 hp engine. This should be compared with a 1986 five-axle unit grossing 37.5 t (Saskatchewan) to 49 t (Quebec) and equipped with a 300 to 350 hp engine. The new Canadian heavy-vehicle weight regulations allow GCW of 46.5 t for five-axle combinations, and 63.5 t for RTAC B-trains which 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 (COE). Conventional design was favoured over COE in North America for some time due to 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. Inter-city buses were also lighter in Brazil.

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

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

The bus supply in Brazil was dominated by Mercedes Benz who offered 11 basic models ranging from integral and platform, rear-engined vehicles for paved road operations, to traditional front-engined, ladder-type chassis versions for use on unpaved routes. There were a number of companies building bus bodies, ranging from robust designs for unpaved roads to designs with air suspension and air-conditioning for long-distance operations on paved roads. All buses crossing state boundaries or travelling 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 bus and truck operations.

Computer applications in trucking management have created an unprecedented potential for productivity improvements, which were technically impossible for the operators participating in the Brazil study. Computerized dispatching and routing systems can aid the dispatcher's judgement in optimizing the company's pickup and delivery

Table 1. Differences in Vehicle Type and Utilization

<u>VEHICLE</u>	<u>CANADIAN PRAIRIE PROVINCES, 1986</u>	<u>BRAZIL, 1976</u>
<u>2-Axle Truck</u> (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
<u>3-Axle Truck</u> (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
<u>5-Axle Truck</u> (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
<u>7-Axle Combination</u> (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	
<u>Bus</u>	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.

operations. Maintenance, parts inventory, fuel and tire control software, when used intelligently, reduce fleet operating costs and increase service reliability. Less than truck-load (LTL) 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 (EDI) between shippers, carriers and consignees eliminates paperwork, speeds up deliveries and enables manufacturers and distributors to synchronize the flow of goods. Hi-tech developments crucial for EDI are 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 (JIT) cost-reducing method of materials and goods management in manufacture and distribution.

3.2 Rolling Resistance

The largest contribution to vehicle rolling resistance arises from the internal friction (hysteresis) in tire materials due to deflection on road surface irregularities (macrotexture). Other contributors are: slippage between the surfaces of the rubber tread and the road; climbing conditions created by the deflection bowl in front of the wheels on thin pavements; turbulence around the rotating tire; and energy dissipation in the suspension system.

Tire mechanical properties which influence rolling resistance depend on the inflation pressure, ambient temperature, and on tire geometry, construction and rubber material. The suspension stiffness and damping characteristics depend primarily on the mechanical design of the suspension system and the viscosity of the damping fluid used.

In the Brazil study, rolling resistance was regressed through controlled experiments on longitudinal road roughness, which was considered primary decision variable for the road cost model. Surface texture, tire and suspension characteristics were ignored although they vary over time and from locality to locality. Tire properties have changed considerably relative to the bias-ply technology prevailing in Brazil. Road-surface texture characteristics are definitely a location-specific variable, depending on materials, methods of construction, and the weathering effects of climate (14). It is thus likely that the HDM3 relationships relating to rolling resistance would need correction in Canada.

Curtayne et al. (13) did not find either load conditions or pavement texture to be significant determinants of test truck rolling resistance, but tire pressure was found highly significant. Hayes and Ivey (16) point out that between a flush seal, various hot mixes and a lightweight aggregate chip seal, the macrotexture varies by almost eight times, while microtexture varies by almost two times. Biggs (20) indicates a 25% higher rolling resistance on deeply textured asphalt compared to medium texture asphalt, and almost 70% higher compared to smooth concrete.

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. Equally important is a quantification of the effect of pavement deflection bowl on rolling resistance. It has been observed in Canada that laden trucks need to gear down in order to climb a gradient which is created in

front of the wheels on thin pavements. An experiment to confirm and quantify this phenomenon could be possibly combined with the coast-down experiments.

3.3 Vehicle Speeds

The HDM3 VOC model has been developed for steady-state speeds encountered under free-flow traffic conditions. Speed change and stop-go cycles along the roadway are not modeled in the present version, but at least one compatible model for these traffic conditions exists (20) and will 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 were recorded in broad weight classes. Truck payload has an important influence on speeds and visual observations are not accurate estimates of loads carried. The Saskatchewan VOC study (12) encountered some complications in calibrating the speed relationships possibly for this reason.

For lack of other measures, the HDM3 roughness-related speed function was adopted from the standard Maysmeter-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. Truck response to road roughness is a subject of ongoing research (15), which will hopefully cast more light on this issue.

3.4 Fuel Consumption

The Brazil study found that fuel consumption could be predicted by using a constant nominal engine speed instead of actual used rpm. Adjustment factors have been introduced to allow corrections for changes in vehicle technology and for driving conditions. The HDM3 default factors are specific to the Brazilian study, and 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 required by the modern Canadian truck combinations and will need corrections.

HDM3 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 tire which are responsible for an additional resistance compared to driving on a surface without texture. A Swedish model (21) predicts a 40% increase in fuel consumption for heavy vehicles travelling on deeply textured surfaces compared to smooth roads.

For free-flow traffic, an Australian model (20) found a reasonable agreement with HDM3 fuel consumption predictions for straight trucks and combinations. A Canadian study (12) found calibration of HDM3 fuel consumption to be one of the easiest adaption tasks.

The omission of texture, an important decision variable in highway management in developed countries, has caused some controversy. Zaniewski (17) 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 (18). The other factor important for fuel consumption is a higher wheel slippage in

Canada due to the presence of slush, snow and ice on the road surfaces in winter, which augment fuel consumption. Winter fuels were not used in the Brazil tests.

There is some question about the performance of the Scania super-heavy tractor. This heavy truck had very high fuel consumption compared with a similar European version from the same manufacturer, particularly when it was running loaded on grades. Investigations by the World Bank following the experiments have revealed that the vehicle was fitted with a low-speed differential which may be partly responsible. This was not realized when the vehicle's fuel data was collected and analyzed, and Brazilian fuel study results for this vehicle type should be used with caution.

3.5 Tires

Tire data are difficult to collect because, at least in large organizations, 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 behaviour. Tire utilization also depends on company policy regarding standards of maintenance of tires and vehicles and regarding frequency and standard of recapping.

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 overall tire costs per kilometre.

The limitation of the rolling resistance coefficient with regard to capturing pavement texture properties also apply to the tire consumption relationships. A survey of bus companies has found that angular stones in the pavement caused accelerated tire wear (13). The HDM3 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.

3.6 Maintenance Costs

HDM3 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 will conduct preventive maintenance. These costs will be balanced by keeping reserve vehicles to a minimum.

In spite of these transferability problems, Curtayne et al. (13) found close agreement between the cost-roughness slope in Brazilian and South African data on bus parts consumption. Maintenance parts and labour costs, and their trade-off with depreciation and interest charges, are likely to prove highly resistant to mechanistic approach. Economics, not technology, is the key factor in the prediction of these components. Calibration of the maintenance cost relationships of HDM3 for

Saskatchewan (12) met some difficulty because of the mathematical structure of the equations.

3.7 Depreciation and Interest

In the Brazil study no data were collected to estimate the relationships between depreciation and interest costs and road characteristics. The approach is more theoretical and relies on more assumptions than that for fuel consumption, tire wear and vehicle speeds.

The HDM3 approach towards depreciation and interest costs considers that there is an interrelationship between speed, utilization and service life. 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 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.

HDM3 has two methods for calculating the average annual depreciation and interest. First, the constant vehicle life method uses a straight-line depreciation for a specified vehicle life, which is assumed to be a constant irrespective of any calculated vehicle speed. The average annual interest is calculated on the average vehicle price over its lifetime. Second, the varying vehicle life method is also based on a straight line, but vehicle life is assumed to decrease (or increase) somewhat as vehicle speed increases (or decreases). This means that the service life (and lifetime kilometerage and depreciation charges) increase or decrease less proportionately than speed. The varying life method was found unsuitable for low vehicle utilization levels in New Zealand (19).

3.8 Occupant and Cargo Delay Costs

In the HDM model, the cost of crew labour 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, 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 hours due to a reduction of truck running speed from 100 km/h to 80 km/h will give rise to a delay cost of 2.9 cents/km.

4. CALIBRATION OF HDM3 FOR CANADIAN HEAVY VEHICLES

4.1 Data for Calibration

Typical Canadian trucks and a bus operating in the prairie provinces were chosen for trial calibrations of the HDM3 model. Vehicle operating characteristics, utilization, automotive data and unit costs were obtained in surveys and interviews of the trucking industry, vehicle dealers and manufacturers. Trimac data (4) was found reliable and was used as the benchmark to calibrate HDM3 for smoother road conditions. For rougher roads, data is not readily available and the slope of the VOC-roughness relationship was adopted from the Brazil study.

Figure 1 shows the total VOC in cents/km as a function of roughness, which is expressed in Riding Comfort Index (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 than the five-axle.

The breakdown into VOC components is shown in Figures 2 to 4 for three-axle truck, seven-axle truck and three-axle bus, respectively. 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 with roughness.

For a seven-axle truck (Figure 3) maintenance costs dominate, followed by depreciation and interest and crew cost. Fuel cost drops at lower RCI values due to reduced speeds on rough roads, but crew time increases then. Dramatic increases are also seen in the maintenance and depreciation components when roads become rougher.

For the three-axle bus (Figure 4), the VOC composition is somewhat different. Tires cost less because there are fewer of them and the load is lighter. Maintenance is less because there are fewer components to break down compared to a seven-axle truck.

Figure 5 summarizes the change in total VOC when roughness decreases from RCI 8 to RCI 4. This type of data can be used in road investment decisions to estimate extra user costs due to deteriorating condition of the road network. Alternatively, it can be used to determine user-cost savings due to road improvements. The two-axle truck experiences the highest marginal rates of increase with roughness, while the bus has the lowest increase. When a delay of 20 passengers is added to the VOC of the bus, the marginal rate halves, indicating a high sensitivity to the number of passengers.

4.3 Sensitivity Analyses

Sensitivity of the total VOC was tested with respect to rolling resistance, engine speed, annual utilization distance and hours driven, and service life of vehicle. The rolling resistance variable was varied between 80% and 140% of the HDM3 default value for three-axle truck (Figure 6) and seven-axle truck (Figure 7). The truck VOC is about three times more sensitive to rolling resistance regardless of roughness. The seven-axle truck VOC sensitivity depends on the level of RCI. Each 20% change in the rolling resistance gives rise to about 5% change of the same sign in the total VOC of heavy vehicles. The change is only 2% for light vehicles.

The calibrated rpm, the utilization and the service life were also changed in 20% increments and the results for medium car and seven-axle truck are compared in Figure 8. The results did not change much in the range of RCI 4 to 8. Increasing engine speed from HDM3 defaults does not have any effect on the total VOC at either roughness level for the medium car, but decreasing rpm results in a 3% drop in the VOC. The seven-axle truck experiences a 5% drop in the VOC with increasing rpm and a smaller drop with decreasing rpm. These differences are due to different engine types of trucks compared to cars.

The sensitivity to utilization parameters was assessed by varying the annual distance driven. The annual time driven was adjusted to maintain the base case

operating speed, and the lifetime distance driven was recalculated using the base case service life years. A 20% change in utilization of the medium car has a very dramatic effect on the total VOC. For the seven-axle truck, the effects are similar in direction, but smaller in magnitude. This is because depreciation and interest are a much smaller percentage of the total cost for trucks compared to cars.

Unlike the other parameters tested, service life was increased by 100% because this is the order of magnitude of the ratio of one utilization stage to the whole life of a heavy truck. For example, truck tractors are used in intensive linehaul for about five years and then for another five or ten years in less demanding service. Again, the medium car is far more sensitive to this variable than the truck (Figure 8) because of its larger proportion of depreciation and interest in the total VOC.

5. CONCLUSIONS

The HDM3 model can fill the need of Canadian road transportation professionals and decision-makers to have a robust analytical tool based on economics, road engineering, and vehicle operation and management principles. Adaptations and calibrations will be required to make the model an accurate simulator of Canadian heavy-vehicle operating conditions. The heaviest vehicles need particular attention because they were not represented in the database from which HDM3 has been developed.

Preliminary calibrations indicate that the model is relatively easy to adapt, owing to the mechanistic form of most of the relationships. The model will become even more useful once the ongoing research into modeling congested traffic flows is finalized and incorporated into a new version of the HDM.

The cost components in need of closer examination are maintenance and depreciation, which are inter-related and further complicated by the manufacturer's practice to include factory warranty costs into the purchase price. Maintenance cost formulas themselves need re-evaluation because they were developed for a low labour cost environment.

The HDM3 relationships for calculating truck utilization should be revised. If the present "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, unless tractors are run 24 hours a day and loading/unloading is not a time constraint.

Relationships for cargo delay and damage due to road conditions need improvement because these costs are relatively more important in developed countries than in developing ones, for which HDM was originally conceived.

Truck transportation cost data from rough routes, including those with textured surfaces, is urgently needed for planning in view of the present shortfall of roadwork funds. These data would enable verification of the slope of the cost roughness functions which are critical in planning and programming road maintenance and rehabilitation. Also, the HDM3 assumptions concerning road surface texture should 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 HDM3 can be regarded with confidence. A similar conclusion has been reached by an independent in-depth research in Australia (20).

A concerted effort would be desirable between the Canadian road infrastructure administrators, the trucking industry and the research community to carry out the adaptations and calibrations of HDM3 road user-cost model for heavy vehicles.

REFERENCES

1. Statistics Canada, Trucking in Canada, Catalogue 53222 Annual, Ottawa, 1984, 1986.
2. Supplement to Traffic World, December 5, 1985.
3. Roads and Transportation Association of Canada, "Adapting the Brazil/UNDP Cost Research to Canadian Conditions," a report prepared by N.D. Lea and Associates Ltd., to be published.
4. Trimac Consulting Services Ltd., "Operating Costs of Trucks in Canada 1986," Transport Canada Policy and Coordination Branch, TP921E, Ottawa, 1986.
5. Roads and Transportation Association of Canada, "Economics of Truck Sizes and Weights in Canada," Final Report, Ottawa, July 1987.
6. GEIPOT, "Research on the Inter-Relationships Between Costs of Highway Construction, Maintenance and Utilization," Final Report, 12 volumes, prepared by the Brazilian Ministry of Transport, the Texas Research and Development Foundation, and the International Bank for Reconstruction and Development, 1982.
7. Watanatada, Harral, Paterson, Dhareshwar, Bhandari and Tsunokawa, "The Highway Design and Maintenance Standards Model HDM-III", Volume 1: Model Description, Volume 2: User's Manual, Highway Design and Maintenance Standards Series, Johns Hopkins, Baltimore and London, 1987.
8. Chesher and Harrison, "Vehicle Operating Costs: Evidence From Developing Countries," Highway Design and Maintenance Standards Series, Johns Hopkins, Baltimore and London, 1987.
9. Watanatada, Dhareshwar and Lima, "Vehicle Speeds and Operating Costs: Models for Road Planning and Management," Highway Design and Maintenance Standards Series, Johns Hopkins, Baltimore and London, 1987.
10. Paterson, "Road Deterioration and Maintenance Effects: Models for Planning and Management," Highway Design and Maintenance Standards Series, Johns Hopkins, Baltimore and London, 1987.
11. Cox, Bein and Lea, "The Potential for Canadian Applications of the Brazil and World Bank Research on Road User Costs and Pavement Deterioration," Paper No. 880108, Transportation Research Board, 68th Annual Meeting, Washington, D.C., 1989.
12. Bein, "Application of HDM3 Vehicle Operating Cost Model in Saskatchewan Pavement Management Information System," to be published in Transportation Research Record, 1989.

13. Curtayne, Visser, du Plessis and Harrison, "Calibrating the Relationship Between Operating Costs of Buses and Road Roughness on Low-Volume Roads," Transportation Research Record, No. 1106, Transportation Research Board, Washington, D.C., 1987.
14. Bond, Williams and Lees, "An Approach Towards the Understanding and Design of the Pavement's Textural Characteristics Required for Optimum Performance of the Tyre," Proceedings Symposium Physics of Tyre Traction, Research Laboratories of General Motors, 1973.
15. Australian Road Research Board, Proceedings Symposium on Heavy Vehicle Suspension Characteristics, Vermont, Victoria, March 1987.
16. Hayes and Ivey, "Texture, Skid Resistance and the Stability of Automobiles in Limit Maneuvers," ASTM Special Technical Publication 583, American Society for Testing and Materials, 1975.
17. Zaniewski, "Fuel Consumption Related to Road Characteristics," Transportation Research Record, No. 901, Washington, D.C., 1983.
18. Claffey, discussion of Zaniewski, Transportation Research Record, No. 901, Transportation Research Board, Washington, D.C., 1983.
19. Bennett, "The New Zealand Vehicle Operating Costs Model," Transportation Research Record, No. 901, Transportation Research Board, Washington, D.C., 1987.
20. Biggs, "ARFCOM - Models for Estimating Light to Heavy Vehicle Fuel Consumption," Australian Road Research Board, Research Report ARR 152, Victoria, September 1988.
21. Hammarström and Karlsson, "VETO - A Computer Program for Calculation of Transport Costs as a Function of Road Standards" (in Swedish), Swedish Road and Traffic Research Institute (VTI), VTI Meddelande 501, Linköping, 1987.

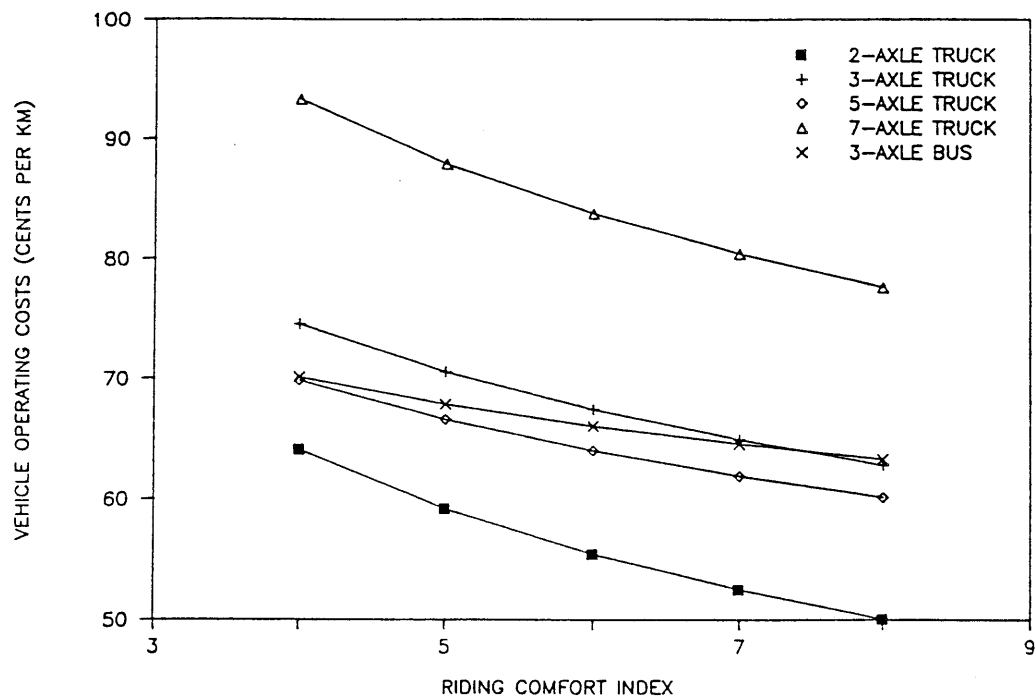


Figure 1. Total VOC of Heavy Vehicles

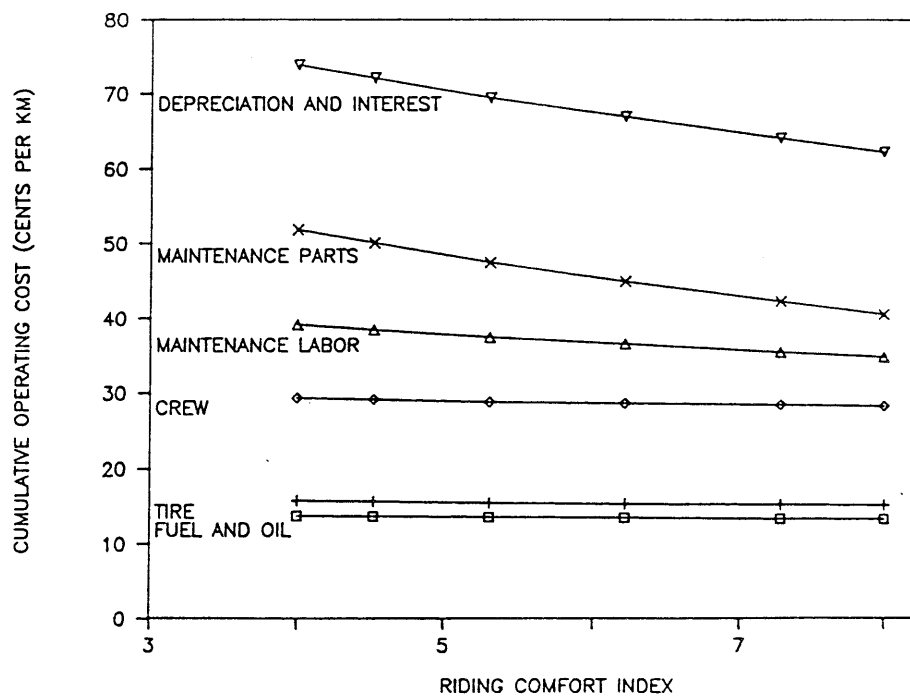


Figure 2. Three-Axle Truck VOC Components

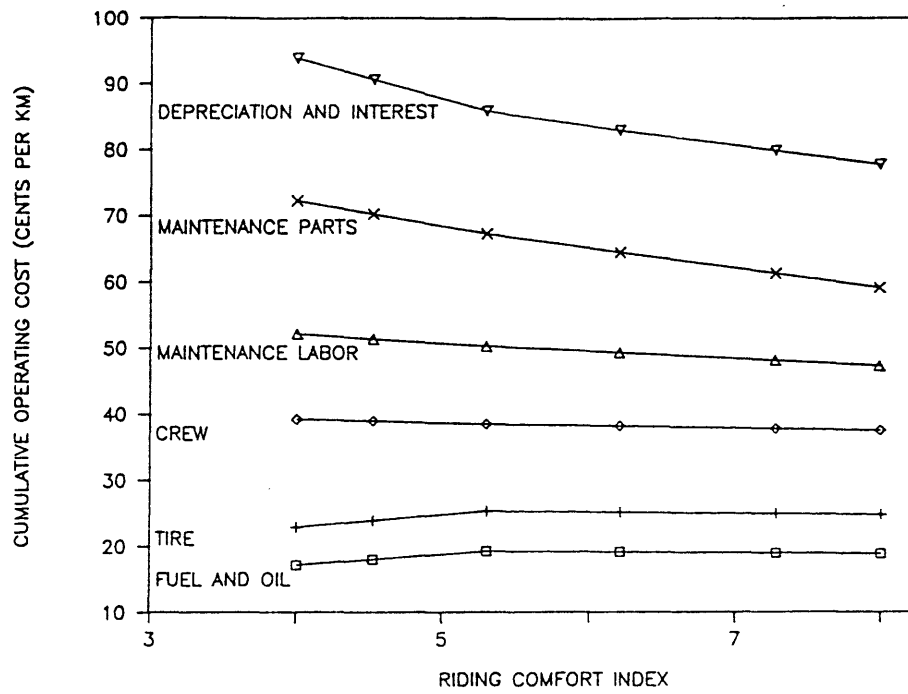


Figure 3. Seven-Axle Truck VOC Components

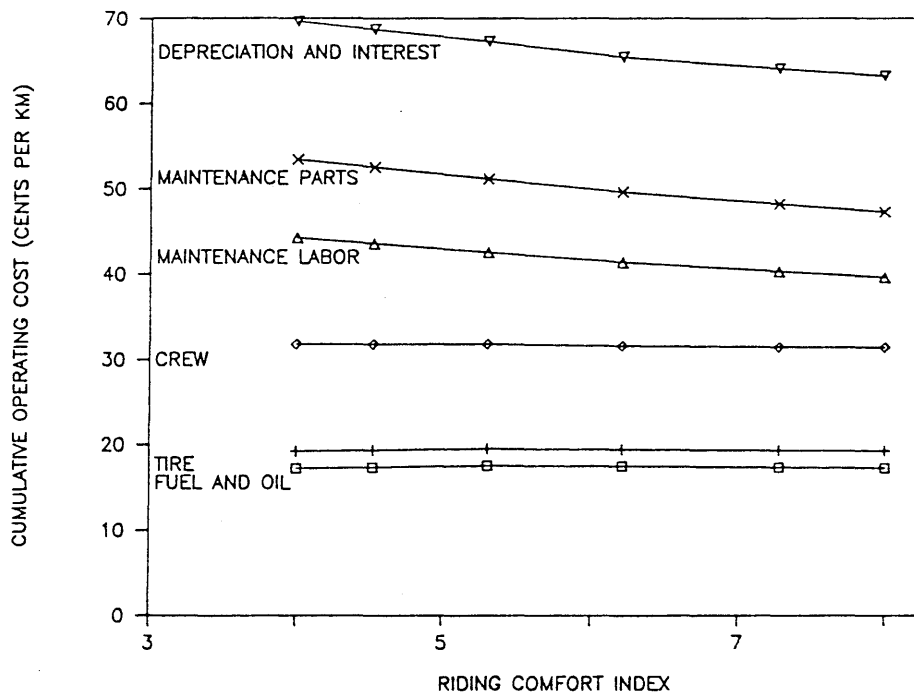


Figure 4. Three-Axle Bus VOC Components

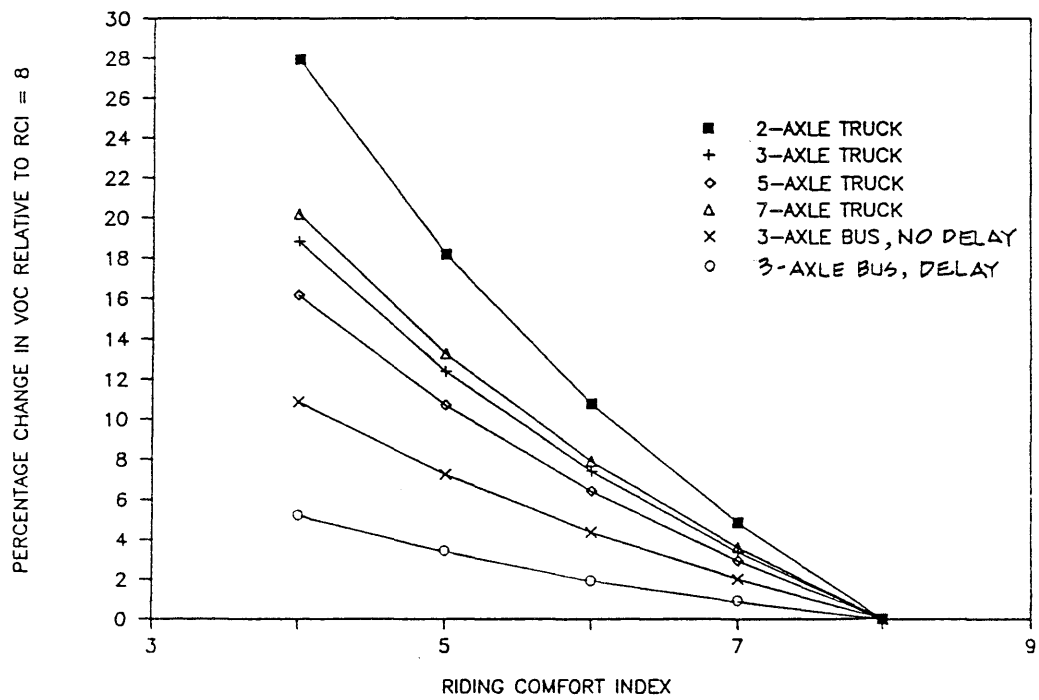


Figure 5. Relative Change in VOC of Heavy Vehicles

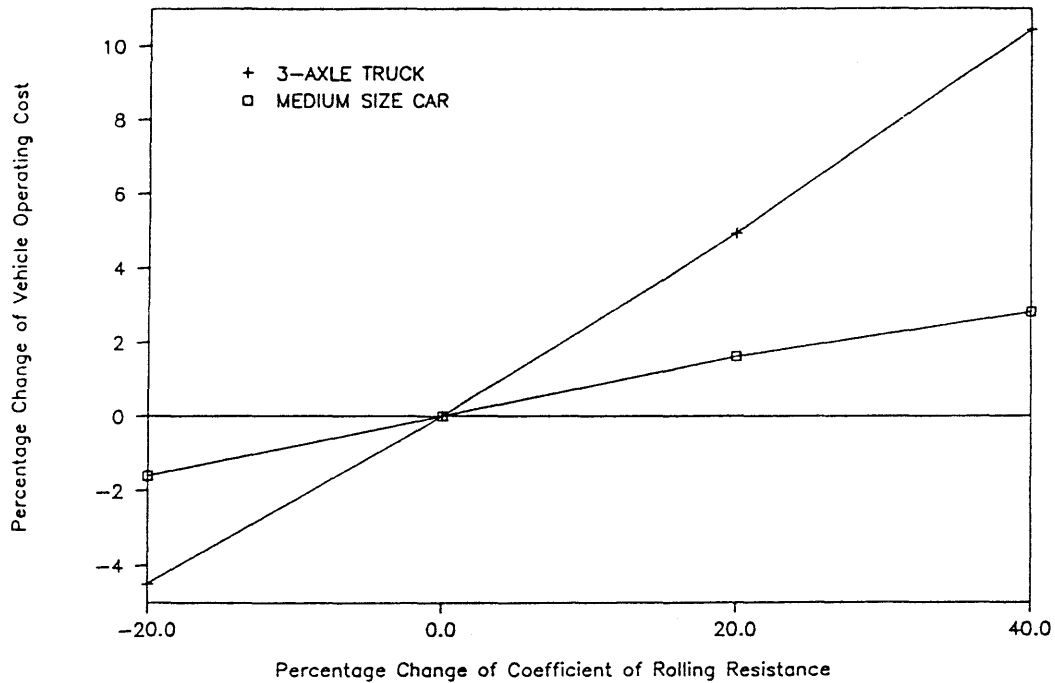


Figure 6. Sensitivity of Medium Car and 3-Axle Truck VOC to Rolling Resistance

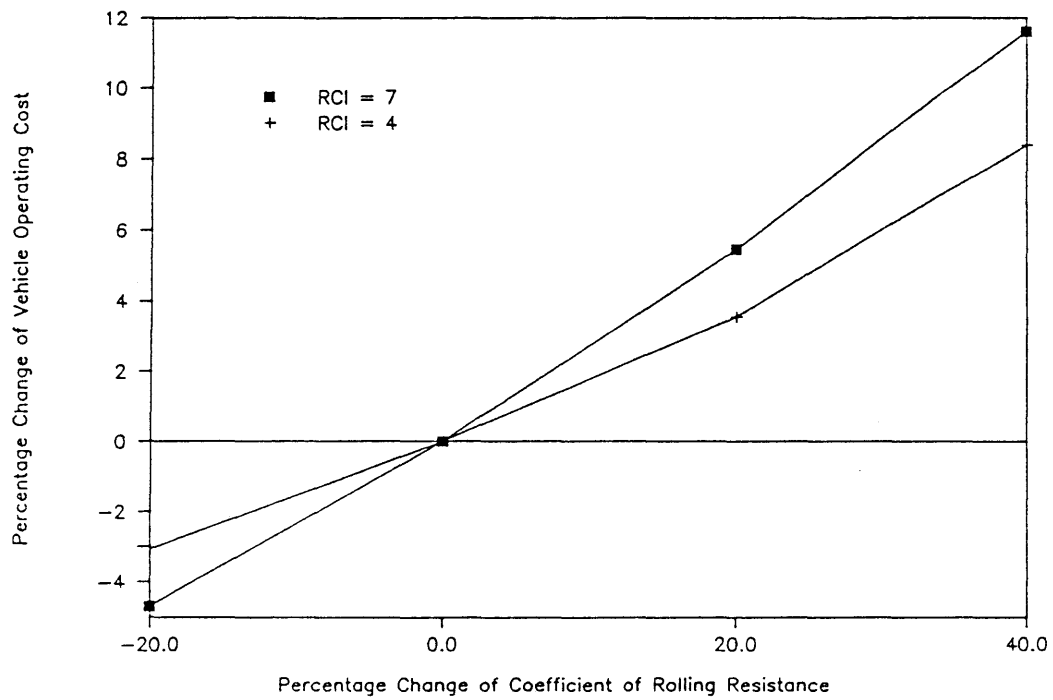


Figure 7. Sensitivity of 7-Axle Truck VOC to Rolling Resistance

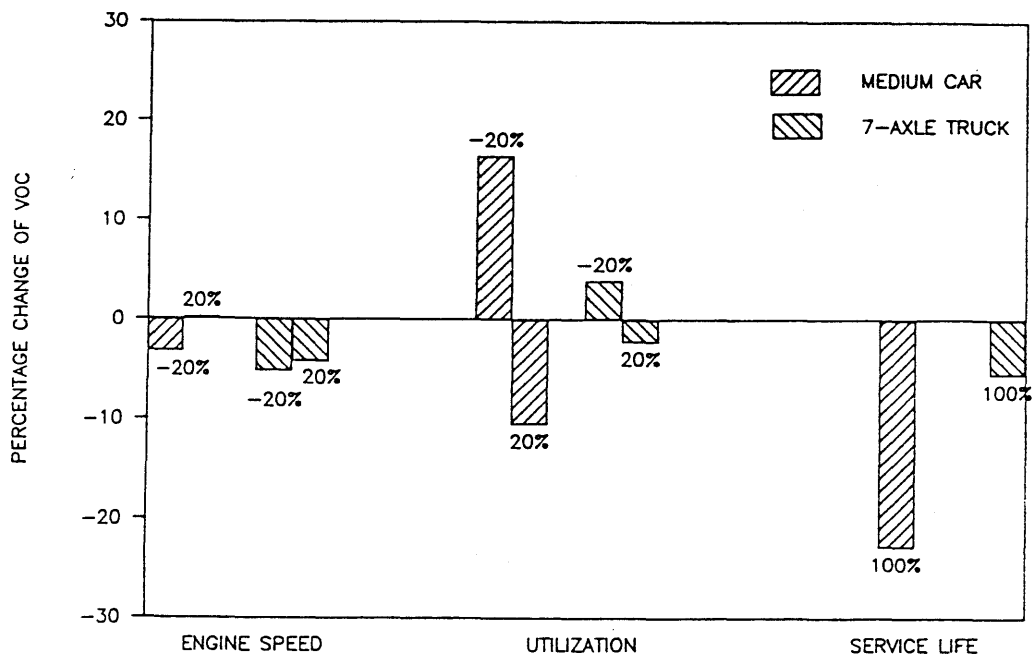


Figure 8. Sensitivity of Medium Car and 7-Axle Truck VOC to Engine Speed, Utilization and Service Life

