Adapting HDM3 User-Cost Model to Saskatchewan Pavement Management Information System

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The World Bank's HDM3 submodel of user costs was applied in the Saskatchewan Pavement Management Information System, which integrates agency and user costs into a life-cycle analysis of construction and maintenance strategies for the provincial highway network. Fleet use and cost data were gathered from public sources and from a pilot survey of highway users. User-cost–road-roughness equations were developed for nine types of vehicles, for the financial and economic cost cases with and without user delay cost. The cost components of cargo delay and damage need further work. Depreciation, interest, and maintenance costs interplay in vehicle owner decisions and should be reinvestigated. Depreciation and maintenance costs overlap because the costs of repair on factory warranties are included in the purchase price. Available vehicle use data are not clear because of mixed urban/highway travel and distinct use staging of lives of all vehicle types. In speed predictions for trucks, more data are required on payload and used engine power. The road surface texture affects speed prediction and fuel and tire consumption, but its effect on user costs remains to be clarified. Tire consumption relationships are inappropriate for the radial tire technology. Maintenance parts and labor cost equations can be calibrated with some difficulty. Further research will depend on large-scale surveys, in order to cover a wide range of paved road roughness and texture and to quantify the experimental errors.

A large-scale study was carried out in Brazil in 1975 to 1981 to develop user-cost models for evaluations of the total transportation costs and benefits of alternative highway investment strategies (*1*). State-of-the-art user-cost relationships were developed by the World Bank from the study data and were incorporated into a life-cycle investment model called the Highway Design and Maintenance Standards Model (*2,3*), whose current version is HDM3. User-cost models are required for the economic analysis of the total life-cycle costs in the Pavement Management Information System (PMIS) developed for the Saskatchewan Highways and Transportation (SHT) (*4*). The province of Saskatchewan has one of the world's most extensive highway networks per capita, the most intensive vehicle use in Canada, annual operating costs of the fleet in the order of some $3 billion, and a provincial highway budget of $200 to $300 million. In the PMIS, calibrated user costs derived from HDM3 help establish optimum intervention levels for rehabilitation, overlay, and maintenance treatments. Alternative strategies composed with these treatments are evaluated with total agency and user-costs criteria, in the budgeting and programming modules of the PMIS. In this paper, the author summarizes the data assembled and the adaptation of the HDM3 user-cost model to Saskatchewan conditions. Details can be found in a report prepared for SHT (*5*).

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COLLECTION OF SASKATCHEWAN DATA

Vehicle operating costs (VOCs) depend on a region's economy as well as vehicle technology, operation, and management. Present Saskatchewan vehicles, trucks in particular, are larger and more energy-efficient than vehicles surveyed in Brazil (Table 1). Brazilian labor was much cheaper, relative to prices of fuel, tires, and vehicles. To account for change in conditions when HDM3 is being transferred to a new environment, the model's relationships have been structured on generic, mechanistic principles. Adaptation of the model to Saskatchewan requires representative local vehicle characteristics and unit costs.

Vehicle Fleet Characteristics and Cost Data

Provincial registration records of cars, ranch wagons, vans, buses, trucks, and power units were compared with SHT vehicle travel statistics to obtain average annual travel per vehicle (Table 2). Representative car characteristics have been derived using relative frequency of makes/models in the provincial registrations as a weighting factor. Car automotive data have been obtained from dealers and catalogues. Registration reports were not available for pickups, vans, and trucks, and data were sought through a survey of fleet operators.

Most of the trips and tonnage on arterial highways are hauled by the common carriers. On collectors and local roads, the private carriers tend to dominate, but common carriers still haul the highest average payloads. Over the last 12 years, the number of combination units has been increasing at the expense of two- and three-axle straight trucks. The most common truck body type is a general merchandise van followed by a flat deck. Bulk cargo hauls are heavier, but less frequent than general merchandise trips. Empties constitute 20 to 40 percent of all trips. Lightly loaded trucks are most frequent on collectors and local roads. The fully laden truck was the most frequent among nonempty hauls.

Economic costs reflect the use of resources. Economic costs plus taxes, subsidies, and duties are required for financial

TABLE 1 COMPARISON OF TYPICAL VEHICLE CHARACTERISTICS, SASKATCHEWAN VERSUS HDM3 DATA BASE

Vehicle Type	Curb Weight tonnes	GVW tonnes	Maximum Rated Engine Power hp	Maximum Rated Engine Speed rpm	Annual Utilization, 10^3 km	Annual Utilization, 10^3 hours	Service (f)
Small Car							
Chevrolet Chevette/VW1300	1.0/1.0	-	65/48	5200/4600	16/20	-	I,U/I
Medium Car							
Ford Granada/Chevrolet Opala	1.4/1.2	-	120/146	4000/4400	16/20	-	I,U/I
Large Car							
Pontiac Parisienne/Dodge Dart	1.6/1.7	-	155/198	4000/4400	16/20	-	I,U/I
Utility							
Ford F-Series/VW Kombi	1.7/1.3	2.5/2.1	225/60	4000/4600	16/89	-	I,U/I
Two-axle Truck							
International(a)/Mercedes 1113	5.7/5.4	14.6/15.0	166/147	2400/2800	40(b)/101	1.2/2.0	U/I
Three-axle Truck							
International/Mercedes 1113	11.0/6.6	21.5/18.5	180/147	2700/2800	32/101	1.0/2.0	U/I
Five-axle Truck							
Kenworth W900(a)/Scania 110-39	14.5/14.7	37.5/22.0	350/285	2150/2200	160(c)/?	1.6(c)/?	I/I
Seven-axle Truck							
Western Star(d)/(e)	16.0/(e)	53.5/(e)	400/(e)	2000/(e)	160/(e)	1.6/(e)	I/(e)
Three-axle Bus							
MCI/Mercedes 0362	12.9/8.1	17.2/11.5	300/149	2100/2800	100/?	1.6/2.4	I/I

Notes:
/ Separation symbol between Saskatchewan data and HDM3 Brazilian database.
\- Not applicable data.
? Not known.
(a) Trimac (1986) data for Saskatchewan province, general merchandise cargo.
(b) Estimate using 32 km/h average running speed in urban service. Utilization in farm service is 5,000 km and 1,200 hours annually (Lea Associates 1986).
(c) Lea Associates 1987 survey of Saskatchewan truckers and "1985 Travel on Saskatchewan Highways" by Saskatchewan Highways and Transportation.
(d) Trimac (1986) data for Saskatchewan province, bulk cargo.
(e) Equivalents to seven-axle trucks did not exist in the Brazil study.
(f) I = inter-city, U = urban, F = farm

costs analysis. Multipliers were developed separately for fuels, materials and equipment, wages, and administration and were applied to the financial unit costs to obtain the economic costs. The financial costs of new and used vehicles and of tires have been surveyed from the press, dealers, and fleet owners. Average fuel costs were assumed. Maintenance shop labor rates were surveyed from repair and maintenance shops. One driver and one passenger in cars, vans, and pickups and 20 passengers in buses were assumed. The value of time was adopted from current SHT planning practice. For all trucks and buses, one driver at average industry rates per hour was assumed.

Survey of Saskatchewan Vehicle Operators

A pilot survey was carried out among Saskatchewan fleet operators in the summer of 1987. The survey asked for 1986

TABLE 2 VEHICLE TYPES AND USE IN SASKATCHEWAN

Vehicle Type	10^3 Registrations (e)		Highway Travel (f) 10^6 km/yr		Vehicle km/yr Hwy.	Vehicle km/yr Total (g)	Vehicle km/yr Assume
Car (a)	380		3,424		9,010	16,200	
Small		57			–	–	16,000
Medium		95			–	–	16,000
Large		228			–	–	16,000
1/2-ton (b)	171		1,541		9,010	16,200	–
Van (c)		46			–	–	16,000
Pickup		125			–	–	16,000
Truck (d)	87		742		–	–	–
2-Axle		71		230	3,200	5,800	40,000
3-Axle		10		60	6,000	10,800	40,000
≥5-Axle		6		452	75,000	135,600	160,000
Total	638		5,707				

Notes: (a) Curb mass: small <1,000 kg; medium 1,000-1,400 kg; large >1,400 kg.

(b) Including farm registration plates.

(c) Including ranch wagons.

(d) Excluding farm trucks, including buses.

(e) Saskatchewan Government Insurance, registration reports, 1986.

(f) "1985 Travel on Saskatchewan Highways," Saskatchewan Highways and Transporation.

(g) Travel on all roads = 1.8 * travel on provincial highways.

TABLE 3 SURVEY RESULTS: CARS AND LIGHT VEHICLES, GOVERNMENT AGENCY

Class	Typical Use	Annual Distance (km)	Average Service Life Time (yr)	Average Service Life Distance (km)	GVW (tonnes)	Average Tire Life (km)	Fuel, Oil and Grease Cost (¢/km)	Tire Cost (¢/km)	Maintenance, Parts, and Labor (¢/km)	Depreciation (¢/km)
Subcompact	Urban	18,000	6	100,000	–	40,000	3.6	0.3	3.5	5.0
Compact	Urban, highway	20,000	5	100,000	–	50,000	3.4	0.2	2.1	4.7
Mid-sized sedan	Highway	24,000	5	100,000	–	80,000	4.7	0.4	2.2	3.9
Mid-sized wagon	Highway	24,000	5	100,000	–	80,000	4.3	0.3	2.1	4.6
Standard sedan	Highway	27,000	4	100,000	–	95,000	4.7	0.3	2.9	5.2
Standard wagon	Highway	25,000	4	100,000	–	95,000	5.3	0.4	2.6	5.0
Compact pickup	Urban	18,000	5	100,000	–	45,000	4.5	0.3	1.5	5.6
Cargo van	Urban, highway	15,000	6	100,000	3–4.5	50,000	7.5	0.3	3.6	4.8
Passenger van	Highway	18,000	5	100,000	3–4.5	60,000	8.0	0.7	3.5	6.5
Four-wheel-drive pickup	Poor road, off-road	20,000	5	80,000	3–4.5	40,000	8.5	0.8	4.9	5.8
Two-wheel-drive pickup	Highway, off-road	26,000	5	100,000	3–4.5	80,000	7.6	0.6	3.2	4.0
1-ton truck	Mixed	15,000	7	100,000	5	40,000	12.3	1.2	6.7	8.0
2-ton truck	Mixed	15,000	8	150,000	10	50,000	16.7	2.0	9.0	13.0

TABLE 4 SURVEY RESULTS FOR BULK COMMODITY CARRIERS

	Carrier No.				
	1	2	3	4	5
Carrier Type	Common	Common	Common	Common	Private
Number of Tractors	22	42	81	15	12
Tractor Axles/hp (SAE)	3/400	3/400	3/400	3/335 & 400	3/400
Tractor Service, years	5	5	9	10	5
Typical Combination	7-axle tank	7-axle tank	7-axle open box	7-axle tank	5 & 7-axle tank
Annual 10^3km (a)	155	110-185	137	67 (e), 173 (f)	230
Annual hours (a)	4000	3000 (b)	1850	?	2600
GVW, t	53.5	47.6 (c)	49.0-53.5	49.0-53.5	34.5-49.9
Tare weight, t	18.5	18.0	15.9	18.5	?
Roundtrip payload, t	17.5	16.5	29.0 (g)	13.5-16.5	?
New Tractor Cost	83000	83000	104000 (d)	65000	120000 (d)
Trailer & Pup Cost	110000	?	50000	100000	?
New Tire Cost	?	350	425	300-450	350
Number/Cost of Recap	?	2/120	2/250	?/150	?/117
New Driving Tire Life, km	?	225000	225000	200000	210000
New Steering Tire Life, km	?	160000	?	?	?
Recap Life, km	?	225000	177000	200000	160000
Fuel, ¢/km	16.5	14.2	17.4	20.0	17.4
Oil and Grease, ¢/km	In maint. cost	In maint. cost	?	?	?
Tires Tractor/Trailer, ¢/km	2.3/?	2.2/2.3	1.4/2.2	3.4	2.4
Maint. Parts " , ¢/km	10.2/?	6.1/6.0	4.2/0.9	19.3	2.4/?
Maint. Labour " , ¢/km	12.1/?	?	?	?	4.0/?
Driver Wage, ¢/km	40.1	33.7	19.9	21.2	26.8

Notes: (a) Tractor only
(b) Including loading/unloading
(c) GVW limited by usage in the U.S.A.
(d) Including sleeper
(e) One driver
(f) Two drivers
(g) 15% haul distance empty, 85% fully loaded
? No data available
All costs in 1986 dollars

data, and 13 trucking companies operating about 700 tractors in Saskatchewan responded to the survey. Response from operators of two- and three-axle straight trucks, vans, and pickups was limited. Car rental and courier companies could not provide compatible data. The only usable data on cars and light vehicles were provided by a government agency (Table 3), but the tire and depreciation costs reflect confidential purchase prices.

The truckers' responses are summarized in Table 4 for bulk and in Table 5 for general merchandise carriers. The number of tractors refers to units used in Saskatchewan, although most of the carriers also operate other units in other provinces. Some scatter is present in the data because of differences in equipment and operating conditions, but trends in the operating costs can be linked to vehicle characteristics and use. Some companies do not manage trailers and could not provide cost data for them. Truckers secure different discount prices on fuel and equipment. Management policies also vary regarding driver selection and speed limits to minimize fuel costs and on-the-road maintenance. Each company controls tire wear uniquely. Maintenance and resale practice to optimize life-cycle cost of tractors also varies, as does the ratio of own

TABLE 5 SURVEY RESULTS FOR GENERAL MERCHANDISE CARRIERS

	Carrier No.						
Carrier No.	1	2	3	4	5	6	7
Carrier Type	Common	Common	Private	Common	Common	Private	Private
Number of Tractors	200	40	119	50	28	8	29
Tractor Axles/hp (SAE)	2-3/350	3/300-400	3/300	3/350	3/240-400	3/210	2-3/300-350
Tractor Service, years	8	4	10	3	6.5	12	10
Combination Axles	5-8	5-7	5	5-8	5-6	5	4-8
Annual km (a)	190,000	160,000	73,000[b]	160,000	170,000	322,000	144,000
Annual Hours (a)	?	2,100	?	?	?	?	?
GVW, t	36.3-53.5	37.2-53.5	36.3	36.3-49.9	36.3-47.7	?	16.0-36.0
Tare Weight, t	?	11.4-18.2	?	?	?	?	10.7-20.7
Roundtrip Payload, t	?	20.4[b]	?	14.5	12.3	?	3.4
New Tractor Cost	?	82,000-100,000	71,000	80,000	70,000	55,000	70,000
Trailer & Pup Cost	110,000	20,000-25,000 van		30,000 reefer	33,000	?	?
New Driving Tire Cost	450[c]	400[c]	280[d]	325	408[c]	350	325
Number/Cost of Recap	1/107	2/240-300	?/230	2/100	?	?/135	?/130
New Tire Life, km	250,000	160,000-240,000	?	180,000	?	55,000	160,000
Recap Life, km	0-100,000	100,000-180,000	?	64,000	?	?	100,000
Fuel/Oil, ¢/km	15.3/1.6	?	?	16.1/?	8.1/0.3	14.0/?	10.8/0.6
Tires Tractor/Trailer, ¢/km	1.3/?	?	2.9 total	1.9/?	0.7/?	1.9/?	0.9/0.7
Maint. Parts " , ¢/km	7.1 total	?	?	1.6/?	3.5/?	8.0/?	6.1/2.1
Maint. Labour " , ¢/km	?	?	?	0.6/?	?	?	?
Driver Wage, ¢/km	31.7[e] , 20.2[f]	?	69.0	17.7(g)	25.5	?	42.8

Notes: (a) Tractor only
(b) Peddle lines
(c) Radial tire
(d) Bias ply tire
(e) Less Than Truckload (LTL) operation
(f) Truck load (TL) operation
(g) Excluding burden
? No data available
All costs in 1986 dollars

equipment to lease-operators for capacity and productivity reasons. These practices are often confidential, and the reported costs may not fully reflect the extra savings achievable.

ADAPTATION OF HDM3 BRAZIL VOC MODEL TO SASKATCHEWAN PMIS

PMIS Requirements

The survey data and operating costs of Canadian cars (*6*) and Saskatchewan trucks (*7*) were input into the HDM3 micro-computer program for calculation of user costs as a function of road roughness. Administration cost has been added as shown in Equation 1. The program was also modified to improve the fitting of Equation 1 to the computed total costs by restricting the rougher limit of road roughness to 5 m/km international roughness index (IRI). The VOC function for vehicle type i in the traffic mix is given by

$$VOC_i = a_i e^{(A_i + B_i \cdot IRI)} \quad (1)$$

where

A_i and B_i = calibrated constants for Saskatchewan vehicle type i,
a_i = administration cost factor for vehicle type i, $a_i \geq 1.0$,
IRI = international roughness index,
$IRI = 1.44 + 29.8\ (10^{-0.2278\ \mathrm{RCI}})$, where $R^2 = 0.89$, $n = 22$, and
RCI = Saskatchewan riding comfort index scale.

Financial and economic costs are required by the PMIS, both with user delay and excluding the delay costs. The calibrated cost equations are used in the PMIS analysis with weights reflecting the traffic mix on each highway section.

Calibration of the HDM3 user-cost model must reflect the differences between typical vehicle technology, operation, management, and price relativities in Saskatchewan and in the HDM3 database. HDM3 relationships based on concepts inadequate for the province need revision, but limited resources only permitted calibrations of designated default values of the HDM3 model. Sensitivity of PMIS results to the uncertain HDM3 relationships will determine the need for further adaptation work. Large-scale interprovincial surveys may prove necessary to validate HDM3, owing to the experimental error normally found in this type of research. Of immediate consequence would be a check of the user-cost–roughness slope, which in PMIS could only be adapted from the Brazil study. Another survey should clarify the effect, if any, of pavement surface texture on rolling resistance, operating speed, fuel, and tire consumption. HDM3 ignores this variable, although other studies indicate significant effects (*8–10*). More work is also required to include cargo delay and damage, because in developed economies large quantities of high-valued cargo are transported. Damage and delay involve direct losses, as well as the disruption of materials and goods flow for manufacturers and distributors who rely on road transportation (*11–14*).

Calibration of Speed

It was first determined what the desirable speed (VDESIR) might be on Saskatchewan highways, and then iteration with the HDM3 model found the travel speed that matches observed average travel speeds. The assumed VDESIR was the 85th percentile, whereas the running speed was the average speed from the SHT 1986 speed survey. The corresponding value of β, the shape parameter of the Weibull distribution, was substituted into the speed equation. VDESIR so computed agreed to 2 percent for cars and 5 percent for trucks with the assumed VDESIR values. The β was calibrated for cars and articulated trucks. It was assumed that buses and half-tons have the same speed characteristics as cars and that all the truck types travel with the speed of five-axle combination units. The trucks were analyzed separately for the empty, fully laden, and average payload conditions to check the effect of averaging vehicle weight over round-trip distance.

The calibrated VDESIR is higher than in Brazil for both cars and trucks (Table 6) because of higher speed limit and possibly a perception of a better traffic safety in Saskatchewan. All values of β are well below unity and lower than HDM3 defaults, which agrees with the theory underlying the speed equation and with the observation of smaller variance of speeds on Saskatchewan highways compared to Brazilian data. For the heavier trucks carrying average network payloads, β needs to be forced to a limiting value of 0.04. This value of β increases the running speeds of empty trucks and decreases the speeds of fully laden units. Also, increasing VDESIR to car levels increases the calculated running speeds of empty trucks substantially, but not for fully laden trucks because β for this load condition is at the limiting value. Further investigation of the speed equation for trucks would be in order.

TABLE 6 SPEED CALIBRATION

Vehicle Type	Payload tonnes	VDESIR, km/h Assumed	VDESIR, km/h HDM3 Default	β Iterated	β HDM3 Default	Calculated Running Speed, km/h
Car	0.1-0.2	111	98.3	0.23	0.274	103.3[b]
1/2-Ton	0.5	108	98.3	0.24	0.274	97.3[b]
2-axle Truck	4.0	105	88.8	0.10	0.310	97.2[b]
3-axle Truck	8.4	105	88.8	0.04	0.310	95.5
Bus	2.0	111	93.4	0.13	0.273	103.2[b]
5-axle Truck	0.0	105	84.1	0.16	0.244	97.1[b]
	10.3[a]	105	84.1	0.04	0.244	96.5
	23.0	105	84.1	0.04	0.244	81.4
7-axle Truck	0.0	105	84.1	0.22	0.244	97.0[b]
	22.0[a]	105	84.1	0.04	0.244	97.3[b]
	37.5	105	84.1	0.04	0.244	81.9

Notes: (a) Average network payload, including empties.

(b) Approximately equal to average speed observed in 1986 survey.

TABLE 7 CALIBRATED ENERGY-EFFICIENCY FACTORS AND MODEL PARAMETERS FOR MAINTENANCE PARTS (CP_o) AND LABOR (CL_o)

Saskatchewan Vehicle	Energy Efficiency Factor	CP_o (10^{-6})	CL_o
Small Car	0.80	20.3	36.2
Medium Car (a)	1.00	20.3	44.5
Large Car	0.66	20.3	53.0
Half-ton Pickup or Van (b)	0.58	26.3	60.5
2-axle Truck	0.80	1.93	136
3-axle Truck	0.65	8.43	179
5-axle Unit	0.75	5.56	232
7-axle Unit	0.65	6.60	296
Bus	1.00	0.445	369

Notes: (a) Analyzed as HDM3 small car.

(b) Analyzed as HDM3 light gasoline truck.

Fuel and Lubricants Consumption

Fuel consumption data exist for the average present road roughness levels in Saskatchewan, but not for rougher conditions. The Brazil study did not find significant increases in fuel consumption in the range of roughness considered in PMIS policy analysis. To calibrate fuel consumption, HDM3 was run for each vehicle with corrected speed parameters, proper vehicle characteristics, and IRI = 2 m/km (RCI 7.5). The model output was compared with typical fuel consumption in Saskatchewan. The energy efficiency factor (Table 7) was calculated as the ratio of data to HDM3 prediction. The HDM3 formula for lubricants consumption is a linear regression with the intercept equal to engine oil volume equivalent of all oils and lubricants. The intercept was adjusted to reflect collected data, whereas the Brazil default coefficient of the roughness variable was assumed to apply to Saskatchewan.

Tire Consumption

The slope coefficient of the roughness variable was assumed to hold for Saskatchewan. The constant term for cars and utilities was calibrated to correspond to tire life of 80,000 km. The regression of rolling resistance on roughness underlies the truck and bus tire consumption formulas in HDM3, and the equations were adopted without any changes. Industry tire consumption data (*7*) and data from the survey of truckers were input into the model, but the solution was not reasonable, possibly because of high sensitivity to vehicle weight, ratio of recapping to new tire cost, and bias ply versus radial tire properties. An adjustment was made in tire price instead.

Maintenance Parts and Labor

The roughness variable appearing in the parts equation is important, because it also determines maintenance labor in HDM3. The parts cost-roughness slope is a function of the HDM3 default constant CP_o. If CP_o is calibrated, the slope changes relative to the Brazil data. Forcing the slopes before and after calibration to be equal produces negative parts consumption. For this reason the HDM3 expression for the slope of the parts and labor relationships was assumed to apply to Saskatchewan. The truckers indicated that parts account for 45 to 60 percent of the total maintenance cost, but the ratio changes with a vehicle's age. A ratio of 0.5 was assumed, and the resulting calibrated constants CP_o and CL_o for the parts and labor equations, respectively, are shown in Table 7.

Depreciation and Interest

To obtain a correct value for depreciation and interest cost, the vehicle price was reduced by its resale value at the end of its highway use stage. This is particularly important for tractors, which are generally used on highways for about the first 5 years and in urban service afterwards. For this reason, the new price of tractors should be taken net of resale value at approximately 800,000 km. The duration of highway use stage of each vehicle and the ratio of scrap value at the end of the stage to new prices are shown in Table 8, based on local data. A more rigorous method should be developed to take account of vehicle-life staging and, if necessary, the effect of warranty maintenance on the purchase price. This will require changes in the program code, which now is structured to accept the same vehicle price for both the maintenance and the depreciation and interest cost calculations.

CALIBRATED USER-COST EQUATIONS

Aggregated User-Cost–Roughness Relationships

The calibrated model parameters were substituted for default values, and the HDM3 was run for each of the nine typical

TABLE 8 DURATION OF HIGHWAY UTILIZATION STAGE AND SCRAP VALUE

Vehicle Type	Highway Utilization Stage, years	Scrap/ New Value
Small Car	7	0.10
Medium Car	7	0.15
Large Car	7	0.15
Half-ton	10	0.15
2-axle Truck	8	0.18
3-axle Truck	8	0.18
5-axle Truck	5[a]	0.40[b]
7-axle Truck	5[a]	0.40[b]
3-axle Bus	13	0.23

Notes: (a) Tractor only, trailer 10 years.

(b) Tractor and trailer combined, based on 0.34 ratio for tractor and 0.50 ratio for trailer.

TABLE 9 CALIBRATED CONSTANTS

	FINANCIAL COSTS					ECONOMIC COSTS				
	Without User Delay			With User Delay		Without User Delay			With User Delay	
Vehicle Type	A_i	B_i	a_i	A_i	B_i	A_i	B_i	a_i	A_i	B_i
Small Car	5.13	0.0256	1.0	5.77	0.0186	4.82	0.0265	1.0	5.45	0.0192
Medium Car	5.34	0.0260	1.0	5.88	0.0206	5.02	0.0272	1.0	5.56	0.0213
Large Car	5.52	0.0249	1.0	5.99	0.0196	5.20	0.0260	1.0	5.67	0.0203
Half-ton	5.42	0.0298	1.0	5.96	0.0216	5.07	0.0320	1.0	5.62	0.0228
2-axle Truck	6.14	0.0564	1.1	-	-	5.79	0.0604	1.1	-	-
3-axle Truck	6.39	0.0394	1.1	-	-	6.04	0.0417	1.1	-	-
5-axle Truck	6.35	0.0343	1.1	-	-	5.98	0.0387	1.1	-	-
7-axle Truck	6.60	0.0421	1.1	-	-	6.24	0.0465	1.1	-	-
3-axle Bus	6.42	0.0236	1.1	7.67	0.0115	6.05	0.0250	1.1	7.33	0.0118

Note: - Not applicable

vehicles to calculate the component user costs and to fit Equation 1 to the aggregate cost. The calculated constants of the exponential equation are assembled in Table 9, which also lists estimated factors a_i for the administration costs of the commercial vehicles.

Calculated financial and economic transportation costs are similar, except for their magnitude. The financial cost-RCI slopes are similar for all light vehicles (Figure 1) and similar for trucks (Figure 2). The breakdown into financial cost components is shown in Figures 3 and 4 for the medium car and seven-axle truck. The largest share of the car operating costs is taken by depreciation plus interest, followed by fuel cost. Crew cost is also significant in the commercial vehicles. The largest cost increase with roughness occurs in the maintenance and depreciation components. Fuel cost drops at lower RCI values because of reduced speeds of large trucks on rough

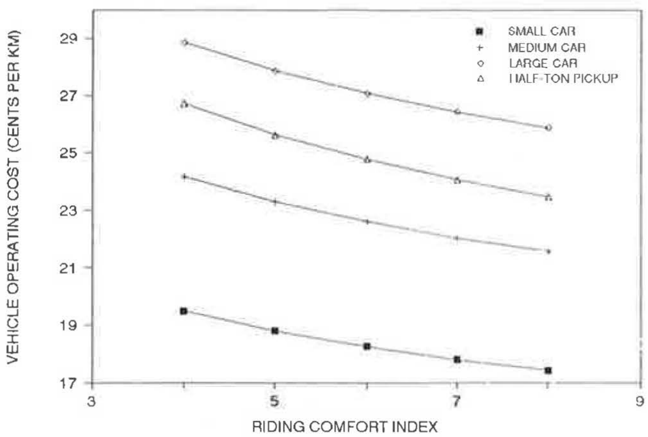

FIGURE 1 Total financial operating cost of light vehicles.

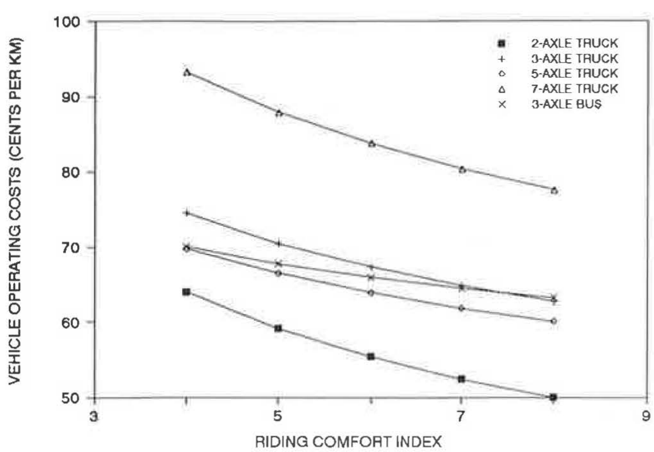

FIGURE 2 Total financial operating cost of heavy vehicles.

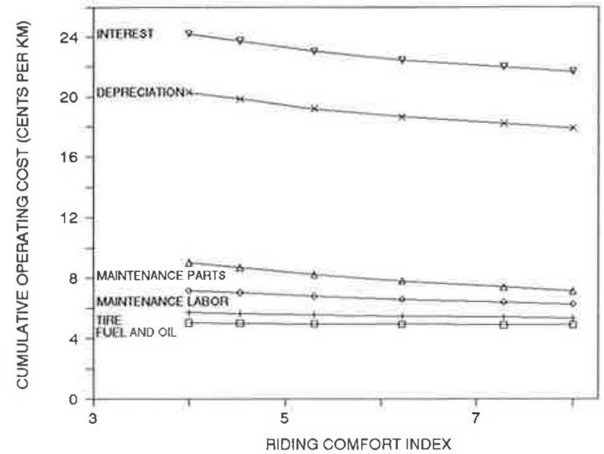

FIGURE 3 Medium-car financial cost components.

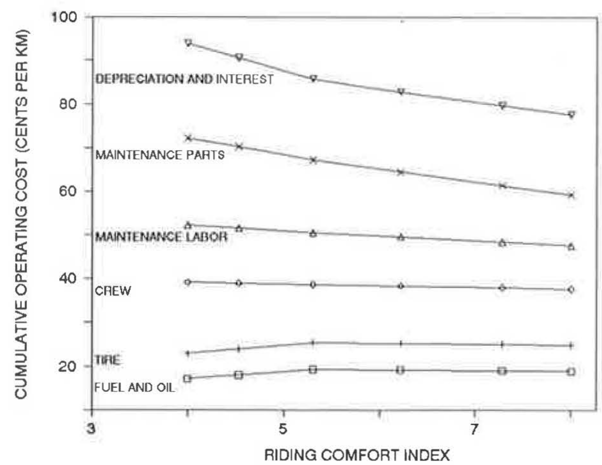

FIGURE 4 Seven-axle truck financial cost components.

roads, but crew time increases. Figure 5 shows the change in total financial costs when roughness decreases from RCI 8 to RCI 4. All cars are represented by the large car. The two-axle truck experiences the highest marginal rates of increase with roughness, whereas the bus has the lowest increase. When user delay is added, the marginal rates drop. The drop is most pronounced for the bus and amounts to halving the marginal rate. One can thus conclude that the bus-cost curve is very sensitive to the number of passengers. Similar conclusions are valid for the economic costs.

Sensitivity Analyses

The rolling resistance was varied between 80 and 140 percent of the default value (Figure 6). The operating cost of trucks is about three times more sensitive to rolling resistance at $RCI = 7$ than the cost of cars. On rougher roads the sensitivity drops because trucks then operate at lower speeds. The calibrated engine speed (rpm), the use, and the service life were also changed in 20 percent increments for medium car and seven-axle truck (Figure 7). Increasing engine speed from the levels recommended by HDM3 does not have any effect on the total costs of vehicle operation at either roughness level

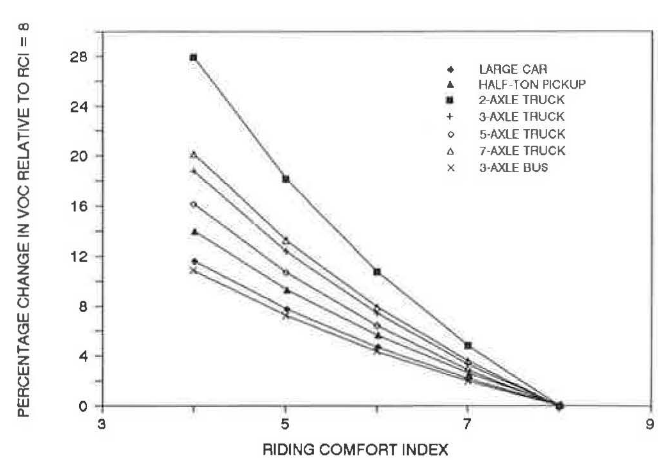

FIGURE 5 Relative change in financial costs.

for the medium car, but decreasing engine speed (rpm) results in a 3 percent drop in the costs. The seven-axle truck experiences a 5 percent drop with increasing rpm and smaller drop with decreasing rpm.

The annual distance driven was varied, but the annual time driven was adjusted to maintain the base case operating speed,

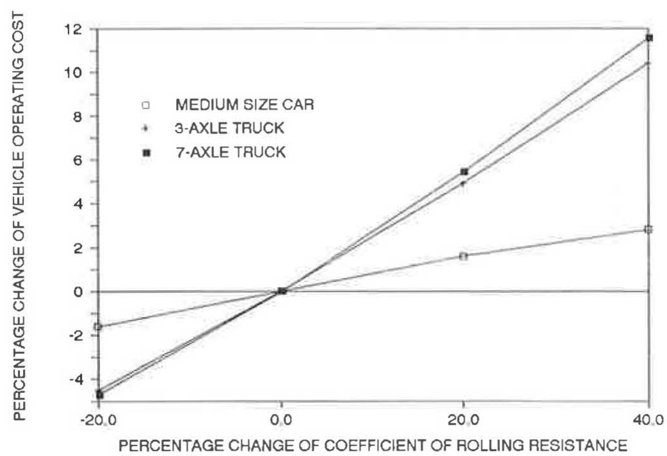

FIGURE 6 Sensitivity of vehicle operating costs to rolling resistance at *RCI* = 7.

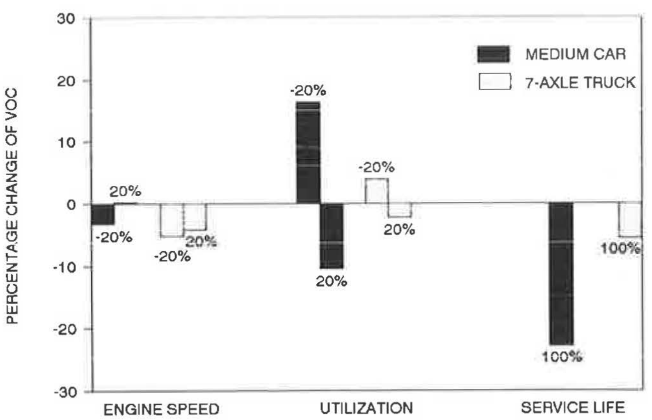

FIGURE 7 Sensitivity of vehicle operating costs to engine speed, utilization, and service life.

and the lifetime distance driven was recalculated using the base case service-life years. A 20 percent change in use of the medium car has a dramatic effect on the total operating costs. For the seven-axle truck, the effects are similar in direction, but smaller in magnitude. Service life was increased by 100 percent because this is the order of magnitude of the ratio of one use stage to the whole life. For example, truck tractors are used in intensive line-haul for about 5 years and then for another 5 to 10 years in less demanding service. Again, the medium car is far more sensitive to this variable than the truck.

CONCLUSIONS

The HDM3 user-cost model proved very useful for the Saskatchewan PMIS and was successfully calibrated to the local conditions, even outside of the inference space covered by the study of user costs in Brazil. The calibration relies on availability of representative vehicle and cost data. It was not possible within the scope of this study to gather vehicle operating cost data from the rougher road surfaces, and the cost-roughness slope found in the Brazilian data will require future verification.

For the needs of Saskatchewan, relationships capturing the costs of delay and damage of cargo in transit should be included into the suite of user-cost models. Depreciation, interest, and maintenance costs also require a closer investigation because of their interplay in vehicle-owner decisions. These decisions depend on the economy, technology, and government regulation, all of which are distinctly different than in the Brazilian study and are also changing quite radically in Canada.

Depreciation and maintenance costs overlap in present-day pricing of vehicles because the costs of repair on factory warranties are included in the purchase price. Available vehicle use data are not clear either, because of mixed urban/highway travel and distinct use staging of lives of all vehicle types. A methodology needs to be developed to address these issues, so that an accurate estimation of user costs can be made for the operation of the PMIS.

More specific observations of truck speeds as a function of payload and engine power are required to calibrate the HDM3 speed relationships for Saskatchewan's heavy trucks. The effect of pavement texture on rolling resistance is significant but remains to be clarified. The texture affects speed prediction, fuel, and tire consumption. Tire consumption relationships are inappropriate for the radial tire technology, but calibration is possible. Maintenance parts and labor cost equations can be calibrated with some difficulty attributable to the mathematical structure of the HDM3 relationships.

Data necessary to clarify these issues should be collected in a national survey to ensure a data base large enough to cover a wide range of paved road roughness and texture and to quantify the experimental error resulting from intercompany differences.

ACKNOWLEDGMENTS

Research reported in this paper has been initiated and sponsored by the Saskatchewan Highways and Transportation. The author wishes to thank Dennis Day, Gary Heiman, Jon Wyatt, and Masood Hassan for valuable inputs into, and constant interest in, the research. Words of gratitude are also due to all the participants of the pilot survey of Saskatchewan vehicle fleets and operating costs.

REFERENCES

1. *Research on the Interrelationships Between Costs of Highway Construction, Maintenance, and Utilization.* Final Report, 12 volumes. Brazilian Ministry of Transport, Texas Research and Development Foundation, and International Bank for Reconstruction and Development, 1982.
2. A. Chesher and R. Harrison. *Vehicle Operating Costs: Evidence from Developing Countries.* Highway Design and Maintenance Standards Series. Johns Hopkins University Press, Baltimore, Md. and London, England, 1987.
3. T. Watanatada, A. M. Dhareshwar and P. R. Lima. *Vehicle Speeds and Operating Costs: Models for Road Planning and Management.* Highway Design and Maintenance Standards Series. Johns Hopkins University Press, Baltimore, Md. and London, England, 1987.
4. J. B Cox, G. H. Heiman, M. U. Hassan and R. A. Deighton. An Integrated Approach to the Development of Pavement Management System for Saskatchewan. *Proc., 2nd North American Conference on Managing Pavements,* Toronto, Ontario, Canada, Vol. 1, 1987.
5. Lea Associates. *Saskatchewan PMIS Engineering Technical Man-*

ual, Appendix 1: Vehicle Operating Costs. Final Report. Saskatchewan Highways and Transportation, Regina, Saskatchewan, Canada, 1988.
6. *1986–87 Car Costs.* Canadian Automobile Association, Ottawa, Ontario, Canada.
7. Trimac Consulting Services Ltd. *Operating Costs of Trucks in Canada, 1986.* Transport Canada Policy and Coordination Branch, Ottawa, Ontario, Canada, 1986.
8. L. W. DeRaad. *The Influence of Road Surface Texture on Rolling Resistance.* Paper 780257. SAE, Warrendale, Pa., 1978.
9. D. C. Biggs. *ARFCOM—Models for Estimating Light to Heavy Vehicle Fuel Consumption.* Research Report ARR152. Australian Road Research Board, Vermont, Victoria, 1988.
10. U. Hammarström and B. Karlsson. *VETO—A Computer Model for Calculation of Transport Costs as a Function of Road Standard.* VTI Meddelande 501. Swedish Road and Traffic Research Institute, Linköping, 1987 (in Swedish with English summary and figure captions).
11. *The Role of Shippers and Transport Operators in the Logistics Chain.* Report of the 76th Round Table on Transport Economics, European Conference of Ministers of Transport, Economic Research Center, Paris, France, 1987.
12. R. K. Whitford. *Aspects of Freight Service Quality for Just-in-Time Transportation Serving the United States Automobile Industry.* VTI Meddelande 537A. Just-in-Time Transport Seminar, Organization for Economic Cooperation and Development and Swedish Road and Traffic Institute, Gothenburg, 1987.
13. J. Lindström. Improved Road Standards and Business Efficiency. *Proc., World Conference on Transport Research*, Vancouver, British Columbia, Canada, Vol. 1, 1986.
14. P. G. Koltnow. User's Perspective of Highway Pavements. *Proc., 2nd North American Conference on Managing Pavements*, Vol. 4, Toronto, Ontario, Canada, 1987.

Publication of this paper sponsored by Committee on Application of Economic Analysis to Transportation Problems.