Application of HDM3 Pavement Deterioration Model in Saskatchewan Pavement Management Information System

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Performance models for roughness progression, rutting, spot sealing, cracking, and patching have been developed for the Saskatchewan Pavement Management Information System using the World Bank's HDM3 model. A correlation between the Saskatchewan Riding Comfort Index and the International Roughness Index was developed. To separate the environmental effects from traffic effects on roughness, 396 km of asphalt pavements that had appreciably different axle loadings on adjacent lanes were examined. The models have been evaluated using 1976–1987 roughness data and recent maintenance records for the entire paved provincial highway network and 1987 condition survey results from 1,909 km of roads. A modified rut-depth model retains pavement age as the most significant variable. Cracking and potholing do not develop to a state critically affecting roughness and were excluded from the model. Regression analyses revealed that the last term in the HDM3 model explains most of the roughness deterioration observed in the field. This is due to grouping of pavement types for model development, which tends to enhance the collinearity between pavement strength and loading data. The age and cumulative axle loading variables were halved because the pavements are frozen half of the time. The calibrated environmental factors $m = 0.035$ for the arid south and $m = 0.050$ for the humid north of Saskatchewan agree with validations of HDM3 by others. Roughness deterioration becomes faster with more advanced age of all pavements, but the increase is relatively small for resealed full-depth and asphalt concrete pavements. Thin asphalt mixes laid directly over subgrade deteriorate most rapidly of all pavement types and faster in the northern than in the southern climatic zones. Maintenance models show similar trends.

Saskatchewan Highways and Transportation (SHT) have 24,000 km of paved roads under their jurisdiction. A pavement management information system (PMIS) was developed on the principles of life-cycle costing of highway investment decisions (*1*). The consideration of user costs and their dependence on road conditions had been one of the main premises of the SHT philosophy. The HDM3 version of the roughness progression submodel in the World Bank's Highway Design and Maintenance Standards Model was evaluated and was found suitable for the PMIS. Although HDM3 has been verified with data from a wide range of climatic regions, no attempts have been made to adapt or calibrate the pavement deterioration model for climatic conditions typical of the Canadian Prairies. This paper reports on the research that has been performed to develop a set of pavement performance models for the PMIS.

HDM3 PAVEMENT DETERIORATION MODELS

The HDM3 model for roughness progression attributes the total loss of rideability to structural, surface condition, age, and environmental factors. Mechanistic principles have guided the general form and combination of parameters in the relationships, so that the models can be transferred to other conditions with a suitable local calibration. The relationships have been derived from road condition data observed over a 5-year period on 116 in-service sections of flexible pavements. The sample covers a wide range of pavement types, maintenance status, strengths, traffic loadings, and age that were selected according to a composite factorial experimental design (*2*). Other empirical studies from climates ranging from arid to humid, and from tropical to temperate freezing, were used to validate the HDM3 models and to determine the effects of environment and materials across regions. The validation was limited by the availability of roughness time-series and by differences in measures of condition adopted in the empirical studies. For temperate freezing climates, the models may require reformulation.

The model has a number of pragmatically important features for the Saskatchewan PMIS. First, it facilitates life-cycle cost evaluation of pavement projects by concentrating on pavement roughness, which determines riding quality and the economic benefits from maintenance and rehabilitation (*3*). Second, the roughness is measured in International Roughness Index (IRI) units, which are time-stable and transferable. The provincial Riding Comfort Index (RCI) scale is largely subjective and depends on the variability of response-type roughness-measuring equipment used in the RCI surveys. Third, the model has an incremental form, which is compatible with

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the annual condition surveys and the PMIS analysis. Fourth, the use of calibration constants in each term facilitates adaptations of the model to the Saskatchewan environment and to local construction and maintenance practices.

Roughness Progression Model

The roughness progression model in HDM3 contains six terms, as follows:

$$\Delta RI = 134 e^{mt} MSNK^{-5.0} \Delta NE4 + 0.114 \Delta RDS + 0.0066 \Delta CRX + 0.003 h \Delta PAT + 0.160 \Delta POT + m RI_t \Delta t \qquad (1)$$

where

ΔRI = increase in roughness over time period Δt (m/km IRI);
RI_t = roughness at time t (m/km IRI);
m = environmental factor;
t = average age of pavement or overlay (years);
Δt = incremental time period of analysis (years);
ΔRDS = increase in rut-depth standard deviation of both wheelpaths (mm);
ΔCRX = increase in indexed area of cracking (percent);
ΔPAT = increase in area of surface patching (percent);
ΔPOT = increase in the total volume of potholes (m^3/lane km);
$\Delta NE4$ = incremental number of equivalent standard-axle loads (ESALs) in period Δt (million ESALs/lane);
$MSNK$ = $1 + MSN - 0.000758\ H\ CRX$;
h = average deviation of patch from original surface profile (mm);
MSN = modified structural number of pavement strength; and
H = thickness of cracked layer (mm).

The first two terms relate to structural factors; the third, fourth, and fifth terms take account of the effects of surface condition; and the sixth term reflects the impact of environment (climate and subgrade factors) and of the present roughness. All terms are affected by maintenance.

Rutting Progression and Other Models

The roughness progression due to traffic loadings and pavement strength is significantly influenced by the longitudinal variation in rut depth (*2*). The HDM3 model predicts the rut depth caused by the accumulated plastic deformation from traffic on asphalt pavements with granular or cemented nonbituminous base construction. In full-depth asphalt concrete pavements, deformation develops by a different mechanism and requires a different model. The mean rut depth was found to increase sharply initially and thereafter at a lower rate in the Brazilian study. The model developed from the data relates the mean rut depth to average compaction of the base course layer, the modified structural number, and the cumulative traffic loading, with effects also from cracking, rainfall, deflection, and rehabilitation status as follows:

$$RDM = K t^{0.166} MSN^{-0.502} COMP^{-2.30} NE4^{ERM} \qquad (2)$$

where

RDM = mean rut depth in both wheelpaths (mm);
K = calibration constant for local conditions;
ERM = $0.0902 + 0.0384\ DEF - 0.009\ RH + 0.00158\ MMP\ MCRX$;
t = age of pavement since construction or most recent overlay (years);
$COMP$ = average level of compaction in unbound layers expressed as fraction of nominal specifications;
DEF = Benkelman beam maximum deflection under 80-kN axle load (mm);
$MCRX$ = weighted area of cracking (percent [weight for 3-mm-wide cracking = 2.0, for narrow 1-mm cracking = 1.0]);
MMP = mean monthly precipitation (m);
$NE4$ = cumulative number of ESALs/lane (relative load damage power of 4);
RH = 0 if original surfacing, = 1 if an overlay; and
MSN = modified structural number of pavement strength.

The variation of rut depth was found to be strongly related to the mean rut depth as follows:

$$RDS = k 2.06 RDM^{0.532} MSN^{-0.422} COMP^{-1.66} NE4^{ERS} \qquad (3)$$

where

RDS = standard deviation of rut depth in both wheelpaths (mm);
k = calibration constant for local conditions;
ERS = $-0.009\ RH + 0.00116\ MMP\ MCRX$;

and other variables are as in Equation 2.

HDM3 also contains models for initiation and progression of cracking, raveling, and potholing. These distress models, however, are of lesser significance for the PMIS since their impact on roughness is relatively small. A sufficiently detailed database does not yet exist to permit calibration of these relationships to Saskatchewan conditions.

Validation of HDM3 Approach

HDM3 approach to pavement deterioration was evaluated early in the PMIS development for applicability to Saskatchewan (*4*). Accurate RCI-IRI correlations were not available at that time, condition data were limited, and the HDM3 model was an earlier edition but the same as Equations 1, 2, and 3 in principle. The HDM3 mean rut-depth model was found to be a reasonable predictor for a sample of five Saskatchewan asphalt concrete pavements constructed without mix problems. A sample of 396 km of pavements with significantly different axle loadings but similar structure in both lanes was selected from the provincial highway network. The objective of the analysis was to estimate the relative contribution of various terms in the HDM3 model to roughness deterioration. The traffic-related terms in the HDM3 roughness deterioration model were found to be small. Environment and maintenance affect the variability of the roughness results to a much greater degree. In the preliminary analysis an increase in roughness by 2.5 percent per year was detected owing to a combination of environmental and maintenance factors in Saskatchewan. This increase should be compared with 1 percent (environmental effect only) observed in the drier Tunisian climate and 2 percent in the tropical Brazilian climate. This finding concurs with those of other studies in Canada that found that age, and not traffic, was the major variable affecting pavement deterioration (*5,6*). It also concurs with the measurement of actual pavement distress in Ontario where the predominant failure modes were related to the environment and not to traffic (*7*).

CALIBRATION OF THE HDM3 PAVEMENT PERFORMANCE MODELS

Data Gathering and Preparation

Preparation of data for PMIS model development and calibration involved compilation of the construction history, highway inventory, maintenance, traffic, RCI, environmental, and condition survey data into a Model Development File residing on an SHT mainframe facility. The modified structural number was calculated, and each piece of road was assigned to a pavement model group. Twelve years of historical RCI data, from 1976 to 1987, and annual ESAL data from 1960 to 1986 were also appended to each record. A correlation between RCI and IRI scales was developed to make using the HDM3 model possible with Saskatchewan roughness data.

Correlation of Roughness Scales

Saskatchewan RCI scale ranges from 0 (an "unpassable" pavement) to 10 (the smoothest pavement possible). The IRI scale is expressed in meters per kilometer. In North America the roughest highways are likely to be 5 or 6 m/km IRI, and a new pavement typically has an IRI of 1 to 2 m/km. The correlation shown in Figure 1 was developed in order to use historical RCI data for model development, and to use current RCI data to operate the modified HDM3 models in the PMIS. It compares reasonably well with the World Bank's formula (*2*).

Pavement Model Groups

Because each highway cannot realistically have its own performance models, groups of similar pavements were set up. The SHT pavements have been designed for a specific design life or built with a standard cross section. Staged C and D pavements are 50 mm and 20 mm of asphaltic mix, respectively, laid directly on the subgrade and provided with gravel shoulder surface. These thin pavements comprise half of the paved SHT network. For pavement model groupings in the PMIS (Table 1), original surfacing consists of full-depth asphalt concrete, asphalt concrete on granular base, double seals, and cold mix on granular base. Reseals, overlays, and recycled pavements add five pavement groups encountered in the network.

Modified Structural Number

The HDM3 model uses the modified structural number (*MSN*) to indicate pavement strength, including a contribution from the subgrade dependent on its *CBR* value. Analysis of the *MSN* in the Brazilian study produced a high correlation with pavement performance. Compared with pavements designed by conventional methods, actual in situ strengths of Saskatchewan pavements increase more quickly with design axle loadings and are more consistent with the range of traffic loadings to which each pavement type is used and with an economic pavement design (*8,9*). The modified structural number was calculated as follows (*2*):

$$MSN = \sum_{i=1}^{n} a_i t_i/25.4 + 3.51 \log_{10}CBR - 0.85(\log_{10}CBR)^2 - 1.43 \qquad (4)$$

where

MSN = modified structural number including subgrade contribution;
n = number of pavement layers, including subbase, base, surface, and overlays;
a_i = strength coefficient of pavement layer i;
t_i = thickness of pavement layer i (mm); and
CBR = in situ California Bearing Ratio of subgrade, percent.

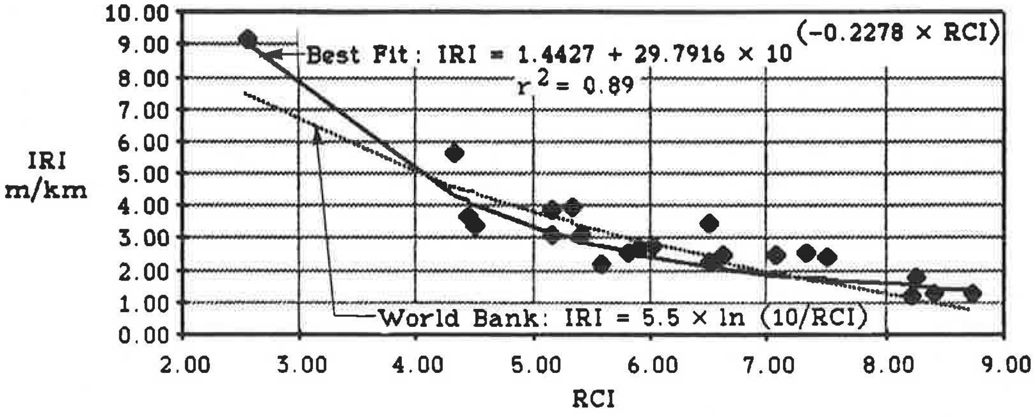


FIGURE 1 Roughness scale correlation.

TABLE 1 SASKATCHEWAN PAVEMENT MODEL GROUPS

Pavement Model Group	Pavement Description
01	Asphalt Concrete (AC) on Granular Base
02	Full Depth Asphalt Concrete (FDAC)
03	Double Seal (DS) on Granular Base
04	Cold Mix on Granular Base, DS or Subgrade,
06	Staged C
07	Staged D
20	Reseal on AC, or on AC Overlay
21	Reseal on FDAC
22	AC Overlay on AC, FDAC, DS, or on Cold Mix
23	Reseal on DS
24	Recycled AC or Recycled FDAC

Pavement Condition Survey

In 1987, 1,909 km of highways were surveyed. SHT collects surface condition data with a minivan towing a Portable Universal Roughness Device (PURD). This unit collects roughness information as well as surface distress and rutting data. Visual rating is accomplished with keyboards used to register observed surface distresses. An on-board computer records information gathered at 50-m intervals. The data collection vehicle is driven at 40 km/h centered in the outside driving lane. A driver and a passenger each operate a keyboard. They must view both lanes of the road surface and determine the severity and extent of surface defects within the 50 m immediately in front of them.

Climatic Zones

The province has been subdivided into four climatic zones for PMIS (Figure 2 and Table 2). Most of the provincial highways are located in climate zones A, B, and C. The climate of Saskatchewan varies from semiarid in the southwest, to dry subhumid in the center, and moist subhumid in the northeast. Negative Thornthwaite Index values in the southwest indicate a negative balance of rainfall to evaporation. Environmental zones follow the general shape of the Thornthwaite Index contours and the pedological soil zones. Soil zones were chosen as the basis of classification because soil types are a reflection of climate.

Pavement performance varies from good in the arid southwest to poor in humid northeast Saskatchewan. Thin pavements, which rely mainly on their subgrade strength for good performance, are particularly sensitive to climate, as is reflected in higher maintenance costs in the wetter zones. Freezing and thawing of subgrades have more impact on a thin pavement than any other climatic factors. Specific weather events or particular seasonal conditions can cause large differences in the performance of thin pavements. The thicker, conventional pavements tend to be less susceptible to climate. Full-depth asphaltic concrete pavements are more susceptible than standard pavements because of their thinner cover over the subgrade.

Subgrades

Subgrades markedly affect the thin pavements, and they also contribute to the strength of conventional pavements. A soaked CBR value is used for pavement design and as a general description of subgrade supportability. Subgrade shear strength varies along and across the highway because of variations in soil types, water contents, and stress history, creating a broad range of shear strengths on the provincial highway system. Modification of the highway subgrade to a design standard reduces some of these variations and provides a preferred soil type in the upper layer. CBR was grouped for the PMIS into four ranges, and each range was assigned a mean value.

Maintenance Data

Maintenance quantities are generally reported as one value for the entire reporting section of road. The data on maintenance quantities contained in the Maintenance Management Information System were distributed along each piece of road in the Model Development File using the actual manual records prepared by the district maintenance engineers, if available. The process consisted of dividing the maintenance cost by its reporting section length, then multiplying by the length of the piece of road in the Model Development File.

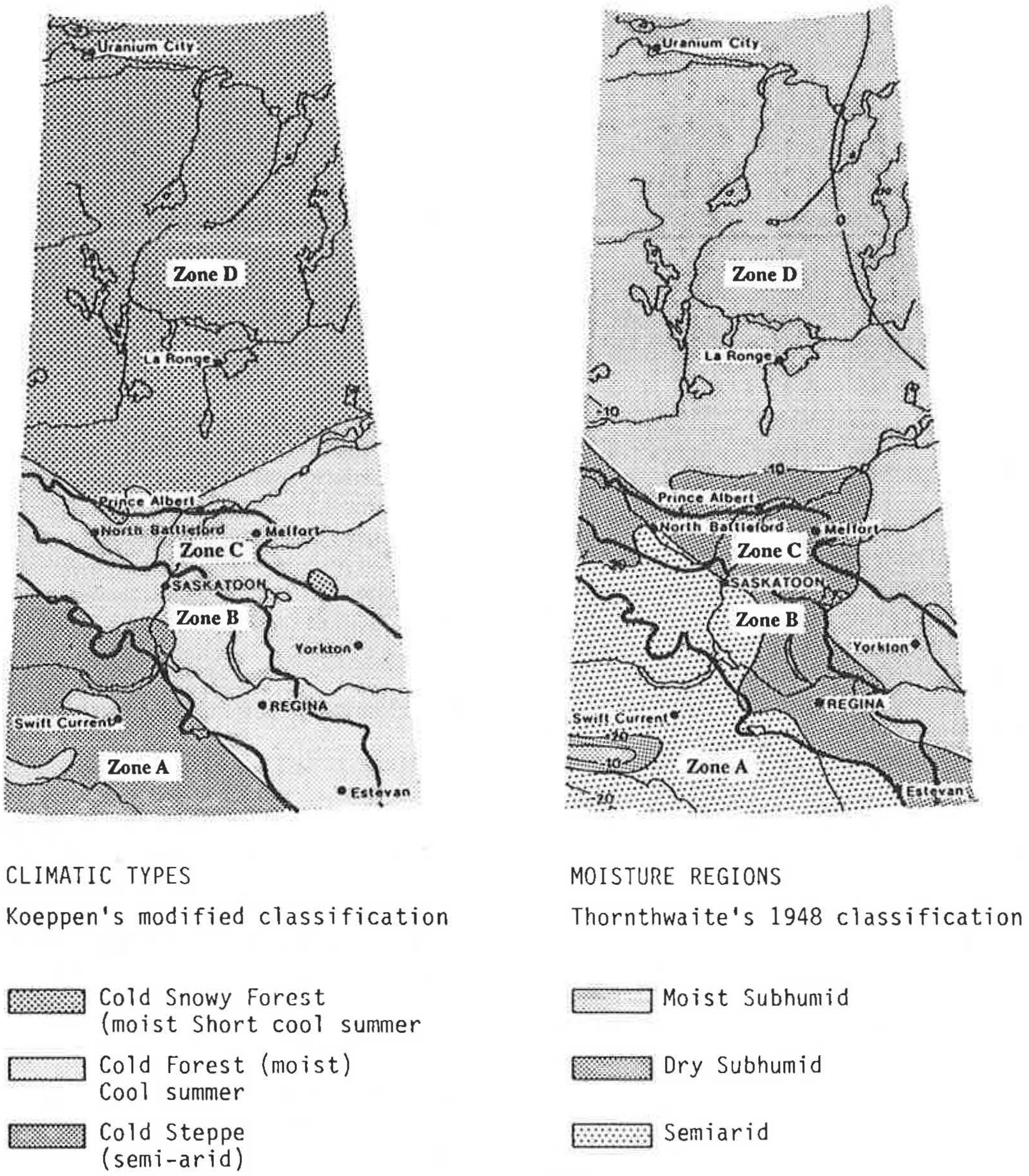
Rut Mean Depth and Standard Deviation Analysis

The 1987 PURD survey data were used in developing the rutting models. An attempt was made to calibrate Equation 2 by identifying the exponents in a linear multiple regression analysis. As data on indexed cracking and compaction index are not available in SHT files, assumptions were made in order to calculate the *ERM* exponent. Deflection was calculated from a Benkelman beam deflection—*MSN* relationship. The regressions found were poor, and the following model was tested instead:

$$RDM = t^A * MSN^B * NE4^C * D * e \tag{5}$$

where A, B, C, D are model parameters, e is the error term, and other symbols are as in Equation 2. The multiple regression was run with intercept and without, but the intercept term D was not found to be significantly different than 1.0 and was dropped for simplicity. The resulting equations violated boundary conditions and predicted unreasonable rut depths for two reasons. First, the observed rut depths in Saskatchewan are often masked by the effect of routine maintenance activities, particularly on thin pavements. Second, rut depths appear fairly independent of the modified structural number and only weakly dependent on the cumulative standard axle loading. There is a well-defined rut progression during the first few years of a pavement's life, but afterward the relationship between rut depth, *MSN*, and *NE*4 is not clear.

Consequently, rut depth was assumed to be independent of *MSN*. Two subsets of data were isolated for each pavement model group. The first subset contained low rut-depth observations at low levels of *NE*4. The second subset contained high rut-depth observations at high *NE*4. Mean *RDM*, *t*, and *NE*4 were calculated for each subset. The mean values defined a set of two equations that were solved for the two unknowns *A* and *C*. There was no a priori reason for rut model differences between the climatic zones, and one set of parameters was developed for the entire province. Model groups 01 and



CLIMATIC TYPES

Koeppen's modified classification

MOISTURE REGIONS

Thornthwaite's 1948 classification

Source: Saskatchewan Atlas

FIGURE 2 Climatic zones of Saskatchewan.

TABLE 2 CLIMATIC ZONES IN SASKATCHEWAN

	CLIMATE ZONE			
	A	B	C	D
Predominant Soil Type	Brown	Dark Brown	Black	Forest
Mean Annual Snowfall (mm)	900	1050	1150	1270
Mean Annual Rainfall (mm)	300	340	380	410
Thornthwaite Moisture Index	-20	-15	-10	-10
Mean January Daily Temp. (^{O}C)	-12	-17.5	-20	-22.5
Mean July Daily Temp. (^{O}C)	18.5	17.5	16.5	15.5
Mean Annual Frost Free Days	100	90	80	70
Mean Annual Hours of Sunshine	1300	1300	1250	1200

02 were merged, as were 03, 04, 06, and 23. No data were available for groups 07, 20, 21, and 24, and rut-depth models for these were adopted by analogy to other model groups. Typical rut-depth progression curves are shown in Figure 3, and data underlying the developed models are summarized in Table 3. Thin pavements rut the fastest, and overlays or reseals on asphalt concrete are the slowest to develop rutting. One rut-depth standard deviation model was derived for all pavements:

$$RDS = 0.5 * RDM \tag{6}$$

where 0.5 is a network average of the coefficient of variation of mean rut depth, *RDM*.

Roughness Progression Analysis

Data for evaluation of the cracking, patching, and potholing terms were not available. The terms were omitted because they are not dependent on time in Saskatchewan. Maintenance is routine, and any cracked area is sealed before it is able to progress. At the time of rehabilitation, the cracking, patching, and potholing affect only a small fraction of the surface area. The PMIS system will make use of cracking and patching parameters for project selection along with roughness; therefore, it is not critical that these terms be reflected in the roughness progression equation. With the *RDS* variable substituted by Equation 6, Equation 1 becomes the following:

$$\Delta RI = 134\, e^{mt}\, (MSN + 1)^{-5.0}\, \Delta NE4 + 0.057\, \Delta RDS + mRI_t \Delta t \tag{7}$$

Pavements and subgrades in Saskatchewan can remain frozen for 6 months per year. Traffic has no apparent effect on structural deterioration during this period. For this reason, the time and traffic variables were halved in Equation 7. The following model was fitted using SAS mainframe regression analysis package:

$$DRI = a + b * \Delta RI + e \tag{8}$$

where

a and b = model parameters;
DRI and ΔRI = the observed and the predicted roughness increments (in IRI m/km units), respectively; and
e = the error term.

Only the regressions with intercept $a = 0$ produced predictive models in agreement with the professional judgment of SHT engineers. The R^2 measure of fit is not defined for regressions without an intercept, and for this reason the general version of the model was run parallel to the no-intercept model in

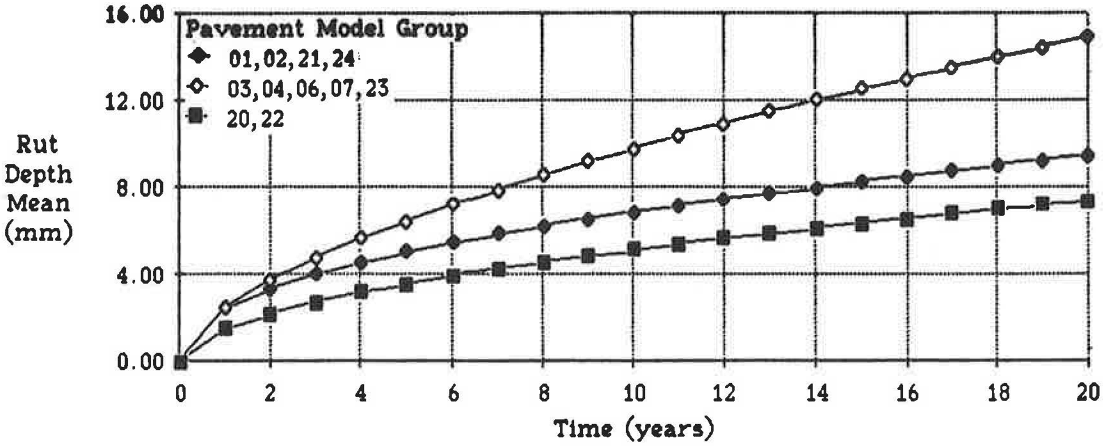


FIGURE 3 Typical mean rut depth progression curves.

TABLE 3 SUMMARY OF DATA FOR THE MEAN RUT DEPTH MODELS

Pavement Model Group	Sample Size, km	RDM, mm			t, years			MSN			NE4, 10^6 ESAL		
		mean	st.dev.	range	mean	st.dev	range	mean	st.dev.	range	mean	st.dev.	range
01	490	5.4	2.5	1-24	16.0	6.6	2-27	3.94	0.84	1.77-7.17	1.15	0.75	0.06-4.73
02	33	4.2	1.3	1-8	14.5	2.2	8-16	4.80	0.64	3.51-5.90	1.51	0.47	0.39-2.07
03	75	5.1	2.6	1-12	5.8	1.7	4-11	2.02	0.42	1.07-3.26	0.35	0.34	0.14-1.07
04	130	5.6	2.7	1-17	5.6	2.7	1-17	2.05	0.62	1.04-3.70	0.41	0.18	0.09-1.59
06	266	7.3	2.9	2-26	9.2	4.1	2-21	1.56	0.42	0.61-2.78	0.29	0.18	0.03-0.63
22	284	4.2	1.7	1-13	10.5	6.1	2-27	5.04	1.12	1.12-8.54	1.46	1.11	0.00-4.56
23	176	6.2	2.1	1-14	8.3	2.6	4-15	2.28	0.63	1.32-4.44	0.28	0.16	0.13-0.81

order to monitor R^2. The observed increment *DRI* was calculated as the difference between the 1987 roughness reading and the starting roughness value immediately following construction or overlay, whichever was latest. Overlaid pieces of road provided one *DRI* record for each subhistory determined between two consecutive overlays. For roughness histories starting prior to 1976, average starting roughness levels were calculated from post-1976 data. Records were weighted by the number of 50-m lengths contained in each piece of road in the Model Development File. The extraction of roughness subhistories and other data transformations were facilitated by a structured programming language built into the SAS package.

The model was analyzed with different values of the environmental factor m. Each climate zone was considered separately, but there were no significant differences and data were lumped for zones A and B, and C and D. The best R^2 and root mean square error of predictions were obtained with $m = 0.035$ for climate zones A and B, and $m = 0.050$ for C and D, consistent with Paterson (*2*). All combinations of terms in Equation 7 were tried, but ΔRI containing only the last term fitted the observed data best. The second-best fits resulted when the rutting term was excluded or, occasionally, when the first term was excluded. This leads to a conclusion that the structural variables are accounted for by the age variable and by the grouping of pavements into model types. Model grouping classifies pavements by general levels of both strength and traffic. The age variable is collinear with cumulative axle loads, which in turn govern pavement thickness design and subsequent overlays.

The data to which the models were fitted are summarized in Table 4. The results of the best regressions are shown in Table 5. All results are significant at the 0.0001 level or better, partly because of the large number of 50-m lengths of road in the sample. However, for model groups 04 and 23, which show large scatter in data, the model slope was assumed from group 03. Group 22 model for climates A and B did not agree with the expert judgment of surfacing and maintenance engineers at SHT and was therefore assumed to be as pavement model 01. Models for groups 21 and 24, for which no field data were available, were assumed from groups 20 and 01, respectively. Typical roughness progression curves based on the models are presented in Figures 4 to 6. The roughness levels in year 0 are network average starting values. The rate of change of slope is increasing toward the more advanced age of pavements, but the increase is relatively small for resealed

TABLE 4 SUMMARY OF DATA FOR ROUGHNESS PROGRESSION MODELS

Pavement Model Group	Sample Size, km	RI, m/km			t, years			MSN			NE4, 10^6 ESAL		
		mean	st.dev.	range	mean	st.dev	range	mean	st.dev.	range	mean	st.dev.	range
01	1696	0.59	0.50	0.01-4.60	15.0	5.8	2-27	3.41	0.79	0.50-7.00	1.15	1.05	0.01-11.63
02	599	0.60	0.45	0.02-3.40	15.2	3.2	5-23	3.81	0.58	2.08-7.00	1.06	0.74	0.14-5.40
03	241	0.28	0.25	0.02-1.61	6.8	3.2	2-15	1.91	0.45	1.01-3.13	0.28	0.21	0.05-0.89
04	409	0.35	0.36	0.03-3.33	15.1	6.0	2-25	2.12	0.59	0.50-3.97	0.35	0.16	0.01-0.76
06	748	0.53	0.46	0.03-5.10	8.8	4.4	2-18	1.19	0.40	0.50-2.83	0.18	0.14	0.01-0.57
07	5748	0.92	0.69	0.02-8.62	14.8	5.5	2-27	0.82	0.26	0.50-1.70	0.14	0.08	0.01-0.55
20	901	0.65	0.46	0.02-4.18	20.2	5.5	4-27	3.24	0.63	1.10-6.16	1.30	0.76	0.01-6.36
22	588	0.57	0.54	0.02-4.32	10.9	5.5	2-23	4.29	0.90	1.10-7.00	1.25	1.05	0.06-6.27
23	484	0.39	0.45	0.02-4.39	8.2	3.5	2-24	1.90	0.47	0.82-3.37	0.23	0.14	0.05-1.14

TABLE 5 REGRESSION RESULTS FOR ROUGHNESS PROGRESSION MODELS

	Climate A+B				Climate C+D			
Pavement Model Group	Sample Size, km	Model Slope b	% Coefficient of Variation of Prediction	R^2	Sample Size km	Model Slope b	% Coefficient of Variation of Prediction	R^2
01	898	0.99	54	0.57	790	0.61	57	0.58
02	271	0.96	61	0.51	328	0.67	54	0.55
03	60	0.87	62	0.35	181	0.73	85	0.14
04	206	0.50	108	0.03	203	0.34	100	0.03
06	381	1.09	66	0.33	367	0.96	73	0.36
07	3420	0.93	64	0.19	2328	0.84	68	0.27
20	507	0.76	50	0.57	394	0.48	52	0.46
22	306	1.35	49	0.59	282	0.66	73	0.48
23	196	0.70	88	0.06	288	0.83	110	0.10

Note: R^2 is taken from a corresponding regression model with intercept $a \neq 0$

full-depth and asphalt concrete pavements. Models shown in Figure 4 differ insignificantly between the climate zones and are represented by one curve for all climates. Resealed asphalt concrete deteriorates the most slowly because more rapidly deteriorating roads receive an overlay and become model group 22. Staged C and D pavements show the highest rates of deterioration (Figure 5), and the northern climate is more detrimental to most of the pavements (Figure 6) than the southern climate.

Maintenance Quantity—Age Relationships

Functions of hand patching, machine patching, deep patching, spot sealing, cumulative cracking, and patching quantities versus age are required to predict maintenance costs and trigger appropriate rehabilitation and maintenance treatments in the PMIS simulation of long-term strategies. The functions have been derived from scatterplots of network data versus age for each pavement model group. The data were lumped beause

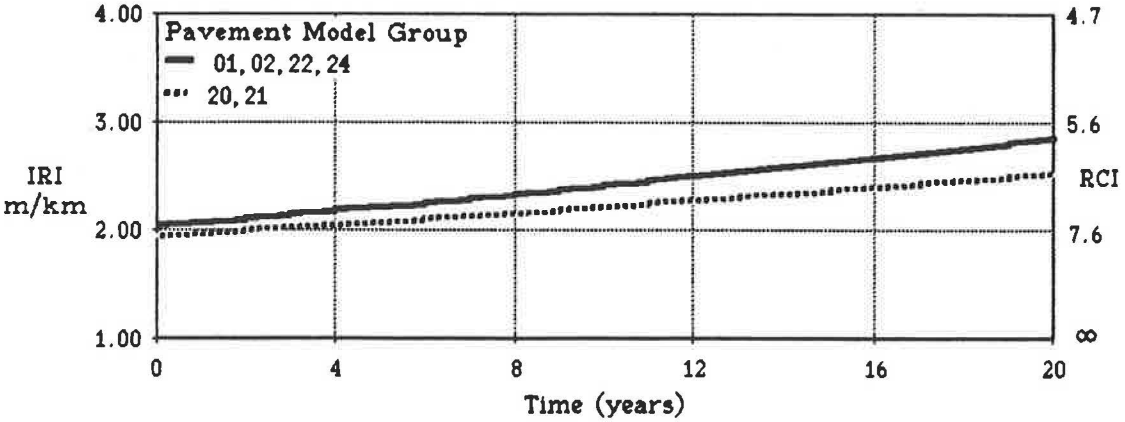


FIGURE 4 Roughness progression of asphalt concrete and full depth asphalt concrete pavements.

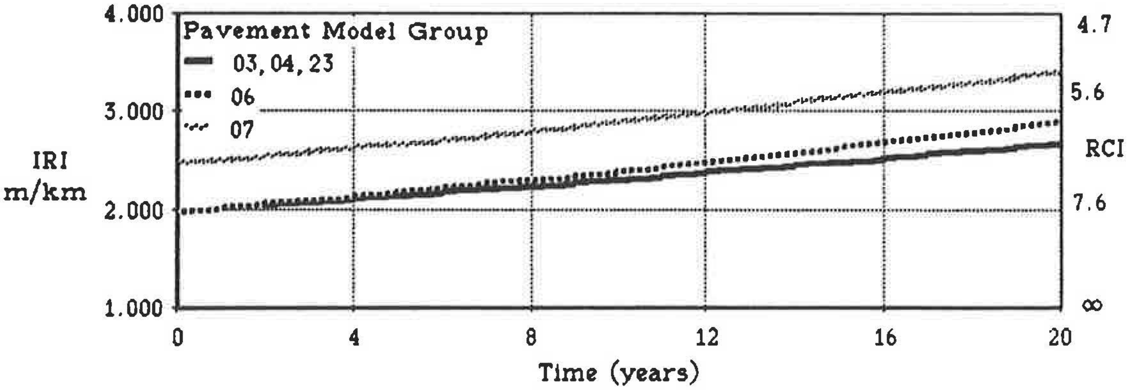


FIGURE 5 Roughness progression in climate Zones A and B.

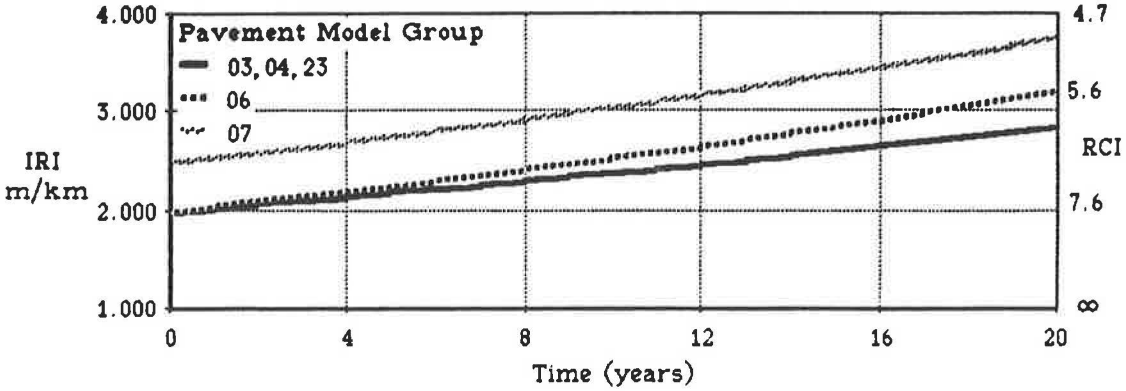


FIGURE 6 Roughness progression in climate Zones C and D.

there were no sufficient data for some climatic zones. For model groups 20, 21, and 24, the function parameters were interpolated from other models. The functions are of a "hinged" form, and the time to initiation and between initiation and the "hinge" were provided through the expert opinion of SHT engineers. The initial slope and the slope after the "hinge" year were estimated from the network sample data.

Hand patching quantities are least on the full-depth asphalt concrete (groups 02 and 21), highest on the staged D (group 07) surfaces, and intermediate on the other original surface types. Little increase in hand patching quantities with age were evident, except in the wetter C and D climatic zones for all surface types except the staged C and D surfaces (Figure 7). Machine patching quantities are least on overlays, highest on the staged C and staged D surfaces, and intermediate on the other original surface types. Machine patching quantities are highest on staged C and D pavements in the northern climate zones (Figure 8). Spot sealing quantities are least on the original asphalt concrete hot mix or overlay surfaces, most on the sealed surfaces, and significant on the cold mix, staged

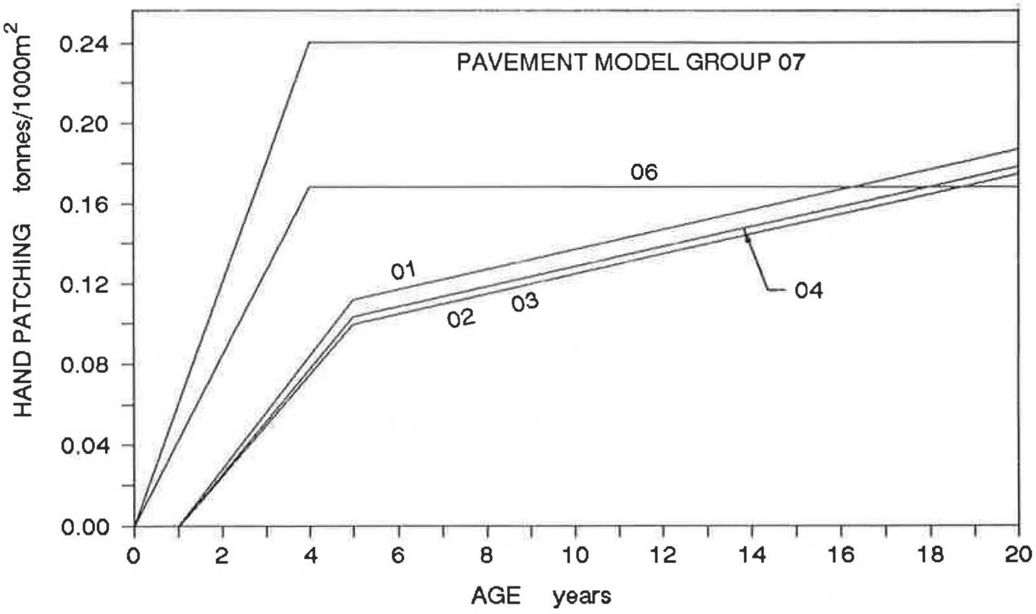


FIGURE 7 Hand patching progression of original pavements in climate Zones C and D.

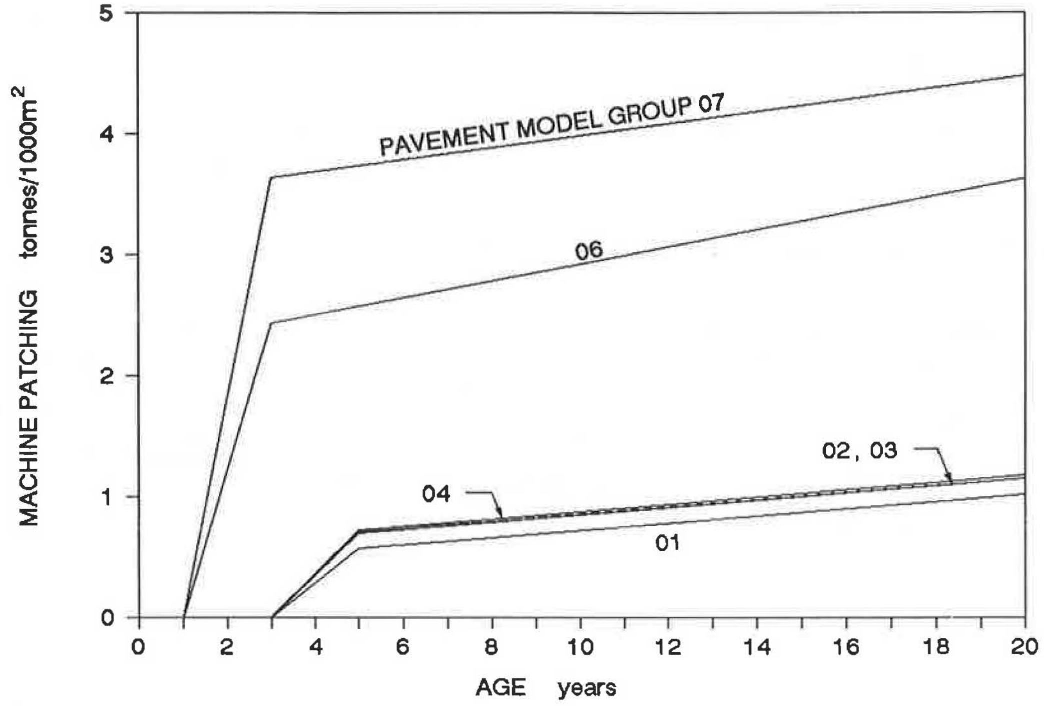


FIGURE 8 Machine patching progression of original pavements in climate Zones C and D.

C and staged D. A slight increase in spot sealing quantities with age was evident in the wetter C and D climate zones.

Deep patching data and cumulative cracking and patching were lumped across all climate zones. Deep patching increases very little with age and is least on the original asphalt concrete hot mix, reseals, or overlays; highest on the staged C and D surfaces. The initial cumulative cracking and patching are least on the cold mix and overlays, highest on the double seal and staged D surfaces. The rate of accumulation of cracking and patching following the "hinge" year is highest on the original and resealed full-depth asphalt concrete pavements.

CONCLUSIONS

A set of pavement performance models has been developed using an approach from the HDM3 model modified for Saskatchewan data, local conditions, and requirements of the pavement management system. The development has been successful because the HDM3 relationships are based on mechanistic principles of pavement behavior and are structured in a way that facilitates local adaptation. Variables relating to pavement structural properties and structural loading as well as to age, maintenance, and environmental factors are included in the models. Models for rutting, roughness progression, and maintenance quantities versus age have been specified for all generic groups of flexible pavements and four climatic zones of Saskatchewan. The rutting model from HDM3 is accurate for pavements without asphalt mix problems, but data are not available to operate the model at present. A modified model was developed showing that age is the most significant independent variable because modified structural number and cumulative axle loading are correlated. The model predicts correctly that thin pavements rut the most quickly, and overlays or reseals on asphalt concrete are the slowest to rut.

In the roughness model, terms relating to environmental deterioration are responsible for the largest part of IRI increase. Cracking and potholing terms were judged the least important, as routine maintenance in Saskatchewan does not allow these distress modes to develop to a state critically affecting roughness. Because the pavements are frozen half the time, the age and cumulative axle loading variables were halved for the IRI progression model. The environmental factor $m = 0.035$ for the arid south and $m = 0.050$ for humid north agree with validations of the HDM3 model by others. Roughness deterioration increases toward the more advanced age of all pavements, but the rate of increase is relatively small for resealed full-depth and asphalt concrete pavements. Staged C and D pavements deteriorate the most rapidly of all pavement types. Thin pavements deteriorate more quickly in the northern climatic zones. Maintenance models also show a steeper increase in maintenance quantities with age than in the southern parts of the province.

ACKNOWLEDGMENT

Research reported in this paper has been initiated and sponsored by the Saskatchewan Highways and Transportation.

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Publication of this paper sponsored by Committee on Pavement Management Systems.