Development of Canadian asphalt pavement deterioration models to benchmark performance

Chris Raymond, Susan Tighe, Ralph Haas, and Leo Rothenburg

Abstract: The Canadian Long Term Pavement Performance (C-LTPP) study, initiated in 1989, involves 65 sections located at 24 sites constructed with various asphalt overlay rehabilitation treatments. This study investigates the impacts of the various alternative rehabilitation treatments on pavement roughness progression. A series of models are developed for predicting the rate of pavement deterioration occurring for the first 8 years of service. The models examine both within-site factors and between-site factors. Site location is found to be the primary influence on the rate of pavement deterioration. Overlay thickness and the amount of cracking prior to rehabilitation are also determined to influence pavement deterioration at a strong statistical level. Models are provided for benchmarking the performance of pavements across Canada, for comparison with individual project designs, and for estimating the performance of designs with different overlay thickness.

Key words: Canadian Long Term Pavement Performance program, roughness, pavement deterioration, site effects, asphalt overlays, benchmark, univariate analysis.

Résumé : Le Projet d'étude du rendement à long terme des chaussées (« Canadian Long Term Pavement Performance : C-LTPP »), lancé en 1989, implique 65 tronçons répartis en 24 sites d'essai construits en utilisant divers traitements de réfection du revêtement bitumineux. La présente étude examine les impacts des divers traitements alternatifs de réfection sur l'évolution de la rugosité de la chaussée. Une série de modèles a été développée afin de prédire le taux de détérioration de la chaussée survenant durant les premiers huit ans d'utilisation. Les modèles examinent les facteurs inhérents au site et les facteurs entre les sites. L'emplacement du site a la plus grande influence sur le taux de détérioration de la chaussée. Des résultats statistiques indiquent fortement que l'épaisseur du revêtement et la quantité de fissuration avant la réfection influencent également la détérioration de la chaussée. Des modèles sont fournis pour déterminer les points de référence du rendement des chaussées à travers le Canada, pour comparer les conceptions de projets individuels et pour estimer le rendement des conceptions ayant diverses épaisseurs de revêtement.

Mots clés : projet canadien de rendement à long terme des chaussées, rugosité, détérioration de la chaussée, effets du site, revêtement bitumineux, point de référence, analyse unidimensionnelle.

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1. Introduction

The Canadian Long Term Pavement Performance (C-LTPP) study began in 1989 with the goal of increasing pavement life and serviceability through the development of cost-effective rehabilitation strategies. Sixty-five test sections were constructed at 24 major highway test sites located across all 10 provinces (Transportation Association of Canada 1989). During the period between 1989 and 1990 the sections were overlaid with various thicknesses of asphalt overlay material on existing, conventional, flexible pavements with granular bases. The research presented in this paper is based on the 59 sections constructed with designs consistent with the performance measures examined. The C-LTPP test sites provide a valuable resource for benchmarking the pavement performance of primary highways across Canada.

Figure 1 shows the distribution of the 24 C-LTPP experimental test sites, as illustrated in the *C-LTPP database user's guide* (Transportation Association of Canada 1997*a*). Each test site contains two to four adjacent test sections to compare alternative rehabilitation strategies under identical traffic loading, environmental region, and subgrade soil conditions. The C-LTPP project also attempts to compare results obtained at different test sites (i.e., across traffic levels, climate zones, and subgrade soil types) by using a statistical analysis of the factorial population. The pavement sections are analysed using the statistical analysis computer software, SPSS® version 10.1 (SPSS Inc. 2001). Several models are developed using univariate analyses. Since the performance indicators incorporated into C-LTPP test sections are spread out over a number of different sites, complete pavement performance models are developed through two separate components, within-site models and between-site models. The within-site models are developed based on the performance indicators that vary within each site (e.g., overlay thickness). A series of site-effect variables are included as part of the within-site models to account for the differential perfor-

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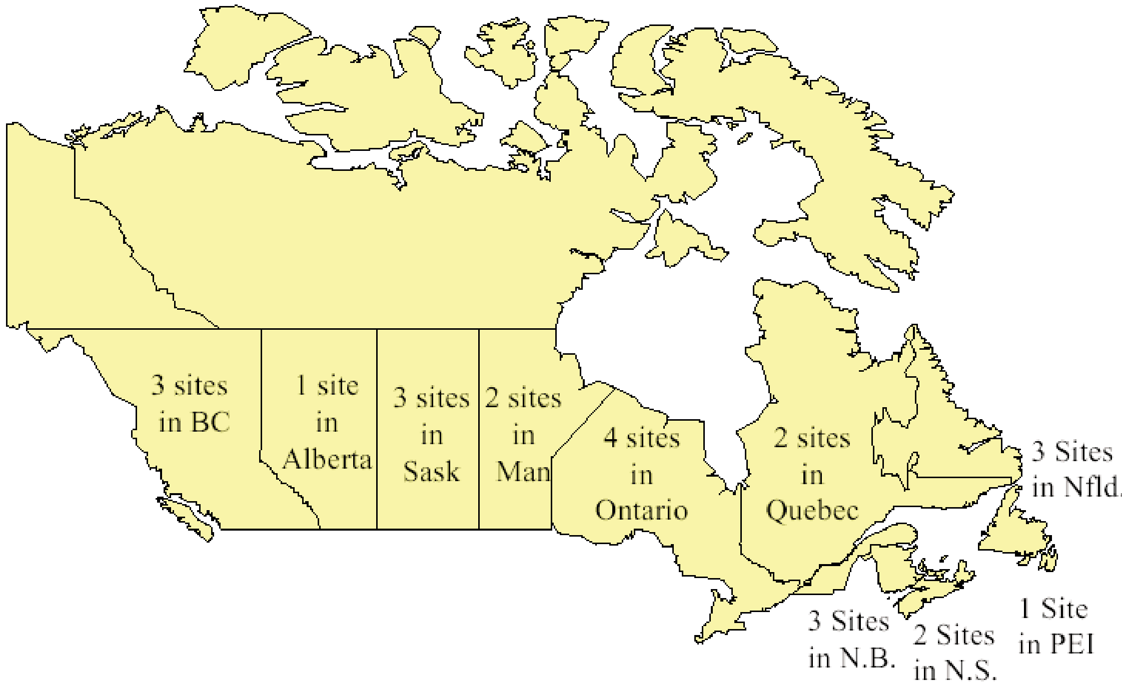
Fig. 1. Distribution of the Canadian Strategic Highway Research Program (C-SHRP) test sites.



mance observed at the individual sites. A second series of models are developed based on the between-site factors. These models estimate the individual site effects based on site factors (e.g., precipitation).

2. Quantification of model variables

Pavement performance for each section is based on the pavement roughness measured as the international roughness index (IRI). International roughness index measurements were taken with a digital incremental profiler (Dipstick) except for the 1999 measurements in the province of Quebec that were recorded using a CSC Profilite 300. Pavement performance is quantified as the average rate of roughness deterioration occurring during the first 8 years after resurfacing. Linear regression was used to determine the average rate of deterioration in each pavement section. Using the pavement deterioration rate eliminates the need to incorporate into the model the as-built roughness of a pavement (i.e., pavement roughness immediately after construction), which has been shown to affect long-term pavement performance (Raymond 2001).

The within-site variables examined in the models are as follows. Overlay thickness is quantified as the as-built thickness of asphalt placed during rehabilitation, including the replacement of any milled pavement. The degree of surface preparation is categorized as either milled or nonmilled. Type of overlay material is categorized as virgin or recycled. Pavement roughness prior to rehabilitation is quantified as the IRI of the pavement. The combined effect of surface preparation and pavement roughness prior to rehabilitation considers only the pavement roughness prior to rehabilitation of nonmilled pavements. Pavement cracking prior to rehabilitation (prior cracking) is the total length of all types of cracking calculated from the amount of sealed cracks and all severity levels of unsealed cracks. The mechanistic–empirical estimations of fatigue damage and rutting damage are based on the analyses of falling-weight deflectometer measurements, which are adjusted to represent the period of maximum pavement deflection based on Benkelman beam measurements taken throughout the year. Fatigue damage is estimated by comparing the tensile strains and the number of equivalent single axle loads (ESALs) in the first 8 years since rehabilitation with the fatigue criteria of the Asphalt Institute (1982). Rutting damage is estimated by comparing the strain at the bottom of the asphalt layer and the number of ESALs in the first 8 years since rehabilitation with the average of the Shell, Chevron, and Nottingham rutting criteria (Asphalt Institute 1982). The Benkelman beam deflection ratio is the ratio of maximum deflection to the average summer deflection as outlined by Samson and Frechette (1995). Composite indicators of the fatigue damage divided by the deflection ratio and rutting damage divided by the deflection ratio are also examined.

The between-site variables examined in the models are as follows. Annual precipitation and annual number of days with precipitation are self-descriptive. Annual freeze–thaw cycles are the annual number of freeze–thaw cycles occurring in the air. The annual freezing index is the annual sum of the negative mean air temperatures (e.g., 5 d at –2°C equals a freezing index of 10°C·d). The average monthly temperature gradient is the difference between the mean monthly maximum and minimum temperatures. Subgrade type is categorized as either coarse grained or fine grained based on Canadian Strategic Highway Research Program (C-SHRP) guidelines (Transportation Association of Canada 1997*b*). Accumulated ESALs after 8 years of service are the estimated number of ESALs occurring during the 8 years since rehabilitation. The average prior roughness of each site is the average roughness for each site prior to rehabilitation.

3. Within-site pavement deterioration models

Within-site pavement deterioration models are developed using the rate of pavement deterioration for each section as the dependent variable, designating each site as a fixed variable and performing a stepwise backward regression on the within-site performance indicators. Transformations of the models were performed based on residual analyses to select the most appropriate form of the terms. During the analyses it was found that preliminary models produced a fanned residual and transformations of the models were required. The cube root of the pavement deterioration rate provided a random scatter of the residuals.

3.1. Model 1: comprehensive within-site pavement deterioration model

The analysis indicates that the best model (maximum adjusted R^2 value) involves six performance variables, namely overlay thickness, prior cracking, deflection ratio, type of overlay material, the estimation of mechanistic–empirical fatigue damage, and the site effect. The model has an R^2 value of 0.901 and an adjusted R^2 value of 0.815. The between-subject effects for the model are presented in Table 1, and the parameter estimates are in Table 2.

The univariate analysis yields model 1 as illustrated in eq. [1]:

$$\text{[1]} \quad \sqrt[3]{\mathrm{PD}} = 0.222 - 0.000998\mathrm{OT} + 0.000504\mathrm{PC} + 0.0354\mathrm{DR} - 0.0266\mathrm{OM} + 0.0380\mathrm{FDE} + \mathrm{SE}$$

where PD is the rate of pavement deterioration (IRI/year), OT is the overlay thickness (mm), PC is the prior cracking (m/150 m), DR is the deflection ratio, OM is the type of overlay material (virgin = 0, recycled asphalt pavement = 1), FDE is the estimate of fatigue damage (percentage of design ESALs), and SE is the site effect (dependent on the individual site; see Sect. 4).

The following observations can be made from an examination of the predictor variable coefficients: (1) the rate of pavement deterioration decreases with thicker pavement overlays, (2) the rate of pavement deterioration increases with greater cracking in the pavement prior to rehabilitation, (3) the rate of pavement deterioration increases with increasing deflection ratio, (4) the rate of pavement deterioration decreases with the presence of recycled asphalt pavement, and (5) the rate of pavement deterioration increases as the estimate of fatigue damage increases.

Three predictor variables have strong statistical relationships in the model. Overlay thickness, prior cracking, and site effect have p values (statistical significance) of less than 1%, which indicates there is a high level of certainty that these variables influence pavement performance in the model. In looking at the sum of squares values for the variables, it is apparent that the model is influenced primarily by site effect, which has a sum of squares considerably larger than those of the other variables. Overlay thickness and prior cracking account for the next largest portions of the relationship of the model. The other three variables have weaker relationships, with p values between 18 and 31%. These weaker statistical relationships indicate that, based on the variability in the data, there is still an 18–31% chance that the variables do not influence pavement performance, as indicated in the model.

Two of the five observations are contrary to current theory. Observation 3, the increase in the rate of pavement deterioration resulting from a large deflection ratio, is one of these observations. The deflection ratio is an indicator of the seasonal variation in pavement strength, which is related to the type of subgrade and degree of drainage at the site. Fine-grained soils have a greater reduction in bearing capacity under wet conditions. Current pavement design practices account for these seasonal variations by providing a stronger pavement design that accounts for the lower bearing capacity of various soils types under wet conditions. The fatigue analysis performed in this research is based on the greatest pavement deflection. A high deflection ratio would result in a higher estimate of fatigue damage than would actually occur, since there would be lower fatigue damage during the nonpeak deflection periods.

Observation 4, the decrease in the rate of pavement deterioration resulting from the presence of recycled asphalt pavement, is the second observation of concern. Recycled asphalt pavement is generally thought to increase the fatigue sensitivity of a pavement. The reason for the overlay material relationship in the model is not known but may be related to the unbalanced distribution of data, as only seven sections were constructed with recycled asphalt pavement overlays. When discussing both contrary observations, it should be noted that deflection ratio and type of overlay material have weak statistical relationships, as indicated by their p values in the model of 18 and 25%, which are well above the 5% significance level typically used to support a strong relationship.

3.2. Model 2: simplified within-site pavement deterioration model

Model 1 has two predictor variables, deflection ratio and estimate of fatigue damage, that can be difficult to quantify because this information is not always readily available. Furthermore, deflection ratio has a questionable contribution, since it is inconsistent with current pavement theory and has a marginal impact on the model based on its F value and statistical significance (i.e., $p > 0.05$). Therefore, the univariate analysis was repeated to see if a simpler model could be developed without the use of the variables derived from a mechanistic empirical analysis (i.e., deflection ratio, estimate of rutting damage, and estimate of fatigue damage).

The analysis indicates that the best model (maximum adjusted R^2 value) involves three variables: overlay thickness, prior cracking, and site effect. The model has an R^2 value of 0.890 and an adjusted R^2 value of 0.814. These values are similar to those from the previous model. The between-subject effects for the model are presented in Table 3, and the parameter estimates in Table 4.

The univariate analysis yields model 2 as illustrated in eq. [2]:

$$\text{[2]} \quad \sqrt[3]{\mathrm{PD}} = 0.291 - 0.00120\mathrm{OT} + 0.000578\mathrm{PC} + \mathrm{SE}$$

Table 1. Between-subject effects of comprehensive within-site pavement deterioration model 1.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F	Statistical significance, p
Corrected model	0.519	26	0.020	10.476	0.000
Intercept	0.038	1	0.038	19.950	0.000
Overlay thickness	0.024	1	0.024	12.587	0.001
Prior cracking	0.017	1	0.017	8.815	0.006
Deflection ratio	0.004	1	0.004	1.867	0.182
Overlay material	0.003	1	0.003	1.374	0.250
Fatigue damage estimate	0.002	1	0.002	1.050	0.324
Site effect	0.350	21	0.017	8.752	0.000
Error	0.057	30	0.002		
Total	6.409	57			
Corrected total	0.576	56			

Table 2. Parameter estimates of comprehensive within-site pavement deterioration model 1.

					95% confidence interval	
Parameter	B	Std. error	t	Statistical significance, p	Lower bound	Upper bound
Intercept	0.222	0.091	2.434	0.021	0.036	0.409
Overlay thickness	–0.000998	0.000	–3.548	0.001	–0.001570	–0.000424
Prior cracking	0.000504	0.000	2.969	0.006	0.000157	0.000850
Deflection ratio	0.0354	0.026	1.366	0.182	–0.018	0.088
Overlay material	–0.0266	0.023	–1.172	0.250	–0.073	0.020
Fatigue damage estimate	0.0380	0.037	1.025	0.314	–0.038	0.114

Table 3. Between-subject effects of simplified within-site model 2.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F	Statistical significance, p
Corrected model	0.513	23	0.022	11.659	0.000
Intercept	0.197	1	0.197	103.104	0.000
Overlay thickness	0.046	1	0.046	23.825	0.000
Prior cracking	0.025	1	0.025	12.808	0.001
Site effect	0.356	21	0.017	8.876	0.000
Error	0.063	33	0.002		
Total	6.409	57			
Corrected total	0.576	56			

Table 4. Parameter estimates of simplified within-site model 2.

					95% confidence interval	
Parameter	B	Std. error	t	Statistical significance, p	Lower bound	Upper bound
Intercept	0.291	0.080	3.659	0.001	0.129	0.453
Overlay thickness	–0.00120	0.000	–4.881	0.000	–0.001700	–0.000698
Prior cracking	0.000578	0.000	3.579	0.001	0.000249	0.000906

The general observations for the predictor variable coefficients are similar to those for the previous model in that the rate of pavement deterioration decreases with thicker pavement overlays and increases with greater cracking in the pavement prior to rehabilitation. The statistical significances of these variables are similar to those of the first model in that there is a strong statistical significance in both models (i.e., $p < 1\%$). Although the type of overlay material is determined to be a predictor variable in the first model, neither it nor any within-site variable other than overlay thickness and prior cracking remains in the final version of this model. An examination of the sum of squares values indicates that site effect is the primary influence on the model, which is consistent with the findings in the first model.

4. Site-effect models

The previous within-site models incorporated an individual site variable, which was found to have a large effect on each model. In developing a complete model to serve as a benchmark for across Canada, it is necessary to examine the factors that affect the site-effect variables. This was performed by investigating the relationship of the between-site variables and the site-effect values determined in the previous within-site models.

4.1. Model 3: site-effect model to accompany comprehensive within-site model

The various between-site variables were analysed to develop a prediction model for the site-effect values determined in model 1 (eq. [1]). This analysis indicates that annual freezing index, annual number of days with precipitation, and accumulated ESAL applications after 8 years are the variables that produce the best model (maximum adjusted R^2 value). The model has an R^2 value of 0.393 and an adjusted R^2 value of 0.292. These values indicate that a considerable amount of unexplained variability remains in the model. The between-subject effects for the model are presented in Table 5, and the parameter estimates in Table 6.

The univariate analysis yields model 3 as illustrated in eq. [3]:

$$[3] \quad SE = -0.0852 - 0.0000827FI + 0.00117DP + 0.0000000223ESAL_8$$

where SE is the site effect, FI is the annual freezing index (°C·d), DP is the annual number of days with precipitation, and $ESAL_8$ is the accumulated ESALs after 8 years.

An examination of the predictor variable coefficients yields the following observations about their influence on site effect and consequently the rate of pavement deterioration: (*i*) the site effect decreases with a larger freezing index, (*ii*) the site effect increases with more annual days with precipitation, and (*iii*) the site effect increases with more ESALs.

The relationships for all variables are generally consistent with current theory. The effect of annual freezing index can be both positive and negative. Under ideal conditions, a pavement would not be subjected to any freezing conditions. In Canada, most pavements are subjected to a considerable amount of freezing action. Some of the high freezing indices in the C-LTPP sites indicate continued freeze conditions, which is considered preferable to lower freezing indices where repeated freeze–thaw conditions occur. Annual freezing index provides the strongest influence in the model but has a weak statistical relationship (p value of 11%).

4.2. Model 4: site-effect model to accompany simplified within-site model

The univariate analysis was repeated to determine the relationship between the various between-site variables and the site-effect values determined in the second within-site model (eq. [2]). The same variables used in the previous model, annual freezing index, annual number of days with precipitation, and accumulated ESALs after 8 years, were determined to produce the best model (maximum adjusted R^2 value). The model has an R^2 value of 0.400 and an adjusted R^2 value of 0.300. The between-subject effects for the model are presented in Table 7, and the parameter estimates in Table 8.

The univariate analysis yields model 4 as illustrated in eq. [4]:

$$[4] \quad SE = -0.131 - 0.0000805FI + 0.00147DP + 0.0000000232ESAL_8$$

The model outlined in eq. [4] is similar to the previous model in eq. [3]. The predictor variables have statistical significance and influence on the model similar to those of the previous model. These similarities can be attributed to the fact that both models were developed from similar within-site models, eqs. [1] and [2].

5. Complete pavement deterioration models

A complete pavement deterioration model can be developed by combining the within-site models with the individual site models. Although the integration of these models is not consistent with pure statistical theory, a combined model provides a practical estimate of pavement deterioration. The most complete estimation of pavement deterioration is determined by combining eqs. [1] and [3] to yield model 5 as shown in eq. [5]. In using this model, it is important to consider the amount of variability existing in the two component models used to develop this model:

$$[5] \quad \sqrt[3]{PD} = 0.137 - 0.000998OT + 0.000504PC + 0.0354DR - 0.0266OM + 0.0380FDE - 0.0000827FI + 0.00117DP + 0.0000000223ESAL_8$$

A simpler model can be determined by combining eqs. [2] and [4]. The integration of these two models results in model 6 as shown in eq. [6]. As previously stated, it is important to consider the amount of variability existing in the two component models used to develop this model. This is the recommended model for estimating pavement deterioration because of its use with commonly available data and the absence of any inconsistent relationships in the individual variables:

$$[6] \quad \sqrt[3]{PD} = 0.160 - 0.00120OT + 0.000578PC - 0.0000805FI + 0.00147DP + 0.0000000232ESAL_8$$

6. Limitations on the application of pavement deterioration models

The pavement deterioration models are developed based on the performance of the asphalt overlay sections in the C-LTPP test sections. These pavement sections are considered to be typical overlay designs subjected to Canadian conditions. The pavement deterioration models should not be applied to pavements with inadequate structural design or pavements that do not meet the typical characteristics of the

Table 5. Between-subject effects for site model 3.

Source of variation	Sum of squares	Degrees of freedom	Mean square	*F*	Statistical significance, *p*
Corrected model	0.136	3	0.045	3.884	0.027
Intercept	0.003	1	0.003	0.283	0.601
Freezing index	0.033	1	0.033	2.808	0.111
No. of days with precipitation	0.017	1	0.017	1.496	0.237
ESAL applications	0.015	1	0.015	1.318	0.266
Error	0.209	18	0.011		
Total	0.363	22			
Corrected total	0.345	21			

Table 6. Parameter estimates for site model 3.

					95% confidence interval	
Parameter	*B*	Std. error	*t*	Statistical significance, *p*	Lower bound	Upper bound
Intercept	–0.0852	0.160	–0.532	0.601	–0.421	0.251
Freezing index	–0.0000827	0.000	–1.676	0.111	–0.000186	0.0000210
No. of days with precipitation	0.00117	0.001	1.223	0.237	–0.000837	0.00317
ESAL applications	0.0000000223	0.000	1.148	0.266	–0.0000000185	0.0000000631

Table 7. Between-subject effects for site model 4.

Source of variation	Sum of squares	Degrees of freedom	Mean square	*F*	Statistical significance, *p*
Corrected model	0.163	3	0.054	3.997	0.024
Intercept	0.008	1	0.008	0.570	0.460
Freezing index	0.031	1	0.031	2.278	0.149
No. of days with precipitation	0.028	1	0.028	2.045	0.170
ESAL applications	0.017	1	0.017	1.221	0.284
Error	0.245	18	0.014		
Total	0.428	22			
Corrected total	0.408	21			

Table 8. Parameter estimates for site model 4.

					95% confidence interval	
Parameter	*B*	Std. error	*t*	Statistical significance, *p*	Lower bound	Upper bound
Intercept	–0.131	0.173	–0.755	0.460	–0.494	0.233
Freezing index	–0.0000805	0.000	–1.509	0.149	–0.000193	0.0000315
No. of days with precipitation	0.00147	0.001	1.430	0.170	–0.000691	0.00364
ESAL applications	0.0000000232	2.099	1.105	0.284	–0.0000000209	0.000000673

C-LTPP sections. Consideration must also be given to the amount of variability existing in the models.

7. Summary of pavement deterioration models

A series of univariate analyses were performed on the C-LTPP data to investigate the factors that influence pavement deterioration. Various models were developed to provide a tool for estimating the rate of pavement deterioration during the first 8 years of pavement life for pavements similar to those examined in the C-LTPP data. The statistical analysis revealed that the primary influence on pavement deterioration was the particular site at which the pavement was located. Two within-site variables, overlay thickness and prior cracking, were determined to strongly influence pavement deterioration, with *p* values less than 1%. Three other within-site variables (deflection ratio, type of overlay material, and the estimation of mechanistic–empirical fatigue damage), the site variables annual freezing index, annual number of days with precipitation, and accumulated ESAL applications after 8 years were found to have weak statistical relationships with pavement deterioration in at least one of the models. Users of these equations are cautioned that a considerable amount of unexplained variation remains in the models. These models provide a tool for benchmarking the performance of asphalt overlay pavements across Canada. They also provide a tool for comparison with individual project designs and estimating the initial performance of different thickness alternatives in an overlay design. Further details of this research can be found in Raymond (2001).

8. Recommendations

Based on this research the following recommendations are provided:

(1) This research provides several models for benchmarking the performance of asphalt overlays across Canada. The current analysis incorporates pavement performance from the first 8 years of service, and continued monitoring and analysis should be conducted to determine longer term results.

(2) Designers should consider the extent of pavement cracking in their overlay design, since prior pavement cracking is shown to affect the rate of pavement deterioration after rehabilitation.

(3) Further research should be undertaken to incorporate pavement cracking prior to rehabilitation into pavement design methodology. Environmental factors such as freezing index and precipitation should also be investigated to determine if these factors, which were beneficial to the pavement deterioration model at a low statistical significance, should be included in pavement design methodology.

(4) A comprehensive life cycle cost analysis should be performed to examine the cost–benefits of thicker asphalt overlays. This should incorporate the lower roughness achieved during construction from thicker asphalt overlays (Raymond 2001).

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