

Estimating the Life of Asphalt Overlays Using Long-Term Pavement Performance Data

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Asphalt concrete overlays of flexible pavements are the most common pavement rehabilitation treatment in Ontario. In this paper the development of mathematical models for the performance prediction of these overlays is described. The modeling approach was based on a statistical evaluation of observed overlay performance and used readily available data. Its objective was to develop performance prediction models that would fit the existing pavement management system and could be used for life cycle economic analyses. The duration of overlay life cycle, for a predetermined terminal serviceability, was estimated as a function of overlay thickness, traffic (in number of equivalent single axes), maintenance patching, and life cycle duration of the initial pavement. The latter variable was included in the model to capture the influence of local field conditions and to characterize the strength of the underlying support structure. Maintenance patching was included to quantify the effect of pavement maintenance on overlay performance. The proposed models are preliminary and should be updated when more data become available. The modeling approach developed in this paper may be used for performance prediction of other pavement rehabilitation treatments. The paper also illustrates some of the benefits and limitations of a long-term pavement performance monitoring program for pavement performance prediction.

One of the basic building blocks of any pavement management system is the prediction of pavement performance. The process of pavement performance prediction, within the pavement management framework, encompasses (1)

1. The time when a pavement preservation action will be required,
2. What this preservation action should be, and
3. The consequences (benefits) of this action.

The last item, the consequences of pavement preservation actions for the most common rehabilitation treatment, asphalt concrete overlays over asphalt concrete pavements, is addressed in this paper. The objective was to develop models that would permit (a) estimation of the immediate effect of an overlay on pavement serviceability, and (b) estimation of its life cycle period. The selection of prediction modeling techniques was strongly influenced by data availability and by the type of results required in the context of the pavement management system of the Ministry of Transportation and Communication (MTC) (2). A determined effort has been made to capitalize fully on the advantages of a pavement management

information database, particularly on the availability of long-term pavement performance data.

DATA COLLECTION

The objective of the data collection process was to obtain, for a number of pavement sections, a complete record of pavement serviceability data spanning its initial life cycle following a new construction or reconstruction, as well as its subsequent life cycle following an overlay. An example of the two pavement performance life cycles is shown in Figure 1. In addition to the long-term pavement serviceability data, other data deemed to influence overlay life, such as traffic data, overlay thickness, life span of the initial pavement (3), and the pavement condition before resurfacing in terms of roughness and various pavement distresses, were also collected.

The estimated lives of the initial and overlaid pavements were not actual lives, but the ages of the pavements when serviceability reaches a pavement condition rating (PCR) of 55. The PCR is a measure of overall pavement serviceability on a scale 0 to 100 (4). Newly constructed pavements generally have a PCR of 95; rehabilitation is mostly done anywhere between 40 and 60.

Data Sources

Because the pavement information data bank was not yet fully functional, additional data had to be obtained from a variety of sources including pavement performance records (4), contract drawings, and traffic files. The requirement of long-term pavement serviceability data for two pavement life cycles, covering up to 40 years, posed considerable problems of data collection.

Because of incomplete records and rather demanding data requirements, it was not possible to obtain the required data for pavement sections selected randomly. Rather, in assembling the data set used for modeling, all readily available observations were used. Altogether, data for 50 pavement sections, ranging in length from 5.0 to 26.7 km, were used for the development of prediction models. Each section had a uniform pavement structure and exhibited a uniform pavement performance. Detailed data on all observation sections are described by Hajek et al. (5).

Data Description

In view of the modeling objectives, and uncertainties as to which variables may significantly influence overlay perfor-

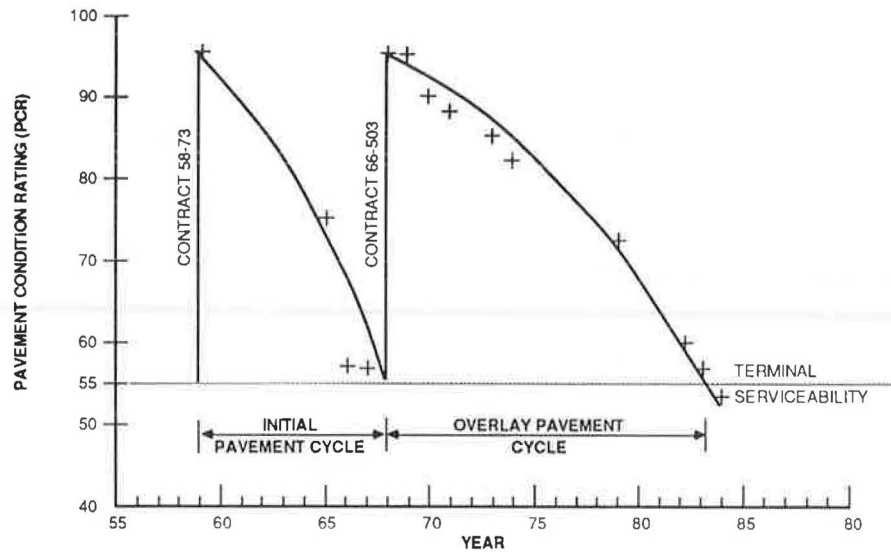


FIGURE 1 Pavement life cycles.

mance, each pavement observation section was initially characterized by more than 30 variables or factors. These variables were grouped into the following categories:

1. Traffic and environmental characteristics,
2. Initial pavement structure and its maintenance,
3. Initial pavement performance,
4. Overlay structure and its maintenance, and
5. Overlay performance.

Some principal characteristic variables collected for the observation sections are described in the following text. Additional variable definitions and detailed data are given by Hajek et al. (5).

Traffic and Environmental Characteristics

System variables were as follows:

AADT83. The 1983 annual average daily traffic volume ranged from 1,000 to 8,000 vehicles; the average was 3,700 vehicles.

TRUCK. The percentage of trucks in 1983 traffic flow ranged from 4 to 24 percent; the average was 14 percent.

FREEZE. The freezing index (6) ranged from 420 to 2,040 degree-days Celsius.

Initial Pavement Structure and Its Maintenance

The initial pavement structure was usually a new construction or a reconstruction. In four cases, the initial pavement structure was an overlay. The maintenance of the initial pavement structures was recorded only in terms of patching. System variables were as follows:

GRANA. The average thickness of granular base, expressed

as granular base course (Granular A) equivalent thickness (7), ranged from 125 to 510 mm; the average was 300 mm.

BEFAC. The total average thickness of asphalt concrete ranged from 50 to 200 mm; the average was 100 mm.

PATCH. The extent of machine (full-width) patching was measured before rehabilitation.

Initial Pavement Performance

In general, pavement performance was characterized by a performance curve and by the results of a detailed pavement distress survey conducted just before overlay placement. System variables were as follows:

BEF55. The life span of the initial pavement was defined as the number of years required for the initial pavement structure to reach a terminal serviceability. The terminal serviceability was arbitrarily set at a PCR level of 55 (Figure 1). This normalized definition of the life cycle length was adopted in order to define pavement life span solely in terms of pavement performance rather than in terms of actual construction timing. If the rehabilitation took place before the pavement reached the 55 level, its BEF55 was obtained by extrapolating the performance curve. The average BEF55 was 13.1 years.

RCR. The riding comfort rating was measured on a scale from 0 to 10, just before rehabilitation; the average RCR was 5.1.

DMI. The distress manifestations index (4) was determined just before overlay placement. DMI was calculated as the sum of 25 individual pavement distresses, characterized by their severity and extent, and weighted according to their contribution to the PCR. Pavements without distresses have DMI equal to 0; pavements with many distresses, such as surface deformation and cracking, may have DMI exceeding 100.

ALLIG. The total alligator cracking, a portion of DMI summarizing all types of alligator cracking, was determined just before overlay placement.

Overlay Structure and Its Maintenance

System variables were as follows:

THOV. The total overlay thickness (mm) was measured including surface and binder courses but not including padding. The overlay thickness ranged from 40 to 175 mm; the average was 70 mm.

PATCH. The extent of patching was measured before rehabilitation. Crack sealing was also recorded but virtually all patched overlays also underwent some crack sealing.

Overlay Performance

The overlay performance was characterized by the performance curve in terms of PCR. System variables were as follows:

AFT55. The life span of the overlay cycle was defined as the number of years before the overlay reached the PCR level of 55 (Figure 1). The reasons for this normalized definition of overlay life were the same as those for BEF55. The average overlay life span was 14.8 years, 1.7 years longer than the average life span of the initial pavement structure.

ΔPCR5. The change in PCR during the first 5 years was measured following overlay placement.

DEVELOPMENT OF PREDICTION MODELS

The result of the data collection phase was a detailed record of pavement performance and pavement structural changes, including major maintenance activities, covering a period of two pavement life cycles. This record was available for 20 pavement sections; the record covering a period of 1½ pavement cycles was available for an additional 30 sections. These records were used to predict overlay performance in terms of the following performance characteristics:

1. Immediate increase in PCR after overlay placement,
2. Duration of overlay life cycle, and
3. PCR change (drop) during the first 5 years after overlay placement.

Immediate Increase in PCR Following Overlay Placement

The PCR directly after an overlay depends on the design intentions for the treatment as well as the workmanship of the contractor. Based on 50 observations, the average increase of PCR after overlay placement, or average PCR jump, was 53 PCR units. The range was from 32 to 66 PCR units. The plot of the PCR jump versus overlay thickness shown in Figure 2 indicates that there was no correlation between these two variables.

The only factor with a statistically significant influence on the PCR jump was the PCR level (or also RCR level) before the overlay. The PCR jump increased as the PCR level before the overlay decreased. This action reflects the fact that the PCR can theoretically reach a level of only 100 regardless of overlay

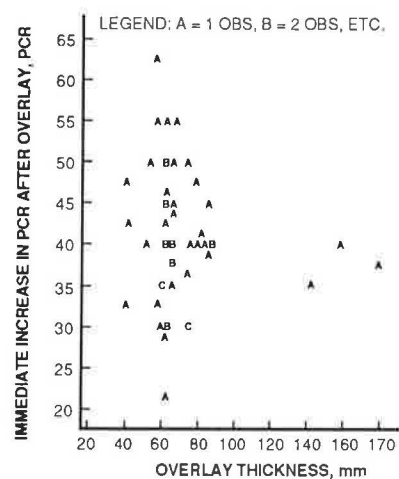


FIGURE 2 Relationship between increase in PCR and overlay thickness.

thickness. Thus, pavements with low PCR level before the overlay have greater opportunity to realize large PCR jumps. Furthermore, the PCR is subjectively assigned and PCR raters, influenced by the halo effect (8), may be inclined to rate all newly overlaid pavements near the top of the PCR scale. This overrating may explain why the average PCR level of newly overlaid pavements was 94.3 with the standard deviation of only 3.2. At any rate, no useful prediction model for the PCR jump could be constructed.

Duration of Overlay Life Cycle

The period an overlay will last before reaching terminal serviceability is a basic performance characteristic necessary for any life cycle economic evaluation. In order to normalize results and eliminate the influence of construction timing, the duration of overlay life cycle must be linked to the terminal serviceability. In this analysis, the terminal serviceability was set at the PCR level equal to 55.

The prediction of the overlay life cycle duration required pavement performance data for two pavement life cycles. Of 50 observation sections, 20 were found to satisfy this condition.

Model Development

Statistically, the modeling approach was based on linear regression techniques. The selection of independent variables was based on past experience that suggests that the prediction of overlay life span depends on the following factors:

- Overlay strength (i.e., overlay thickness, quality of overlay materials, and quality of their placement),
- Strength and condition of pavement structure being overlaid,
- Maintenance effort, and
- Traffic and environment exposures.

Several different models were constructed and evaluated. The

evaluation was based on rational formulation, behavior of the model, and its statistical parameters. The following model was selected for the prediction of the overlay life cycle:

$$\text{AFT55} = 1.32 \cdot \text{BEF55}^{0.33} \cdot \text{THOV}^{0.47} \cdot \text{ESAL}^{-0.097} \cdot 1.14^{\text{PATCH}} \quad (1)$$

where

- AFT55 = duration of overlay life cycle corresponding to the terminal PCR level of 55 years,
 BEF55 = duration of initial pavement structure life cycle corresponding to the terminal PCR level of 55 years,
 THOV = thickness of overlay (mm), and
 ESAL = number of equivalent single axle loads per day calculated using the equation.

$$\text{ESAL} = (\text{AADT83} \cdot \text{TRUCK} \cdot \text{TRUCKF} \cdot \text{LDF})/200 \quad (2)$$

where

- AADT83 = 1983 annual average daily traffic,
 TRUCK = truck percentage,
 TRUCKF = truck factor, and
 LDF = lane factor.

The final variable is PATCH, an indicator (dummy variable) used to account for the presence of patching during the initial cycle. PATCH introduced into the regression analyses patching information originally measured on a nominal (nonnumerical) scale (9). PATCH was set to 0 for no or a limited amount of patching and to 1 for all other cases.

The selected model was not the one with the best statistical parameters, but was the best model when both the statistical parameters and rational model formulation were considered.

Model Evaluation

Statistical parameters of the model represented by Equation 1 are summarized in Tables 1–3. The model was highly statistically significant with R^2 (10) of 0.72. This means that 72 percent of the total variance was explained by the model. The model root mean square error, an estimate of the standard deviation of the error term, was 1.12 years. All partial regression coefficients of the independent variables were statistically significant; the intercept was not statistically significant (Table 1).

The data in Table 3 show values and statistical significance of correlation coefficients for variables of Equation 1. There was only a limited amount of intercorrelation between the independent variables. The overlay thickness, although exhibiting no significant correlation with PCR jump ($R = -0.11$) or with PCR before resurfacing ($R = 0.19$), had somewhat significant correlation with RCR ($R = 0.24$). This indicates that overlays tended to be thicker when the RCR of the initial pavement was lower, and to allow for distortion.

A plot of measured versus calculated overlay life spans is shown in Figure 3. The residuals, differences between the predicted and observed AFT55 values, were normally distributed.

The prediction model defined by Equation 1 can be advantageously used to isolate and quantify the effects of the model variables. The effect of individual variables and evaluation of rational behavior of the model, in view of the factors known to influence the overlay performance, are discussed in the following.

Overlay Thickness

The overlay thickness was the only variable used to characterize the overlay strength. Equation 1 can be rearranged to

TABLE 1 ANALYSIS OF VARIANCE IN OVERLAY LIFE PREDICTION MODEL

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Level of Significance (%)
Regression model	4	0.0919	0.0230	9.84	0.04
Error	15	0.0350	0.0023	—	—
Corrected total	19	0.1270	—	—	—

TABLE 2 PARTIAL REGRESSION COEFFICIENTS IN OVERLAY LIFE PREDICTION MODEL

Parameter	Estimate	Std. Error of Estimate	Student's <i>t</i> Value for HO: Para = 0	Level of Significance (%)
Intercept	0.121	0.264	0.46	65.0
log THOV	0.472	0.140	3.37	0.4
log ESAL83	-0.097	0.026	-3.74	0.2
log BEF55	0.331	0.098	3.38	0.4
PATCH	0.058	0.022	2.62	1.9

TABLE 3 CORRELATION COEFFICIENTS IN OVERLAY LIFE PREDICTION MODEL^{a,b}

	THOV	ESAL83	BEF55	PATCH	AFT55
THOV	1.00				
ESAL83	0.25	1.00			
BEF55	0.03	0.05	1.00		
PATCH	-0.14	-0.01	0.16	1.00	
AFT55	0.41	-0.41	0.45	0.35	1.00

^aAll correlation coefficients are based on 46 to 50 observations with the exception of correlation coefficients involving AFT55, which are based on 20 observations.

^bCorrelation coefficients based on 50 observations are significant at 10 percent level of significance if their value exceeds 0.24. The corresponding value for correlation coefficients based on 20 observations is 0.36.

predict overlay thickness for a desired length of overlay life cycle:

$$THOV = \left(\frac{AFT55}{1.32 \cdot BEF55^{0.33} \cdot ESAL^{-0.097} \cdot 1.14^{PATCH}} \right)^{2.13} \quad (3)$$

The relationship between overlay thickness and overlay life is illustrated in Figures 4a and 4b. Both figures assume that the initial pavement life cycle was 13 years, the data set average. Furthermore, Figure 4a assumes that none or only a small amount of maintenance patching was done in the first cycle; Figure 4b assumes that more extensive patching was done. For a typical range of overlay thickness, the doubling of thickness results in a 5- to 7-year increase in overlay life. However, the relationship between overlay thickness and overlay life is not linear.

Figures 4a and 4b also show a corresponding relationship obtained by inputting average data set values and a subgrade layer coefficient M_s , equal to 5,000, to a mechanistically based OPAC prediction method (7). The model results from Equation 3 and the OPAC results are quite similar, particularly for the case with the maintenance patching.

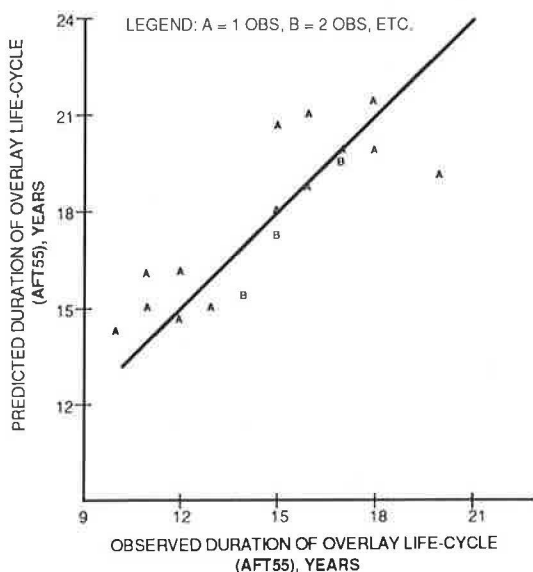


FIGURE 3 Comparison of observed and predicted length of overlay life cycle (AFT55).

The compatibility of the two prediction methods may be attributed, to some extent, to coincidental selection of average OPAC input data. However, the shapes of curves relating overlay thickness to overlay life are similar. Also, the empirical model of Equation 1 requires only readily available data, whereas the mechanistically based OPAC prediction method requires considerably more detailed data that is not always available.

Figures 4a and 4b can be used for rough estimation of overlay thickness requirements. An example is shown from Figure 4a. For a desired overlay life of 15 years and assuming

- No significant amount of patching,
- Initial pavement life of 13 years, and
- 100 ESAL/day (approximately an AADT of 3,000 with 14 percent of trucks),

the recommended overlay thickness is 70 mm.

Patching

According to Figure 5, the presence of patching during the initial pavement cycle increased the overlay life by about 2 years. It appears that patching, usually done near the end of the initial pavement cycle, strengthened the pavement structure where such strengthening was most required. The overlay performance benefited from this action, assuming that patches were overlaid before they deteriorated.

Patching during the initial pavement cycle occurred about 15 or 20 years ago and data describing patching extent and timing lack many details. Nevertheless, even in this crude form, the effect of patching was statistically significant (Tables 2 and 3).

Equation 1 represents a pavement damage equation that includes the effect of maintenance. Historically, pavement damage functions have been unable to include and quantify the effect of maintenance (10, 11). Equation 1 does this in a format fully compatible with the requirements of life cycle economic analyses.

The effect of maintenance patching in the second (overlay) cycle was also evaluated but could not be quantified. There were also problems with data. Patching is usually done at the end of the pavement life. Thus, the effect of the second cycle patching may not be fully accounted for if the serviceability limit is set at the PCR level equal to 55 or if the patching has not been done yet.

Traffic

The traffic exposure was characterized by the number of equivalent single axles in 1983 (Equation 2). The relationship between traffic and overlay life (AFT55), illustrated in Figure 6, is expressed both in terms of number of equivalent single axle loads (ESALs) and annual average daily traffic (AADT) volumes. AADT volume is assumed to contain 14 percent of trucks and to have a typical truck factor.

Duration of Initial Pavement Structure Life Cycle

Variables related to the strength of the pavement being overlaid and variables characterizing environmental exposure could be expected to be useful in predicting the overlay life. These types

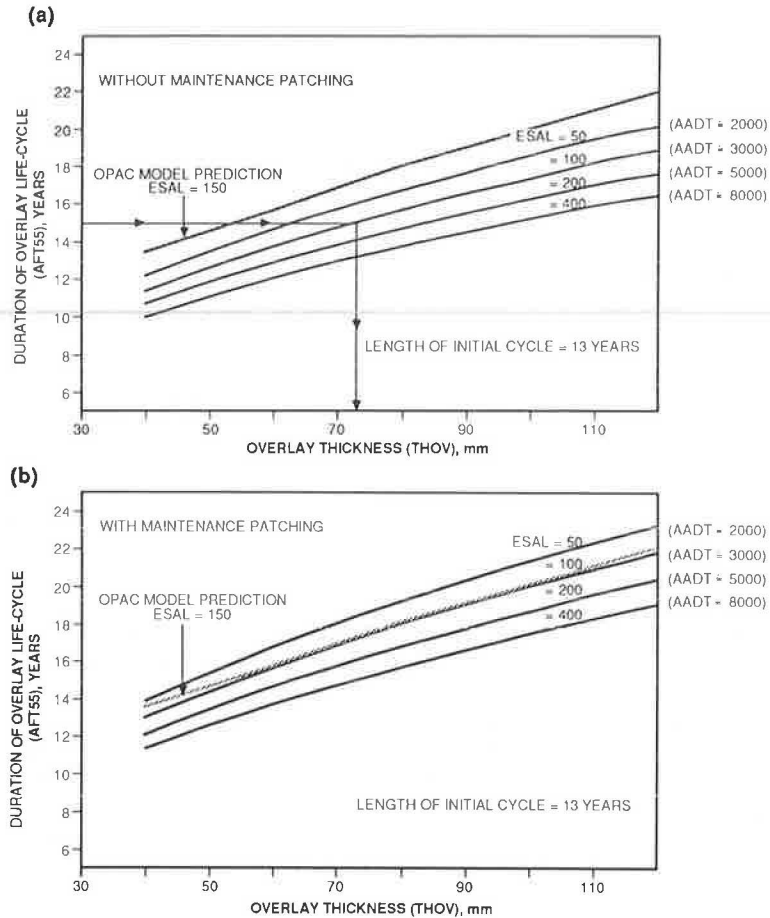


FIGURE 4 (a) Effect of overlay thickness on overlay life, no maintenance patching. (b) Effect of overlay thickness on overlay life, with maintenance patching.

of variables available in the data bank included, for example, thickness of asphalt concrete, granular base equivalency thickness, subgrade type, and freezing index, but did not include any results of pavement deflection tests (5). None of the available variables exhibited any predictive potential with the exception of the duration of the initial pavement life cycle. It appears that it is more important to know the life span of the initial pavement than its thickness.

Figure 7 illustrates the observed relationship between the duration of the initial pavement life cycle and the subsequent overlay cycle, both cycles being referenced to the same terminal performance level of PCR equal to 55. The effect of the initial cycle is quite pronounced; on average, all other variables being equal, a 5-year increase in the initial pavement life cycle resulted in a 2-year increase in the overlay life.

The life span of the initial pavement structure embodies site-

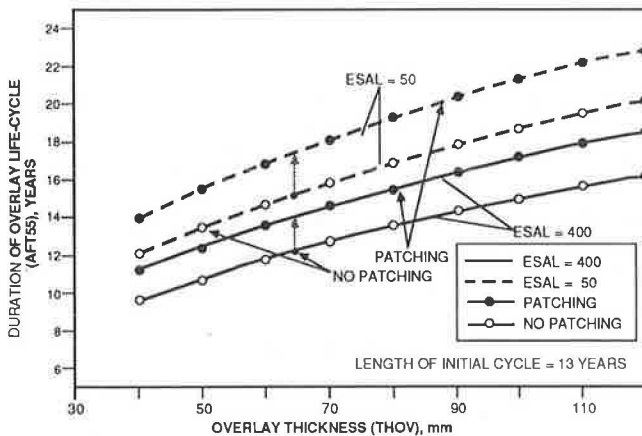


FIGURE 5 Effect of maintenance patching on overlay life.

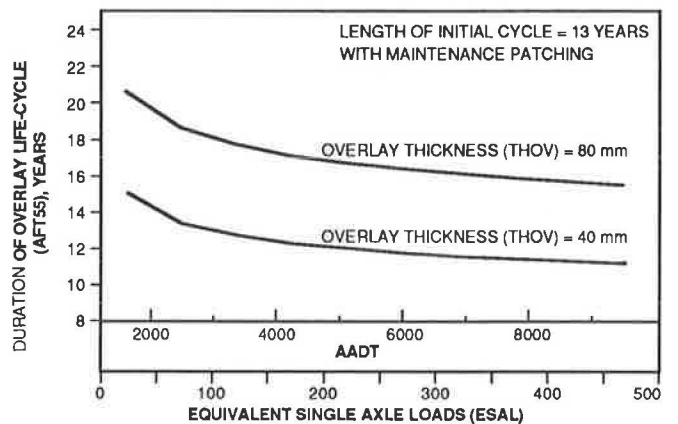


FIGURE 6 Effect of traffic on overlay life.

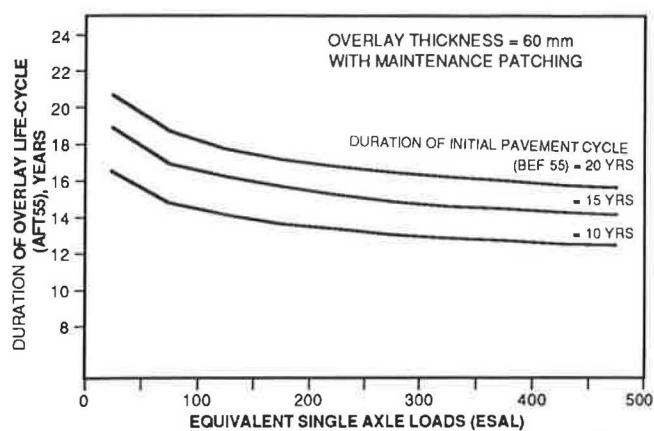


FIGURE 7 Effect of initial pavement life on overlay life.

specific, long-term interaction between the pavement structure, including maintenance, and traffic and environmental exposures. If, for example, the initial pavement structure performs poorly, perhaps because of local soil or drainage conditions or unusually heavy traffic loads, chances are that the overlay performance is also negatively influenced by the same conditions. The duration of the initial pavement life cycle is thus a comprehensive, site-specific, and readily available predictor of overlay performance that should not be overlooked even by mechanistically based overlay design methods.

Model Verification

Because of the relatively small number of observations available for the model development (20) and the method used for their selection, an additional six observations were selected in a random manner to evaluate the model accuracy independently.

The results of this evaluation, presented in Table 4, indicate that the accuracy of the model is roughly in line with expectations. The standard deviation of the difference between measured and predicted overlay life spans for the six additional observations was 2.07 years, comparable to the model root mean square error of 1.12 years.

PCR Change During the First 5 Years After Overlay (Δ PCR5)

The prediction of PCR change during the first 5 years of overlay life (Δ PCR5) complements the prediction of overlay life cycle span and was motivated by two reasons.

Data Availability

The development of the overlay life cycle prediction model required pavement performance data for the same basic pavement structure spanning two pavement life cycles or approximately 25 to 40 years. Because the Δ PCR5 prediction modeling required considerably less historical data, an additional 30 observations were available for a total of 50 observations. Also, it was hoped that the Δ PCR5 prediction could serve as a surrogate of the total life cycle prediction.

Performance Curve

Prediction of Δ PCR5 helps to define the shape of the pavement performance curve. The shape of the performance curve, in addition to its length, is often used in economic analyses.

Model Description

A number of Δ PCR5 prediction models were constructed and evaluated. These models related Δ PCR5 with variables characterizing pavement structure and pavement condition before overlay, as well as overlay itself. The following prediction model for Δ PCR5 was selected because of its rational structure, statistical parameters, and simplicity.

$$\Delta\text{PCR5} = 36.31 \cdot \text{THOV}^{-0.65} \cdot \text{ESAL}^{0.16} \cdot \text{DMI}^{0.21} \quad (4)$$

Statistical parameters of the model represented by Equation 4 are summarized in Tables 5–7. Even though the multiple correlation coefficient of the model was relatively low ($R^2 = 0.26$), the model itself and its partial regression coefficients

TABLE 4 MODEL VERIFICATION

Observation No. ^a	Initial Cycle Life BEF55 (years)	Overlay Thickness THOV (mm)	Traffic Loads ESAL (axles)	Maintenance Patching PATCH (0 or 1)	Overlay Life AFT55		Difference, Observed-Predicted (years) ^c
					Observed (years)	Predicted ^b (years)	
1	16	55	102	1	18	16.0	2.0
2	8	60	37	1	16 ^d	14.6	1.4
3	6 ^e	60	15	1	11	14.5	-3.5
4	11	50	177	0	12	11.2	0.8
5	16	60	77	0	17 ^d	15.0	2.0
6	13	40	50	1	14	13.8	0.2

^aListed as observation sections 51 through 56 in Reference 5.

^bUsing Equation 1.

^cAvg = 0.48; SD = 2.07

^dExtrapolated for next 5 years.

^ePavement structure before overlay included 100 mm of cold mix.

TABLE 5 ANALYSES OF VARIANCE OF Δ PCR5 MODEL

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Level of Significance (%)
Regression model	3	0.398	1.33	5.08	0.4
Error	42	1.098	0.026		
Corrected total	45	1.496			

TABLE 6 PARTIAL REGRESSION COEFFICIENTS OF Δ PCR5 MODEL

Parameter	Estimate	Std. Error of Estimate	Student's <i>t</i> Value for HO: Para = 0	Level of Significance (%)
Intercept	1.555	0.367	4.24	0.1
log THOV	-0.655	0.208	-3.15	0.3
log ESAL83	0.161	0.060	2.68	1.0
log DMI	0.211	0.116	1.82	7.6

were statistically significant. There was no intercorrelation between model variables. The correlation coefficient between Δ PCR5 and the duration of overlay life cycle (AFT55) was -0.47, indicating that Δ PCR5 can serve as a surrogate for AFT55.

The prediction of Δ PCR5 suffered more from the subjectiveness of the PCR scale than did the prediction of the overlay life. The change in Δ PCR5 starts at the top of the PCR scale which may be also influenced by the halo effect.

Equation 4 is graphically represented in Figures 8a and 8b. Figure 8a illustrates the influence of overlay thickness on Δ PCR5. Figure 8b shows that DMI at the time of overlay placement influences the rate at which the overlay deteriorates, at least in the first 5 years of its life. Equation 4 thus quantifies, on a statistical basis, the effects of deferring overlays: A postponement of overlay placement increases DMI and the increase in DMI accelerates pavement deterioration (Δ PCR5). Alligator cracking (ALLIG) had a similar influence on Δ PCR5 and was also highly correlated with DMI (Table 4).

CONCLUSIONS AND RECOMMENDATIONS

1. Long-term pavement performance data can be used to develop reliable empirical models for performance prediction

of various rehabilitation treatments. These models can include the effect of maintenance effort and can be used for life cycle economic analyses.

2. Using long-term pavement performance monitoring data, a damage model has been developed for asphalt concrete overlays over existing asphalt concrete pavements. The model predicts the span of the overlay life cycle for a predetermined terminal serviceability as a function of overlay thickness, traffic, maintenance patching, and the life cycle span of the initial pavement. The last variable, included in the model to characterize the interaction between the initial pavement structure and its traffic and environmental exposures, appears to be useful, readily available, and site specific.

3. The model developed for prediction of the drop in pavement serviceability during 5 years following the overlay placement (Δ PCR5) quantifies the influence of pavement distress conditions before overlay placement on the overlay performance. Deterioration in the overlay occurs at an accelerated rate when there is a delay in placing the overlay.

4. The proposed overlay performance prediction models and their coefficients were statistically significant despite many assumptions, simplifications, and possible sources of error (e.g., variability due to section length, subjective nature of PCR, and difficulties in quantifying maintenance effort). These problems can be eliminated or considerably reduced by better

TABLE 7 CORRELATION COEFFICIENTS OF Δ PCR5 MODEL^{a,b}

	THOV	ESAL83	DMI	Δ PCR5	ALLIG	RCR
THOV	1.00					
ESAL83	0.25	1.00				
DMI	0.27	0.15	1.00			
Δ PCR5	-0.28	0.12	0.19	1.00		
ALLIG	-0.16	-0.07	0.54	0.30	1.00	
RCR	0.24	0.13	0.13	-0.08	-0.03	1.00

^aCorrelation coefficients are based on 46- to 50-observation sections.

^bStatistical significance of correlation coefficients is outlined in footnote b, Table 3.

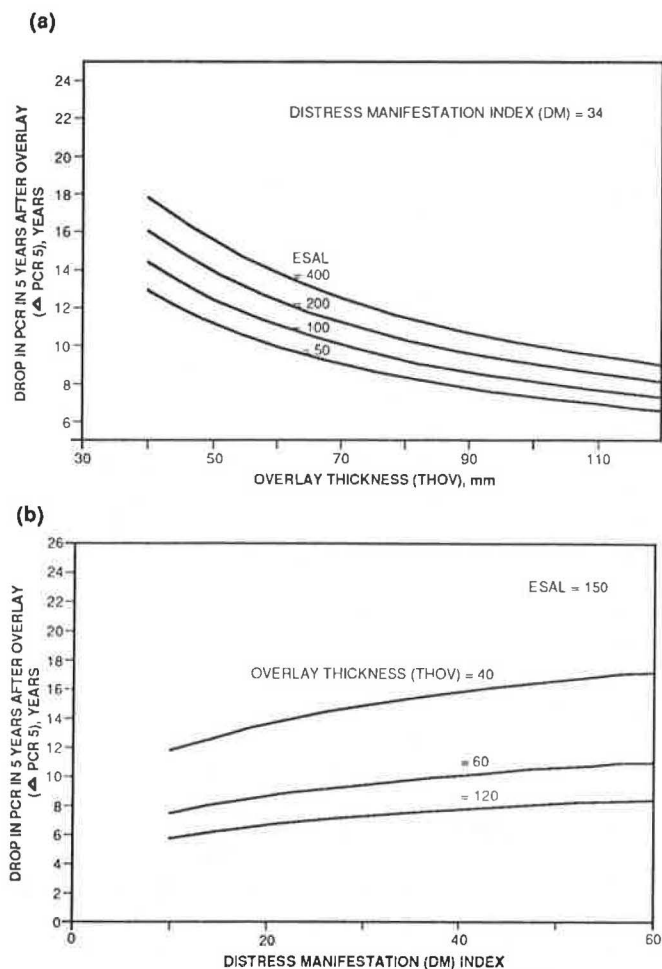


FIGURE 8 (a) Effect of overlay thickness on PCR drop. (b) Effect of DMI on PCR drop.

designed and executed long-term pavement performance programs (13).

5. The proposed models should be updated when more data become available both to increase the model database and as an ongoing adjustment to reflect overlay design changes. The modeling can be also improved by developing different prediction equations for different climatic regions. Additional models should be developed for other rehabilitation treatments.

6. The prediction models developed in this study are based on statistically documented experience obtained by a long-term pavement performance monitoring program. The results detail some of the significant benefits such programs can provide for pavement performance prediction. However, the results also indicate some limitations of using long-term pavement performance data for prediction purposes. Because the span of overlay life cycle appears to depend on the life span of the initial pavement, the duration of time the pavement should be monitored may exceed 20 years. During this time, the pavement construction technology and traffic loads may undergo some significant changes. Yet, the results of the long-term pavement performance monitoring apply to the pavements built at the beginning of the program. At the end of the program, perhaps 20 years later, new materials may be already used (e.g., asphalt additives and granular materials) for which the long-term monitoring results may not fully apply. Similarly, in the

early 1960s, typical truck tire pressures were in a range of 70 to 90 psi, whereas the current range may be closer to 100 to 130 psi. While some limitations are unavoidable, a judicious selection of pavement sections for long-term monitoring may ameliorate some of the limitations.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to University of Waterloo engineering students, R. Little and A. Lane-Smith, for their help with data collection and to A. Lane-Smith and C. Kingdon for conducting statistical analysis. Appreciation is also extended to members of the MCT regional geotechnical sections for providing invaluable long-term pavement performance data.

REFERENCES

1. J. J. Hajek, W. A. Phang, A. Prakash, and G. A. Wrong. Performance Prediction for Pavement Management. In *Proc., North American Pavement Management Conference*, Toronto, Canada, March 1985, pp. 4.122-4.134.
2. W. A. Phang and G. A. Wrong. *Maintenance of the Highway Infrastructure, Pavement Management and Preservation*. Report ONT-014. Ontario Ministry of Transportation and Communications, Downsview, Ontario, Canada, March 1985.
3. T. L. Nelson and R. V. LeClerc. *Development and Implementation of Washington State's Pavement Management System*. Report WA-RD 50.1. Washington State Department of Transportation, Olympia, Feb. 1983.
4. G. J. Chong, W. A. Phang, and G. A. Wrong. *Manual for Condition Rating of Flexible Pavements*. Report SP 004. 2nd ed., Ontario Ministry of Transportation and Communications, Downsview, Ontario, Canada, April 1982.
5. J. J. Hajek, W. A. Phang, and A. Prakash. *Estimating the Life of Asphalt Overlays*. Report PAV-86-02. Ontario Ministry of Transportation and Communications, Downsview, Ontario, Canada, May 1986.
6. R. A. Chisholm and W. A. Phang. Measurement and Prediction of Frost Penetration in Highways. In *Transportation Research Record 918*, TRB, National Research Council, Washington, D.C., 1983, pp. 1-10.
7. R. Kher, and W. A. Phang. OPAC Design System. In *Proc., 4th International Conference on Structural Design of Asphalt Pavements*, Ann Arbor, Mich., Aug. 1977, pp. 841-854.
8. B. G. Hutchinson. Principles of Subjective Rating Scale Construction. In *Highway Research Record 46*, HRB, National Research Council, Washington, D.C., 1964, pp. 60-70.
9. D. B. Suits. Use of Dummy Variables in Regression Equations. *American Statistical Association Journal*, Dec. 1957, pp. 548-551.
10. SAS Institute Inc. *SAS User's Guide: Statistics, Version 5 Edition*. SAS Institute, Cary, N.C., 1985.
11. R. D. Pedigo, W. R. Hudson, and F. L. Roberts. Pavement Performance Modelling for Pavement Management. In *Transportation Research Record 814*, TRB, National Research Council, Washington, D.C., 1981, pp. 14-21.
12. D. R. Luhr, B. F. McCullough, and A. Pelzner. Development of an Improved Pavement Management System. In *Proc., 5th International Conference on Structural Design of Asphalt Pavements*, Vol. 1, University of Michigan, Ann Arbor, 1982, pp. 553-563.
13. Strategic Highway Research Program. *Section 2: Research Design Summary*. TRB, National Research Council, Washington, D.C., May 1986, pp. 8-20.