Application of Probabilistic Approach for Predicting Pavement Maintenance Requirement: A Case Study on Ontario Highways

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ABSTRACT

In pavement management system (PMS), the time to maintenance is generally estimated based on the predicted condition of the pavement. A deterministic approach is applied in the PMS to estimate the time to maintenance by following the deterioration equation of performance index. However, the probabilistic approach will further estimate the probability of failure over the estimated time to maintenance. For this reason, a probabilistic approach is applied in this study to estimate the probability of failure of pavement based on both overall condition and individual distress. In this approach, the probability of failure is estimated from the distribution of the mean time to maintenance. These mean time to failure or maintenance are calculated from the overall condition of pavement in terms of the pavement condition index (PCI) when the trigger value becomes 65 or less. However, the pavement may expect failure due to any specific distress (if the target value of failure is reached for any individual distress) before reaching the PCI trigger value of failure. For this reason, the probability of failure of each specific distress is also investigated along with the overall condition of the pavement.

Key Words: Probability of Failure, Pavement Deterioration, Time to Maintenance, Overall Condition Index

1. INTRODUCTION

The deterioration of pavement varies significantly depending on the characteristics of traffic and the properties of materials (1). In the same way, pavement service life is found to be highly sensitive to traffic characteristics and pavement structure (2, 3 and 4). In any Pavement Management System (PMS), the remaining service life of the pavement is estimated from the predicted future deterioration of the overall condition. The future deteriorated condition is calculated in terms of pavement performance index following a general equation of sigmoidal form, with different model coefficients (5). The time to maintenance is usually estimated from the predicted deterioration condition by a deterministic approach.

Recently in many types of research, a probabilistic approach is found to be used to assess the reliability of pavement performance assessment. A probabilistic analysis based on the use of probabilistic duration modeling techniques by hazard function is also found in PMS (6). Moreover, the effect of performance index model accuracy is also investigated on optimal design and life cycle costs by using regression and probabilistic models (7).

However, it is required to investigate whether the estimated time to maintenance by the deterministic approach is realistic and reasonably probable. For this reason, a probabilistic approach is applied to estimate the probability of failure. This study will investigate the probability of failure of pavement based on the pavement overall condition and individual distress as well.

2. SELECTED ROAD SECTIONS AND ROAD PERFORMANCE DATA

The pavement condition data and performance evaluation results reported into the database of the Ministry of Transportation Ontario (MTO) Pavement Management Systems (PMS) which is known as MTO PMS-2 is used in this study.

The experimental design consists of 128 highway sections. These highway sections consist of 113 sections with Marshall mixes and 15 sections with Superpave mixes. In this study, 161 performance cycles are investigated for predicting pavement performance deterioration patterns. The uninterrupted service life, which began after new construction or overlay design and ended before applying any other treatment (if improvement in performance index is observed due to that treatment, which may not reflect the improvement due to minor treatment), is considered as one 'performance cycle' in this study.

3. INVESTIGATION OF PROBABILTY OF FAILURE BASED ON THE PAVEMENT OVERALL CONDITION

The expected time to maintenance is estimated from the future deteriorated condition of the pavement. The future deterioration condition of pavement is calculated in terms of pavement performance index such as Pavement Condition Index (PCI), Riding Comfort Index (RCI) and of Distress Manifestation Index (DMI) following a general equation of sigmoidal form, with different model coefficients (5).

The future performance of pavement is estimated by the following equation (8):

$$P = P_0 - 2e^{(a-bc^t)} \qquad (1)$$

Where,

P = Performance Index, RCI or DMI

Po = P at Age o

t = Log e(1/Age)

a,b,c = Model Parameters

Depending on the model parameters, the shape of the performance curve may be a straight line, convex, concave or S-shaped, with varying degrees of curvature. With this flexibility offered by the curve, the coefficients of the models are estimated to fit into different pavement performance deterioration trends due to change in AADT and surface layer materials. The model coefficients are determined by using the least squares, nonlinear regression method.

Since the deterioration of pavement varies significantly depending on the characteristics of traffic and the properties of materials, the equation [1] is estimated based on three categories of AADT in the first year of performance. These are AADT ≤25,000, >25,000 to ≤ 50,000, and >50,000. The pavement structure of the selected highway sections with Marshall mixes is mainly found with a surface layer of dense friction course (DFC) and different types of hot laid (HL) asphalt surfaces layers such as HL-1, HL-3, HL-3M, HL-4, and HL-8. For this reason, the pavement deterioration equation is estimated for these available HL layers along with Superpave layer. The estimated parameters of the equation [1] for three levels of traffic and surface layer are listed in Table 1.

For each category of traffic level and the surface layer, mean time to failure or maintenance is calculated from the predicted condition of pavement in terms of the pavement condition index (PCI) when the trigger value becomes 65 or less. The estimated time to maintenance is listed in Table 2.

Table 1: Estimated Parameters of the Pavement Deterioration Model

Surface Material Type	**AADT**	**Parameters of PCI Model :** $P = P_0 - 2e^{(a-bc^t)}$		
		a	**b**	**c**
DFC	≤25,000	2.369	4.746	2.786
	>25,000 to ≤ 50,000	2.750	4.500	3.600
	>50,000	2.980	1.910	2.000
HL1	≤25,000	4.396	5.594	1.521
	>25,000 to ≤ 50,000	4.418	5.144	1.429
	>50,000	N/A[2]		
HL3	≤25,000	2.990	6.230	2.939
	>25,000 to ≤ 50,000	4.570	5.500	1.570
	>50,000	N/A		
HL3M	≤25,000	2.590	5.630	2.900
	>25,000 to ≤ 50,000	N/A		
	>50,000	N/A		
HL4	≤25,000	7.229	9.249	1.364
	>25,000 to ≤ 50,000	7.345	8.780	1.340
	>50,000	N/A		
HL8	≤25,000	1.866	15.361	16.865
	>25,000 to ≤ 50,000	2.369	4.746	2.786
	>50,000	N/A		
Superpave (SP 12.5 FC2)	≤25,000	2.369	4.746	2.786
	>25,000 to ≤ 50,000	2.650	2.400	1.900
	>50,000	2.880	2.386	1.869

[2] N/A=Not Available

Table 2: Summary of Expected Time to Maintenance

Surface Material Type	AADT	Time to Maintenance/Failure (Year)		
		Mean	Standard Deviation	Coefficient of Variation
DFC	≤25,000	17.0	7.24	0.43
	>25,000 to ≤ 50,000	14.0	2.87	0.21
	>50,000	13.2	7.63	0.58
HL1	≤25,000	13.7	4.64	0.34
	>25,000 to ≤ 50,000	13.0	2.86	0.22
	>50,000	N/A		
HL3	≤25,000	13.2	5.32	0.40
	>25,000 to ≤ 50,000	9.0	1.54	0.17
	>50,000	N/A		
HL3M	≤25,000	10.8	3.28	0.30
	>25,000 to ≤ 50,000	N/A		
	>50,000	N/A		
HL4	≤25,000	9.1	1.26	0.14
	>25,000 to ≤ 50,000	6.7	0.81	0.12
	>50,000	N/A		
HL8	≤25,000	7.0	0.90	0.13
	>25,000 to ≤ 50,000	6.4	0.89	0.14
	>50,000	N/A		
Superpave (SP 12.5 FC2)	≤25,000	16.8	1.60	0.10
	>25,000 to ≤ 50,000	15.9	2.98	0.19
	>50,000	14.2	7.56	0.53

The distribution of time to failure or maintenance may vary depending on the material types and traffic. For this reason, the distribution of time to maintenance is plotted for each category to identify the type of distribution. Probability paper plots are compared for each category and distribution types are selected. Figure 1 shows the probability plots for DFC (for AADT >50000). It is found that the Weibull distribution is the best fit for this category. For all other categories of traffic and surface materials, the 'best-fit' distribution of time to maintenance is identified accordingly. Table 3 summarizes the distribution parameters of time to maintenance for all categories. The distribution parameters are estimated from the probability paper plot and following the method of moments for Weibull distribution.

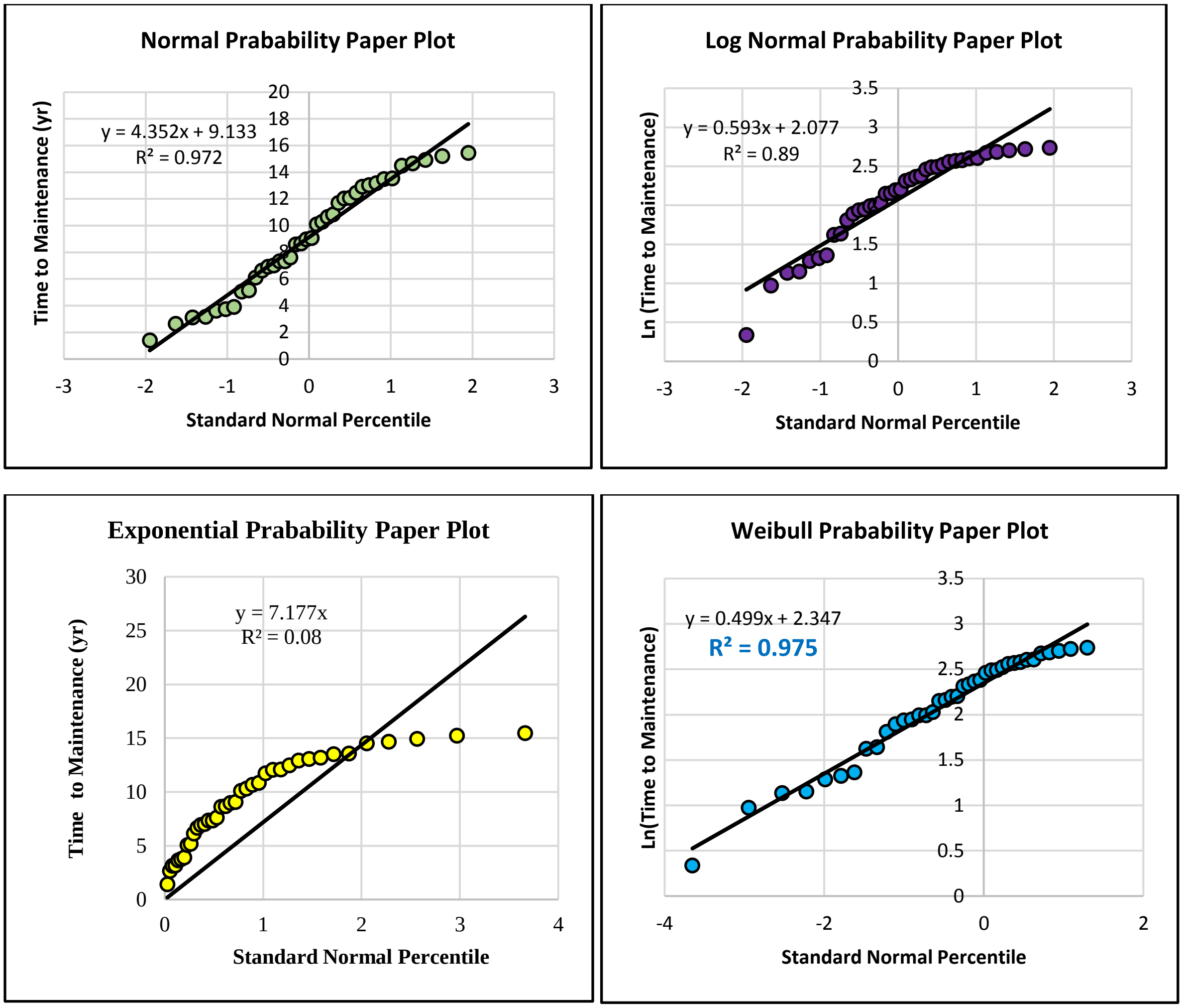

Figure 1: Probability Paper Plot of Time to Maintenance for DFC (AADT >50,000)

After comparing the probability paper plots, the highest R^2 value of the 'best fit' distribution for each sub-category is shown in bold font in Table 3. It is observed from Table 3 that for most of the categories, the distribution of the time to maintenance is 'best fit' by the Weibull distribution. However, the normal distribution is found as 'best fit' for HL1 with AADT ≤25,000, HL3 with AADT ≤25,000, and HL-8 with AADT ≤25,000. The log-normal distribution is found as 'best-fit' for sections with Superpave mixes in the case of AADT >50,000. The exponential distribution is also found as 'best- fit' for only one category of HL-3M with AADT ≤25,000.

Even though there are some exceptions, the Weibull distribution is followed in the next step while estimating the probability of failure for all categories in a consistent way and also for simplicity of application. Moreover, the Weibull distribution is considered as flexible and it is commonly used to model time to failure of any component (9, 10 and 11).

Table 3: Distribution Parameters of Time to Maintenance based on PCI

Surface Material Type	AADT	Normal Distribution			Log-Normal Distribution			Exponential Distribution		Weibull Distribution				
		R^2	Location	Scale Parameter	R^2	Scale Parameter	Shape Parameter	R^2	Scale Parameter	R^2	Scale Parameter from Probability Paper Plot	Shape Parameter from Probability Paper Plot	Scale Parameter by Method of Moments	Shape Parameter by Method of Moments
DFC	≤25,000	0.863	17.021	7.238	0.802	0.408	2.751	0.065	0.059	**0.867**	19.853	1.855	19.181	2.518
	>25,000 to ≤ 50,000	0.669	14.024	2.873	0.625	0.203	2.620	-6.270	0.071	**0.730**	15.256	4.437	15.168	5.649
	>50,000	0.972	13.226	7.627	0.898	0.429	2.120	0.084	0.109	**0.975**	10.457	2.004	10.305	2.366
HL1	≤25,000	**0.970**	13.707	4.639	0.901	0.329	2.564	0.932	0.073	0.968	15.454	2.822	15.292	3.248
	>25,000 to ≤ 50,000	0.901	12.950	2.861	0.835	0.218	2.537	-4.691	0.077	**0.917**	14.212	4.196	14.073	5.201
	>50,000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HL3	≤25,000	**0.958**	13.174	5.320	0.944	0.389	2.503	0.213	0.076	0.955	14.989	2.380	14.820	2.667
	>25,000 to ≤ 50,000	0.765	9.016	1.544	0.727	0.170	2.185	-10.240	0.111	**0.840**	9.690	5.711	9.648	6.859
	>50,000		N/A											
HL3M	≤25,000	0.983	10.798	3.280	0.968	0.297	2.335	**0.989**	0.093	0.984	12.099	3.135	11.972	3.663
	>25,000 ≤ 50,000		N/A											
	>50,000		N/A											
HL4	≤25,000	0.850	9.089	1.258	0.795	0.138	2.198	-15.320	0.110	**0.868**	9.667	6.807	9.617	8.619
	>25,000 to ≤ 50,000	0.792	6.655	0.806	0.774	0.121	1.888	-21.800	0.150	**0.870**	7.022	7.962	6.998	9.926
	>50,000		N/A											
HL8	≤25,000	**0.747**	7.047	0.901	0.775	0.127	1.944	-17.520	0.142	0.740	7.382	8.993	7.428	9.371
	>25,000 to ≤ 50,000	0.856	6.371	0.891	0.834	0.139	1.842	-13.900	0.157	**0.901**	6.798	6.258	6.745	8.517
	>50,000		N/A											
Superpave(SP 12.5 FC2)	≤25,000	0.645	16.823	1.602	0.642	0.095	2.818	-38.110	0.059	**0.746**	17.509	10.799	17.514	12.790
	>25,000 to ≤ 50,000	0.753	15.862	2.981	0.732	0.186	2.747	-6.563	0.063	**0.807**	17.245	4.511	17.066	6.203
	>50,000	0.850	14.159	7.563	**0.935**	0.501	2.525	0.815	0.071	0.888	16.260	1.908	15.968	1.952

In solving the following equations, the Probability Density Function (PDF) and Cumulative Distribution Function (CDF) for the respective distribution is estimated.

For normal distribution, the PDF is calculated by using the following equation (9, 10 and 11):

$$f(x) = \frac{1}{\sqrt{2\,\pi\sigma}}\, e^{\frac{-(x-\mu)^2}{2\sigma^2}} \quad -\infty \leq x \leq \infty \tag{2}$$

Where,

μ= mean of distribution or location parameter

σ = standard deviation or scale parameter

For exponential distribution, the PDF is calculated by using the following equation:

$$f(x) = \lambda\, e^{-\lambda x} \tag{3}$$

Where,

λ= scale parameter and $x > 0$

The CDF of exponential distribution is calculated by using the following equation:

$$F(x) = 1 - e^{-\lambda x} \tag{4}$$

For log-normal distribution, the PDF is calculated by using the following equation:

$$f(x) = \frac{1}{\sqrt{2\,\pi x\zeta}}\, e^{\frac{-(lnx-\lambda)^2}{2\zeta^2}} \quad x \geq 0;\ \zeta > \infty \tag{5}$$

Where,

ζ = shape parameter or slope

λ= scale parameter or intercept

The CDF of the log-normal distribution is calculated by using the following equation:

$$F_X\,(x) = \int_{-\infty}^{x} f_X\,(x)dx = \phi\,(\frac{lnx-\lambda}{\zeta}) \tag{6}$$

$$\lambda = \ln(\mu) - \frac{1}{2}\,\zeta^2 \tag{7}$$

$$\zeta = \sqrt{ln(1+\delta^2)} \tag{8}$$

Where,

δ = coefficient of variation

The PDF of the Weibull distribution is calculated by using the following equation:

$$f(x) = \frac{\alpha}{\beta^{\alpha}} x^{\alpha-1} e^{-(\frac{x}{\beta})^{\alpha}} \quad (9)$$

Where,

α =shape parameter or slope,

β = scale parameter or intercept

$$\text{mean}, \bar{x} = \beta\Gamma\,(1 + \frac{1}{\alpha})$$

$$\text{Standard deviation}, s = \beta\sqrt{\Gamma\left(1 + \frac{2}{\alpha}\right) - \Gamma\left(1 + \frac{1}{\alpha}\right)^2}$$

Γ= gamma function

The CDF of the Weibull distribution is calculated by using the following equation:

$$F(t) = 1 - e^{-\left(\frac{t}{\beta}\right)^{\alpha}} \quad (10)$$

The Weibull reliability function is calculated by using the following equation:

$$R(t) = e^{-(\frac{t}{\beta})^{\alpha}} \quad (11)$$

The Weibull hazard rate function is calculated by using the following equation:

$$h(t) = \frac{\alpha}{\beta}\left(\frac{t}{\beta}\right)^{\alpha-1} \quad (12)$$

Where,
T = age
α =shape parameter or slope,
β = scale parameter or intercept

Based on the distribution parameters listed in Table 3 and using the above equations, the probability of failure is estimated for each category. Table 4 presents the summary of the probability of failure for each for 5-year interval up to the 30th year. From Table 4 the survival probability up to the fifth year is approximately 80% to 90% for each category. Corresponding probability of failure of up to the fifth year is found as 0% to 13%. Therefore, this probability indicates the minimum requirement of maintenance up to first 5th year after the treatment.

Table 4: Probability of Failure over the Service Life

Surface Material Type	AADT	Mean Time to Maintenance from Distribution of Field-evaluated PCI model, in Year	Parameter of Weibull Distribution		Probability of Failure						
			Shape Parameter, α	Scale Parameter, β	Survival Probability up to 5th Year	Probability of Failure up to 5th Year	Probability of Failure up to 10th Year	Probability of Failure up to 15th Year	Probability of Failure up to 20th Year	Probability of Failure up to 25th Year	Probability of Failure up to 30th Year
DFC	≤25,000	17.021	2.518	19.181	0.967	0.033	0.176	0.416	0.671	0.858	0.954
	>25,000 to ≤ 50,000	14.024	5.649	15.168	0.998	0.002	0.091	0.609	0.992	1.000	1.000
	>50,000	13.226	1.794	14.870	0.868	0.132	**0.388**	0.638	0.818	0.921	0.970
HL1	≤25,000	13.707	3.248	15.292	0.974	0.026	0.222	0.609	0.908	0.993	1.000
	>25,000 to ≤ 50,000	12.950	5.201	14.073	0.995	0.005	0.156	0.752	0.998	1.000	1.000
	>50,000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HL3	≤25,000	13.174	2.667	14.820	0.946	0.054	0.295	0.644	0.892	0.982	0.999
	>25,000 to ≤ 50,000	9.016	6.859	9.648	0.989	0.011	**0.722**	1.000	1.000	1.000	1.000
	>50,000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HL3M	≤25,000	10.798	3.663	11.972	0.960	0.040	**0.404**	0.898	0.999	1.000	1.000
	>25,000 to ≤ 50,000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	>50,000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HL4	≤25,000	9.089	8.619	9.617	0.996	0.004	**0.753**	1.000	1.000	1.000	1.000
	>25,000 to ≤ 50,000	6.655	9.926	6.998	0.965	0.035	**1.000**	1.000	1.000	1.000	1.000
	>50,000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HL8	≤25,000	7.047	9.371	7.428	0.976	0.024	**1.000**	1.000	1.000	1.000	1.000
	>25,000 to ≤ 50,000	6.371	8.517	6.745	0.925	0.075	**1.000**	1.000	1.000	1.000	1.000
	>50,000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Superpave(SP 12.5 FC2)	≤25,000	16.823	12.790	17.514	1.000	0.000	0.001	0.129	0.996	1.000	1.000
	>25,000 to ≤ 50,000	15.862	6.203	17.066	1.000	0.000	0.036	0.362	0.931	1.000	1.000
	>50,000	14.159	1.952	15.968	0.902	0.098	0.330	0.587	0.788	0.909	0.967

From Table 4, it is also observed that up to 10^{th} year after treatment, a higher probability of failure is found for the case DFC with >50,000 AADT (38.8%), HL3 with AADT 25,000 to ≤50,000 (72.2%), HL3M with AADT ≤25,000 (40.4%), HL4 with AADT ≤25,000 (75.3%), HL4 with AADT 25,000 to ≤50,000 (100%), HL8 with AADT ≤25,000 (100%) and HL8 with AADT 25,000 to ≤50,000 (100%). Since the estimated mean maintenance time is less than 10 years for HL3 with AADT 25,000 to ≤50,000 (9 years), HL4 with AADT ≤25,000 (9 years), HL4 with AADT 25,000 to ≤50,000 (6.6 years), HL8 with AADT ≤25,000 (7 years) and HL8 with AADT 25,000 to ≤50,000 (6.37 years), it justifies to have a higher probability of failure.

The probability of failure is found as 67% to 100%, 85% to 100% and 95% to 100%, up to the 20th, 25th and 30th year respectively for all categories. This probability of failure depending on the pavement age will help pavement engineers set a priority of the road sections for next period of maintenance.

4. INVESTIGATION OF PROBABILTY OF FAILURE BASED ON THE INDIVIDUAL DISTRESS

In the previous section, the probability of failure is estimated from the distribution of the mean time to maintenance. In the previous section, the time to maintenance mainly focuses on the overall condition of the pavement. However, the pavement may expect failure due to any specific distress (if the target value of failure is reached for any individual distress) before reaching the PCI trigger value of maintenance. For this reason, the probability of failure of each specific distress needs to be investigated along with the overall condition of the pavement.

At first, the distribution of each individual distress is investigated. The distribution of IRI, permanent deformation, thermal cracking, bottom-up fatigue cracking, top-down fatigue cracking, along with the distribution of DMI and PCI, are observed for years for the selected road sections. For each road section, the yearly performance in terms of the condition of each individual distress is observed. A Monte Carlo simulation is carried out by considering the distribution of performance of the individual distress. The probability of failure of each individual distress is estimated for the corresponding threshold value of failure. The time to maintenance is triggered if there is any failure of any specific distress over the performance cycle regardless of the PCI value. Table 5 summarizes the probability of failure considering each category of distress separately.

From Table 5, it is found that the probability of failure for individual distress is very low (less than 10% for each category) over the performance cycle of estimated mean time to maintenance. The resultant probability of maintenance is also very low (less than 10%) for each category.

This analysis will help pavement engineers make decisions regarding the selection of treatment in terms of the surface layer. The estimation of the probability of failure for surface layer types for specific traffic groups and corresponding time to maintenance will help pavement management decide on effective maintenance strategies.

Table 5: Probability of Failure and Maintenance due to Failure in Individual Distress

Surface Material	AADT	Probability of Failure					Probability of Maintenance due to Failure in Individual Distress
		Bottom-up Fatigue Cracking	Top-down Fatigue Cracking	Thermal Cracking	Rut Depth	IRI	
DFC	≤25,000	0.000	0.000	0.000	0.000	0.000	0.000
	>25,000 to ≤ 50,000	0.000	0.001	0.000	0.000	0.000	0.001
	>50,000	0.000	0.001	0.005	0.000	0.004	0.005
HL1	≤25,000	0.000	0.000	0.000	0.002	0.001	0.002
	>25,000 to ≤ 50,000	0.000	0.000	0.000	0.002	0.008	0.008
	>50,000	N/A	N/A	N/A	N/A	N/A	N/A
HL3	≤25,000	0.000	0.000	0.010	0.000	0.001	0.010
	>25,000 to ≤ 50,000	0.000	0.000	0.031	0.000	0.015	0.031
	>50,000	N/A	N/A	N/A	N/A	N/A	N/A
HL3M	≤25,000	0.000	0.000	0.002	0.000	0.003	0.003
	>25,000 to ≤ 50,000	N/A	N/A	N/A	N/A	N/A	N/A
	>50,000	N/A	N/A	N/A	N/A	N/A	N/A
HL4	≤25,000	0.000	0.000	0.015	0.001	0.000	0.015
	>25,000 to ≤ 50,000	0.000	0.000	0.020	0.006	0.000	0.020
	>50,000	N/A	N/A	N/A	N/A	N/A	N/A
HL8	≤25,000	0.000	0.000	0.000	0.000	0.000	0.000
	>25,000 to ≤ 50,000	0.000	0.000	0.000	0.004	0.000	0.004
	>50,000	N/A	N/A	N/A	N/A	N/A	N/A
Superpave(SP 12.5 FC2)	≤25,000	0.000	0.000	0.000	0.007	0.029	0.029
	>25,000 to ≤ 50,000	0.000	0.000	0.000	0.008	0.041	0.041
	>50,000	0.000	0.000	0.000	0.041	0.062	0.062

5. CONCLUSIONS

This study investigates the probability of failure of pavement based on the both pavement overall condition and individual distress. The expected time to maintenance for the overlay with DFC and Superpave is found as higher than hot-laid layers. On the other hand, HL-8 requires early maintenance compared to other types of overlay layers. The traffic level for the same surface layer also affects the required time to maintenance.

Since the distribution of time to failure or maintenance varies depending on the types of materials and traffic, these distributions are further investigated. It is found that the Weibull distribution is the best fit for most of the categories of traffic and materials. In the probabilistic approach, the probability of failure is estimated for each category. It is found that the survival probability up to the 5th year is approximately 80% to 90% for each category and the corresponding probability of failure up to the 5th year is very low for each category. Therefore, this probability indicates the minimum requirement of maintenance up to the first 5th year after the treatment. For all categories, the probability of failure up to the 20th, 25th, and 30th year are very high. This probability of failure depending on the pavement age will help pavement engineers set a prioritized maintenance schedule for the road sections.

The probability of failure due to each specific distress is investigated as well. For this purpose, a Monte Carlo simulation is carried out by considering the distribution parameters for each category of materials and traffic levels. From the Monte Carlo simulation, it is found that the probability of failure for individual distress is very low over the performance cycle. The corresponding probability of maintenance is also very low for each category.

This analysis will help pavement engineers to make an informed decision in selecting treatment types. The estimated probability of failure for surface layer types for specific traffic groups will help select priority lists of road sections for maintenance and enable management to decide on effective maintenance strategies. The results of the investigations can be used for predicting the future pavement conditions for different levels of traffic and materials and thereby can be used in M&R decisions in a realistic way.

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REFERENCES

1. Prozzi, J.A. 2001. “Modelling of pavement performance by Combining Field and Experimental Data.” Doctor of Philosophy Thesis, University of California, Berkeley, 2001.
2. Jannat, G., and Tighe, S. 2015. “An Experimental Design based Evaluation of Sensitivities of Mechanistic-Empirical Pavement Design Guide (MEPDG): Investigating Main and Interaction Effects of Input Factors.” International Journal of Pavement Engineering , Vol. 17 (7) , pp.615-625
3. Jannat, G., and Tighe, S. 2016. “Developing New Performance Index for Assessing Overall Pavement Condition by Incorporating of Mechanistic-Empirical Approach for Ontario Highways.” 2016 Transportation Association of Canada (TAC) Conference, Toronto.

4. Jannat, G. and Tighe, S. 2017. “Developing Performance Prediction Models based on Traffic and Materials by Incorporating Mechanistic-Empirical Approach for Ontario Highways.” Transportation Research Board (TRB) Meeting, Washington D.C.

5. Ningyuan, L., T. Kazmierowski, T., Tighe, S. and Haas, R. 2001. “Integrating Dynamic Performance Prediction Models into Pavement Management Maintenance and Rehabilitation Programs.” 5th International Conference on Managing Pavements.
6. Prozzi , J. A. and S. M. Madanat, S.M. 2000. “Using Duration Models to Analyze Experimental Failure Data.” Transportation Research Record: Journal of the Transportation Research Board, No. 1699, pp 87-94.

7. Madanat, S. M., Prozzi, J.A. , and Han, M. 2002. “Effect of Performance Model Accuracy on Optimal Pavement Design.” Journal of Computer-Aided Civil and Infrastructure Engineering, Vol. 10, No. 1, pp. 22-30

8. Transportation Association of Canada (TAC).2013. *Pavement Asset Design and Management Guide*. Transportation Association of Canada (TAC).

9. Benjamin, J.R., and Cornel C.A. 1970. “Probability Statistics and Decisions for Civil Engineers.” McGraw-Hill, New York.

10. Ang, A.H-S, and W. H. Tang, W.H. 1975. “Probability Concepts in Engineering Planning and Design.” Vol 1 & 2 John Wiley and Sons, New York.

11. Pandey, M.D. 2014. “Engineering Risk and Reliability.” Lecture Notes, University of Waterloo.