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NEW PAVEMENT ROUGHNESS THRESHOLDS TO REDUCE DYNAMIC TRUCK LOADING

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ABSTRACT

In this paper, roughness threshold values and corresponding life extensions are determined using relative damage and reduction in pavement life concepts. Using the 4th power law, relative damages from the 95th percentile dynamic load at different roughness index values, and the corresponding percent reduction in life were calculated and plotted for 333 pavement sections. A newly developed roughness index called the dynamic load index (DLI) was used for this purpose. Estimates of pavement life extension resulting from smoothing its surface were then generated for different Remaining Service Life (RSL) values. The results were presented in tables showing the expected life extension for a range of RSL- and DLI- values. These tables would enable a highway agency to determine when a particular pavement needs to be smoothed to obtain a given (desired) life extension. The analysis was done for the three pavement types (rigid, flexible and composite). RSL-values were calculated for 805-m (0.5-mile) sections using actual distress growth over time. The results showed that for rigid pavements, 17 to 51% of sections would have life extensions of more than 3 years depending on roughness level. For composite pavements, none of the sections would have life extensions of 3 years or more. For flexible pavements, 9 to 34% of sections would have life extensions of more than 3 years depending on roughness level. These results indicate that preventive maintenance by smoothing action is best suited for rigid pavements.

INTRODUCTION

Roughness thresholds aimed at minimizing dynamic loads can play an important role in pavement management and preventive maintenance (PM) program. If a PM action, in the form of smoothing the pavement surface, is taken when the critical roughness level is reached it could extend the service life of the pavement by several years, since it will reduce roughness-generated dynamic loads. In this paper, a new roughness index called the Dynamic Load Index (DLI) described in Reference (1,2) was used to develop tables of predicted life extension for pavements with various Remaining Service Life (RSL) values. The analysis was based on mechanistic principles. Dynamic axle loads obtained from the TruckSim™ program were used to calculate the relative damage at different roughness (DLI) levels. The corresponding reduction in pavement life was then used to calculate the life extension that would be achieved, if a PM smoothing action were to be taken, at different RSL-values. These tables can be used to decide on preventive maintenance candidates for smoothing action.

DEVELOPMENT OF A DYNAMIC-LOAD-BASED ROUGHNESS INDEX

The Dynamic Load Index (DLI) is a profile-based index that represents dynamic truck-axle loading. The DLI is calculated as a weighted index of variances of the profile elevation in the frequency ranges 1.5-4 Hz and 8-15 Hz. The first frequency range corresponds to truck body bounce, while the second frequency range corresponds to axle bounce. DLI is calculated using the following equation (1,2):

$$DLI = \sqrt{V_1 + 14V_2} \qquad (1)$$

where: V_1 is the variance in elevation of Profile 1 (unit: 10^{-2} in; 1 in = 25.4 mm); with Profile 1 containing only waves in the wavelength range of 6.7 to 17.9 m (22 to 59 ft), which corresponds to a frequency range of 1.5-4.0 Hz for a truck travelling at 96 km/hr (60 mph);

V_2 is the variance in elevation of profile 2 (unit: 10^{-2} in; 1 in = 25.4 mm); with Profile 2 containing only waves in the wavelength range of 1.8 and 3.3 m (6 to 11 ft), which corresponds to a frequency range of 8.0-15.0 Hz for a truck traveling at 96km/hr (60 mph).

The weighting factor of 14 in Equation (1) was determined by trying different values, plotting the variation of the Dynamic Load Coefficient (DLC) and 95th percentile dynamic load, respectively, with DLI for rigid, composite and flexible pavements and selecting the value which gave the overall highest R^2-value for all pavement types. The analysis used 333 pavement sections representing a large range of ride quality index (RQI) values[1].

The DLC is an "average" measure of the magnitude of the dynamic variation of axle load over a given pavement surface profile, and is calculated as the ratio of the standard deviation of the dynamic load fluctuations over the static load. The DLC-value for a perfectly smooth pavement surface would theoretically be zero. DLC-values less than 8% indicate moderately smooth pavements, while DLC-values higher than 10% are considered to be indicative of moderately rough pavements, and DLC-values higher than 15% indicate very rough pavement surfaces (4). The 95th percentile axle load is an "extreme" measure of dynamic loading that is indicative of "hot" spots within the pavement surface.

The DLI was tested over a range of road profiles from in-service pavements, and it was found that for any particular value of ride quality index (RQI), the DLI can cover a wide range of values, and this variation in DLI was found to correlate very well with dynamic load, as predicted by a truck simulation program. This was not the case for the International Roughness Index (IRI), which gave a low coefficient of correlation with dynamic load for the same range of profiles. Therefore, the new index can differentiate between profiles that generate high dynamic loads and those having the same RQI but generating low dynamic loads. Most importantly, the use of the DLI index negates the need for running a truck simulation program. This makes it possible for a state highway agency to decide whether a particular pavement with a given surface profile needs smoothing (to extend its service life) based on the DLI-value.

The relationships between DLI and dynamic load were plotted for each pavement type. In this analysis, actual pavement surface profiles of the 333 (161-m or 0.1-mile) sections from 37 projects were used. The pavements included all types (rigid, flexible and composites) with age varying from zero to 39 years. Rigid pavements were mainly jointed reinforced pavements (JRCP) with slab lengths ranging from 8.2 to 30.2 m (27 to 99 ft). Distress levels included the entire range from no distress to distress levels exceeding the threshold for rehabilitation. The average daily commercial traffic volume varied from 70 to 8,900, and the project lengths varied from 2.4 km (1.5 mi) to 26.7 km (16.6 mi). The profiles were input to the truck simulation program, TruckSim™; axle load time histories were generated from a typical 5-axle tractor-semi-trailer. From these dynamic axle-load profiles, DLC and 95th percentile axle loads were calculated and plotted against the corresponding DLI-values, as shown in Figure 1. The figure shows a very good relationship between DLI and the two measures of dynamic loading.

DEVELOPMENT OF DLI-THRESHOLDS AND RESULTANT LIFE EXTENSIONS

The damage induced in pavements by a dynamic load relative to static load can be expressed as the equivalent number of static load passes, using a power law:

$$\text{Relative Damage} = \left(\frac{L_{dynamic}}{L_{static}} \right)^n \qquad (2)$$

where n is the damage exponent (typically, $n = 3\text{-}5$).

The theoretical percent reduction in pavement life can be calculated as (5):

$$R = \textit{Percent Reduction in Pavement Life} = 100\% \, [1 - (\textit{Relative Damage})^{-1}] \qquad (3)$$

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[1] The RQI is a ride number that was developed by the Michigan DOT in the 1970's. It is calculated from three PSD wavelength bands according to the equation shown below (3):

$$RQI = 3 \ln (Var1) + 6 \ln (Var2) + 9 \ln (Var3)$$

where $Var1$, $Var2$ and $Var3$ are variances for 7.6-15.2 m (25-50ft), 1.5-7.6m (5-25ft) and 0.6-1.5 m (2-5 ft) wavelengths, respectively. These wavelengths were found to correlate at 90 percent with subjective opinions obtained from a series of "psychometric" tests conducted on passenger car users.

Using the 4th power law, relative damages from the 95th percentile dynamic load at different DLI values, and the corresponding percent reduction in life were calculated and plotted in Figure 2 for each pavement type. The general equation for the curves relating relative damage to DLI can be written as:

$$y = a\,(DLI)^3 + b\,(DLI)^2 + c\,(DLI) + 1 \qquad (4)$$

where y is the relative damage and a, b, and c are regression constants.

The corresponding R^2-values were between 0.914 and 0.954, with the higher values being for rigid pavements. Table 1 summarizes the relevant regression parameters of the best-fit curves.

The life extension that can be achieved by smoothing a pavement section of a given remaining service life (RSL) can be determined as:

$$Life\ extension = (R-R_o)\,RSL \qquad (5)$$

where R corresponds to the reduction in life at the current DLI value;
R_o corresponds to the reduction in life at the DLI value immediately after smoothing.

The following example shows how to calculate life extension for given RSL and DLI values. The calculation of the life extension expected from smoothing a rigid pavement surface that has an RSL of 14 years and a DLI of 10 is as follows: From Figure 3 (a-2), the R-value corresponding to a DLI of 10 is 43.6%. The R_o-value corresponding to DLI of 3 is 21.9%. Therefore, the life extension can be calculated as $LE = (0.473-0.218)\times 12 = 3.0$ *years.*

The analysis was done for rigid, flexible and composite pavements with RSL values ranging from 20 to 6 years. For the calculation of life extension, the DLI value corresponding to a pavement condition immediately after the smoothing action was determined to be 3 based on Figure 2. Tables 2 through 4 show the life extension that can be expected for a range of RSL- and DLI- values. If a minimum life extension of 3 years were to be adopted, then the shaded areas within each table would represent conditions where smoothing PM action is warranted. Note that the life extension calculations are based on a DLI-value of 3 (and not zero) after the smoothing action, since no pavement is perfectly smooth. This should translate in more realistic estimates shown in the tables. Also note that while the tables give life extension predictions of all possible combinations of RSL and DLI values, the combinations of high RSL and DLI values are less likely to occur in practice.

POTENTIAL LIFE EXTENSION FOR IN-SERVICE PAVEMENTS

Determining the remaining service life (RSL) of pavement sections at different roughness levels is important since it allows for determining the applicability of the life extension tables developed in this study in the context of the current MDOT pavement management system. Superimposing the predicted RSL-values from actual pavement performance on the life extension tables allows for determining the proportion of pavement sections that would be favourable candidates for PM smoothing action, i.e., those with a minimum RSL value to get the desired life extension of 3 years or more. For example, a rigid pavement section with a DLI of 10 needs to have a minimum RSL of 14 to yield a life extension of 3 years or more upon smoothing. The proportion of rigid pavement sections with DLI of 10 having RSL-values greater than 14 would determine the usefulness/applicability of any PM smoothing action.

A large data set from MDOT PMS system was used for this analysis. Remaining service lives were calculated for those 0.5-mile pavement sections that have DLI greater than 7. This was done using the Distress Index (DI) prediction model developed by MDOT. This model uses a logistic function having the following form,

$$DI(t) = \frac{(a+b)a}{a + b \times \exp(-rt)} - a \qquad (6)$$

where t = age, and a, b and r are regression parameters.

Figure 3 illustrates how to calculate the RSL given past DI-values. The RSL is defined by MDOT as the number of years needed to reach the threshold DI-value of 50, from the current DI-value. The DI is defined as the sum of distress points corresponding to different distresses normalized to a unit pavement section of 161 m (0.1 mi). Individual distress points vary with distress type, level and extent, with their values calibrated to reflect MDOT's pavement management practice. The DI threshold of 50 corresponds to the value at which rehabilitation should be scheduled. RSL distributions for pavement sections that have DLI-values between 7 and 11, and between 11 and 15 are shown in Figure 4 for each pavement type. The number of sections with a DLI greater than 15 was too small to show a reliable distribution of RSL-values.

Rigid Pavements

Figure 4 indicates that rigid pavements have the largest RSL-values. All rigid pavement sections analysed have positive RSL-values. About 29% of the rigid pavement sections that have DLI-values ranging from 7 to 11 have RSL-values greater than 13 years, which according to Table 2 is the minimum required RSL for getting a life extension of 3 years or more. Combining the information in Table 2 and Figure 4(a), one can determine that about 60% of these sections (17% of rigid pavement sections with DLI between 7 and 11) would have life extensions of more than 3 years if they were to be smoothed. On the other hand, 57% of the pavement sections with DLI-values ranging from 11 to 15 have RSL-values greater than 10 years (the minimum required RSL for getting a life extension of 3 years or more for DLI range 11-15), and about 89% of these sections (51% of rigid pavement sections with DLI between 11 and 15) would have life extensions of more than 3 years, i.e., they would be PM candidates.

Composite Pavements

According to Figure 4 (b), about 92% of composite pavement sections with DLI-values ranging from 7 to 11 have positive RSL-values, as compared to 67% with DLI-values ranging from 11 to 15. However, none of these pavement sections have RSL-values corresponding to a life extension of 3 years or more, as can be seen in Table 3. The maximum RSL for pavements with DLI between 7 and 11 is 9 years, which corresponds to a maximum life extension of 2.9 years. For pavement sections with DLI between 11 and 15, the maximum RSL is 6 years, which corresponds to a life extension of 2.5 years.

Flexible Pavements

For flexible pavements, more sections have negative RSL-values in the above DLI ranges, as can be seen in Figure 4(c). About 48% of sections with DLI-values ranging from 7 to 11 and 32% with DLI-values ranging from 11 to 15 have negative RSL-values. This means that these pavements sections already reached the DI threshold (RSL=0) before they reach the roughness level at which smoothing action would be needed. Nonetheless, about 14% of pavement sections with DLI between 7 and 11 have RSL-values greater than 12 years (the minimum required RSL for getting a life extension of 3 years or more for the DLI range 7-11). Combining the information in Table 4 and Figure 4(c), one can determine that about 62% of these sections (9% of all flexible pavement sections with a DLI between 7 and 11) would have life extension of 3 years or more. For sections with DLI between 11 and 15, about 39% have RSL-values greater than 9 years (the minimum required RSL for getting a life extension of 3 years or more for DLI range 11-15). Combining the information in Table 4 and Figure 4(c), one can determine that 88% of these sections (34% of all flexible pavements with DLI between 11 and 15) would have life extensions of 3 years or more, i.e., they would be PM candidates for smoothing action.

Summary

Figure 5 summarizes the relative distribution of life extension for each pavement type within the DLI ranges of interest. Figure 6 summarizes the distribution of pavement sections with different life extensions, as a percentage of the total population within each pavement type. The figures show that rigid pavements have the highest proportion of sections that would benefit from smoothing action, with about twenty percent of the total population having a potential life extension (LEx) of 3 years or greater. About ten percent of flexible pavement sections would benefit from such action, while no composite pavement section is expected to have a life extension of 3 years or more. However, more composite sections have positive RSL than flexible pavements. These results indicate that, in terms of life extension gain, preventive maintenance action in the form of smoothing the pavement surface is most suited for rigid pavements. It can be applied to flexible pavements with relatively less success. However, under the current MDOT pavement management system, it would appear that such smoothing actions might not be as useful for composite pavements.

CONCLUSION

In this paper, a newly developed dynamic load index (DLI) was used to determine roughness threshold values and corresponding life extensions based on relative damage and reduction in pavement life concepts. Using the 4th power law, relative damages from the 95th percentile dynamic load at different DLI values, and the corresponding percent reduction in life were calculated and plotted for 333 sections. Estimates of pavement life extension resulting from smoothing its surface were then generated for different Remaining Service Life (RSL) values. The results were presented in tables showing the expected life extension for a range of RSL- and DLI- values. These tables would enable a highway agency to determine when a particular pavement needs to be smoothed to obtain a given (desired) life extension. The analysis was done for the three pavement types (rigid, flexible and composite). Based on the results of this analysis, it can be stated that in terms of life extension gain the preventive maintenance action in the form of smoothing the pavement surface is most applicable to rigid pavements.

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TABLES & FIGURES

Table 1- Regression Parameters for DLI-Relative Damage Relationships

Pavement Type	Regression Parameters				
	a	*b*	*c*	R^2	SE
Rigid	2.81E-4	-6.75E-3	1.16E-1	0.954	0.081
Composite	-2.52E-5	2.63E-3	5.31E-2	0.914	0.187
Flexible	2.67E-4	-5.81E-3	1.09E-1	0.932	0.145

Table 2- Life Extension for Different RSL and DLI-values for Rigid Pavements

	RSL														
DLI	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
5.0	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.6	1.7	1.8
6.0	0.7	0.9	1.0	1.1	1.2	1.3	1.5	1.6	1.7	1.8	2.0	2.1	2.2	2.3	2.4
7.0	0.9	1.0	1.2	1.3	1.5	1.6	1.8	1.9	2.1	2.2	2.4	2.5	2.7	2.8	**3.0**
8.0	1.0	1.2	1.4	1.6	1.7	1.9	2.1	2.3	2.4	2.6	2.8	2.9	**3.1**	**3.3**	**3.5**
9.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.5	2.7	2.9	**3.1**	**3.3**	**3.5**	**3.7**	**3.9**
10.0	1.3	1.5	1.7	2.0	2.2	2.4	2.6	2.8	**3.0**	**3.3**	**3.5**	**3.7**	**3.9**	**4.1**	**4.3**
11.0	1.4	1.7	1.9	2.1	2.4	2.6	2.9	**3.1**	**3.3**	**3.6**	**3.8**	**4.0**	**4.3**	**4.5**	**4.8**
12.0	1.6	1.8	2.1	2.3	2.6	2.8	**3.1**	**3.4**	**3.6**	**3.9**	**4.1**	**4.4**	**4.7**	**4.9**	**5.2**
13.0	1.7	2.0	2.2	2.5	2.8	**3.1**	**3.4**	**3.6**	**3.9**	**4.2**	**4.5**	**4.8**	**5.0**	**5.3**	**5.6**
14.0	1.8	2.1	2.4	2.7	**3.0**	**3.3**	**3.6**	**3.9**	**4.2**	**4.5**	**4.8**	**5.1**	**5.4**	**5.7**	**6.0**
15.0	1.9	2.3	2.6	2.9	**3.2**	**3.6**	**3.9**	**4.2**	**4.5**	**4.8**	**5.2**	**5.5**	**5.8**	**6.1**	**6.5**
16.0	2.1	2.4	2.8	**3.1**	**3.5**	**3.8**	**4.1**	**4.5**	**4.8**	**5.2**	**5.5**	**5.9**	**6.2**	**6.6**	**6.9**
17.0	2.2	2.6	2.9	**3.3**	**3.7**	**4.0**	**4.4**	**4.8**	**5.1**	**5.5**	**5.9**	**6.2**	**6.6**	**7.0**	**7.4**
18.0	2.3	2.7	**3.1**	**3.5**	**3.9**	**4.3**	**4.7**	**5.1**	**5.5**	**5.9**	**6.2**	**6.6**	**7.0**	**7.4**	**7.8**
19.0	2.5	2.9	**3.3**	**3.7**	**4.1**	**4.5**	**5.0**	**5.4**	**5.8**	**6.2**	**6.6**	**7.0**	**7.4**	**7.8**	**8.3**
20.0	2.6	**3.0**	**3.5**	**3.9**	**4.4**	**4.8**	**5.2**	**5.7**	**6.1**	**6.5**	**7.0**	**7.4**	**7.8**	**8.3**	**8.7**

Table 3- Life Extension for Different RSL and DLI-values for Composite Pavements

	RSL														
DLI	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
5.0	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	2.0	2.1
6.0	0.9	1.0	1.2	1.3	1.5	1.6	1.7	1.9	2.0	2.2	2.3	2.5	2.6	2.8	2.9
7.0	1.1	1.3	1.5	1.7	1.9	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.3	3.5	3.7
8.0	1.3	1.6	1.8	2.0	2.2	2.5	2.7	2.9	3.1	3.3	3.6	3.8	4.0	4.2	4.5
9.0	1.5	1.8	2.1	2.3	2.6	2.8	3.1	3.4	3.6	3.9	4.1	4.4	4.6	4.9	5.2
10.0	1.7	2.0	2.3	2.6	2.9	3.2	3.5	3.8	4.1	4.4	4.6	4.9	5.2	5.5	5.8
11.0	1.9	2.2	2.6	2.9	3.2	3.5	3.8	4.2	4.5	4.8	5.1	5.5	5.8	6.1	6.4
12.0	2.1	2.4	2.8	3.1	3.5	3.8	4.2	4.5	4.9	5.2	5.6	5.9	6.3	6.6	7.0
13.0	2.2	2.6	3.0	3.4	3.7	4.1	4.5	4.9	5.2	5.6	6.0	6.4	6.7	7.1	7.5
14.0	2.4	2.8	3.2	3.6	4.0	4.4	4.8	5.2	5.6	6.0	6.4	6.8	7.2	7.6	8.0
15.0	2.5	3.0	3.4	3.8	4.2	4.6	5.1	5.5	5.9	6.3	6.7	7.2	7.6	8.0	8.4
16.0	2.7	3.1	3.5	4.0	4.4	4.9	5.3	5.8	6.2	6.6	7.1	7.5	8.0	8.4	8.8
17.0	2.8	3.2	3.7	4.2	4.6	5.1	5.5	6.0	6.5	6.9	7.4	7.9	8.3	8.8	9.2
18.0	2.9	3.4	3.8	4.3	4.8	5.3	5.8	6.2	6.7	7.2	7.7	8.2	8.6	9.1	9.6
19.0	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	7.9	8.4	8.9	9.4	9.9
20.0	3.1	3.6	4.1	4.6	5.1	5.6	6.1	6.7	7.2	7.7	8.2	8.7	9.2	9.7	10.2

Table 4- Life Extension for Different RSL and DLI-values for Flexible Pavements

	RSL														
DLI	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
5.0	0.6	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
6.0	0.8	0.9	1.0	1.1	1.3	1.4	1.5	1.6	1.8	1.9	2.0	2.1	2.3	2.4	2.5
7.0	0.9	1.1	1.2	1.4	1.5	1.7	1.8	2.0	2.2	2.3	2.5	2.6	2.8	2.9	3.1
8.0	1.1	1.3	1.4	1.6	1.8	2.0	2.2	2.3	2.5	2.7	2.9	3.1	3.2	3.4	3.6
9.0	1.2	1.4	1.6	1.8	2.0	2.2	2.5	2.7	2.9	3.1	3.3	3.5	3.7	3.9	4.1
10.0	1.4	1.6	1.8	2.1	2.3	2.5	2.7	3.0	3.2	3.4	3.6	3.9	4.1	4.3	4.6
11.0	1.5	1.8	2.0	2.3	2.5	2.8	3.0	3.3	3.5	3.8	4.0	4.3	4.5	4.8	5.0
12.0	1.6	1.9	2.2	2.5	2.7	3.0	3.3	3.6	3.8	4.1	4.4	4.7	4.9	5.2	5.5
13.0	1.8	2.1	2.4	2.7	3.0	3.3	3.6	3.9	4.2	4.4	4.7	5.0	5.3	5.6	5.9
14.0	1.9	2.2	2.6	2.9	3.2	3.5	3.8	4.2	4.5	4.8	5.1	5.4	5.7	6.1	6.4
15.0	2.1	2.4	2.7	3.1	3.4	3.8	4.1	4.5	4.8	5.1	5.5	5.8	6.2	6.5	6.8
16.0	2.2	2.6	2.9	3.3	3.7	4.0	4.4	4.8	5.1	5.5	5.8	6.2	6.6	6.9	7.3
17.0	2.3	2.7	3.1	3.5	3.9	4.3	4.7	5.1	5.4	5.8	6.2	6.6	7.0	7.4	7.8
18.0	2.5	2.9	3.3	3.7	4.1	4.5	4.9	5.3	5.8	6.2	6.6	7.0	7.4	7.8	8.2
19.0	2.6	3.0	3.5	3.9	4.3	4.8	5.2	5.6	6.1	6.5	6.9	7.4	7.8	8.2	8.7
20.0	2.7	3.2	3.7	4.1	4.6	5.0	5.5	5.9	6.4	6.8	7.3	7.8	8.2	8.7	9.1

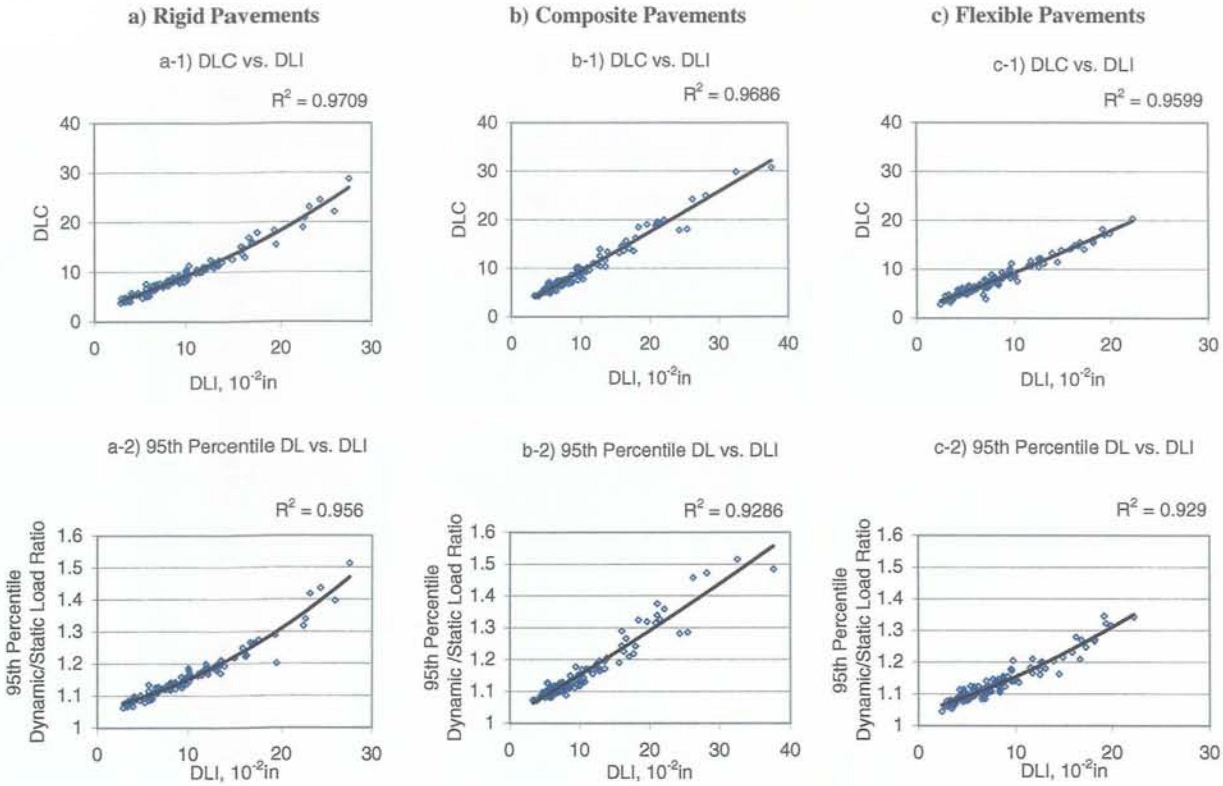

Figure 1 - Dynamic Truck-load Response vs. DLI for Each Pavement Type

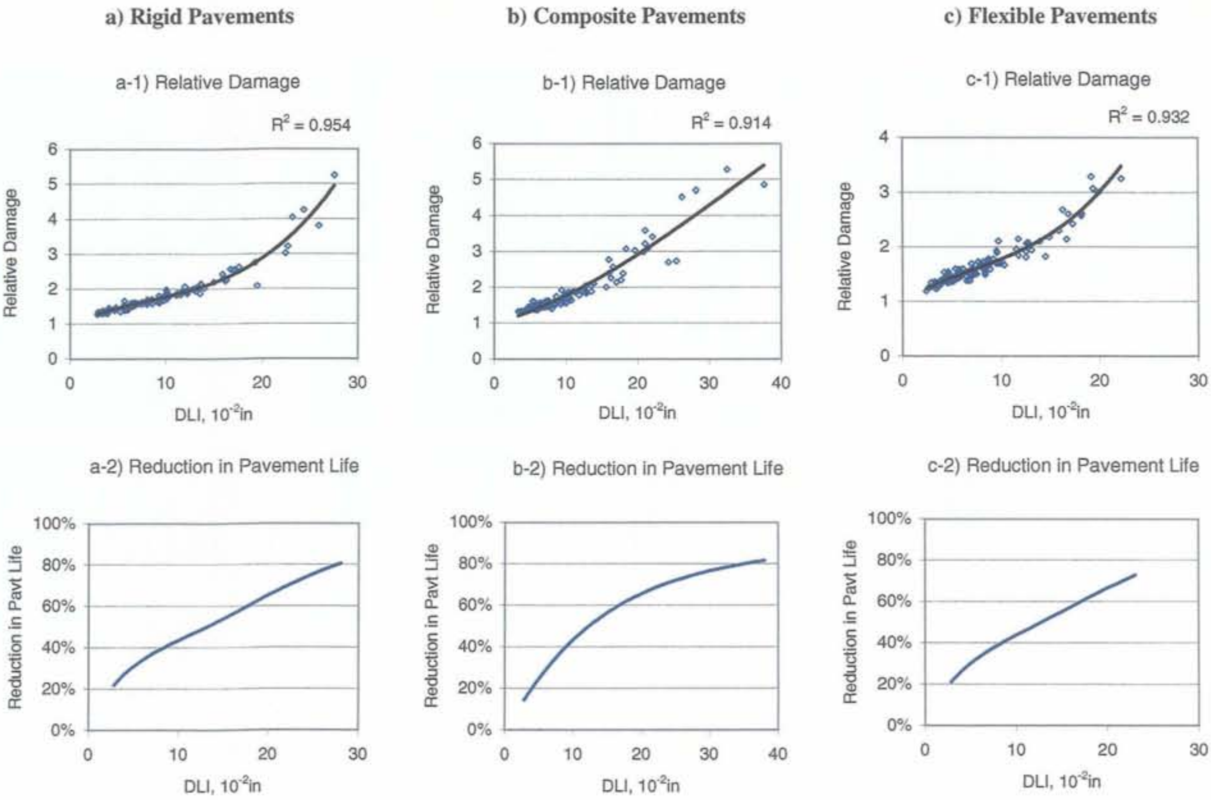

Figure 2 - Relative Damages from the 95th Percentile Dynamic Load as a function of DLI for Each Pavement Type

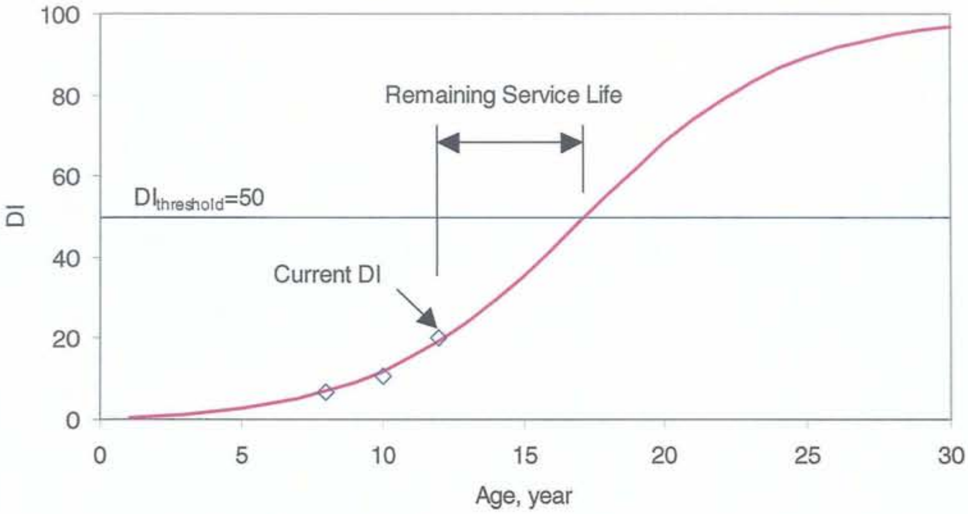

Figure 3 - Illustration of Remaining Service Life Calculation

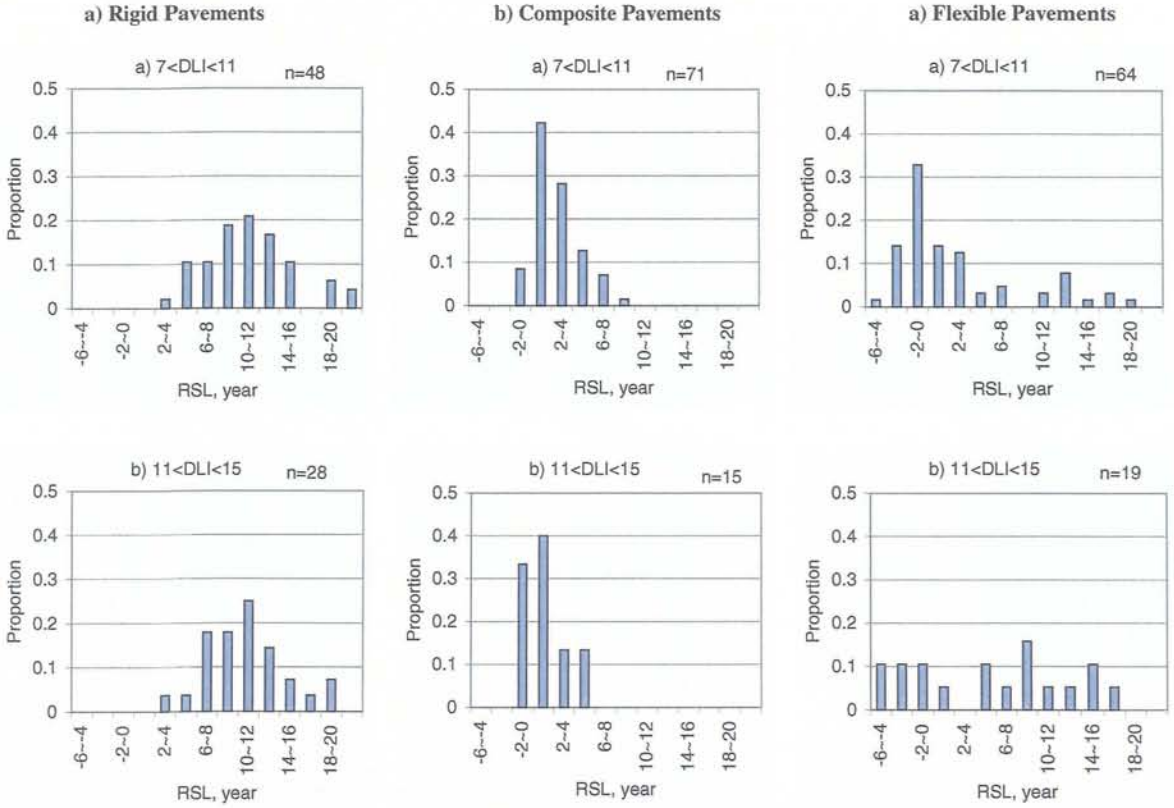

Figure 4 - Remaining Service Life Distributions for Each Pavement Type

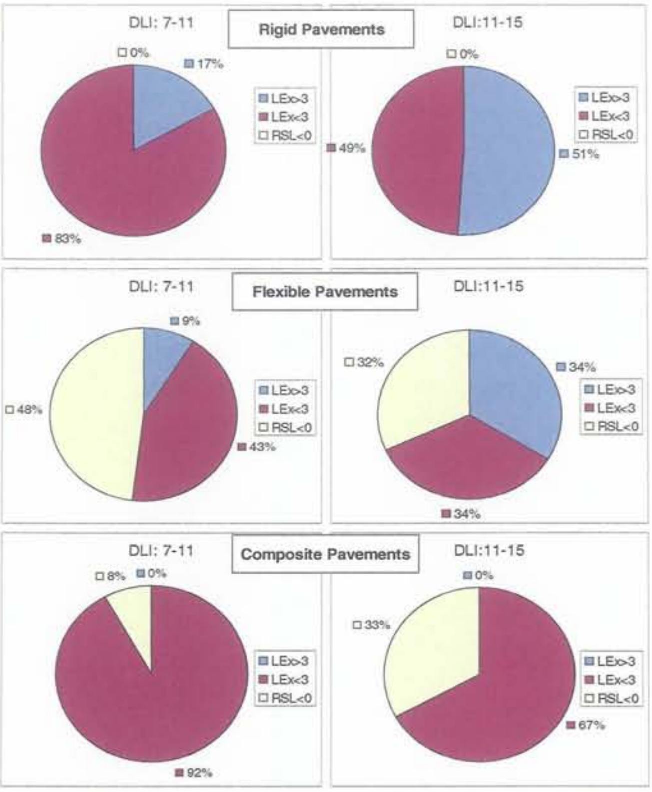

Figure 5 – Relative Distributions of Life Extension for Each Pavement Type

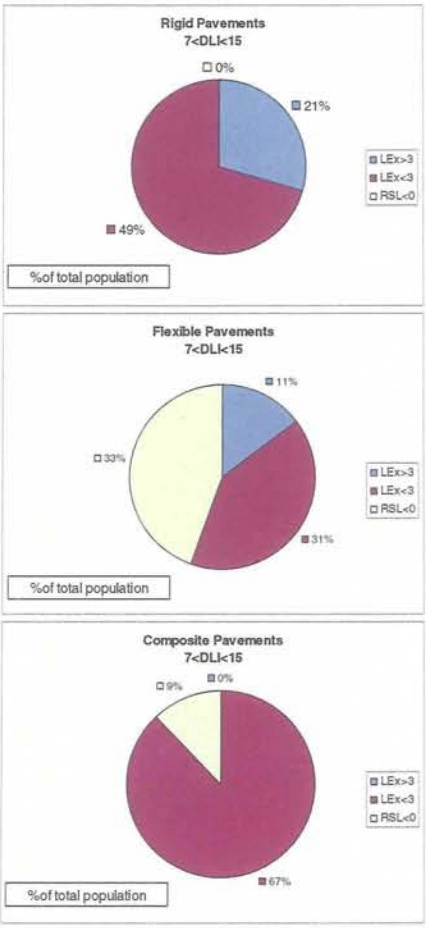

Figure 6 – Distributions of Pavement Sections with Different Life Extensions for Each Pavement Type