

EFFECT OF SURFACE ROUGHNESS ON TRUCK DYNAMIC LOADING AND PAVEMENT DAMAGE

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ABSTRACT

In this paper, some 1,437 pavement sections from ninety-seven projects in Michigan were analyzed to investigate the interaction between pavement surface roughness and distress. The main hypothesis of this research is that an increase in roughness leads to higher dynamic axle loads, which in turn can lead to a tangible acceleration in pavement distress. If this relationship is established, then it will be possible to plan a preventive maintenance (PM) action to smooth the pavement surface. Such a PM action is bound to extend the service life of the pavement by several years. The objectives of this research were to: 1) test the above hypothesis; 2) develop roughness thresholds; and 3) determine the optimal timing of the PM action. The selected projects include all pavement types. The Ride Quality Index (RQI) and Distress Index (DI) were used as measures of surface roughness and distress, respectively. The analysis showed good relationships between DI and RQI for rigid and composite pavements; however for flexible pavements there was significant scatter. A logistic function was used to fit the data. Roughness thresholds were determined as the RQI-values corresponding to peak acceleration in distress. In addition, actual surface profiles of 335 in-service pavement sections from thirty-seven projects were used to generate dynamic axle load using the TruckSim® truck simulation program. Good correlations between dynamic axle load and RQI were obtained. Based on these relationships, roughness threshold values were determined for all pavement types. Rigid pavements had higher RQI threshold values than flexible and composite pavements. The results agreed reasonably with those obtained using MDOT PMS distress data.

INTRODUCTION

All road surfaces have some level of roughness even when they are new, and they become increasingly rougher with age depending on pavement type, traffic volume, environment etc. An increase in pavement roughness leads to higher dynamic axle loads in certain portions of the road. This amplification in the load magnitude can lead to a tangible acceleration in pavement distress; the increased distress, in turn, makes the pavement surface rougher. This process is the result of the interaction between vehicles and pavements. The relationship between pavement damage and roughness (due to truck-pavement interaction) can be used to give an early warning to the pavement management agency under the following hypothesis: that there is a critical value of roughness at which a sharp increase in dynamic load occurs, which would lead to an acceleration in pavement damage.

In this paper, the relationship between the distress index (DI) and the roughness index (RQI) is sought using measured distress and roughness data for 97 projects that have different ages and different levels of distress and roughness. RQI-DI relationships were generated for the three pavement types. The existence of critical roughness values where a sharp increase in distress occurs was confirmed at the network level using these relationships.

SITE SELECTION

Three independent data sets (for a total of 97 projects) were selected from the Michigan pavement network. The first data set has thirty-seven pavement projects: Ten projects with known performance records and having exhibited some distress, and twenty-seven projects where preventive maintenance activities were done during 1997 and 1998. Thirteen of the thirty-seven sites were rigid; fifteen were flexible; and nine were composite pavements. The second and third data sets were selected randomly from the Michigan pavement network. Each data set has

thirty projects: ten rigid, ten composite and ten flexible pavements. These selected projects cover a wide range in pavement age and traffic volume. The length of these pavement projects varies from 2.4 to 36.8 km (1.5 to 23 mi) with an average project length of 11.8 km (7.4 mi). Their ages range from 1 to 39 years. The commercial daily traffic volume ranges from 70 to 12,300. The great majority of rigid pavements were jointed reinforced (JRCP) with slab lengths ranging from 8.2 to 30.2 m (27 to 99 ft). The distribution of these projects in traffic volume and pavement age is shown in Figure 1. This figure shows that, as expected, rigid pavements have higher traffic volumes than flexible and composite pavements. The age for selected rigid pavements is as high as 39 years while composite and flexible pavements have ages less than 25 years.

DATA COLLECTION

For these selected sites, DI and RQI data as well as road surface profiles were obtained from the MDOT PMS database. DI values were available for 1993, 1995 and 1997; whereas RQI values and road profiles were available for the period between 1992 and 1996. The DI and RQI data were available for each 161-m (0.1-mi) long section. Surface profile data were converted to ASCII files containing surface elevations at 76 mm (3 in) intervals. Detailed distress data in the form of distress type, severity and extent were also available at 3 m (10 ft) intervals.

Ride Quality Index (RQI)

As its name suggests, the RQI describes the ride quality of the road. In the early 1970's MDOT conducted a study to determine an objective measure that would correlate ride quality to the subjective opinions of highway users. Using "Psychometric" tests, it was found that some components of a road have a strong effect on user opinion, while others have a significantly lesser effect (1). The Power Spectral Density (PSD) was found to correlate at 90 percent with subjective opinions. Based on this, the profile is split into three wavelength bands: 0.6-1.5 m (2-5 ft), 1.5-7.6m (5-25ft), and 7.6-15.2 m (25-50ft). Wavelengths shorter than 0.61 m (2 ft) mostly create tire noise and those longer than 15.2 m (50 ft) fail to disturb the vehicle suspension. The RQI is calculated from these three PSD wavelength bands according to the equation shown below (2):

$$RQI = 3 \ln(Var_1) + 6 \ln(Var_2) + 9 \ln(Var_3) \quad (1)$$

where Var_1 , Var_2 and Var_3 are variances for 7.6-15.2 m, 1.5-7.6m and 0.6-1.5 m wavelengths, respectively.

An RQI value between zero and 30 indicates excellent ride quality; RQI-values from 31 to 54 indicate good ride quality; values from 55 to 70 indicate fair ride quality, while pavements with RQI-values of more than 70 are considered as having poor ride quality (2). The longitudinal profile for the entire pavement network in Michigan is measured annually using a Rapid Travel Profilometer (RTP). The data is used to calculate both the RQI and the IRI, which is reported to the Federal Highway Administration (FHWA). Figure 2 shows the correlations between RQI and IRI for rigid, flexible and composite pavements.

Pavement Distress Evaluation

The MDOT collects both functional and structural distress data to assess the surface condition of the pavement. Distress data are collected by videotaping 50 percent of the pavement network every year. The videotapes are reviewed in the office and each distress on the pavement surface within each 10-ft (3m) long section is identified, reviewed, checked, scored and stored in the PMS databank. Hence the data includes information on the status of each crack and its location within the 10-ft (3m) long section. The distress data are then grouped into surveying unit sections that are 0.1-mile (161 m) long. Thus the PMS databank contains, for each 0.1-mile (161 m) segment of the road, detailed data for each type of pavement distress and the severity and extent of the 'associated distress'. The term 'associated distress' is used in MDOT rehabilitation practice to denote secondary distresses associated with the principal distress. For example, 'spalling' associated with a transverse crack would be considered as 'associated distress' for the transverse crack.

The MDOT PMS group has developed a rating system whereby each type of principal distress and its associated distress level are ranked and assigned 'Distress Points' (DP) based on their impact on pavement performance and on experience. For any pavement section, the Distress Index (DI) can be calculated as the sum of distress points along the section normalized to the section length. The length of the pavement section (L) is expressed in terms of 161 m (0.1mi) unit-sections. The equation for the DI follows:

$$DI = \sum DP/L \quad (2)$$

where: DI = Distress Index
 Σ DP = Sum of the distress points along the pavement section
 L = Length of the pavement section in 161m (0.1 mile) unit sections

The DI scale starts at zero for a perfect pavement and it increases (without a limit) as the pavement condition worsens. MDOT categorizes DI into three levels: Low (DI < 20), Medium (20 < DI < 40), and High (DI > 40). A pavement with a DI of 50 is considered to have exhausted its service life; hence its remaining service life (RSL) is zero, and it is a candidate project for rehabilitation. This DI threshold-value was established based on historical pavement performance data and on experience.

RELATIONSHIP BETWEEN DI AND RQI

The DI-values for 805 m (0.5 mi) sections were plotted against the corresponding RQI-values from three data sets for rigid, composite and flexible pavements as shown in Figures 3 to 5. The logistic model (3) having the following form was used for the regression analysis.

$$DI = a \times \frac{\exp(b + c \times RQI)}{1 + \exp(b + c \times RQI)} \quad (3)$$

where a , b and c are regression constants.

DI-RQI Relationship from the First Data Set

Regression analysis relating the DI to the RQI for the first data set resulted in R^2 values for rigid and composite pavements of 0.488 and 0.522, respectively. For flexible pavements, there is no good trend and the scatter in the data is very large, with an R^2 -value of 0.311. This probably reflects the higher variability in flexible pavements, indicating that weak spots in the pavement will tend to "attract" damage as opposed to rougher spots inducing higher dynamic axle loads.

Relationships between RQI and DI show that the increased rate in distress is not constant, with the DI sharply increasing at a critical RQI level. This RQI value corresponds to the point at which the acceleration in pavement distress is maximal. Mathematically, it is where the second derivative of DI-RQI function is maximal. Acceleration in the accumulation of DI- vs. RQI-values for each pavement type is shown in Figure 3. The RQI-value where the DI sharply increases was determined to be 57 for rigid pavements. This corresponds to an IRI of 1.70 m/km (106 in/mile). For composite pavements, this RQI-value was found to be 44. This corresponds to an IRI of 1.22 m/km (76 in/mile) for composite pavements. For flexible pavements, the corresponding RQI-value was found to be 45; however this value is not reliable because of the high scatter in the data. Scatter is high in all cases and very high for flexible pavements.

It should be noted that these RQI-values represent the overall behaviour of the pavement network, and therefore cannot be applied to a particular project. In other words, they are useful only for planning at the network level and not at the project level. It is also interesting to note that the critical RQI-value for rigid pavements corresponds to a DI of 8, as opposed to a DI of 18 and 22 for composite and flexible pavements, respectively. This may imply that the optimal time window for preventive maintenance actions corresponds to a lower distress level (higher remaining service life) for rigid pavements than for composite or flexible pavements.

DI-RQI Relationship from the Second and Third Data Sets

For each pavement type, the DI-values for 800 m (0.5 mi) sections were again plotted against the corresponding RQI-values using the data from the second and third independent data sets (see Figures 4 and 5). The same logistic model that was used for the first data set was used in the regression analysis for these data sets. For rigid pavements, plots of DI against RQI from the new data sets have R^2 -values of 0.699 and 0.731. For composite pavements, the R^2 -values from the new data sets are 0.511 and 0.603. For flexible pavements, the R^2 -values from the new data sets are 0.448 and 0.507. Again, the critical RQI-values were determined as the RQI-values where the acceleration in pavement distress (DI) is maximal. The critical RQI-values from the new data sets were determined to be 54 and 57 for rigid pavements. These values agree very well with that from the first data set that (RQI=57). For composite pavements, the critical RQI-values were determined to be 48 and 42. For flexible pavements, they

were 40 and 44. These values agree reasonably well with the values obtained from the first data sets, which are 44 and 45 for composite and flexible pavements, respectively.

The critical RQI-values were also determined using all data sets including the original data set and the two independent data sets (see Figure 6). Using all data sets, the critical RQI-values were determined to be 55, 45 and 41 for rigid, composite and flexible pavements, respectively. Finally, the critical RQI-values determined from the original data set, two independent data sets and all data sets are summarized in Table 1.

Interpretation of the Results

The above results indicate that rigid pavements have higher critical RQI-values than composite and flexible pavements. This seems to be caused by the following three factors:

First, the mechanisms of how the pavement surface becomes rough with time are different in rigid and flexible (or composite) pavements. For rigid pavements, the pavement surface becomes rough because of faulting, curling and warping. These distresses can happen without the existence of cracks. This means that the pavement surface can be rough without the existence of cracks, i.e., a rigid pavement can have high RQI-values without an increase in DI-value under the MDOT distress index pointing system. For flexible pavements, on the other hand, the pavement surface becomes rough mainly because of cracks. This difference makes rigid pavements exhibit high critical RQI-values.

The second factor could be the initial smoothness (or roughness) of a newly constructed or rehabilitated pavement. Generally, the initial roughness for rigid pavements is higher than that for flexible pavements because of the existence of joints. This high initial roughness may cause the critical RQI-values to shift up to a higher value.

Finally, the third factor could be the material behavior. Portland cement concrete is stronger than asphalt concrete; therefore, rigid pavements should be able to sustain higher dynamic axle loads than do flexible pavements. All the above-cited factors may lead to a higher critical RQI-value for rigid pavements.

RELATIONSHIP BETWEEN DYNAMIC TRUCK RESPONSE AND RQI

Correlation between Dynamic Loads from Different Axles and Trucks

The TruckSim™ program was used to generate dynamic loads from three truck types: 2 and 3-axle single unit trucks and a 5-axle tractor semi-trailer (see Table 2). To study spatial repeatability of dynamic loads for all truck axles, the correlation between the different axles were studied. The analysis showed a strong correlation between aggregate axle loads for the different trucks with coefficients of correlation higher than 0.77. Cole has shown that a p-value of 0.707 is indicative of good spatial repeatability (4). Aggregate axle loads for each truck and the second axle of the 5-axle tractor semi-trailer also showed very good correlation with values around 0.7. This indicates that this axle can be used to represent the aggregate load from all trucks. It should be noted that the combination of 5-axle tractor semi-trailers and 2- and 3-axle single unit trucks constitute more than 80% of the truck population in Michigan. The details of this analysis can be found in (5).

Relationship between Ride Quality Index and Dynamic Load

To get dynamic load vs. RQI curves for each pavement type, several 161 m (0.1mi) sections for each roughness level (RQI=30, 40, 50, 60, 70, and higher than 80) were selected randomly from the 37 projects for a total 333 sections. Table 3 shows the number of samples used for each roughness level and pavement type. Dynamic axle load profiles were generated along each 161 m (0.1-mi) section, using actual pavement surface profiles as input to the truck simulation program, TruckSim™. The second axle of a typical 5-axle tractor-semi-trailer, was considered as representative of the aggregate loads from all trucks, as discussed above. From these dynamic axle-load profiles, DLC (Dynamic Loading Coefficient) and the 95th percentile axle load were calculated and plotted against the corresponding RQI-values. Figure 7 (a) shows the relationship between DLC and RQI for rigid, flexible and composite pavements. The relationship between the 95th percentile axle load and RQI is shown in Figure 7 (b). The data were fit to fourth-order polynomial curves, with the resulting R²-values ranging from 0.85 to 0.95. The DLC-RQI curves had slightly better R²-values (R² = 0.91 to 0.95) than the 95th percentile axle load curves (R² = 0.85 to

0.93), with the highest values being for rigid pavements and the lowest values for flexible pavements. This is expected because of the variability in asphalt-surfaced pavements.

Dynamic-load-induced Pavement Damage and Corresponding Reduction in Pavement Life

The relative dynamic load-induced damage in pavements can be estimated by using a power law (6):

$$\text{Relative Damage} = \left(\frac{L_{\text{dynamic}}}{L_{\text{static}}} \right)^n \quad (4)$$

where n is the damage exponent from the failure criterion (typically, $n = 3-5$).

Using the 4th power law, relative damages from the 95th percentile dynamic load at different RQI levels were calculated and plotted in Figure 8 for all pavement types. The corresponding R^2 -values were between 0.83 and 0.92, with the higher values being for rigid pavements. The general equation for these curves can be written as:

$$y = a \times RQI^4 + b \times RQI^3 + c \times RQI^2 + d \times RQI + e \quad (5)$$

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

The theoretical percent reduction in pavement life can be calculated as (7):

$$Y = \text{Percent Reduction in Pavement Life} = 100\% [1 - (\text{Relative Damage})^{-1}]$$

Determination of Roughness Threshold Values

A range of RQI-values where pavement damage sharply increases can be determined from the *derivatives* of the above function (Percent Reduction in Pavement Life) as follows:

The *lower bound* for the critical RQI-value can be taken as the *minimum* of the first derivative (minimum slope of the curve), beyond which the rate of damage or reduction in pavement life starts increasing:

$$RQI_{\min} = \min f'(RQI) \text{ where: } f'(RQI) = \frac{dY}{dRQI} \quad (6)$$

The *upper bound* for the critical RQI-value can be taken as the *maximum* of the second derivative (maximum acceleration of the curve), beyond which the acceleration in damage is highest, or the rate of increase in the reduction of pavement life is highest:

$$RQI_{\max} = \max f''(RQI) \text{ where: } f''(RQI) = \frac{d^2Y}{dRQI^2} \quad (7)$$

The functions $f(RQI)$ and $f'(RQI)$ for each pavement type are also shown in Figure 8. The function $f(RQI)$ decreases with increasing RQI down to a minimum point after which it starts to increase. The RQI-value where $f(RQI)$ is minimum can be taken as the *lower bound* value. The function $f'(RQI)$ vs. RQI increases with increasing RQI up to a maximum point beyond which it starts to decrease. The RQI-value where $f'(RQI)$ is maximum can be taken as the *upper bound* value.

The critical RQI-value would be the RQI value that corresponds to this reduction in pavement life. The critical RQI-values from the mechanistic analysis are as follows:

Rigid pavements:	RQI = 61 (lower bound) ; RQI = 77 (upper bound).
Flexible pavements:	RQI = 47 (lower bound) ; RQI = 66 (upper bound).
Composite pavements:	RQI = 50 (lower bound) ; RQI = 70 (upper bound).

At the lower bound value, reduction in pavement life starts to accelerate, while the acceleration is highest at the upper bound value. Beyond the upper bound value, reduction in pavement life decelerates. The optimal timing for preventive maintenance action would be between the lower and upper bound values. However, the range in dynamic load for a given RQI value is wide.

These values are not very sensitive to the exponent used in the power damage law, as shown in Table 4, and the lower-bound values are in reasonable agreement with field-derived values based on surface distress accumulation. The field-derived values are lower than the dynamic-load-based values; this can be explained by the fact that distress accumulation in in-service pavements is due to many factors such as structural and material integrity of the pavement components and environmental effects. These additional factors will cause an earlier increase in distress. Since the field-derived roughness thresholds are based on the rate of increase in distress, they are bound to be lower than those predicted mechanistically solely on the basis of the increase in dynamic loading.

These threshold values represent the overall behaviour of pavements at the network level, and may not be applicable for a particular pavement project. Therefore, such thresholds can be used for network-level pavement management, and not necessarily at the project level.

CONCLUSION

The MDOT PMS database was used to develop relationships between distress (Distress Index, DI) and roughness (Ride Quality Index, RQI) for all pavement types. Three independent data sets for a total of 97 projects, or 1,437 (0.5-mile) sections, that have different ages and levels of distress and roughness were used for this analysis. DI-RQI relationships for rigid pavements had the highest R^2 -values (0.488, 0.699 and 0.731). Flexible pavements had the lowest R^2 -values (0.311, 0.448 and 0.507), and composite pavements had in-between R^2 -values (0.522, 0.511 and 0.603). Critical RQI-values corresponding to maximum distress acceleration were obtained from these relationships. These were 57, 54 and 57 for rigid pavements; and 44, 48 and 42 for composite pavements. For flexible pavements, critical RQI-values were found to be 45, 40 and 44; however, these values are not reliable because of the high scatter in the data. This variability is due to the fact that distress is caused not only by axle loads but also by many other factors.

In the mechanistic approach, the mathematical expression for the reduction in pavement life as a function of roughness allowed for the determination of lower and upper bound roughness (RQI) threshold values. The lower bound values were taken as those corresponding to the minimum slope of the RQI-life reduction curves. These values were found to be equal to 61, 50 and 47 for rigid, composite and flexible pavements, respectively. The upper bound values were taken as those corresponding to the maximum acceleration of the RQI-life reduction curves. These values were found to be equal to 77, 70 and 66 for rigid, composite and flexible pavements, respectively. Mechanistically determined RQI-threshold-values were not sensitive to the exponent used in the power damage law. The lower bound RQI-threshold values compared reasonably well with field-derived values based on surface distress accumulation.

Finally, these threshold values represent the overall behaviour of pavements at the network level, and may not be applicable for a particular pavement project. Therefore, such thresholds can be used for network-level pavement management and not necessarily at the project level.

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TABLES & FIGURES

Table 1 - Summary of Critical RQI Values

Pavement Type	First Data Set	Second Data Set	Third Data Set	All Data Sets
Rigid Pavements	57	54	57	55
Composite Pavements	44	48	42	45
Flexible Pavements	45	40	44	41

Table 2 - Truck Matrix Sizes and Weights




Truck Configuration	Configuration Name	GCVW (kN)	Axle Loads (kN)	Wheel Base (m)
	2 Axle Truck	125	49/76	4.3
	3 Axle Truck	150	56/94	6.1
	5 Axle Semi-Trailer	356	54/151/151	3.6/11.0

Table 3 - Number of Samples (n) for RQI vs. Dynamic Load Analysis

Rigid Pavements	RQI	35	45	55	65	75	> 80	Subtotal
	n	16	15	23	20	13	22	109
Flexible Pavements	RQI	20	30	40	50	60	> 70	
	n	9	22	23	16	18	23	111
Composite Pavements	RQI	30	40	50	60	70	> 80	
	n	12	19	24	21	12	25	113
Total								333

Table 4 - RQI Threshold Values from Different Power Laws

Pavement Type	Power Law	Lower Threshold	Upper Threshold	Field-derived Threshold
Rigid Pavements	4 th Power	61	77	55
	5 th Power	61	76	
	6 th Power	62	75	
Flexible Pavement	4 th Power	47	66	38
	5 th Power	47	64	
	6 th Power	49	63	
Composite Pavements	4 th Power	50	70	45
	5 th Power	52	69	
	6 th Power	54	69	

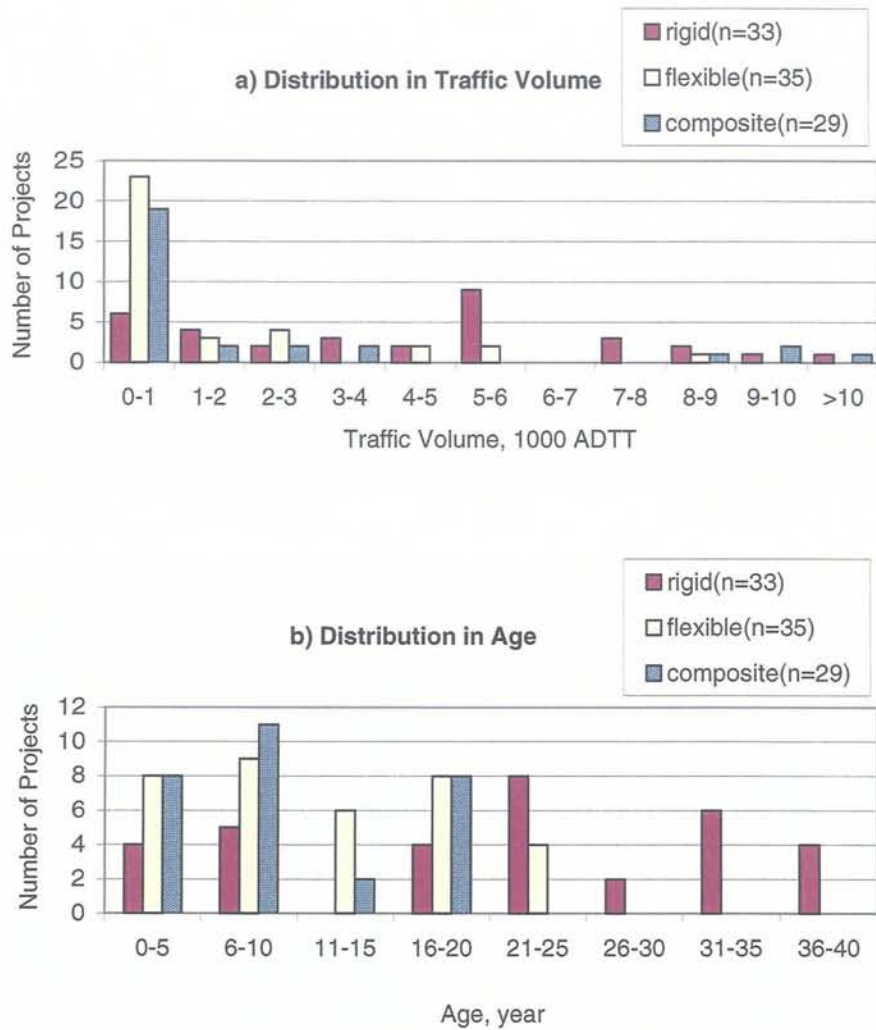


Figure 1 - Distribution of Projects in Traffic Volume and Pavement Age

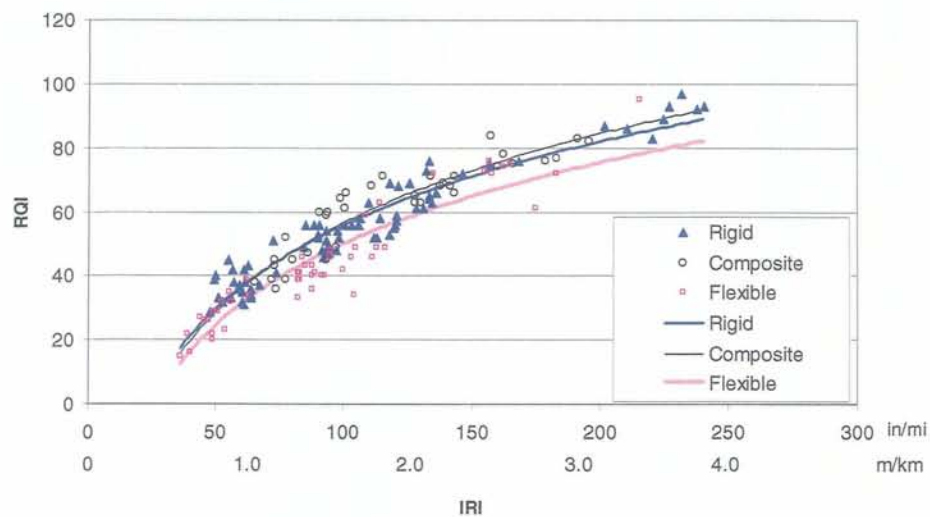


Figure 2 - Relationship between RQI and IRI

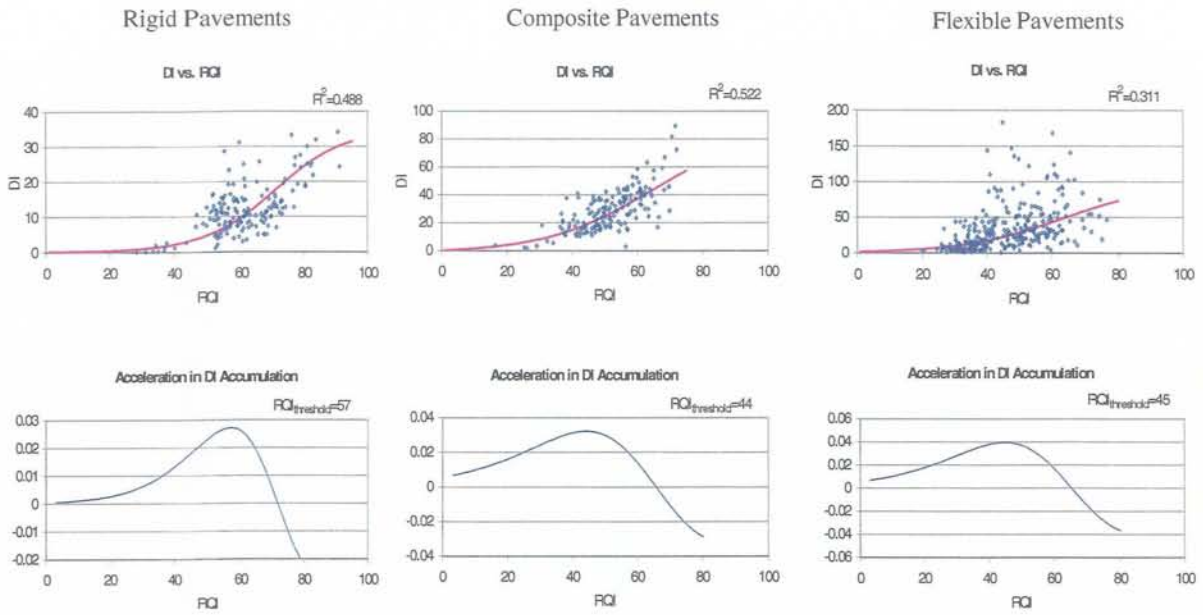


Figure 3 - Relationship Between DI and RQI for All Pavement Types from Data Set #1

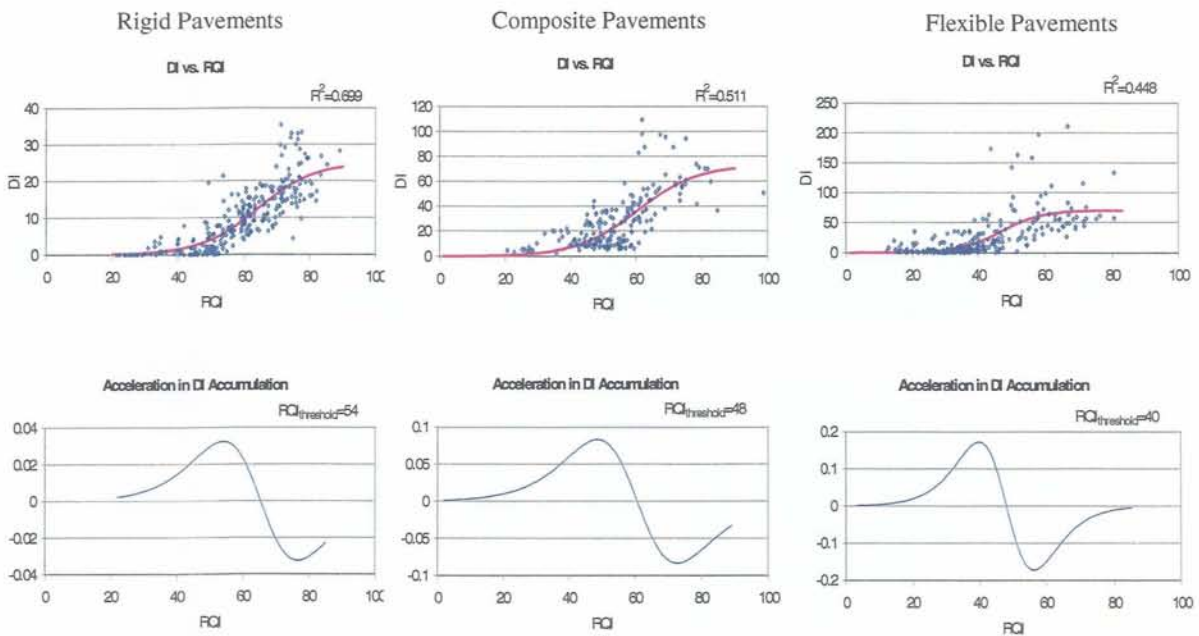


Figure 4 - Relationship Between DI and RQI for All Pavement Types from Data Set #2

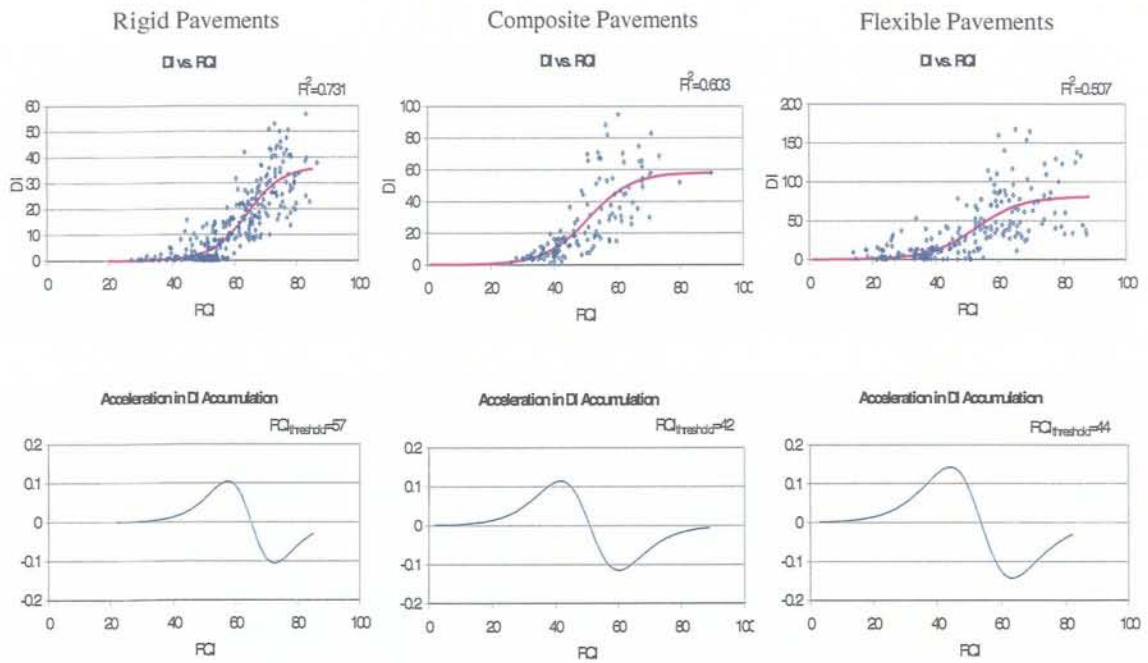


Figure 5 - Relationship Between DI and RQI for All Pavement Types from Data Set #3

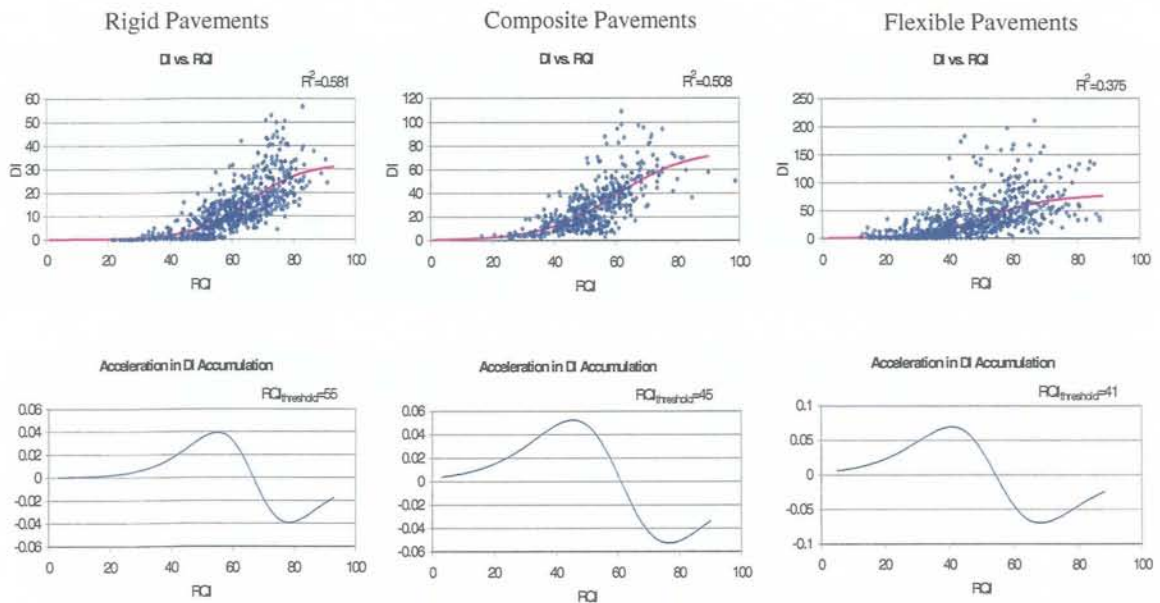


Figure 6 - Relationship Between DI and RQI for All Pavement Types from All Data Sets Combined

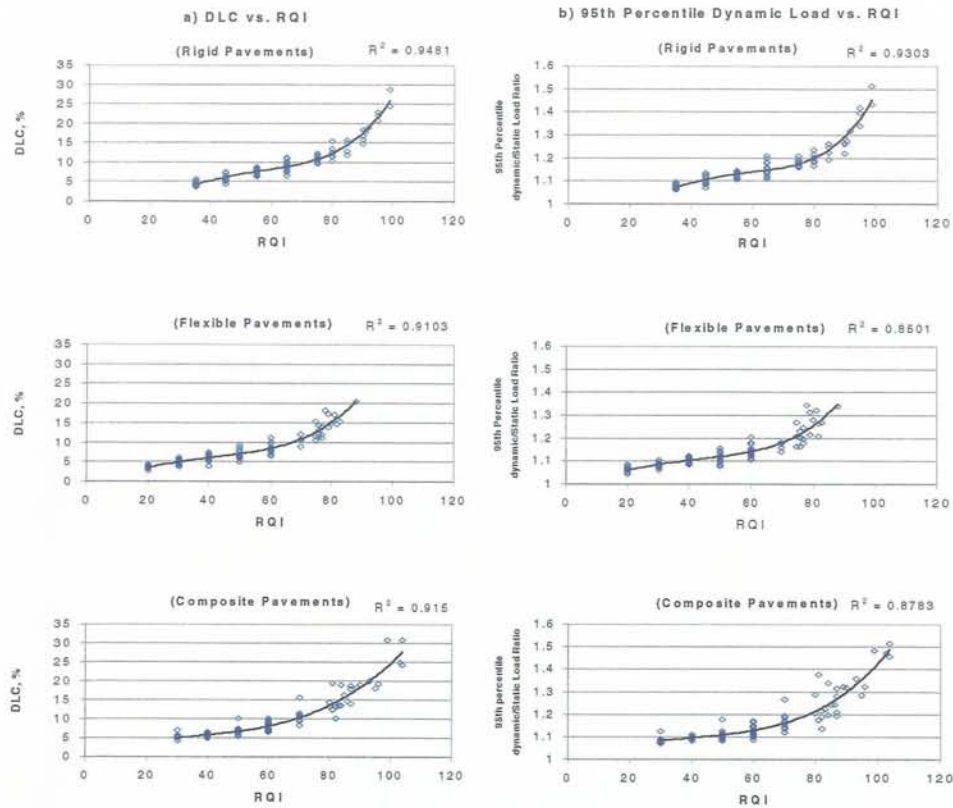


Figure 7 – Relationship between Dynamic Load and RQI

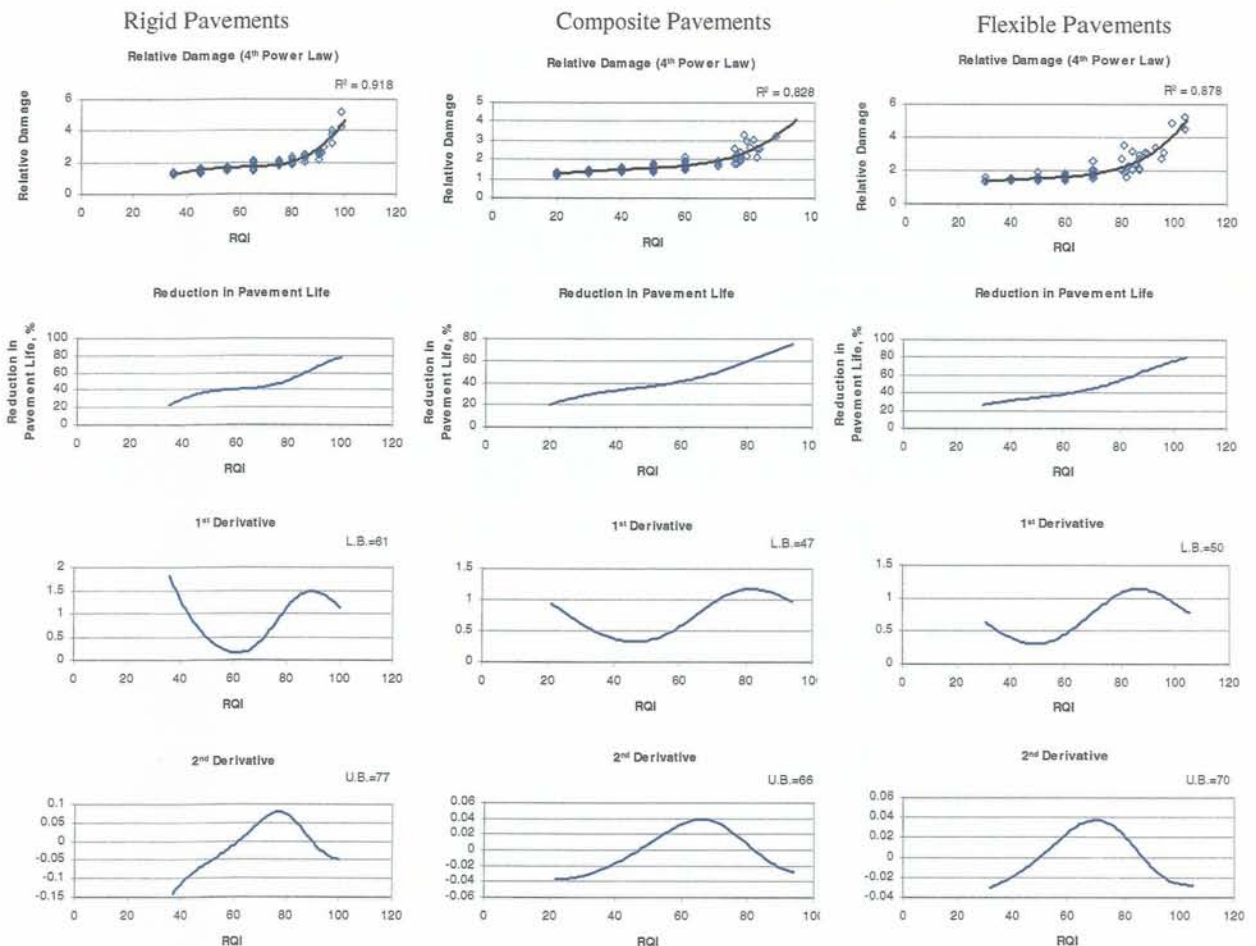


Figure 8 - Relative Damage (4th Power Law) and Reduction in Pavement Life vs. RQI

