A PROFILE BASED TRUCK DYNAMIC LOAD INDEX (DLI)

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ABSTRACT

In this paper, a new roughness index called the Dynamic Load Index (DLI) is developed for the purpose of identifying pavement profiles that are likely to generate high dynamic truck-axle loads. 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. The analysis showed a very good relationship between DLI and dynamic load. The DLI was tested on 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 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.

INTRODUCTION

A number of profile indices have been developed for characterizing pavement surface roughness in terms of serviceability or ride quality. Such indices include "ride numbers" such as the Ride Quality Index used by the Michigan department of Transportation (MDOT). The most used roughness index is the International Roughness Index (IRI). All of these indices are based on the response of passenger cars to the pavement profile. While they can generally have a good correlation with dynamic truck loading, these indices are not able to determine whether a specific pavement section is "truck friendly" or not. This makes it difficult to decide whether or not a particular pavement section should be smoothed based on such indices because damage in pavements is caused mainly by heavy truck axle loads. An accurate prediction of roughness level that will excite trucks requires the evaluation of dynamic truck axle loading likely to be generated by the profile characteristics of the individual pavement section. One way to predict dynamic axle loads, given a surface profile, is to use a truck simulation computer program. This would require some knowledge of truck dynamics and a minimum fluency in truck parameters for specific components such as the suspension system, the chassis and the tires. Therefore it would be impractical for a state highway agency such as MDOT to adopt such an approach. An alternative method would be to determine the relative increase in dynamic axle loads directly from the profile itself, since dynamic axle loading is a function of the pavement surface profile characteristics. In this paper, a new roughness index termed the Dynamic Load Index (DLI) is developed. This new index negates the need for running a truck simulation program to determine whether a pavement profile is friendly/unfriendly from a dynamic loading aspect. The DLI can be a useful pavement management tool since it makes it possible to decide whether a particular pavement with a given surface profile needs smoothing for the purpose of reducing dynamic truck-axle loads and preventing accelerated pavement damage.

BACKGROUND

The Michigan DOT has funded a research study to develop roughness thresholds aimed at minimizing dynamic truck-axle loads (1). Because MDOT uses the RQI as its roughness index, it was decided to first investigate the feasibility of using RQI for developing these thresholds.

Ride Quality Index (RQI)

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. The Power Spectral Density (PSD) of pavement surface profiles 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 15.2m (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):

$$RQI = 3 \ln (Var1) + 6 \ln (Var2) + 9 \ln (Var3)$$
(1)

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.

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 (3).

Relationship between RQI and Dynamic Load

In this analysis, actual pavement surface profiles of 333 (161-m or 0.1-mile) sections from 37 projects were used as input to the truck simulation program, TruckSimTM. 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 spatial repeatability¹ of dynamic truck-axle loading was analysed using three different truck types: 2 and 3-axle single unit trucks and a 5-axle tractor semi-trailer. All trucks were equipped with leaf spring suspensions. Tables 1 and 2 summarize the trucks characteristics. A total of 168 actual pavement profiles from ten in-service pavement projects (5 rigid, 3 flexible and 2 composite pavements) were used for this purpose. Based on the findings of this analysis, the 2nd axle load in the 5-axle tractor semi-trailer was determined to be representative of the three truck types used (5). This "reference" axle was therefore used in developing relationships between RQI and dynamic load.

Using the time histories of the reference axle, the Dynamic Loading Coefficient (DLC) and the 95th percentile axle load were calculated and plotted against the corresponding RQI-values. The DLC is an "average" measure of the magnitude of the dynamic variation of axle load over a given 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. Cases of DLC-values higher than 20% could occur when the truck is equipped with an unfriendly suspension system such as the walking-beam type (an older, rugged suspension system that is used mainly in off-road trucking nowadays), with maximum values possibly reaching 30 to 35% (6). The 95th percentile axle load is an "extreme" measure of dynamic loading that is indicative of "hot" spots within the pavement surface.

Figure 1 (a) shows the relationship between DLC and RQI for rigid, flexible and composite pavements. Figure 1(b) shows the relationship between the 95th percentile axle load and RQI. While these plots of truck dynamic axle loading against RQI have high R^2 -values, they show a wide range of dynamic load magnitudes for a given RQI value. This is because RQI is calculated from a wide range of wavelengths ranging from 0.3 to 15.1 m (2-50 ft).

DEVELOPMENT OF A DYNAMIC-LOAD-BASED ROUGHNESS INDEX

According to the literature, various experimental and theoretical studies have shown that vehicle bounce occurs in the range of frequencies between 1.5 and 4 Hz, and axle bounce occurs between 8 and 15 Hz (7,8). These

¹ See reference (4) for a literature review on the subject.

frequencies correspond to wavelengths between 6.7 and 17.9 m (22-59 ft) and between 1.8 and 3.3 m (6-11 ft) at a vehicle speed of 96 km/hr (60mph). The remaining wavelength ranges have little to do with dynamic truck-axle loads. Thus, if a profile based index is focused only on the above wavelengths, i.e., 6.7-17.9 m (22-59 ft) and 1.8-3.3 m (6-11 ft), it could have a better correlation with truck dynamic axle loading than car-response based pavement roughness indices such as RQI and IRI.

Formulation of the New Profile Index

According to linear random vibration theory, the PSD of truck response is obtained by multiplying the square of the truck response function by the PSD of the surface profile. Figure 2 shows this relationship schematically. The variance of truck response can be expressed mathematically as (9),

$$V_{y} = \frac{1}{v} \int \left| G(w) \right|^{2} S_{\chi}(\frac{w}{v}) dw = \int \left| G(w) \right|^{2} S_{\chi}(w) dw \tag{2}$$

where V_y is the variance of truck dynamic load; G(w) is the truck response function;

 $S_x(k = \frac{w}{v})$ is the PSD function of the surface profile;

w is circular frequency;

v is vehicle speed;

k is wavenumber; and

$$S_x(w) = \frac{1}{v} S_x(k = \frac{w}{v})$$
 is the PSD of the temporal input to the truck suspension system.

The area under the PSD curve of the profile at a given frequency range can be approximated as the profile variance for that frequency range. If only the frequency ranges of 1.5-4.0 and 8.0-15.0 Hz, which correspond to truck body and axle bounces, are considered, V_y can be approximated as,

$$V_y \approx |G(w_1)|^2 V_1 + |G(w_2)|^2 V_2$$
 (3)

where $G(w_1)$ is the peak value of truck response function at the frequency range of 1.5-4.0 Hz; $G(w_2)$ is the peak value of truck response function at the frequency range of 8.0-15.0 Hz; V_1 is the variance of the elevation in the frequency range of 1.5-4.0 Hz; and V_2 is the variance of the elevation in the frequency range of 8.0-15.0 Hz.

The standard deviation of truck response is therefore,

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$$\sigma_{y} = \sqrt{V_{y}} = \sqrt{\left|G(w_{1})\right|^{2} V_{1} + \left|G(w_{2})\right|^{2} V_{2}}$$
(4)

Equation (4) suggests the following form for the new roughness index, called Dynamic Load Index (DLI):

$$DLI = \sqrt{a_1 V_1 + a_2 V_2}$$
 (5)

where: V_1 is the variance of elevation of Profile 1 (unit: 10^{-2} in, 1 in = 25.4 mm); Profile 1 contains only waves in the wavelength range of 6.7 to 17.9 m (22 to 59 ft), corresponding 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 of elevation of Profile 2 (unit: 10^{-2} in, 1 in = 25.4 mm); Profile 2 contains only waves in the wavelength range of 1.8 and 3.3 m (6 to 11 ft), corresponding to a frequency range of 8.0-15.0 Hz for a truck travelling at 96km/hr (60 mph); and

 a_1 and a_2 are weighting factors.

Profiles 1 and 2 are obtained by filtering out the content from all wavelengths of the original profile that has been transformed in the wavenumber domain except for the critical wavelength ranges. This process is done according to the following steps:

1. Transform the original profile into the wave number domain using the Fast Fourier Transform (FFT).

- Split the transformed profile into two profiles that have wavelength ranges of 6.7-17.9 m (22-59 ft) and 1.8 -3.3 m (6-11 ft), respectively. This can be done by forcing zero amplitudes for all wavelengths except for the above critical wavelength ranges.
- 3. Transform the above two profiles back to the space domain using the Inverse FFT (IFFT) algorithm.
- 4. Calculate variances (V_1 and V_2) from both profiles for each 161-m (0.1-mile) section.
- 5. Calculate DLI for each 161-m (0.1-mile) section using the above equation.

The weighting factor a_1 for V₁ is set equal to one for convenience. The value for the weighting factor, a_2 , was determined as that which gives the highest correlation between the DLI and dynamic load.

Calibration of the New DLI Index

The overall relationship between DLI and dynamic load was determined for rigid, composite and flexible pavements, respectively. The analysis used all 333 pavement sections representing a large range of RQI values. Figures 3 (a-1) and (a-2) show the variation of DLC and 95th percentile dynamic load, respectively, with DLI for rigid pavements. Figure 3 (a-3) shows R²-values for different weighting factors. Figures 3 (b) and (c) show the same things for composite and flexible pavements, respectively. These plots have higher R²-values and lower standard error (SE) values than those using RQI. Based on the variation of R² with weighting factors for each pavement type a weighting factor of 14, corresponding to the overall highest R²-value for all pavement types, was selected for the DLI equation, which can then be written as:

$$DLI = \sqrt{\frac{V_1 + 14V_2}{2}} \tag{6}$$

with V_1 and V_2 as defined above.

ILLUSTRATIVE EXAMPLE

Figure 4 shows the wavelength ranges used for the RQI and DLI. It can be seen that there are gaps between the ranges of wavelengths used in calculating the RQI and DLI. These gaps help explain the possibility of obtaining an inflated RQI-value because of noise in the profile in the range of 0.6 to 1.8 m (2 to 6 ft) and 3.3 to 6.7 m (11 to 22 ft). On the other hand, if the profile contains high elevations at wavelengths greater than 15.1 m (50 ft), the RQI value will be deflated.

Figures 5 (a-1) and (b-1) show surface profiles of two 161-m (0.1-mile) rigid pavement sections that have the same RQI (equal to 65) but different DLC-values. Section #1 (WB US-10, CS18024, M.P. 7.0-7.1) has an "unfriendly" surface profile with a DLC-value of 11.3%. On the other hand, Section #2 (EB US-10, CS18024, M.P. 2.3-2.4) has a DLC-value of 6.6%, and therefore has a "friendly" surface profile. The corresponding axle load profiles (2^{nd} axle load in 5-axle semi-trailer) are shown in Figures 5 (a-2) and (b-2). The power spectral density (PSD) curves of the dynamic axle load are shown in Figures 5 (a-3) and (b-3). The figures show that in Section #1, large axle loads occurred at frequencies between 1.5 and 4 Hz while there was no such amplification in Section #2. At frequencies between 8 and 15 Hz, both sections show small dynamic loading; while at all other frequencies, the dynamic axle load is negligible. The above clearly illustrates that dynamic truck axle loading is related to profile elevations having a wavelength between 6.7 and 17.9 m (22-59 ft) and between 1.8 and 3.3 m (6-11 ft). As stated above, these frequencies / wavelengths excite the truck body bounce and axle bounce, respectively.

In Figure 6, PSD curves of the two profiles are plotted together. The two wavelength ranges that excite the truck bounce are marked on Figure 6(a), while those used for the calculation of RQI are shown in Figure 6(b). Figure 6(a) shows that at the critical wavelength ranges, the PSD curve of Section #1 has much higher amplitude relative to Section #2. The areas under the profile PSD curve between wavelengths of 6.7 and 17.9 m (22 and 59 ft) are $3,006 \text{ mm}^2$ (4.66 in^2) for Section #1 and 884 mm^2 (1.37 in^2) for Section #2. Areas between wavelengths of 1.8 and 3.3 m (6 and 11 ft) are 136 mm² (0.211 in^2) for Section #1 and 78 mm^2 (0.121 in^2) for Section #2. These areas represent the amplitudes of the surface elevations for the critical wavelength ranges. The results indicate that Section #1 has a much larger area for wavelengths between 6.7 and 17.9 m (22 and 59 ft) than Section #2. The high amplitude of these waves for Section #1 excited the body bounce of the truck and led to high dynamic axle loads.

Figure 7 shows DLC values and areas under PSD curves for each wavelength range used in calculating the RQI for both sections. The figure shows that the profile of Section #1 contains high roughness at the high range of wavelengths (7.6-15.1 m, or 25-50 ft). On the other hand, the profile of Section #2 contains high roughness at the low range of wavelengths (0.6-1.5 m, or 2-5 ft). This range of wavelengths does not excite the truck; hence the RQI-value for Section #2 is inflated from the point of view of dynamic loading because of this noise. Note that Section #2 does not contain much roughness in the range of wavelengths between 7.6 and 15.1 m (25 and 50 ft), which does excite the truck. The roughness contents in the wavelength range of 0.6 to 1.5 m (2-5 ft) for Section #1 and in the wavelength range of 7.6-15.1 m (25-50 ft) for Section #2 explain why both sections have the same RQI-value.

VERIFICATION OF THE NEW DLI INDEX

To verify the relationship between the variances of the two filtered profiles (containing the critical wavelengths only) and dynamic load, twenty rigid pavement sections having the same RQI (RQI = 65) but different DLC-values were analysed. The profiles have DLC-values ranging from 6.56% (low to no dynamic loading) to 11.32 % (relatively high dynamic loading). This means that the RQI was not able to differentiate between cases of high versus low dynamic loading. On the other hand, based on the above discussion, the variance of the two filtered profiles should differentiate between high and low dynamic loading cases.

Using the filtered profiles, the DLI was calculated for each of the twenty sections using Equation (6). Figure 8 (a) shows the relationship between DLI and DLC, with $R^2 = 0.742$. The curve for DLI versus 95th percentile dynamic load is shown in Figure 8 (b), with $R^2 = 0.839$. A linear equation was used to fit the data. The high R^2 values show that the DLI is able to differentiate between cases of high versus low dynamic loads for these twenty sections. However, when the same analysis was done using the International Roughness Index (IRI), very low R^2 -values were obtained between DLC or 95th percentile load and IRI, as shown in Figure 8 (c) and (d), respectively.

The same analysis described above was done at different RQI-levels (RQI ranging from 35 to 90) and for all pavement types. The analysis used the same 333 pavement sections. The results are shown in Figures 9 through 11. Figure 9 shows the DLI-DLC plots at constant RQI-values for rigid pavements. The figure shows good correlations for most RQI-levels except for lower RQI-values (RQI=35 and RQI=45). This RQI-level represents a relatively new pavement, with very low DLC-values (DLC less than 8). The pavement surface is essentially smooth, and both RQI and DLI are able to characterize that. Therefore this difference is of no real consequence. Figure 10 shows the DLI-DLC plots at constant RQI-values for composite pavements. Again, good correlations exist for higher RQI-levels. Figure 12 shows the DLI-DLC plots at constant RQI-values for flexible pavements. The figure shows lower R²-values, indicating higher variability in flexible pavement surfaces.

Finally, Figure 12 shows the DLI-RQI plots for rigid, composite and flexible pavements. The figure clearly shows that for a given RQI-value the DLI can cover a wide range of values, confirming the results detailed above. As expected, the variation in DLI-values is minimal at low RQI-values. Also, the DLI-RQI relationship is similar to that between DLC and RQI confirming that DLI is representative of truck dynamic loading.

CONCLUSION

In conclusion, it can be stated that the DLI is a good indicator of dynamic truck-axle loads. The DLI was tested on 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. The DLI can therefore differentiate between profiles that generate high dynamic loads and those having the same RQI but generating low dynamic loads. Most importantly, the use of DLI negates the need for running a truck simulation program. This makes it possible for a highway agency to decide whether a particular pavement section with a given surface profile needs smoothing or not based on the DLI-value. Thus the DLI can be used as a project-level roughness index for deciding whether or not to smooth a pavement based on dynamic load considerations.

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TABLES & FIGURES

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

Table 1- Truck Matrix Sizes and Weights

Table 2- Vertical Suspension Properties

Suspension Location	Suspension Type	Upper Envelope Stiffness (kN/m)	Lower Envelope Stiffness (kN/m)	β1	Linear Damping Coefficient (kN-s/m)	Unsprung Weight (kN)
Steer Axle	Flat Leaf	28.5	28.5	0.04	0.50	6.2
Single Drive Axle	Flat Leaf	47.8	41.3	0.08	0.02	11.1
Tandem Drive Axle	Flat Leaf	47.8	41.3	0.08	0.02	22.7
Tandem Semi- trailer Axle	Flat Leaf	47.8	41.3	0.08	0.02	16.9

 ${}^{1}\beta \equiv \text{Decay Constant}$



Figure 1 - Dynamic Load versus RQI Curve for Each Type of Pavements

PSD of Truck Response

Truck Response Function

PSD of Surface Profile

PSD of Truck Response, Sy(w) Truck Response Function, G(w) PSD of Elevation, Sx(w) G(w2) humany G(w1) V1 V2 w1 w2 1.5-4.0 Hz 8.0-15.0 Hz Frequency Frequency Frequency

Figure 2 - Schematic Figures of PSD of Surface Profile, Truck Response Function and PSD of Truck Response



Figure 3 - Dynamic Load vs. DLI for Rigid, Composite and Flexible Pavements



Figure 4 - Wavelength Ranges used for RQI and DLI



Figure 5 - Surface Profile and Axle Load for Section #1 (WB US-10) and Section #2 (EB US-10)



PSD of Profile and Wavelength Ranges used for DLI











Figure 8 - Relationship between Roughness Indices (DLI and IRI) and Dynamic Load for 20 Sections



Figure 9 - DLI-DLC Plots at Constant RQI-Values for Rigid Pavements



Figure 10 - DLI-DLC Plots at Constant RQI-Values for Composite Pavements



Figure 11 - DLI-DLC Plots at Constant RQI-Values for Flexible Pavements



a) Rigid Pavements

Figure 12 - Relationship between DLI with RQI for Rigid, Composite and Flexible Pavements