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1 **An Alternative Roughness Index to IRI for Flexible Pavements**

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Abstract

The International Roughness Index (IRI) is widely accepted as a measure of pavement condition. However it was developed as an indicator of passenger comfort as they travel in a vehicle on the pavement. In this paper, for the assumed failure model adopted, IRI is not found to be a good indicator of remaining pavement service life. The 3D continuous wavelet transform is proposed and shown to be a more effective indicator. Specific scales related to natural frequencies of the vehicle fleet, particularly the body mass frequency, are more significant than others. A weighted mean of the wavelet coefficients for these scales is used as an indicator of remaining life. 100 randomly generated class A profiles are generated and their histories of damage progression throughout their lives are simulated. The new indicator is applied to the initial profiles to determine which ones are more vulnerable to damage than others. In numerical simulations using the assumed damage model, the wavelet based indicator is shown to be well correlated with service life.

Keywords: Wavelet, IRI, pavement, dynamic, deterioration, damage, traffic.

1. Introduction

Road authorities need to routinely monitor flexible pavements to determine their condition in order to facilitate better maintenance planning. As a proxy of pavement condition, most developed countries measure the surface profiles of their main roads, typically with inertial profilers (Sayers and Karamihas 1996). Some studies have

incorporated 3D laser-range sensors, video cameras and global positioning systems (GPS) to provide 3D reconstruction of road surfaces (Boyko and Funkhouser 2011; Huang et al. 2014; Yang et al. 2012; Yu et al. 2007). However, road profiles or surfaces have too much information to be used at a network level – at this level, a simple indicator of pavement condition is needed. Most road owners use the International Roughness Index (IRI), a single number that is intended to provide a measure of pavement condition. In this paper, it will be shown that IRI is not well correlated with pavement remaining service life and a better indicator is proposed.

The IRI is a widely used measure of the roughness of a longitudinal road surface profile. This index is obtained from the response of a specific quarter car model travelling on the pavement profile. It is a mathematical representation of the accumulated suspension stroke of the vehicle, divided by the distance travelled (Sayers 1989; Sayers and Karamihas 1996; Sun 2003). Du et al. (2014) propose a low-cost IRI measurement system using z-axis accelerometers and GPS. The relationship between IRI and Straightedge (SE) Index is considered by Mucka (2012). SE can be calculated based on the measurement of clearance between the road surface and a straightedge laid on it. Fuzzy and Gray theories are used in (Wang and Li 2011) for pavement roughness prediction. This study improves the regression they used to obtain the IRI of pavements. Sun (2003) proposed a method that can obtain the IRI of the pavement from the PSD of pavement roughness. The IRI can be simply calculated using the square root of the sum of the weighted regression coefficients of PSD roughness.

Gonzalez et al. (2008) propose the use of vehicle acceleration for the estimation of road roughness. The resulting profile can be used for monitoring the pavement condition and predicting its remaining life. The profile can be transformed into the frequency domain using the Fourier transform and presented in the form of a Power Spectral Density (PSD) graph. The PSD can be used to describe the road roughness or as a basis for generating road profiles (Andrn 2005). PSD uses the Fourier transform to present the road profile as a function of its spatial frequencies (Lak et al. 2011; Ramji et al. 2004). Some researchers have investigated the relationship between PSD and the vehicle forces on pavements (Kropac and Mucka 2008; Labuschagne and Kululanga 2008; Lak et al. 2011). For example, Kropac and Mucka (2008) investigate the relation between PSD and road roughness on the one hand, and between dynamic vehicle response and the level of ground vibration on the other hand. Ambassa et al. (2013) investigate fatigue life prediction of an asphalt pavement subjected to multiple axle loadings using a viscoelastic finite element method.

PSD gives general information about frequency content but no spatial or time information (Brigham 1988; Pidwerbesky et al. 2006). Furthermore, it masks local features such as potholes. Wavelet analysis is a powerful method of transforming a signal in both the time and frequency domains simultaneously. In the analysis of longitudinal road profiles, time becomes distance and frequency is represented by spatial frequency. A wavelet transform computes the correlation between the signal and a selected wavelet function (Daubechies 1988; Lovsz et al. 1986) for a range of frequencies for each point in space/time. Unlike the Fourier transform, wavelets

preserve the spatial information of the original signal. The wavelet transform can be implemented in two ways: Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT) (Newland 1993). In the context of road profiles, the Wavelet Transform can be used to determine the density of a range of frequencies at all points along the profile. Wei et al. use the Wavelet Transform as a tool to manage the pavement network (Wei et al. 2005). Papagiannakis et al. (2007) use DWT to interpret the dynamic axle load due to rubber and air suspension. They use the 5-axle semi-trailer with an air and a rubber suspension in the drive and trailer axles, respectively. They use the DWT to decompose the original signal into sub-bands to interpret the dynamic load.

In this paper, a CWT is used to determine the weighted mean of the intensities for a range of frequencies in a road profile which in turn give an indication of remaining pavement life. It is therefore proposed as the basis for a more appropriate roughness index than IRI when pavement damage is of interest. A truck fleet model is used to simulate millions of vehicles passing over the pavement. Initial IRI and wavelet transform are used for the prediction of remaining life of the pavement. It is shown that the road profile frequencies that are important for dynamic tyre forces are the natural frequencies that occur in the vehicle fleet. The hypothesis is that a profile with a high intensity of vehicle fleet frequencies is more vulnerable to damage and will deteriorate faster. It is also shown that the sum of the weighted mean squares of wavelet coefficient is well correlated with remaining pavement life and has the potential to provide more information compared to IRI.

2. Truck Fleet Model

The pattern of dynamic load distribution plays an important role in the design and assessment of flexible pavements. A large number of numerical truck model runs, is usually employed for the assessment of flexible pavements (Belay et al. 2008). In this paper, a quarter car model (Fig. 1) is used to simulate dynamic tyre forces which is simple and widely used in the literature (Cebon 1999; Cole and Cebon 1992; Collop and Cebon 1995; Turkay and Akcay 2005). Although, more complicated vehicle models such as a half car can also be used, the quarter car is employed in this study because it is the common vehicle normally used for calculating IRI in the literature. The unsprung mass (representing the mass of the wheel and suspension) and sprung mass (representing part of the mass of the vehicle body) are denoted m_u and m_s respectively. The suspension system is represented by a linear spring of stiffness k_s and a linear damper with coefficient c_s , while the tyre is modelled by a linear spring of stiffness k_t and the road input irregularities are represented by y_r . Some of the more complex behaviours that occur in real suspensions, e.g. the effect of suspension friction, have been neglected here. It is acknowledged that the true behaviour of a suspension may be different and that this could have a significantly impact on the response of the pavement to a passing axle.

Figure 1 - Linear two-degree of freedom quarter car model

For the truck fleet models described here, all the vehicle parameter properties are assumed to be Normally distributed, with the means and standard deviations taken from the literature and given in Table 1 (Belay et al. 2008; Cebon 1999; Grave 2002; OBrien and Enright 2011). The vehicle speed, v , is also assumed to be Normally distributed with mean and standard deviation taken from measurement records for a highway site on the RN10 near Angers, France (Grave 2002).

Table 1 – Vehicle parameters of quarter car fleet model

No.	Vehicle parameter	Mean	Standard Deviation
1	Unsprung mass, m_u (kg)	420 (Belay et al. 2008; Cebon 1999)	40 (Belay et al. 2008)

2	Sprung mass, m_s (kg)	4535 (OBrien and Enright 2011)	500 (OBrien and Enright 2011)
3	Suspension stiffness, k_s (N/m)	1 000 000 (Belay et al. 2008, Cebon 1999)	100 000 (Belay et al. 2008)
4	Suspension damping, c_b (Ns/m)	20 000 (Belay et al. 2008; Cebon 1999)	2,000 (Belay et al. 2008)
5	Tyre stiffness, k_t (N/m)	1 950 000 (Belay et al. 2008; Cebon 1999)	200 000 (Belay et al. 2008)
6	Velocity, v (m/s)	22.43 (Belay et al. 2008; Grave 2002)	2.40 (Grave 2002)

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145 **3. Initial IRI and pavement permanent deformation**

146 The IRI is a profile-based roughness statistic that has become a standard indicator of
 147 road roughness and ride comfort around the world (Sayers and Karamihas 1996).

148 Technically, IRI is a mathematical representation of the accumulated suspension stroke
 149 of a specific vehicle travelling at 80 km/h, divided by the distance travelled along the
 150 profile. The index is normally reported in m/km. In order to calculate the IRI, the quarter

car parameters for masses, stiffnesses and damping are set to represent a reference car, named the “Golden car”. The parameters (normalized to $m_s=1$) for the Golden car are:

$$c_s = 6 \text{ [1/s]}, \quad k_t = 653 \text{ [1/s}^2\text{]}, \quad k_s = 63.3 \text{ [1/s}^2\text{]}, \quad m_u/m_s = 0.15 \quad (1)$$

To investigate the correlation between IRI and remaining pavement life, 200 simple sine wave profiles are chosen with a range of frequencies. The amplitudes (A) are all taken as 5 mm, but the frequencies are changed from 0.01 cycles/m to 2 cycles/m in steps of 0.01 cycles/m. The equation of motion for this two degree of freedom system is:

$$\begin{bmatrix} m_s & 0 \\ 0 & m_u \end{bmatrix} \begin{bmatrix} \ddot{y}_s \\ \ddot{y}_u \end{bmatrix} + \begin{bmatrix} c_s & -c_s \\ -c_s & c_s \end{bmatrix} \begin{bmatrix} \dot{y}_s \\ \dot{y}_u \end{bmatrix} + \begin{bmatrix} k_s & -k_s \\ -k_s & k_s + k_t \end{bmatrix} \begin{bmatrix} y_s \\ y_u \end{bmatrix} = \begin{bmatrix} 0 \\ y_r k_t \end{bmatrix} \quad (2)$$

where $\ddot{y}_s$ and $\dot{y}_s$ are the nodal acceleration and velocity of the sprung mass, respectively and $\ddot{y}_u$ and $\dot{y}_u$ are the nodal acceleration and velocity of the unsprung mass, respectively. The regular nature of the road profile results in a harmonic oscillation of the quarter car. The dynamic component of the force exerted by the tyre (F_y) is as follows:

$$\frac{F_y}{A} = k_t \omega^2 \sqrt{\frac{(k_t(m_s+m_u)-m_u m_u \omega^2)^2 + c_s^2 (m_s+m_u) \omega^2}{f(\omega)^2 + c_s^2 \omega^2 g(\omega)^2}}$$

(3)

where

$$\mathbf{y}_r = A \sin(\omega t)$$

(4)

$$f(\omega) = \mathbf{m}_s \mathbf{m}_u \omega^4 - (\mathbf{k}_t \mathbf{m}_s + \mathbf{k}_s (\mathbf{m}_s + \mathbf{m}_u)) \omega^2 + \mathbf{k}_t \mathbf{k}_s$$

(5)

$$g(\omega) = (\mathbf{m}_s + \mathbf{m}_u) \omega^2 - \mathbf{k}_t$$

(6)

The notional pavement has an asphalt thickness of 250 mm. The stiffness modulus of the asphalt layer is calculated assuming the following properties: annual range of mean monthly air temperature 4°C to 18°C, void content 10%, binder content 3.5%, Specific Gravity of binder 2700 kg/m³, Specific Gravity of aggregate 1020 kg/m³ and proportion of binder 7.9%. The granular layer has a modulus of elasticity of 400 MPa and is 200 mm thick. The subgrade layer is assumed to be infinitely thick with a modulus of 50 MPa.

A mechanistic-empirical approach, proposed by Collop and Cebon (1995), is used to assess the remaining service life of the pavement. The model has been used extensively in the literature (Bilodeau et al. 2017; Goodrum and Cebon 2016; Malekjafarian et al. 2017) and validated using real measurements by De-Pont et al. (2004). This method calculates pavement damage in the form of permanent deformation and loss of stiffness through fatigue, although there may be other sources of pavement deterioration e.g. freeze/thaw. The pavement is deemed to have reached the end of its service life when it reaches either of these two limit states. The permanent deformation (rutting)

influences the vehicle/pavement dynamic interaction and a feedback loop is necessary to periodically update the profile and recalculate the pattern of applied forces. The process of accumulating damage in the road profile is repeated for millions of wheel passes until the pavement has reached the end of its serviceable life, defined here as when the accumulated permanent deformation reaches 20 mm. Details of the model are outlined in (OBrien and Taheri 2012).

Monte Carlo simulation is used to find the relative number of occurrences of each natural frequency in the quarter car fleet. The simulated speeds are used to convert the time frequencies to spatial frequencies. Fig. 2 shows the distribution for each spatial natural frequency in the fleet.

Figure 2 - Quarter car fleet spatial frequencies

Vehicles from this fleet are run 10 million times over each of the 200 sine wave profiles. The permanent deformation of the pavement for each sine wave is calculated (Fig. 3).

208 It can be seen in this figure that the pavements with natural frequencies near those of
 209 the fleet (0.08 and 0.595 cycles/m), are subject to resonance and hence greater damage.

Figure 3 - Permanent deformation and IRI for 200 different sine wave profiles

213 IRI is also calculated when the Golden Car vehicle, which has frequencies of 0.054 and
 214 0.495 cycles/m, runs over 200 sine waves (Fig. 3). The Golden Car is excited by the
 215 sine wave profiles which have frequencies closest to its frequencies. It is shown in Fig.
 216 3 that there is a small peak on IRI at the first frequency but a dominant peak at the
 217 second unsprung mass frequency. It can be seen that those road profiles that have high
 218 IRI are, in general, not those with greater permanent deformation.

219 The permanent deformation for each sine wave profile is plotted versus IRI in Fig. 4.
 220 There is a peak in damage at a road profile frequency of $f = 0.08$ cycles/m, when IRI is
 221 quite low (about 2.1 m/km). The damage then falls and remains reasonably constant, as
 222 IRI increases, until a road profile frequency of about $f = 0.31$ cycles/m. There is a region

in the graph after this when both damage and IRI increase until IRI reaches its peak at $f = 0.495$ cycles/m. After this, damage continues to increase, as IRI falls until it peaks at $f = 0.595$ cycles/m. Beyond that point, both damage and IRI fall.

Figure 4 - Correlation between initial IRI and permanent deformation for 200

different sine wave profiles after 10 million quarter cars (red line: linear regression).

It might be expected that an initially smooth pavement (low IRI) would have little damage while a rough pavement would have greater damage. However, it is clear from Fig. 3 that different pavement frequencies influence damage and IRI. Fig. 4 confirms that the correlation between damage and IRI is poor.

4. Wavelet Transform as a damage index

4.1 Wavelet Transform of contact force

It is assumed here that the natural frequencies of the fleet are excited by the road profile and that the presence of these frequencies in the profile makes it more susceptible to high dynamic forces and hence to damage. Therefore, it is important to know at which points along the profile, the natural frequencies of the fleet are excited most. The Wavelet Transform represents a signal in the time and frequency domains. It uses a mother wavelet which can have many different forms. The Daubechies 3 (db3) mother wavelet is chosen in this study as it is found to provide adequate resolution in both frequency and time (distance) simultaneously (Papagiannakis et al. 2007; Wei et al. 2005). A randomly generated class A initial road profile is generated with a sample interval of 100 mm (Fig. 5). A vehicle with the mean fleet properties (Table 1) is simulated to pass over this profile. The contact force between the vehicle and the pavement is calculated using Eq. 3 (Fig. 6).

Figure 5 - Randomly generated Class A initial profile

Figure 6 - Contact force on initial profile.

The CWT of the contact force pattern is shown in Fig. 7(a). The scale axis in the CWT corresponds to the inverse of frequency while the Wavelet coefficient is a kind of density for any given scale and point in time or space. The fleet frequencies are, from Fig. 2, around $f = 0.595$ and $f = 0.085$ cycles/m. The corresponding scale values are 14 and 94 respectively. Cross sections through the CWT at these scales are shown in Figs. 7(b) and 7(c). The CWT of the force signal shows high density around the important body mass frequency (scale = 94) at distances along the profile such as $x = 145$ m. It is therefore expected that damage will accumulate in these parts of the profile until the pattern of forces changes.

(a)

(b)

(c)

Figure 7 – Time history and CWT of contact force, (a) Wavelet transform of force (absolute values of coefficients), (b) Scale 14 ($f = 0.595$) and (c) Scale 94 ($f = 0.085$).

4.2 Wavelet transform of the profile

The changes in the road profile after 10 and 15 million axles have passed, are calculated using the method explained in (Taheri et al. 2012). The CWT is applied to the initial and two changed profiles. Fig. 8 shows the wavelet coefficients for the profiles.

(a)

(b)

(c)

Figure 8 – CWT of changing road profile (absolute values of coefficients), (a) Initial profile, (b) Profile after 10 million axles and (c) Profile after 15 million axles.

The important scales are those corresponding to the fleet body mass and unsprung mass frequencies. Using the relative number of occurrences in Fig. 2, a weighted mean of the Wavelet coefficients around the body mass frequency is calculated and plotted in Fig. 9. The Peak A in Fig. 8(a) (at about $x = 80.6$ m) does not occur at a critical scale. It therefore does not appear in Fig. 9 and does not grow greatly as pavement damage progresses (see Figures 8 (b) and (c)). On the other hand Peak B in Fig. 8(a) does occur near a critical frequency and a corresponding peak is apparent at $x = 165.2$ m in Fig. 9. The peak in the CWT plot suggests a likelihood of resonance and correctly predicts damage near this point. The CWT is not always perfect however.

Figure 9 - Weighted mean of Wavelet coefficients corresponding to body mass

frequency

The corresponding permanent deformations are shown in Fig. 10. At about $x = 140$ m, Fig. 10 shows a relatively high density, but the magnitude of the peak force does not develop at this point with increasing number of axles. However, the pavement deformation (Fig. 10) is large near both $x = 140$ m and $x = 165.2$ m.

Figure 10 - Permanent deformation (after 10 and 15 million quarter cars)

5. Prediction of remaining pavement life

5.1 Sine wave profiles

As it is the absolute value of wavelet coefficient that indicates strong correlation with the mother wavelet, an energy term that is always positive is defined:

$$\text{wavelet energy} = \sum_{i=1}^{n_f} \sum_{j=1}^{n_p} a_i s_{ij}^2$$

(7)

where s_{ij} is the wavelet coefficient at scale/frequency i and point j along the profile, a_i is the relative number of occurrences of scale/frequency i in the fleet and n_f and n_p are the numbers of scales/frequencies and points respectively. In this case, the

scales/frequencies include only the body mass frequencies as Fig. 3 indicates that these are the more critical for permanent deformation. The same 200 simple sine wave profiles as were used to test IRI are used in this section to test wavelet energy as a predictor of remaining service life. It can be seen in Figures 2 and 3 that damage occurs in profiles other than those with the fleet frequencies but that damage is maximum for the body mass frequency. The results are shown in Fig. 11 where it can be seen that there is a good correlation between maximum permanent deformation and wavelet energy. There are a number of outlying points but these pure sine waves are atypical profiles. Further, the correlation is much better than it was with initial IRI (Fig. 4).

Figure 11 - Correlation between wavelet parameter and maximum permanent deformation for 200 different sine wave profiles after 10 million axles (red line: linear regression).

5.2. Random profiles

To develop a predictor of remaining pavement life, 100 randomly generated class A (Malekjafarian and OBrien 2014) initial road profiles are generated that are 200 m long with a sample interval of 100 mm. Due to the fact that discontinuities occur at the edges of a road signal, a “Hanning window” is used at the edge. (The Hanning window attenuates the elevations near the edges, while leaving intact the profile values near the middle).

The mechanistic-empirical approach is again used to assess the remaining service life of the pavement for each profile. Fig. 12 shows initial IRI and maximum permanent deformation after 25 million passes of quarter cars from the fleet (Table 1), for each of the 100 profiles. The permanent deformation ranges from about 5.5 mm up to about 19 mm. As can be seen, there is some correlation with initial IRI, showing that it is a reasonable predictor of remaining life. The correlation coefficient is 0.66.

Figure 12 - Correlation between initial IRI and maximum permanent deformation after 25 million axles (red line: linear regression).

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330 The same 100 randomly generated class A initial road profiles are also used to test
331 wavelet energy as a predictor of remaining service life. The wavelet energy is calculated
332 for each scale by summing, at 100 mm intervals, throughout the 200 m length of each
333 profile and taking the weighted mean around the vehicle fleet scales/frequencies. Fig.
334 13 shows the initial wavelet energy and the maximum permanent deformation after 25
335 million passes of quarter cars for each of the 100 profiles. As can be seen, there is good
336 correlation, showing that wavelet energy is a good predictor of remaining life. The
337 correlation coefficient is 0.92, as opposed to 0.66 for the IRI. There are several possible
338 reasons for this improvement. The IRI is calculated using a reference quarter car, while
339 a truck fleet is employed for the alternative approach. The output suspension stroke rate
340 of the reference quarter car is considered for IRI which gives the average rectified value,
341 but the proposed method uses tire load variation to estimate the wavelet energy. Further
342 investigations, e.g. optimization of the golden car properties, may improve the
343 correlation factor for that approach.

Figure 13 - Correlation between wavelet parameter and maximum permanent deformation after 25 million axles (red line: linear regression).

6. Conclusions and discussion

This paper investigates the effectiveness of a Continuous Wavelet Transform (CWT) parameter as an indicator of remaining pavement life. Truck fleet frequencies are shown to be important for pavement damage but significant damage also occurs in simple sine wave profiles with other frequencies. Nevertheless, a wavelet energy parameter that sums the weighted mean squares of wavelet coefficients is shown to be well correlated with remaining pavement life. The weighting is based on the relative numbers of occurrences of natural frequencies in the vehicle fleet.

For more general application, the accuracy of the assumed distribution of body mass frequencies in the vehicle fleet will reduce the effectiveness of the predictor although there is some evidence to suggest that these can be extracted from multiple-sensor

Weigh-in-Motion systems. Further, the correlation can be expected to be weaker when non-vehicle sources of damage such as extreme weather events are considered. The new wavelet energy parameter is a structural performance indicator which performs better than the current IRI and would appear to have good potential as an indicator of remaining pavement life. However, performance of the new indicator needs to be validated using field measurements.

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