Research Repository UCD

Title	Pavement damage model incorporating vehicle dynamics and a 3D pavement surface
Authors(s)	Taheri, A., O'Brien, Eugene J., Collop, Andrew
Publication date	2012-02-16
Publication information	Taheri, A., Eugene J. O'Brien, and Andrew Collop. "Pavement Damage Model Incorporating Vehicle Dynamics and a 3D Pavement Surface" 13, no. 4 (February 16, 2012).
Publisher	Taylor and Francis
Item record/more information	http://hdl.handle.net/10197/7059
Publisher's statement	This is an electronic version of an article published in International Journal of Pavement Engineering, 13(4): 374-383 (2012). Journal of Pavement Engineering is available online at: www.tandfonline.com/doi/abs/10.1080/10298436.2012.655741
Publisher's version (DOI)	10.1080/10298436.2012.655741

Downloaded 2023-04-07T10:52:29Z

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)

© Some rights reserved. For more information

Mechanistic-Empirical Pavement Damage Model with a Three Dimensional Pavement Profile

A. Taheri¹, E.J. OBrien¹, A.C. Collop²

¹*University College Dublin, Dublin, Ireland.*

²*University of Nottingham, Nottingham, United Kingdom*

*E-mails: rahim.taheri@ucd.ie, eugene.obrien@ucd.ie,
andrew.collop@nottingham.ac.uk*

Abstract

This paper proposes a mechanistic-empirical pavement damage model to predict changes in 3-dimensional road profiles due to dynamic axle loads. The traffic is represented by a fleet of quarter cars which allows for statistical variability in model parameters such as velocity, suspension stiffness, suspension damping, sprung mass, unsprung mass and tyre stiffness. The fleet model generates statistical distributions of dynamic force at each point which are used to predict pavement damage. As the pavement deteriorates, the distributions of dynamic axle force are changed by the changing road profile. This paper introduces a 3-dimensional approach – the transverse position of the wheel is represented by a Laplace probability distribution. This influences the extent to which the force patterns are spatially repeatable. Differences in the range of 10% to 30% are found between 2-dimensional and 3-dimensional predictions of pavement life.

Keywords: Pavement, statistical spatial repeatability, Laplace distribution, carpet profile, mechanistic-empirical, dynamic.

1. Introduction

The traditional approach to pavement life assessment considers all axle weights that are anticipated and calculates the number of equivalent axles of standard weight. It does not explicitly calculate the local effect of dynamic oscillation of axle forces about the static weight. More significantly, the traditional approach to pavement assessment does not account for ‘spatial repeatability’, the fact that the mean pattern of dynamic forces applied by a truck fleet to a pavement is repeatable. Many researchers [1-5] have presented evidence showing that for a given speed, the dynamic wheel force time histories generated by a particular heavy vehicle are concentrated and repeated at specific locations along the road for repeated test runs. DePont and Pidwerbesky [6] use dynamic vehicle models in an attempt to generate the mean patterns of dynamic force. However, they use a stochastic road profile so it is not surprising that they do not get a good match to the measured mean patterns. Cole and Cebon [2] also reproduce patterns of spatial repeatability in the vehicle dynamic properties. This paper uses a numerical model that predicts the dynamic behaviour

of a truck fleet as opposed to an individual vehicle. Repeatability of the *mean* force pattern for many axles – so called statistical spatial repeatability (SSR) – has been demonstrated by measurements at a multiple-sensor Weigh-in-Motion site [7]. Wilson et al [8] succeeded in predicting SSR patterns using a Bayesian approach. In the new American guide for pavement design (MEPDG) [9], the traffic data are included based on the number and weights of axles. However, it does not incorporate the influence of vehicle suspension or the dynamic forces due to road roughness.

A mechanistic-empirical approach [2, 4, 5] can be used to assess the remaining service life of a pavement. 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. A 2-dimensional approach is outlined in a previous paper [10]. In this paper, a 3-dimensional approach is developed, which allows for variation in the transverse position of the wheel on the pavement.

2. Truck Fleet Model

The quarter-car model of Fig. 1 is used to study the response of the vehicle to profile-induced excitation with randomly varying traverse position and forward velocity [1, 2, 4, 11]. The unsprung mass (representing the mass of the wheels and suspension) and sprung mass (representing part of the mass of the vehicle body) are denoted as m_u and m_s respectively. The suspension system is represented by a linear spring of stiffness k_s and a linear damper c_s , while the tyre is modelled by a linear spring of stiffness k_t and the road input irregularities are given by y_r .

Fig. 1 Linear two-degree of freedom quarter car model

The differential equations of motion controlling this suspension system are given in equations (1) and (2):

$$m_s \ddot{y}_s = k_s (y_u - y_s) + c_s (\dot{y}_u - \dot{y}_s) \quad (1)$$

$$m_u \ddot{y}_u = -k_s (y_u - y_s) - c_s (\dot{y}_u - \dot{y}_s) + k_t (y_r - y_u) \quad (2)$$

where y_u and y_s are the displacements of the unsprung and sprung masses respectively and $\dot{y}_u, \dot{y}_s, \ddot{y}_u$ and $\ddot{y}_s$ are the corresponding velocities and accelerations. For the truck fleet models described here, all the vehicle parameter properties are assumed to be normally distributed, with the means and standard deviations given in Table 1 [1, 12-14].

Table 1 – Vehicle parameters of quarter car fleet model

Number	Vehicle parameter	Mean	Standard Deviation
1	Unsprung mass, m_1 (kg)	420 [1,12]	40 [12]
2	Sprung mass, m_2 (kg)	4535 [14]	500 [14]
3	Suspension stiffness, k_s (N/m)	1 000 000 [1,12]	100 000 [12]
4	Suspension damping, c_s (Ns/m)	20 000 [1,12]	2,000 [12]
5	Tyre stiffness, k_t (N/m)	1 950 000 [1,12]	200 000 [12]
6	Velocity, v (m/s)	22.43 [12,13]	2.40 [13]

In this paper, an artificial initial profile is generated. For artificial profiles, the randomness of the road surface roughness is represented with a zero mean Gaussian random field in a (two dimensional) spatial domain and becomes a normal stationary ergodic random process in the distance domain [1, 15, 16].

3. Statistical Spatial Repeatability

The dynamic wheel forces applied by an axle to a pavement depend on road roughness, suspension type and vehicle speed. Wilson et al. [8] use Bayesian updating to find the statistical distributions for a truck fleet model when applied dynamic forces are known, as would be the case with a dynamically calibrated multiple-sensor weigh-in-motion system. They then use the truck fleet model to predict patterns of statistical spatial repeatability (SSR). The basic concept of SSR for tyre forces generated by heavy vehicles was presented by O'Connor et al. [7] and is summarised here. O'Connor et al. describe a section of highway near Paris, France, which was instrumented with a multiple sensor Weigh-in-Motion (MS-WIM) system. Data was collected for a large number of vehicles over fourteen days between June 1994 and May 1995. The average of a large number of dynamic forces applied to the pavement is shown to be repeatable as illustrated in Fig. 2 [7]. (Impact Factor is defined here as the ratio of dynamic force to corresponding static force).

Fig. 2 Statistical spatial repeatability of Impact Factor – Mean of measured Gross Weights on pavement for 1 day [7].

4. Mechanistic-Empirical Method damage prediction

The mechanistic-empirical approach [1, 2, 4], illustrated in Fig. 3, can be divided into four main areas: dynamic vehicle simulation; pavement primary response calculation; pavement damage calculation and damage feedback mechanism. The inputs to the model are:

- (i) the details of the pavement being simulated (layer thicknesses, mix specifications etc);
- (ii) the initial conditions (road surface profile and material stiffnesses);
- (iii) the traffic loading and
- (iv) the climatic conditions.

With these specifications, a section of pavement is divided along its length into many equally spaced sub-sections. A time domain vehicle simulation is used to generate dynamic tyre forces as a function of distance. Primary response 'influence functions' for each pavement sub-section and each mode of damage are used to calculate peak strains as each wheel passes. In this implementation of the mechanistic-empirical approach, the simplified Method of Equivalent Thickness [17] is used. For each passing wheel, the primary response is combined with the appropriate pavement damage models to predict damage as a function of distance along the pavement. Damage manifests itself in the model in two ways:

- (i) Rutting has the effect of changing the surface profile (permanent deformation).
- (ii) Fatigue damage reduces the stiffness modulus. This has the effect of reducing the ability of the pavement to disperse the wheel load, resulting in greater strains for a given load.

An updated surface profile is generated by subtracting the calculated permanent deformation in the wheel path from the profile after each wheel passes [1, 4]. This mechanism accounts for the effects of changing surface profile on the excitation of the wheel and hence the change in the pattern of spatial repeatability as the profile evolves. The

process is repeated for millions of wheel passes until the pavement has reached the end of its serviceable life. The process of calculating many millions of dynamic responses is computationally very demanding. An integration approach is therefore adopted [10] which allows for the changing SSR pattern with orders of magnitude improvement in computational efficiency.

Fig. 3 Long-term pavement performance methodology [4]

4.1 Asphalt Layer Properties

The stiffness modulus of the bituminous binder E_b (MPa) is calculated using equation (3) [4]:

$$E_b = 1.157 \times 10^{-7} t_l^{-0.368} \times 2.718^{-PI^{(R)}} (T_{RB}^{(R)} - T_{asp})^5 \quad (3)$$

where:

$T_{RB}^{(R)}$ is the recovered bitumen ‘Ring and Ball’ softening temperature ($^{\circ}\text{C}$)

T_{asp} is the temperature of the asphalt layer

$PI^{(R)}$ is the recovered bitumen ‘Penetration Index’ and

t_l is the loading time (sec).

$$\log_{10}(t_l) = 5 \times 10^{-4} * h_{asp} - 0.2 - 0.94 * \log_{10} V \quad (3a)$$

where h_{asp} is the thickness of the asphalt layer (mm) and

V is the vehicle speed in (km/hr)

The stiffness modulus of the asphalt mixture E_m (MPa) is calculated using the empirical equation [4, 18]:

$$E_m = E_b \left[1 + \frac{257.5 - 2.5 \times VMA}{n \times (VMA - 3)} \right]^n \quad (4)$$

where,

$$n = 0.83 \times \log_{10} \left(\frac{4 \times 10^4}{E_b} \right) \quad (5)$$

VMA is the percentage of voids in mixed aggregate equal to the percentage by volume of air voids plus the percentage by volume of bitumen. Changes in the temperature of the asphalt layer affect the elastic and viscous properties of the bitumen. The variation in the monthly mean air temperature T_{air} ($^{\circ}\text{C}$) is assumed to be sinusoidal of the form [4]:

$$T_{air} = \left[\frac{(T_{air}^{max} + T_{air}^{min})}{2} \right] + \left[\frac{T_{air}^{max} - T_{air}^{min}}{2} \right] \times \cos \left[\frac{(U - U_0)\pi}{6} \right] \quad (6)$$

where:

T_{air}^{max} is the maximum of the monthly mean air temperatures in the year ($^{\circ}\text{C}$)

T_{air}^{min} is the minimum of the monthly mean air temperatures in the year ($^{\circ}\text{C}$)

U is the month number from the new year

U_0 is the month number corresponding to the maximum monthly temperature.

4.2 Pavement Degradation Model

It has been widely accepted that under nearly all circumstances, fatigue damage initiates at the bottom of asphalt layer and propagates towards to the surface. So the fatigue damage chosen for this paper assumes that the cracks originate at the bottom of the asphalt layer, where the tensile strain is greatest [1]. Laboratory tests on asphaltic specimens lead to a relationship between fatigue life and strain of the form:

$$N_f^{(i)} = k_1 \varepsilon_i^{-k_2} \quad (7)$$

where: N_f is the number of cycles to failure at strain level ε_i (microstrain)

k_1 and k_2 are fatigue constants and

ε_i is the horizontal tensile strain at the bottom of the asphalt layer.

The parameters of k_1 and k_2 are fatigue constants as a function of the properties of the asphalt mix (percentage volume of bituminous binder and initial ‘Ring and Ball’ softening temperature of the bitumen).

The permanent deformation due to rutting occurring in the transformed equivalent thickness is calculated from equation 8. The incremental rut depth (permanent deformation) due to a single wheel load may be expressed as [18]:

$$\delta_i = L_1 \varepsilon_c^{L_2} \quad (8)$$

where ε_c is the vertical compressive strain at the top of the subgrade and L_1 and L_2 are material constants. This model is regarded as subgrade rutting model which used the vertical compressive strain to calculate subgrade rutting related to strain cycles of different magnitudes [1].

Odemark’s Method of Equivalent Thickness (MET) is used to transform a pavement consisting of multiple layers with different moduli into an equivalent system where all layers have the same modulus. This enables the use of the Boussinesq equation, i.e., a radial dispersion of pressure [7]. The equivalent depth for n layers is:

$$h_{e,n} = f \times \sum_{i=1}^n \left\{ h_i \times \left(\frac{E_i}{E_n} \right)^{\frac{1}{3}} \right\} \quad (9)$$

where E_i is the modulus of elasticity of layer i , h_i is the depth of the layer to be transformed, and f is a correction factor. The approximate method of transformation that is used in Odemark’s method needs a correction factor (f) in order to validate the method against the elastic layer theory. Frequently used values for the correction factor are 0.9 for a two-layer system and 0.8 for a multi-layer system. The assumption inherent in Odemark’s method is that stresses and strains below a layer depend only on the stiffness of that layer. The reduced asphalt stiffness [4] is calculated using:

$$\left(\frac{E}{E_0} \right) = \exp^{-C_3 D} \quad (10)$$

where E_0 is the initial elastic modulus, C_3 is a constant and D is a damage term given by:

$$D = \sum_{i=1}^j \left(\frac{N^{(i)}}{N_f^{(i)}} \right) \quad (11)$$

where j is the number of different strain levels considered.

The term $N^{(i)}$ represents the number of cycles at a given level of tensile strain, ε_i , at the bottom of the asphalt layer and $N_f^{(i)}$ is the number of cycles to failure at that strain level. E/E_0 is the elastic modulus normalised by its initial value (relative modulus). The critical level is taken as $E/E_0 = 0.2$. When the reduction in elastic modulus has reached this critical level, the asphalt is assumed to have failed and the modulus is not reduced further.

5. Evolution of the 2D Road Profile

The fleet of quarter cars is tested on the 50 m length of randomly generated class A initial road profile illustrated in Fig. 4(a) with a sample interval of 200 mm. The pavement has an asphalt thickness of 250 mm. The stiffness modulus of the asphalt layer is calculated assuming typical 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/m^3 , Specific Gravity of aggregate 1020 kg/m^3 , proportion of binder 7.9%. The granular layer has a modulus of elasticity of 400 MPa and is 0.2 m thick. The subgrade layer is assumed to be infinitely thick with a modulus of 50 MPa. The constants, L_1 and L_2 are 26 000 and 4 respectively and the respective fatigue constants, k_1 and k_2 are 1.52×10^{10} and 4.25.

Fig. 4(a) shows the evolution of the pavement profile throughout its life. The corresponding force patterns for the section $30 \leq x \leq 50$ are illustrated in Fig. 4(b). Some of the points can be seen to be subject to higher mean forces than others and both the profile and the mean force pattern are evolving over time. For example, from the beginning, there is high mean force around $x = 44 \text{ m}$, probably arising from the mean natural frequency of the wheel fleet. Over time, this causes progressively more damage at this location. After 20 million wheels, the profile at this point is 12 mm below its initial level. This reinforces the oscillating pattern of mean forces whose amplitude tends to increase (Fig. 4(b)). As a result, the rate of permanent deformation per million wheels tends to increase at particular points (e.g., $x = 17$ and $x = 44 \text{ m}$ in Fig. 4(a)). This increasing rate of deformation is accelerated by the reducing modulus of elasticity.

(a) Profile evolution

(b) Force evolution

Fig. 4 Surface profile at all stages of the pavement life and corresponding force pattern in 5 million wheel intervals

Fig. 5 Surface profile damage at intervals of 5 million wheels

It is noteworthy that the process is non-linear, i.e., deformations in response to a group of 5 million wheel forces are much greater in the later stages of the life of the pavement. Fig. 5 shows this nonlinear process of pavement damage development. Subtle changes in the pattern over time can be seen, with the relative amplitude of the troughs, in particular, changing.

6. Prediction of Deterioration in 3-Dimensional Profiles

For a single vehicle doing repeat runs along a given stretch of road, there is strong spatial repeatability but with significant differences in the pattern of applied forces for each run. This is because the vehicle travels at slightly different transverse positions on the road in each run and is therefore subject to a slightly different dynamic excitation. The nature of this variability is not reflected in a 2-dimensional road profile model. In this section, the road is represented by a series of correlated 2-dimensional profiles which together represent a full 3-dimensional ‘carpet’ profile.

Cebon & Newland [19] describe a method for generating homogenous, isotropic and Gaussian artificial road surfaces with single, twin or multiple correlated tracks, from a one-dimensional spectral density such as that specified in the ISO classification [20]. For single tracks, the profile is generated by applying a set of uniformly distributed random phase angles between 0 and 2π to a series of coefficients derived from the desired direct spectral density and taking the inverse discrete Fourier transform. They also describe the method for generating correlated tracks from the originally generated profile in order to simulate a 3-dimensional pavement surface (Fig. 6). This is the preferred method for road profile simulation used in this paper [20].

Fig. 6 Isotropic, multi-track artificial road surface

A carpet profile is generated with length 50 m and width 0.8 m. The carpet profile comprises nine parallel correlated profiles, 100 mm apart. The profile elevations in two adjacent tracks are well correlated with their correlation reducing for tracks that are further apart. Fig. 7 gives the profiles of two adjacent tracks and illustrates the extent of the correlation.

Fig. 7 Profile elevations at two adjacent tracks ($y = 0.4$ and $y = 0.5$ m) in carpet profile

A two-degree-of-freedom quarter car model is used again here (Fig. 1). When the wheel travels on the carpet profile, Monte Carlo simulation is used to select one of the tracks. In this paper, the transverse location of the wheel is assumed to follow a Laplace probability distribution [21]. In field measurements, Blab and Litzka [21] used this distribution and found different standard deviations for the transverse position depending on rut depth. Their findings are presented in Table 2. In this model, the maximum rut depth is recalculated after every 100 000 wheel passes and the standard deviation is updated if necessary.

Table 2 – Statistical properties of transverse wheel position

Rut Depth (RD)	Mean (μ)	Standard deviation (σ)
RD < 10 mm	0.4 m	0.3 m
10 mm < RD < 15 mm	0.4 m	0.2 m
15 mm < RD < 20 mm	0.4 m	0.1 m

The histogram of transverse position (track number) for $\sigma = 0.1$ m, is illustrated in Fig. 8.

Fig. 8 Frequency of transverse position

Transverse position is used to determine which of the nine parallel tracks excites the wheel. Hence, for each run, one parameter is Laplace distributed and six are Normally distributed: velocity, sprung mass, unsprung mass, suspension stiffness and damping and tyre stiffness.

When a wheel passes on one of the nine parallel profiles, the damage is imposed on adjacent profiles, assuming a radial dispersion of pressure [16]. In this calculation, the stiffness of the track in which damage is being calculated, is assumed. The primary response in this case is the tensile strain at the bottom of the asphalt layer for fatigue failure (stiffness reduction) and vertical compressive strain at the bottom of the granular layer for rutting failure (permanent deformation). Primary response influence functions are used to determine these strains in each profile due to an applied load in any profile. These primary response influence functions are combined with the dynamic tyre forces, to give primary pavement response time histories for each wheel load.

6.1 Carpet Damage

A simulation of the complete process of degradation is carried out for the artificially generated initial surface profile. As the pavement degrades, the deformations increase in response to repeated loading. As the mean transverse position is 0.4 m, the greatest damage occurs near this track. Fig. 9 illustrates the permanent deformation after 10, 20 and 30 million quarter cars.

(a) Damage in carpet due to 10 million wheels

(b) Damage in carpet due to 20 million wheels

(a) Damage in carpet due to 30 million wheels

Fig. 9 Developing carpet profile during pavement life

Fig. 10 illustrates in detail the damaged profile for each track after the passage of 30 million quarter cars. As expected, the central tracks are more damaged than those remote from the centre but the differences are more pronounced at some points than others.

Fig. 10 Comparison of damage in tracks of 3D carpet profile

To compare results from the 2-dimensional profile with the 3-dimensional carpet profile model, the central track of the carpet is compared to the 2-dimensional profile. Figs. 11 and 12 show the relative damage to the centre track results from the 2-D and 3-D models. It can be seen in Fig. 11 that the calculated damage in the 2-D model is greater. There is an approximate equivalence in the damage due to 10 million wheels in the 3-D model and 8 million wheels in the 2-D model (Fig. 12(a)). There is a similar correspondence after 22/30 million wheels (Fig. 12(b)).

Fig. 11 Comparison of damage in 2 and 3 dimensional profiles due to 10 million wheels

(a) Permanent deformation after 8/10 million wheels

(b) Permanent deformation 22/30 million wheels

Fig. 12 Comparison of damage in 2 and 3 dimensional profiles

The 3-D model predicts less damage because many wheels are in tracks other than the central one and therefore induce less rutting strain, i.e., strain ε_i , at the bottom of the asphalt layer, under that central track. There are two elements that affect the reduction:

- (i) the extent of the transverse variability in wheel position, a function of driver behaviour and rut depth, and
- (ii) the transverse dispersion of the stresses in the pavement layers, a function of layer depth and stiffness.

For the dimensions and properties assumed here, the relative rutting strains due to dispersion of stresses in the layers, are given in Fig. 13. The result of the transverse variability is a reduction in the mean rutting strain but also an increase in its standard deviation, as can be seen in Fig. 14 for 10,000 wheels. This comes from an increase in the frequency of smaller stains as many wheels are not directly over the central track.

Fig. 13 Ratio of the centre track rutting strain due to load on each track, relative to corresponding strain due to load on centre track

(a) Rutting strain under the centre track of the 3D carpet profile

(b) Rutting strain under the 2-D profile

Fig. 14 Comparison of rutting strain distributions between 2-D and 3-D profiles ('std' = standard deviation)

The histogram of the rutting strain is given in Fig. 15 for the point, $x = 40$ m. This illustrates the increase in frequency of smaller strains in the 3-dimensional model. There is a corresponding reduction in mean strain and an increase in standard deviation.

Fig. 15 Distribution of strain under the centre track of the 3D profile (mean = 330, standard deviation = 43) and under the 2-D profile (mean = 357, standard deviation = 35)

Conclusions

This paper extends the Mechanistic Empirical approach with dynamic vehicle fleet model, to three dimensions. It is a common believe that vehicles other than heavy vehicles do not cause pavement damage. Hence, the truck fleet model corresponding to the heavy vehicle has been selected. The transverse position of the wheel is assumed to follow a Laplace distribution while other fleet properties are assumed to be normally distributed. The increased distance of many wheels from the central track of the 3D carpet profile has the effect of reducing calculated pavement damage. For the example considered, the 2D profile reduces calculated pavement life by an average of 24% with respect to the more accurate 3D carpet profile.

References

- [1] D. Cebon, *Handbook of vehicle-road interaction*, Swets and Zeitlinger Publishers, 1999.
- [2] D.J. Cole, D. Cebon, Spatial repeatability of dynamic tyre forces generated by heavy vehicles, *J. Automobile Engineering*, I. Mech. E, Part D, 206, 17-27, 1992.

- [3] T.D. Gillespie, *Effects of heavy vehicle characteristics on pavement response and Performance*, NCHRP Report No. 35, Transportation Research Board, 1993.
- [4] A.C. Collop, D. Cebon, 'A model of whole-life flexible pavement performance', *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering*, vo. 209, 1995.
- [5] M.S.A. Hardy, D. Cebon, The importance of speed and frequency in flexible pavement design, *Journal of Engineering Mechanics*, vol. 120, pp. 463-482, 1994.
- [6] J. DePont, B.D. Pidwerbesky, The impact of vehicle dynamics on pavement performance, *4th International Symposium on Heavy Vehicles Weights and Dimensions*, Ann Arbor, Michigan, Ed. C.B. Winkler, University of Michigan Transportation Research Institute, 1995.
- [7] T. O'Connor, E.J. OBrien, B. Jacob, An experimental investigation of spatial repeatability, *International Journal of Vehicle Design*, vol. 7, No.1, pp. 64-81, 2000.
- [8] S.P. Wilson, N.K. Harris, E.J. OBrien, The use of Bayesian statistics to predict patterns of spatial repeatability, *Transport Research C - Emerging Technologies*, vol. 14, pp. 303-315, 2006.
- [9] Anon, 'Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. Final Report. Part 2 Design Inputs. Chapter 4 Traffic', ARA Inc., ERES Consulting Division, Champaign, Illinois, 2004.
- [10] E.J. OBrien, A. Taheri, 'Numerical integration approach to the problem of simulating damage in an asphalt layer', *International Journal of Pavement Engineering*, published online, doi: 10.1080/10298436.2011.575135, June 2011.
- [11] S. Turkay, H. Akçay, A study of random vibration characteristics of the quarter-car model, *Journal of Sound and Vibration*, vol. 282, pp. 111-124, 2005.
- [12] A. Belay, E.J. OBrien, E. Kroese, 'Truck fleet model for design and assessment of flexible pavements', *Journal of Sound and Vibration*, doi: 10.1016/j.jsv.2007.10.019, 2007.
- [13] S. Grave, *Modelling of site-specific traffic loading on short to medium span bridges*, PhD thesis, Trinity College Dublin, 2001.
- [14] E.J. OBrien, B. Enright, Modeling same-direction two-lane traffic for bridge loading, *Structural Safety*, published online, doi: 10.1016/j.strusafe.2011.04.004, 2011.
- [15] R.T. Fobes, R. P. laBarre, S. Andrew, *The measurement and analysis of road surface roughness*, Motor Industry Research Association Report, No 1970/5.
- [16] ISO/TC 108/WG, *Proposals for generalised road inputs to vehicles*, vol. draft 3e, 1972.
- [17] P. Ullidtz, B.K. Larsen, Mathematical model for predicting pavement performance, *Transportation Research Record*, no. 949, pp 45-55, 1983.
- [18] S.F. Brown, J. M. Brunton, *An introduction to the analytical design of bituminous pavements*, University of Nottingham, Department of Civil Engineering, UK, 1992.
- [19] D. Cebon, D. E. Newland, Artificial generation of road surface topography by the inverse FFT method, *Vehicle System Dynamics*, vol. 12, pp. 160-165, 1983.
- [20] N.K. Harris, *Characterization of factors affecting dynamic heavy vehicle infrastructure interaction*, PhD thesis, University College Dublin, 2007.

[21] R. Blab, J. Litzka, 'Measurement of the transverse distribution of heavy vehicles and its effects on the design of road pavements', *Proceeding of the Fourth International Symposium on Heavy Vehicle Weights and Dimensions*, Ann Arbor, 1995.