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ADVANCED ROAD PROFILE SIMULATIONS AND THE DYNAMIC TYRE FORCES GENERATED BY HEAVY VEHICLES

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Despite the growing popularity of alternative transport networks, road transport remains the dominant method for transporting goods and equipment. In order to remain competitive, the allowable mass limits of heavy vehicles are regularly increasing, enabling them to distribute more products per shipment. As heavy vehicles travel over the road surface, a complex dynamic interaction occurs, generating dynamic loads through the tyres and imparting these loads onto the pavements they traverse. Generally, the increased mass limits result in higher dynamic forces being exerted on pavements. These excessive dynamic loads can lead to rapid pavement deterioration, reducing the expected life of roads, and increasing the frequency of maintenance. In order to predict the dynamic tyre forces generated by these heavy vehicles, road elevation profiles (measured or synthesised) are used with vehicle dynamic models. The current approaches for simulating road profiles are, however, not adequate to excite the actual vehicle modes of vibration during transport; namely the heave, pitch, and roll motions. This paper presents a numerical investigation into the use of improved pavement elevation profiles and their influence on the dynamic tyre forces exerted by heavy vehicles. A complete four-wheeled heavy vehicle multibody model was developed using the in-house developed EasyDyn library, and simulated to travel over numerous road elevation profiles synthesised using MatLab. A comparison between the various profiles is presented, demonstrating their influence on the generated dynamic tyre forces.

Keywords: heavy vehicles, dynamic tyre force, pavement profiles, road roughness.

1. Introduction

Despite the emergence of alternative transport networks such as rail and air, road remains the dominant mode of freight transport. Across the 28 European Union member countries from 2010 to 2015, the total amount of freight transported by road was approximately 75 % (rail accounted for approximately 18 %) [1]. In order to facilitate this, modern economies rely heavily on a developed and well-maintained road network. As the volume of road freight transportation continues to increase steadily, there is an inevitable strain on the road network and performance of freight transport vehicles due to pavement damage, leading to rapidly deteriorating pavement surfaces.

In order to predict the dynamic tyre forces induced into pavements, numerical simulations are invaluable, particularly in the early design and prototyping stages. However, one limitation is the unrealistic synthesization of pavement profiles, limited to stationary single-track profiles. This paper presents an investigation into the dynamic tyre forces generated by a multibody heavy vehicle with an improved approach for road profile synthetisation. In particular, the generation of left and right track profiles using a realistic coherence function is examined and compared to the standard approach.

2. Model Development

This section outlines the development of the multibody model for the heavy vehicle, and the different types of synthesised pavement elevation profiles.

2.1 Multibody heavy vehicle model

The heavy vehicle multibody model was developed using EasyDyn, a C++ library developed in-house at the University of Mons [2]. The multibody model, illustrated in Fig. 1, is comprised of five bodies – one sprung mass and four individual unsprung masses – and has seven degrees of freedom. The sprung mass of the vehicle has three configuration parameters; heave (bounce), pitch, and roll. The four unsprung masses are each connected to the sprung mass via a spring and damper to represent the suspension system and there is only a single configuration parameter for each wheel (vertical). The tyres are modelled using a spring (no damping), each wheel is excited by a specified pavement elevation profile and the forces at all four wheels are measured as the vehicle travels at a constant speed. The heavy vehicle parameters used in this initial study were obtained from [3-4].

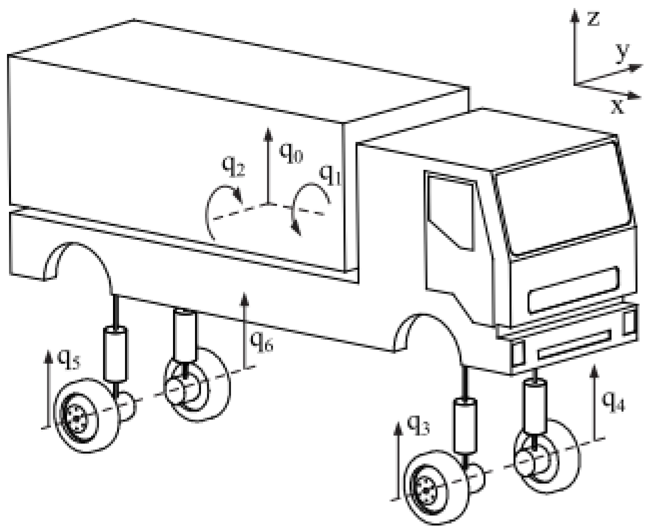

Figure 1: Illustration of the heavy vehicle multibody model and degrees of freedom for each body.

Table 1: Selected parameters for the multibody heavy vehicle.

Parameter	**Value**	**Parameter**	**Value**
Sprung Mass	9,000 kg	Front Suspension Stiffness	160 kN/m
Rear Axle Masses	600 kg	Front Suspension Damping	5 kNs/m
Front Axle Masses	400 kg	Rear Suspension Stiffness	305 kN/m
Pitch Inertia (I_P)	35,000 kg.m^2	Rear Suspension Damping	8 kNs/m
Roll Inertia (IR)	11,667 kg.m^2	Wheel Radii	0.39 m
Track width	2.00 m	Front Tyres Stiffness	750 kN/m
Wheelbase	5.21 m	Rear Tyres Stiffness	1,500 kN/m

2.2 Pavement elevation profile synthesis

Pavement profile analysis and synthesis has been a topic of research for many years. The spectral model outlined by the International Organisation for Standardisation (ISO) under standard ISO 8608 [5] is the most widely used model for the synthesis of pavement elevation profiles:

$$\boldsymbol{G(n) = G(n_0)\left(\frac{n}{n_0}\right)^{-w}}, \tag{1}$$

where n is the spatial frequency in cycles per metre, n_0 is, and w is the spectral exponent, recommended to be 2.0.

There are numerous valid concerns regarding the exact value of the spectral exponent *w*, and Mucka [6] undertook a study on the influence of the spectral exponent on the relative dynamic tyre forces of a quarter car model. He varied the exponent from 1.5 – 2.5 in steps of 0.25 and found that there is no significant influence (less than 5 % from the standard model) [6]. Another consideration is the widely-used assumption that road surfaces are isotropic, and the ISO8608 standard states that it is convenient to follow this assumption and accept the coherence function implied by this. However, it is not good practice to accept this since one wheel could be on a trough while the other is on a crest.

This paper compares three different pavement elevation profiles and their influence on the dynamic tyre forces generated by a heavy vehicle travelling at constant speed. Before each of the different profile types are discussed, a general overview of the synthesis method must first be discussed. The pavement elevation profiles are synthesised using a uniformly-distributed phase spectrum, a target power spectral density function, and the inverse fast Fourier transform. Due to the uniform phase spectrum, the generated profiles are Gaussian in nature. For the improved pavement elevation profile synthesis (section 2.2.3), a coherence is introduced to dictate the correlation between the left and right wheel paths. For further details on the synthesis of pavement elevation profiles, see [7].

It should be noted that other features of real pavement elevation profiles such as nonstationarity and transients are not part of this initial study. The following sections describe the three distinct types of pavement elevation profiles to evaluate and are all based on the ISO 8608 spectral model.

2.2.1 Simultaneous excitation (P1)

The first pavement elevation profile type to synthesise is a single profile simultaneously applied to each of the wheels, akin to placing a vehicle on a large-scale vibration table. While two different profiles could be generated for the left and right wheel paths, they would be uncorrelated and have significant differences in elevation at any time.

2.2.2 Time-delayed excitation between the front and rear wheels (P2)

It is reasonable to assume that the front and rear wheels travel over the same path during transit. Therefore, the first improvement over the simultaneous excitation is to introduce a time-delay between the front and rear wheels (from the vehicle speed and wheelbase). The same profile is used for the left and right paths, and the time-delay induces pitching motion in the vehicle.

2.2.3 Realistic coherence between the left and right profiles (P3)

It was previously stated that isotropy is not a valid assumption, and in order to synthesise realistic left and right pavement profiles, a suitable coherence function is required. Studies have shown that the left and right wheel paths are almost identical for long wavelengths (low spatial frequency), while the coherence tends to zero as the wavelength decreases to become a function of the surface roughness [8]. Mucka [9] conducted an evaluation of several published models for the coherence function between the left and right wheel paths (γ) using the Long-Term Pavement Performance data sets and found the most accurate model was the function proposed by Ammon and Bormanns [10], shown in Eq. (2).

$$\boldsymbol{\gamma = (1 + (1.497\Omega)^{1.427})^{-0.555}}, \tag{2}$$

where Ω is the angular spatial frequency (rad/m).

The left and right pavement elevation profiles are generated using the coherence function in Eq. (2) to accurately represent the relationship between the left and right wheel path profiles.

3. Numerical Simulation Procedure and Analysis

This section describes the numerical simulations undertaken and the analysis methods.

3.1 Numerical simulation procedure

For each pavement profile type, two different constant speeds, and two different road roughness classes (according to ISO 8608) are simulated. The road classes describe different bands of overall roughness, with A considered "very smooth" and C considered "average" [5]. The time-step for all simulations is 2 ms, and a summary of the simulations and the designated profile types are presented in Table 2.

Table 2: Outline of the synthesised pavement elevation profiles for the numerical simulations.

Profile Type	Pavement Profile Description	Profile Length [km]	Vehicle Speed v_s [km/h]	ISO 8608 Road Class
P1	Simultaneous excitation to all wheels.	11	60, 80	A, C
P2	Left and right the same, time-delay between front and rear wheels.	11	60, 80	A, C
P3	Time-delay between front and rear wheels, coherence function between left and right profiles.	11	60, 80	A, C

3.2 Tyre force analysis

The four contact forces between the tyres-ground are obtained from the numerical simulations and then analysed using MatLab. The Dynamic Load Coefficient (DLC) is a commonly used indicator for characterising heavy vehicle dynamic loading. The DLC, given in Eq. (3), is used in this study to examine the influence of the generated pavement elevation profiles on the dynamic tyre forces.

$$\boldsymbol{DLC} = \frac{\sigma_f}{F_S}, \tag{3}$$

where σ_f is the standard deviation of the dynamic tyre force (N), and F_S is the tyre's static load (N).

In addition to the DLC, the statistical distributions of the dynamic tyre forces are also examined to assess the influence of the various pavement elevation profiles. The normalised Probability Density Function (PDF) is computed for each of the dynamic tyre forces. The computed PDFs are then linearised [11] to make it easier to identify any significant outliers which may occur due to the different pavement elevation profiles. The linearised PDF is obtained by taking the natural logarithm of the probability density, and the tyre forces are multiplied by their absolute value (i.e. $\ln(Force)$ and $Force|Force|$, respectively) [11]. Finally, the kurtosis k and skewness s of the PDFs are also calculated to determine if they deviate from the Gaussian ($k = 3$, $s = 0$).

4. Numerical Results

The comparison of the generated dynamic tyres forces generated by the heavy vehicle multibody model are presented and discussed in this section. First, some typical visual comparisons of the DLC are presented in Fig. 2 and Fig. 3 for the heavy vehicle travelling over a class A and C road, respectively. All calculated DLCs of the dynamic tyre forces at each wheel for the different pavement types and vehicle speeds are given in Table 3. From the results, it is evident that there is only a minor variation in the DLC between the different profile types. The DLC is affected far more significantly by the heavy vehicle speed and the road roughness than the introduction of correlated left and right pavement elevation profiles. As expected, there is a minor variation in the DLC between the four tyres for the correlated profiles (P3), however, the variation is relatively insignificant.

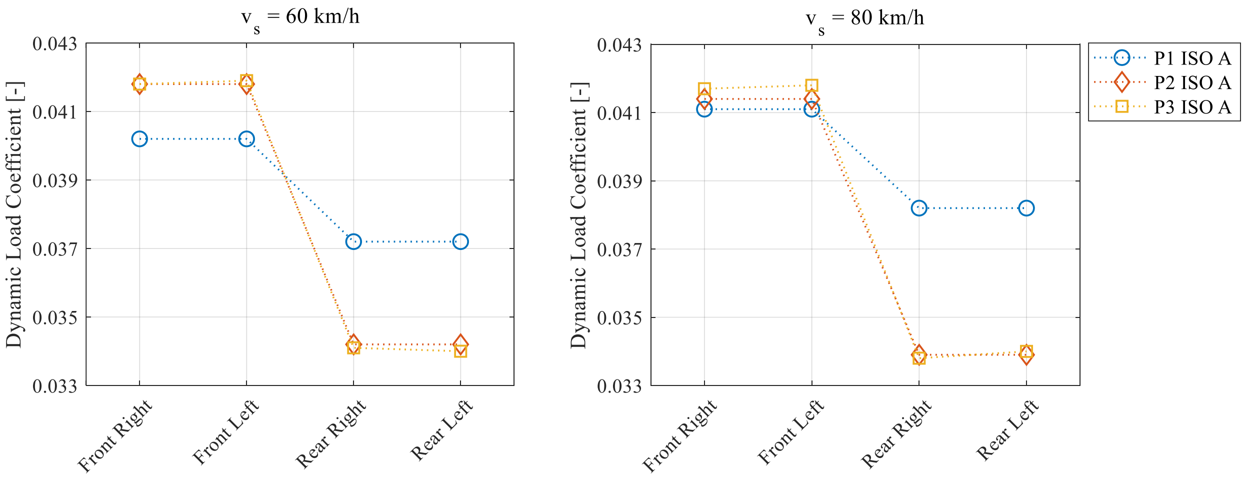

Figure 2: The dynamic load coefficient for each of the heavy vehicle's tyres subjected to the different pavement elevation profiles travelling over a class A road at 60 km/h (left), and 80 km/h (right).

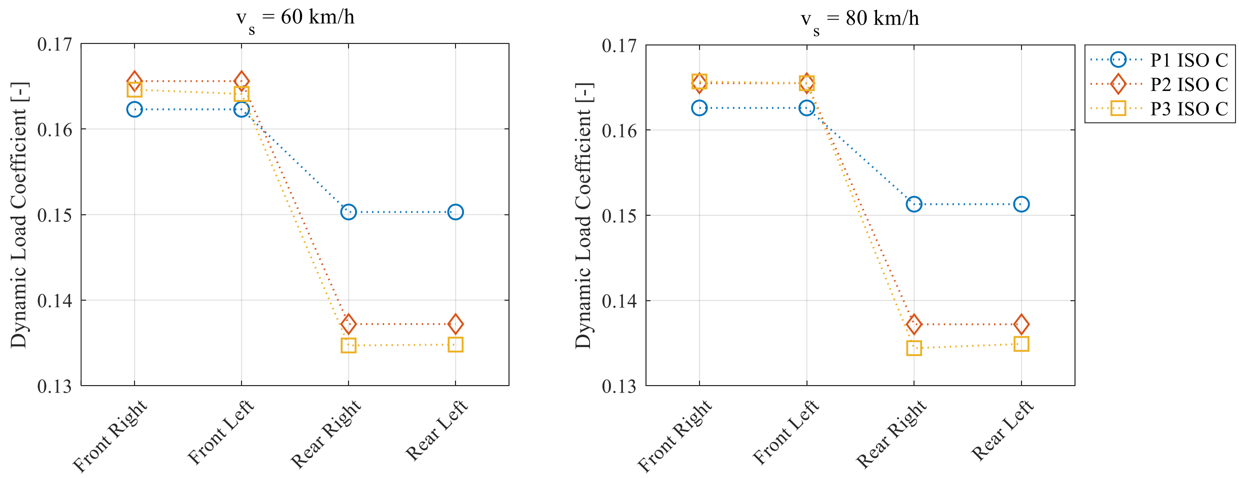

Figure 3: The dynamic load coefficient for each of the heavy vehicle's tyres subjected to the different pavement elevation profiles travelling over a class C road at 60 km/h (left), and 80 km/h (right).

Table 3: The dynamic load coefficient for all four vehicle tyres from the numerical simulations.

Profile Type	Vehicle Speed [km/h]	ISO 8608 Road Class	Front Right	Front Left	Rear Right	Rear Left
P1	60	A	0.0402	0.0402	0.0372	0.0372
		C	0.1623	0.1623	0.1503	0.1503
	80	A	0.0411	0.0411	0.0382	0.0382
		C	0.1626	0.1626	0.1513	0.1513
P2	60	A	0.0418	0.0418	0.0342	0.0342
		C	0.1656	0.1656	0.1372	0.1372
	80	A	0.0414	0.0414	0.0339	0.0339
		C	0.1655	0.1655	0.1372	0.1372
P3	60	A	0.0418	0.0419	0.0341	0.0340
		C	0.1646	0.1641	0.1347	0.1348
	80	A	0.0417	0.0418	0.0338	0.0340
		C	0.1657	0.1655	0.1344	0.1349

Next, a statistical analysis of the dynamic tyre forces is performed to investigate if the introduction of a realistic correlation between the left and right wheel paths yields any significantly different distributions. The normalised PDF of each tyre force time history is computed and the kurtosis and skewness of the distributions are obtained. Fig. 4 presents a typical example of the linearised and normalised PDFs from the dynamic tyre forces at the front right tyre, and the complete list of the kurtosis and skewness values from each simulation are presented in Table 4. From the results, there is some slight variation observed, which deviates from the Gaussian further as the vehicle speed and road roughness level increase. However, the variations are within 5 % and there is no appreciable difference that can be discerned from the results. This provides further indication that the introduction of the correlation function between wheel paths does not have an appreciable influence on the dynamic tyre forces generated by the heavy vehicle.

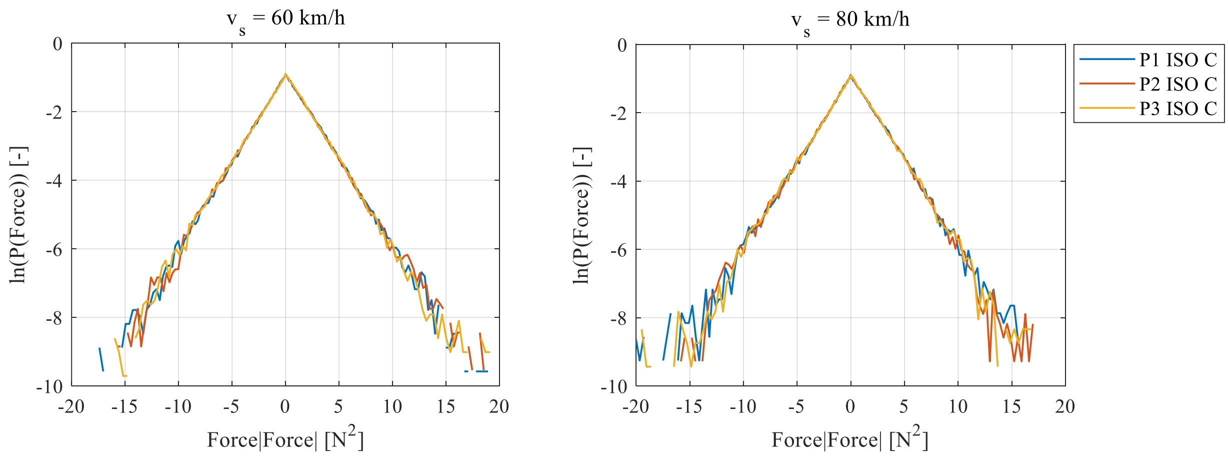

Figure 4: Typical example of the linearised normalised probability density functions of the dynamic tyre forces of the front right tyre obtained from the heavy vehicle travelling on a class C road at 60 km/h (left), and 80 km/h (right).

Table 4: The kurtosis and skewness of the normalised PDFs of the dynamic tyre forces generated by the heavy vehicle travelling over various synthesised pavement elevation profiles.

Profile Type	Vehicle Speed [km/h]	Road Class	Front Right		Front Left		Rear Right		Rear Left	
			k [-]	s [-]	k [-]	s [-]	k [-]	s [-]	k [-]	s [-]
P1	60	A	2.9829	0.0038	2.9829	0.0038	3.0033	0.0004	3.0033	0.0004
		C	2.9696	0.0075	2.9696	0.0075	2.9647	0.0042	2.9647	0.0042
	80	A	3.1081	-0.0269	3.1081	-0.0269	3.0547	-0.0112	3.0547	-0.0112
		C	3.0106	0.0013	3.0106	0.0013	2.9890	0.0196	2.9890	0.0196
P2	60	A	2.9993	0.0100	2.9993	0.0100	3.0021	0.0002	3.0021	0.0002
		C	2.9753	-0.0062	2.9753	-0.0062	3.0276	0.0114	3.0276	0.0114
	80	A	3.0433	0.0112	3.0433	0.0112	3.2330	-0.0381	3.2330	-0.0381
		C	2.9802	-0.0087	2.9802	-0.0087	3.0516	0.0211	3.0516	0.0211
P3	60	A	2.9872	-0.0240	3.0256	0.0149	2.9590	0.0040	3.0476	0.0034
		C	2.9753	-0.0236	2.9960	-0.0182	3.0268	-0.0241	3.0345	-0.0131
	80	A	2.9881	-0.0122	2.9721	-0.0140	2.9893	-0.0097	3.0080	0.0175
		C	3.0251	-0.0227	3.0391	-0.0171	3.0521	-0.0040	3.0482	0.0214

5. Discussion and Conclusions

A heavy vehicle multibody model was developed to examine the influence of different methodologies for synthesising pavement elevation profiles on the generated dynamic tyre forces. The initial stage, and focus of this paper, is on the accurate replication of the correlation between the left and right wheel tracks and their influence on the dynamic tyre forces. Various simulations performed to examine the difference produced by three different types of synthesised pavement elevation profiles. The first profile applied a simultaneous excitation to all wheels, similar to a large-scale vibration table. The second introduced a time-delay between the front and rear wheels to induce pitching in the vehicle. Finally, the third profile type not only had a time-delay between the front and rear wheels, but also a correlation function between the left and right wheel paths to realistically excite the roll motion of the heavy vehicle.

The dynamic tyre forces were obtained from the simulations and then processed to obtain the DLC, and the PDF for each case. While the results of the simulation found some variation between the different profile types, no significant difference was observed. The results indicate that introducing a correlation function between the left and right wheel paths has no substantial influence on the dynamic tyre forces generated by the heavy vehicle. The difference between the front and rear wheels has a far greater effect; this is mainly due to the differences in suspension parameters and mass.

There are several avenues for further research that can be pursued. First, a wider range of heavy vehicles should be investigated, such as vehicles with different dimensions and properties, and tractor-trailer combinations. Further work to improve pavement elevation profiles for realistic simulations should focus on varying the overall roughness in pavement sections (nonstationary), transients (such as potholes), difference in profiles depending on track width, wheelbase etc., and using actual road roughness information to develop improved statistical models.

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