

# Development of a new response-type road roughness measuring system

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**ABSTRACT:** Evaluation of pavement roughness is essential in road management, both for the understanding of pavement response under loading and for the definition of maintenance and rehabilitation strategies. Several techniques have been proposed and implemented into practice, ranging from simple rod and level static measurements to more advanced high-speed non-contact surveys. Although analytical tools have been derived for rigorously describing road surface profiles, they are still difficult to implement into ordinary pavement management systems due to associated financial and technical constraints. In order to improve this situation the Authors developed a new response-type road roughness measuring system, which is a simple and economic tool for rapid profiling applications. Investigations reported in this paper show that the new device is capable of providing a reliable description of road surface profiles, both in terms of spectral components and indirect statistics, leading to a straightforward assessment of roughness-induced dynamic amplification of vehicle loading.

## 1 INTRODUCTION

### 1.1 Background

Roads are designed to provide planar support to traveling vehicles. Planarity however is only an ideal assumption since deviations of road surface geometry from such a condition are often present as a consequence of pavement construction techniques and materials' properties (NCHRP 2000). Pavement elevation points along any longitudinal alignment can be regarded as the result of a stationary random process (Dodds & Robson 1973, Sun 2001, Múčka 2012), with spectral components that can be grouped according to the conventional categories of texture, encompassing wavelengths up to 0.5 m, and roughness, defined by wavelengths in the range of 0.5-50m (ISO 1998, CEN 2006, Múčka 2012).

While texture components for wavelengths up to 50 mm affect skid resistance and are therefore required for functional performance purposes (NCHRP 2000), roughness should be minimized in order to avoid undesired effects on the user-vehicle-pavement system.

It has been proven that roughness is strongly related to user perception of infrastructure conditions, due to the detrimental effect of its induced ride vibrations on comfort sensations (Carey & Irick 1960, Sayers et al. 1986a,b). Analytical formulations have been proposed to relate roughness indirect statistics

to the Present Serviceability Index (PSI) (Al-Omari & Darter 1994, Gulen et al. 1994, Sun 2001) which is the parameter derived from the AASHO road test quantifying the capability of a pavement to serve high-speed, high volume, mixed traffic in its existing condition (Carey & Irick 1960).

Roughness also directly affects pavement loading which is inherently dynamic as a consequence of inertial effects on travelling vehicles. Nowadays these effects have become predominant in pavement response due to the increase in speed, volumes and weights of modern traffic (Sun & Deng 1998) and specific design criteria are therefore required to withstand them, assessing the actual loading condition by explicit consideration of the combined effects of vehicle speed and pavement roughness. Neglecting the dynamic character of vehicle loads in pavement design, as in the case of standard methods which consider static loads only (AI 1991, AASHTO 1993, NCHRP 2004), leads to an underestimate of pavement damage progression and to untimely failure of pavement structures.

Based on the brief discussion provided above, road roughness characterization and assessment of its induced dynamical effects on traveling vehicles qualify as critical, both for deriving decision criteria for maintenance purposes and for the investigation of pavement damage mechanisms.

Approaches to roughness characterization can be divided into two main families: profilometric tech-

niques and response-type measurements. Profilometric methods attempt to exactly measure profile elevation heights and therefore profile description is usually provided via estimate of their Power Spectral Density (PSD). Response-type measurements, instead, characterize pavement profiles by considering their induced response in the measuring device itself. As a consequence, results are affected by the dynamics of the measuring system, and need to be related to a common scale of reference. In order to correlate measurements, statistical indexes have been derived for profile description, such as mean slope variance (MSV) of profile elevations, root-mean-square (RMS) of profile elevations and of profile vertical accelerations (RMSVA), ride number (RN) and others (Sayers et al. 1986a,b). Among them, the IRI (International Roughness Index) has been chosen as the common reference parameter due to its demonstrated compatibility with profilometric methods and due to its high degree of correlation with response-type measurements.

### 1.2 Motivations and objectives

In the context of profilometric measurements the theme of vehicle-pavement interaction is split into two topics: the profile is reconstructed independently of vehicle dynamics, while simulation of its effects on vehicles is obtained via mathematical manipulation. With such an approach, effects of roughness in terms of comfort and dynamical amplification of vehicle loads can be evaluated, even though vehicle simulation introduces uncertainties in obtained results.

Although nowadays direct measurements of road profiles can be achieved at high speed by means of non-contact sensors, interest in response-type measurements is still relevant. This is due to the fact that they implicitly take into account every aspect of vehicle-pavement interaction, providing a synthetic and valuable means for pavement performance evaluation. In any case, it should be considered that the value of road profile reconstruction does not exclusively rely on its accuracy but also on its capability of capturing features affecting vehicle response and user perception of pavement conditions.

Moving from these considerations, a new Response-Type Road Roughness Measuring System (RTRRMS) was developed and used in experimental measurements. Analyses presented in this paper demonstrate the suitability of the new device in assessing the overall level of pavement roughness and its induced effects on traveling vehicles, providing a simple and economic tool for pavement performance monitoring.

### 1.3 Summary

The paper introduces a newly developed instrument intended to be used for the study of road profiles and vehicle-pavement interaction. Description of the device is provided, together with an outline of the procedure employed for calibrating measurements to the IRI reference scale. Road profile reconstruction is performed via numerical integration of vehicle axle accelerations and road profile spectral description is provided by means of PSD. Vehicle body and axle accelerations are then combined to achieve an estimate of dynamic vehicle loads. Statistical description of dynamic pavement loading is carried out investigating the effects of speed and overall roughness level on the dynamic amplification of vehicle loads.

## 2 THE NEW RTRRMS DEVICE

The measuring system, called "Profimatic", was conceived as an economic and simple device capable of providing, by referring to the quarter-car mathematical model, an effective description of road roughness and of its induced effects on traveling vehicles. Despite its simplicity, the quarter-car model leads to an accurate description of ride quality and dynamic pavement loading (Todd & Kulakowsky 1991) and has been extensively used as the reference model for studying vehicle-pavement interactions (Sayers et al. 1986a,b, Hardy & Cebon 1993, Pappiannakis 1995, Sun & Deng 1998, Sun 2001a,b, Loizos 2008). More complex models in fact do not grant a better accuracy of results, due to the uncertainties involved in the characterization of the larger number of parameters required for analysis. Moreover, difficulties related to the assessment of representative values of several parameters negatively affect general validity of results (Todd & Kulakowsky 1991, Sun & Deng 1998). Analogy between the measuring system and the quarter-car model is apparent by referring to Figure 1.

The new system is constituted by a frame which allows sensors to be anchored to the measuring vehicle. The upper part of the system holds an accelerometer and a laser telemeter, and is fixed to the vehicle via the vacuum-pneumatic mechanism schematically represented in Figure 2. The lower part, fixed to the rear axle trim, holds a second accelerometer and an incremental encoder for wheel rotational speed detection. The lower and upper parts are joined together by a system of shafts, ball bushings and ball bearings designed to prevent sensor rotation, allowing the necessary freedom of relative movements between the parts.



Figure 1. System-model analogy

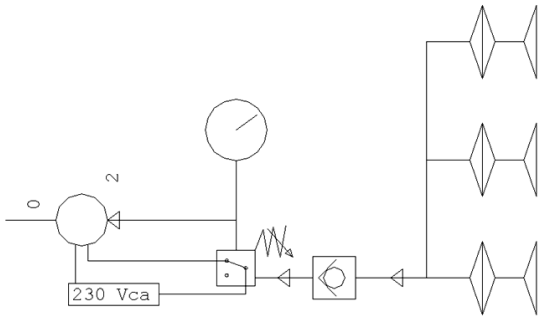


Figure 2. Vacuum-pneumatic system

### 3 EXPERIMENTAL INVESTIGATION

Use of the Profimatic device was tested in three experimental campaigns carried out at six months interval along selected urban and suburban roads in the city of Turin. Since measurements were performed in ordinary traffic conditions, sets of data associated to constant speed intervals were identified and thereafter processed. Localized irregularities were removed as suggested in Dodds & Robson (1973).

Since road roughness encompasses spectral components with wavelengths in the range of 0.5-50m, which corresponds to frequencies from 0.44 to 44.44 Hz for a speed of 80 km/h (which is the maximum speed for the experiment), a sampling frequency of 200 Hz was set for data logging. This corresponds to a Nyquist frequency of 100 Hz, which can avoid aliasing in the frequency range of interest.

#### 3.1 Estimate of vehicle parameters

Since measurements depend on the mechanical properties of the vehicle hosting the device, an estimate of model parameters is required. Equations of motion for the quarter-car mathematical model are expressed by:

$$m_t \ddot{y}_t + c_s (\dot{y}_t - \dot{y}_s) + k_s (y_t - y_s) + k_t (y_t - \xi) = 0 \quad (1)$$

$$m_s \ddot{y}_s - c_s (\dot{y}_t - \dot{y}_s) - k_s (y_t - y_s) = 0 \quad (2)$$

where  $\xi$  represents pavement surface elevations and  $y_s$  and  $y_t$  are absolute displacements of sprung mass and unsprung mass, respectively.

Equation 2 can be rewritten as:

$$m_s \ddot{y}_s = (\dot{y}_t - \dot{y}_s) c_s + (y_t - y_s) k_s \quad (3)$$

Since masses are known and absolute velocities and displacements can be retrieved via numerical integration of measured accelerations, Equation 3 can be written in matrix form as:

$$\mathbf{M} \cdot \mathbf{a} = \mathbf{b} \quad (4)$$

where:

$$\mathbf{M} = \begin{bmatrix} \dot{z}_s(1) & z_s(1) \\ \dot{z}_s(2) & z_s(2) \\ \vdots & \vdots \\ \dot{z}_s(n) & z_s(n) \end{bmatrix}; \quad (5)$$

$$\mathbf{a} = \begin{bmatrix} c_s \\ k_s \end{bmatrix}; \quad (6)$$

$$\mathbf{b} = m_s \begin{bmatrix} \dot{y}_s(1) \\ \vdots \\ \dot{y}_s(n) \end{bmatrix}; \quad (7)$$

$$z_s(i) = y_t(i) - y_s(i); \quad (8)$$

$$\dot{z}_s(i) = \dot{y}_t(i) - \dot{y}_s(i); \quad (9)$$

leading to a least squares estimate of the unknown suspension parameters according to:

$$\mathbf{a} = (\mathbf{M}^t \cdot \mathbf{M})^{-1} \cdot \mathbf{M}^t \cdot \mathbf{b} \quad (10)$$

Tyre stiffness estimate can be achieved by referring to a test configuration with the vehicle in stationary position. By applying a pulse load to the sprung mass in the absence of motion the quantity  $(y_t - \xi)$  becomes equal to  $y_t$ . Equation 1 therefore can be rewritten in the form:

$$m_t \ddot{y}_t + c_s (\dot{y}_t - \dot{y}_s) + k_s (y_t - y_s) + k_t y_t = 0 \quad (11)$$

thus determining  $k_t$  as:

$$k_t = \frac{1}{y_t} [c_s (\dot{y}_s - \dot{y}_t) + k_s (y_s - y_t) - m_t \ddot{y}_t] \quad (12)$$

Model parameters of the vehicle used in the experimental investigation are provided in Table 1, togeth-

er with the parameters of the reference quarter-car model for IRI evaluation (Sayers et al. 1986a,b).

Table 1. Vehicle and reference model parameters

	Vehicle	Reference Quarter-Car
$m_s$ [kg]	465	245
$m_t$ [kg]	65	36
$k_s$ [N/m]	64000	15500
$c_s$ [Ns/m]	1100	1470
$k_t$ [N/m]	230000	160000

### 3.2 Calibration of measurements

Once the parameters of the mathematical model have been identified, a numerical calibration procedure is implemented to retrieve IRI values from the measured ARS (Average Rectified Slope).

IRI is defined as the ratio between the accumulated suspension motion and the distance traveled by a reference quarter-car at the reference speed of 80 km/h. ARS is the ratio between the accumulated suspension motion and the distance traveled by a generic model, which is the case of the quarter-car model assumed in representing the vehicle used in the experimental investigation.

A direct relationship between road profile PSD and IRI was derived by Sun (2001b) in the form:

$$IRI = \frac{2}{\sqrt{\pi v^3}} \int_0^{\infty} \omega^2 |H_s(\omega)|^2 G_{\zeta}(\Omega) d\omega \quad (13)$$

where  $v$  is vehicle speed (the reference speed for IRI calculation is 22.22 m/s);  $\omega$  is angular frequency;  $\Omega$  is spatial frequency and  $H_s(\omega)$  is the frequency response function of the sprung mass of the quarter-car, defined as:

$$H_s(\omega) = \frac{-\frac{k_t}{m_t} \omega^2}{\omega^4 - i \left( \frac{c_s}{m_t} + \frac{c_s}{m_s} \right) \omega^3 - \left( \frac{k_t}{m_t} + \frac{k_s}{m_s} + \frac{k_s}{m_t} \right) \omega^2 + i \frac{c_s}{m_s} \frac{k_t}{m_t} \omega + \frac{k_t}{m_t} \frac{k_s}{m_s}} \quad (14)$$

Since road profiles have been demonstrated to be the result of zero mean Gaussian random processes (Dodds & Robson 1973, Sun 1998, Múčka 2012), it is assumed that they can be fully described via their PSD.

A simplified analytical road profile PSD approximation has been proposed by Dodds & Robson (1973), in the form:

$$G_{\zeta}(\Omega) = \begin{cases} G_o \left( \frac{\Omega}{\Omega_o} \right)^{-m_1} & , \quad \Omega \leq \Omega_o \\ G_o \left( \frac{\Omega}{\Omega_o} \right)^{-m_2} & , \quad \Omega \geq \Omega_o \end{cases} \quad (14)$$

where  $G_o$  is the roughness parameter, defined as  $G_o = G_{\zeta}(\Omega_o)$ ;  $\Omega_o$  is the datum frequency, fixed equal to  $1/2\pi$  [cycle/m];  $m_1$  and  $m_2$  are regression coefficients.

The roughness parameter values presented in Table 2, combined with values of  $m_1 = -3$  and  $m_2 = -2.25$  (ISO, 1972), were used for the numerical generation of random profile PSDs, in the form represented in Figure 3.

Table 2. Classification based on roughness parameter

Road class	$G_o(\Omega_o)/10^{-6}$
A	$2 \div 8$
B	$8 \div 32$
C	$32 \div 128$
D	$128 \div 512$
E	$512 \div 2048$

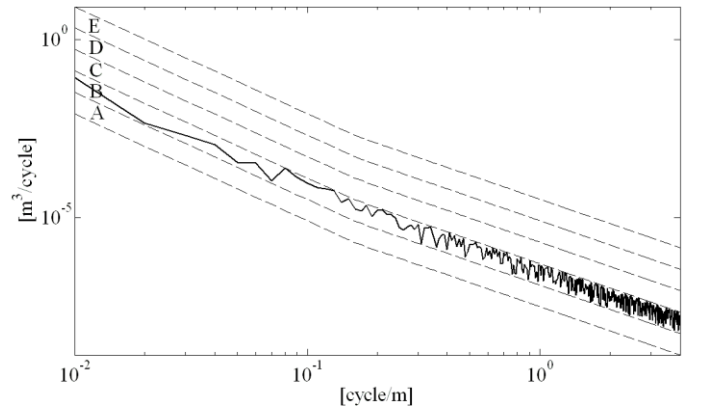


Figure 3. Numerically generated profile PSD

The PSDs were then used in Equation 13 to evaluate the profile's corresponding IRI. Equation 13 was then run a second time, employing the set of parameters representative of the vehicle used in the investigation, to evaluate the corresponding ARS. A correlation between the two indexes was established as indicated below and in Figure 4:

$$IRI = -0.0252 + 0.6824 \cdot ARS - 0.0002 \cdot ARS^2 \quad (15)$$

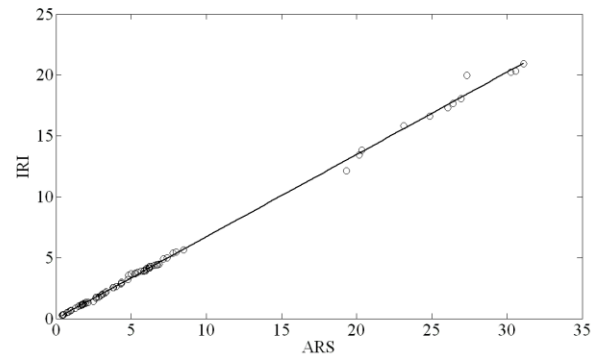


Figure 4. Correlation between IRI and ARS

## 4 INTERPRETATION OF MEASURED DATA

### 4.1 Road profile reconstruction

Road profile PSDs were reconstructed via numerical integration of axle accelerations, thus neglecting tyre compliance (Lin & Weng 2001).

Analysis was performed in the frequency domain, where integration is carried out by dividing the waveform by the frequency axle. The axle acceleration PSD is obtained from acceleration measurements via Welch modified periodogram method (Welch 1967) as suggested by Gonzales et al. (2008), and the corresponding axle displacement PSD is calculated by means of the following formula (Sun 1998):

$$G_{y_t}(\omega) = \frac{1}{\omega^4} G_{\ddot{y}_t}(\omega) \quad (16)$$

Figure 5 shows the comparison between a reconstructed road profile PSD and the ISO draft road roughness classification scheme, described in the previous section.

Road profile PSD reconstruction was found to be effective in properly assessing profile roughness class. Referring to the example of Figure 5, an IRI value of 9.82 [m/km] was measured for the investigated road section, while PSD estimate led to  $G_0 = 2600 \cdot 10^{-6}$  [m<sup>3</sup>/cycle], therefore qualifying the road as poor (which is actually the case).

It should be noted that high frequency components are almost absent in the spectrum, which may be interpreted as a consequence of the low-pass filtering action exerted by tyre geometry. As a consequence, the profile PSD reconstructed from axle accelerations cannot be approximated according to Equation 14. However, while  $m_1$  and  $m_2$  are parameters which describe the spectral distribution of profile irregularities,  $G_0$  is the parameter representative of the overall roughness level of the pavement, and classification according to  $G_0$  values can still be performed. This is demonstrated by the correlation between  $G_0$  and IRI shown in Figure 6, that can be approximated by the following equation:

$$G_0 = 0.0018 \cdot \text{IRI}^3 - 0.0249 \cdot \text{IRI}^2 + 0.2614 \cdot \text{IRI} + 0.5954 \quad (17)$$

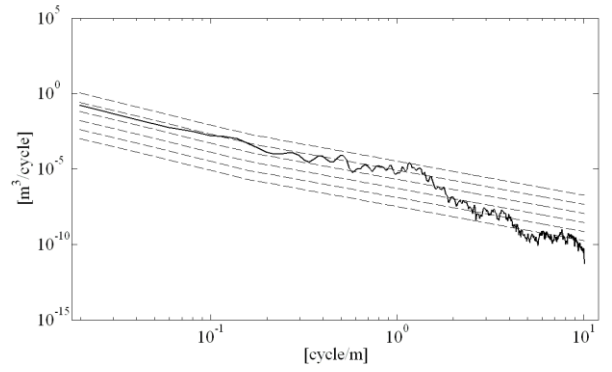


Figure 5. Road profile PSD reconstructed from measured axle accelerations

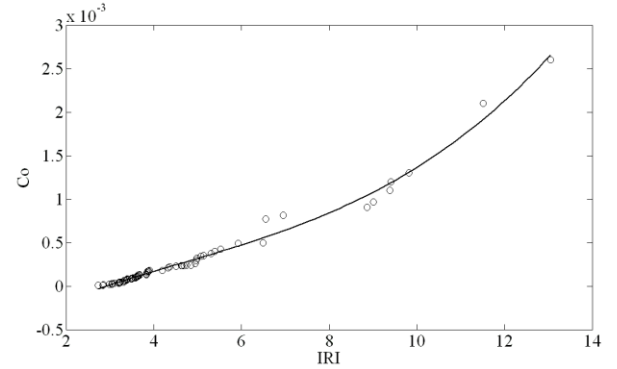


Figure 6. Correlation between IRI and  $G_0$

### 4.2 Dynamic amplification estimate of vehicle loads

By combining Equations 1 and 2 with Newton's Law, as suggested in Sun (2001a) an estimate of dynamic pavement loading (DPL) can be derived:

$$\text{DPL} = k_t z_t + c_t \dot{z}_t = -(m_t \ddot{y}_t + m_s \ddot{y}_s) \quad (18)$$

which can be easily calculated from the recorded time series of acceleration measurements.

Figure 7 represents a PSD estimate of the DPL for a road section considered in the experimental investigation. Results show the typical band-pass filter action of the vehicle, with peaks in the low frequency range of 1-3 Hz and in the high frequency range of 10-15 Hz (Sun & Deng 1998, Sun 2001, Sun & Kennedy 2002).

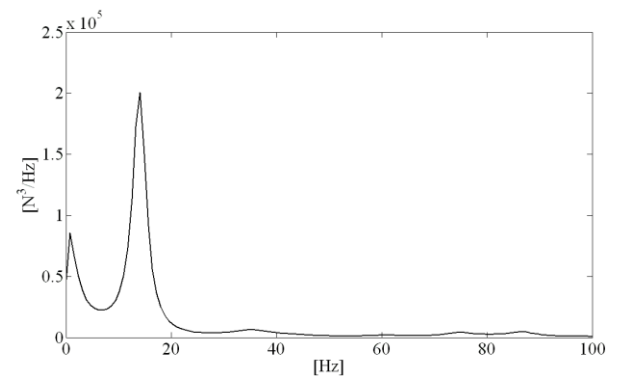


Figure 7. PSD of DPL

Statistical description of DPL can be achieved through estimate of the standard deviation,  $\sigma_p$ , and of the coefficient of amplification with respect to static vehicle loads,  $\alpha$ .

The standard deviation of DPL can be determined from the single-sided PSD of DPL,  $G_{DPL}(\omega)$ , assuming that dynamic amplification effects follow zero-mean Gaussian random processes (Sun 2001a), according to the formula:

$$\sigma_p = \left( \int_0^{\infty} G_{DPL}(\omega) d\omega \right)^{1/2} \quad (19)$$

while the coefficient of dynamical amplification of vehicle loads can be evaluated (Sun 2001a) as:

$$\alpha = \frac{\sigma_p}{(m_s + m_t)g} \quad (20)$$

The combined effect of speed and roughness on DPL is represented in Figure 8, where the coefficient  $\alpha$  is determined for a subset of 21 road sections characterized by IRI values ranging from 3.2 to 9.02, for the three different speeds of 35, 50 and 80 km/h.

It can be observed that coefficient  $\alpha$  increases with increasing roughness level and that such a sensitivity is magnified at higher speeds. An increase of IRI of 60% leads to an  $\alpha$  increase of about 150% at a speed of 35 km/h whereas the same increase in  $\alpha$  can be obtained for an IRI increase of 40% at a speed of 80 km/h.

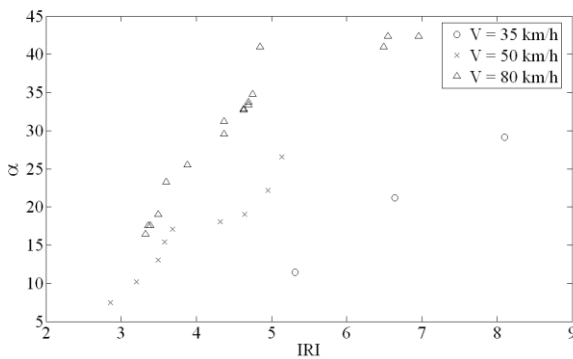


Figure 8. Amplification of vehicle loads as a function of road roughness and vehicle speed

Table 3 provides values of peak frequencies, amplitudes and  $\alpha$  coefficients determined for 33 measured road sections and for different overall roughness levels and vehicle velocities.

Table 3. DPL descriptive statistics

Section	V [km/h]	IRI [m/km]	f1 [Hz]	A1 [N]	f2 [Hz]	A2 [N]	$\alpha$ [%]
DC2D2	37	5.3098	1.56	95	12.50	155	11.4
PT2L1	55	5.5308	1.76	231	13.09	332	35
PC3L1	56	5.3914	1.56	150	13.28	230	17.4
OB1D	65	4.514	1.47	155	9.47	228	35.4
RG3L1	66	3.3083	1.37	69	9.38	337	17.3
DR1D1	51	4.945	2.34	120	12.50	181	19.1
DR2D1	52	5.9208	1.17	137	12.50	327	49.5
DN1D1	54	4.9797	1.56	79	12.50	203	17.9
DN1D2	49	4.3236	1.56	64	14.06	121	10.2
M1D1	50	5.136	2.73	127	12.89	176	22.2
SP2D1	51	3.2004	-	-	14.65	170	15.4
AN1D1	49	3.5768	-	-	16.41	107	13
AN3D3	50	2.8557	-	-	16.99	271	26.6
RG1L1	53	3.9004	1.47	115	12.89	222	37.8
PC1L1	49	9.0153	1.56	262	12.89	310	36
CS1L1	48	4.6411	1.56	129	12.50	150	17.1
TL3D1	73	3.3237	1.37	83	10.35	460	29.5
TL3D3	74	3.5991	1.86	206	10.45	368	32.9
TAL	74	3.8793	1.17	161	10.55	306	23.3
RC2D1	75	8.8606	1.95	166	10.55	347	21.1
RC3D1	77	6.9574	1.37	101	10.94	403	25.6
RC4D1	73	6.4925	1.17	86	10.55	262	19.1
BV1D4	76	4.8548	1.66	116	11.13	368	34.8
BV1D5	76	9.408	1.56	107	11.13	526	26.7
BV2D2	76	3.4915	1.17	113	10.94	377	16.5
BV2D4	75	4.7469	1.95	161	10.74	332	32.7
R6L1	77	4.6876	1.56	158	11.23	741	42.4
SV1L1	78	4.6319	1.76	149	10.94	589	41
BV1D3	85	6.5507	1.66	102	10.45	339	33.4
BV2D5	78	9.3807	1.95	138	11.13	525	28.6
SV2L1	79	4.3661	1.56	113	11.33	345	17.6
TL6D1	72	3.3614	1.66	147	10.35	341	31.3
BV2D1	69	3.3939	1.47	73	9.96	458	33.7

It is worth noting that the second peak amplitude falls in a frequency range that matches pavement design criteria, which assume dynamical modulus of bituminous mixtures to be determined at a frequency of 8 Hz (NCHRP 2004). On the contrary, the first peak, even if of reduced amplitude (ranging from 1.6 to 4% of static load, as shown in Table 3), falls in a range of frequencies (of the order of 1-2 Hz) that can be considered critical for the response under loading of pavement materials. This finding suggests that the extent of road surface damage predicted by typical design criteria is lower than the damage which can be computed by taking into account dynamic effects.

## 5 CONCLUSIONS

The paper presents a new experimental device, which qualifies as a RTRRMS for profile reconstruction and vehicle-pavement interaction analysis. The device can be easily mounted on almost any kind of vehicle, and a procedure based on the quarter-car mathematical model has been established to interpret recorded data. Furthermore, a methodology for the numerical calibration of measurements has been suggested. The interpretation procedure utilizes the same set of the numerically-calibrated measurements and can therefore be automatically run at every measurement campaign, providing timely and up-to-date results.

The device proved to be capable of providing a straightforward reconstruction of the profile elevation PSD, together with road roughness evaluation via IRI estimate. Moreover, it led to a statistical description of dynamic pavement loading, showing to be particularly suitable for pavement-performance monitoring and for the analysis of the actual pavement loading conditions.

Further investigations are necessary to assess the uncertainties related to tyre compliance in road profile reconstruction from axle acceleration measurements. Moreover, results obtained by using the newly developed device should be compared with those deriving from other direct profiling devices.

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