Pages 142 - 160

# DYNAMIC INTERACTION BETWEEN INSTRUMENTED VEHICLES AND PAVEMENTS

*Bernard JACOB (Laboratoire Central des Ponts et Chaussées, Paris, F)*
*Victor DOLCEMASCOLO, (Laboratoire Régional de l'Ouest Parisien, F)*

---

## ABSTRACT

In the scope of the OECD/DIVINE project (Element 5) experiments were carried out in France on several road sections with different profiles. Dynamic responses of two instrumented vehicles travelling at speed were investigated. Axle load variations were studied in the frequency/wavelength domain by spectral analysis, in order to identify the vehicle vertical dynamic motions. Amplitudes of such load variations were also related to the vehicle characteristics and the pavement profile. Comparisons are made between steel leaf spring and air 'road-friendly' suspension for one vehicle. Frequency and wavelength matching phenomena are pointed out, which in some cases, cause dramatic increases in the dynamic loads. Some recommendations are suggested to reduce road damage, and to increase vehicle comfort and safety, which deal with heavy vehicle design, driving rules, and pavement maintenance.

**Key words:** axle load, vehicle load, dynamic load, vehicle dynamics, suspension, instrumented vehicles, road profile, spectral analysis, vehicle pavement interaction.

Content

## 1. INTRODUCTION

The OECD DIVINE project 1993-97 (Dynamic Interaction between Vehicle and Infrastructure Experiment) was a scientifically-planned series of investigations, analyses and tests carried out, co-ordinated and interpreted by the OECD Scientific Expert Group IR6 (Dynamic Loading of Pavements) with the collaboration of institutes and companies from participating member countries (OECD 1997).

The main purpose of DIVINE was to provide scientific evidence of the effects of heavy vehicles and their suspensions systems on pavements and bridges, in support of transport policy decisions affecting infrastructure costs and road freight transport costs. This project was divided into six elements:

1. Accelerated Dynamic Pavement Test
2. Pavement Primary Response Testing
3. Road Simulator Testing
4. Computer Simulation of Heavy Vehicle Dynamics
5. Spatial Repeatability of Dynamic Loads
6. Dynamic Loading of Bridges

Heavy vehicles apply wheel/axle loads to roads that may be higher than the nominal axle loads. These loads are caused by a variety of static and dynamic processes, and are responsible for pavement deteriorations and bridge damage (OECD 1992, Ullidtz 1987). Moreover analysing these loads, induced by vertical accelerations of suspended and non-suspended masses of vehicles, provides fruitful information about vehicle dynamic behaviour, comfort and safety.

Dynamic wheel/axle loads are generated from the pavement/vehicle interaction and depend on:

- pavement profile and road roughness,
- vehicle characteristics: silhouette, masses, static gross weight and axle loads, suspension type and conditions, tyre and wheel dimension, etc.,
- travelling conditions of the vehicle: speed, horizontal accelerations (braking, etc.), lateral position on the traffic lane, etc.

The aim of the Element 5 of DIVINE (Jacob & Dolcemascolo 1997), was to investigate dynamic loads on pavements and their spatial repeatability, to assess the sensitivity to the above mentioned parameters, and to derive their effects both on vehicles and the infrastructure. ‘Spatial repeatability’ can be defined as the tendency for a vehicle, or a set of vehicles, to impose the same load patterns during different passes on a road surface with a given profile (Gyenes & Mitchell 1992).

There is also the potential for dynamic (over)loads to concentrate at, or near, particular points on the road surface. If spatial repeatability is significant, then the response of the pavement to that concentration of loads will clearly influence the deterioration of the pavement in that area.

In this paper, the response of two instrumented vehicles travelling at speed on different road profiles, were focused on. Three test sites were considered, with excellent, good and medium pavement evenness, in order to check the sensitivity of the dynamic loads and of heavy vehicle vertical motions to the road roughness. Spectral analysis of the axle load variations were carried out in the frequency/wavelength domain, to identify vehicle vertical dynamic motions, and to link them to the vehicle characteristics and the pavement profile. Amplitude of these load variations were also considered, and comparisons were made between steel leaf spring and air 'road-friendly' suspension for one vehicle.

# 2. EXPERIMENTAL WORK

## 2.1. Test sites

Measurements of dynamic loads were carried out on three road sections, all located 35 km south-west of Paris (Yvelines), nearby the town of Trappes. Two are main highways, operated by the state, called national roads (RN), and the third one is a secondary road operated by the local administration (RD):

- the RN12, links Paris area with the west part of France, South Normandy and Brittany;
- the RN10, links Paris to the south-west of France (Spanish border) through Chartres, Tours and Bordeaux;
- the RD983 is a local road, northbound linked to the RN12.

Both RN's have two lanes in each direction with semi-rigid pavement and were resurfaced in 1993. The pavements are made with mixed structure including cement-bound materials, bitumen-bound materials, and bituminous concrete. The RN12 has a surface draining bituminous concrete layer (4 cm thick). The traffic on the RN10 is dense and heavy with approximately 30,000 vehicles per day (veh/day), 25 % of which are lorries. The traffic on the RN12 is 9,900 veh/day, of which 20 % are lorries. The RD983 has an old flexible pavement with a thin bituminous surface layer. It carries 2,700 veh/day (20 % of lorries).

Table 1 gives the index road roughness (IRI) indices and the APL (Analyseur de Profil en Long) ratings of each road section (Delanne 1992). The APL is a profilometer, which consists of twin single-wheel instrumented trailer, and measures continuously at 20 m/s the angle between sensing arms fitted with a wheel and an inertial pendulum, on the right and left paths of a traffic lane. The wheel perimeter is 1.80 m. The APL ratings are calculated after low-pass and high-pass filtering, in three wavelength domains: (i) short (sw) 0.71 - 2.83 m, (ii) medium (mw) 2.83 - 11.31 m, and (iii) long (lw) 11.31 - 45.25 m. These ratings are linked to the energy of the signal in each bandwidth, and they characterise the road evenness/roughness, on a continuous scale from 10 (excellent evenness) to 1 (poorest pavement). As an example, a sinusoidal profile should have an amplitude (in level) of 1.9 - 5.0 - 20 mm in the sw - mw - lw to be quoted at APL 1-2, or 0.77 - 2.1 - 8.2 mm to be at 5-6, or 0.31 - 0.84 - 3.4 mm to be at 9-10. The evenness is excellent on the RN12, good on the RN10 and poor on the RD983.

**Table 1 - Evenness of each site**

| Site | IRI (m/km) | APL (sw) | APL (mw) | APL (lw) | Quality |
|---|---|---|---|---|---|
| RD983 | 3.57 | 4.1 | 3.6 | 3.7 | Poor |
| RN10 | 1.73 | 7.0 | 5.7 | 6.0 | Good |
| RN12 | 0.8 | 9.6 | 9.3 | 8.9 | Excellent |

## 2.2. Instrumented vehicles and test plan

Both instrumented vehicles are instrumented with strain gauges stuck on the axle(s) (which measure shear strains), and with accelerometers on the body. This on board instrumentation provides the data to calculate dynamic wheel impact forces at high frequency (200 or 500 Hz). The common measurement principle is described in detail in (LeBlanc et al. 1992).

Dynamic motions of a vehicle involve the body (sprung mass), and the axles and wheels (unsprung masses). The body motion can be decomposed into three components:
- vertical vibration: bounce motion,
- rotation around a horizontal transversal axle: pitch motion,
- rotation around a horizontal longitudinal axle: roll motion.

Axles and wheels (unsprung mass), are subjected to axle hop and axle roll motions.

### 2.2.1. The NRC instrumented vehicle

During the OECD/DIVINE project, the Canadian National Research Council (CNRC) provided the use of its instrumented heavy vehicle. This vehicles is a 3-axle (one tandem) tractor, with a tandem semi-trailer additionally fitted with a liftable intermediate axle, carrying a tank with 4 compartments. The vehicle, of which the suspension are interchangeable between steel leaf and air suspension, was fitted in France with the air suspension. **Figure 1(a)** shows the NRC's vehicle and its dimensions. The wheel perimeters are respectively 3.48, 3.30 and 3.21 m for axles 1, 2 and 3, 4 to 6.

Each axle of the vehicle was instrumented to measure dynamic wheel loads with a sampling frequency of 500 Hz, and vehicle speeds. The wheel load instrumentation comprised two strain gauge bridges and two accelerometers per axle, configured as full bridge circuits, but installed in such a way as to be sensitive to shear force. The stated precision was ± 3%.

The main eigenfrequencies of the instrumented NRC lorry are reported in Table 2. The pitching motion eigenfrequencies are: (1) 2.5 Hz for the semi-trailer, and (2) 3 Hz for the tractor. The eigenfrequencies depend on the axle rank:
- axle hop : 10.5 Hz for the second and third axles and 11.5 Hz for the fifth and the sixth axles.
- axle roll : 15.5 Hz for the second and third axles and 17.5 Hz for the fifth and the sixth axles.

**Table 2 - Natural frequencies of the NRC vehicle**

| Unit | Body - Air suspension | | | | Axles | |
|---|---|---|---|---|---|---|
| Motion | roll | bounce | pitch (1) | pitch (2) | Hop | Roll |
| Eigenfrequency (Hz) | 0.2 - 0.3 / 0.55 / 0.80 | 1.6 | 2.5 | 3.0 | 10.5 - 11.5 | 15.5 - 17.5 |

### 2.2.2. The IKH instrumented trailer

In November 1995, an instrumented vehicle owned by IKH (University of Hanover, Germany), came to France, also in the scope of the OECD/DIVINE project. This vehicle is a two axle tractor with a single axle instrumented trailer (Becher 1991). **Figure 1(b)** shows the dimensions and the silhouette of the IKH vehicle. The trailer wheel perimeter is 3.30 m. The instrumented trailer was able to measure the dynamic wheel loads with a sampling rate of 200 Hz and a stated accuracy of ± 4%.

The instrumented trailer may be equipped with two suspension types: air or steel leaf spring. It was possible to interchange between the two during the experiment. The main eigenfrequencies of the instrumented trailer given by the IKH are reported in Table 3. There is no pitching motion for a single axle trailer.

**Table 3 - Natural frequencies of the IKH trailer**

| Unit | Body (trailer) | | | | Axle | |
|---|---|---|---|---|---|---|
| Motion | roll | | bounce | | Hop | |
| Suspension | Steel | Air | Steel | Air | Steel | Air |
| Eigenfrequency (Hz) | 0.4 - 0.7 | | 2.3 - 2.5 | 1.5 - 2.0 | 15.5 | 15.5 |

### 2.2.3. Test plan

The NRC lorry made 91 passes on the RN10 site, while measuring wheel loads along 120 m, at five load levels and three speeds as illustrated in Table 4. The impact force signals were filtered by a 45 Hz low pass filter to eliminate noise and remote harmonics, as the highest natural frequencies of the lorry do not exceed 25 Hz.

**Table 4 - Test plan with the NRC vehicle on the RN10 site (passes are at 80, 50 and 30 km/hr)**

| | | | | | | |
|---|---|---|---|---|---|---|
| Date (1994) | 1/6 | 2/6 | 2/6 | 3/6 | 3/6 | 6/6 |
| Gross weight (kN) | 250 | 359 | 364 | 442.5 | 442.5 | 173.9 |
| Number of axles | 5 | 5 | 6 | 5 | 6 | 5 |
| Passes | 4-3-3 | 3-3-3 | 3-3-3 | 6-6-6 | 9-9-9 | 6-6-6 |

**Table 5 - Test plan with the IKH trailer**
**(passes are at 80, 60 and 40 km/hr; A means air and S means steel leaf spring suspensions)**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Date (1995) | 20/11 | 22/11 | 23/11 | 24/11 | 27/11 | 27/11 | 28/11 |
| Gross weight (kN) | 222.5 | 222.5 | 193.7 | 156.8 | 156.0 | 194.3 | 214.6 |
| Instrumented axle load (kN) | 82.4 | 82.4 | 62.55 | 24.9 | 25.5 | 62.6 | 83.1 |
| Suspension | A | A | A | A | S | S | S |
| Passes (RD983) | | 1-1-1 | 1-1-1 | 1-1-1 | 1-1-1 | 1-1-1 | 1-1-1 |
| Passes (RN10) | 7-6-6 | 9-7-9 | 6-5-5 | 5-6-5 | 5-7-6 | 6-5-7 | 4-6-5 |
| Passes (RN12) | | 1-1-1 | 1-1-1 | 1-1-1 | 1-1-1 | 1-1-1 | 1-1-1 |

*N.B.:In tables 4 and 5, load and weight units were converted from kg into kN using a factor 10.*

Table 5 illustrates the 163 passes made by the IKH trailer at three load levels, with 2 types of suspension (air or steel leaf spring) and three speeds, on the three test sites. This vehicle cannot be considered representative of a common vehicle from the traffic flow. However the impact force signals supplied are easier to analyse than those measured by the NRC vehicle.

The dynamic wheel load measurements were made over 240 m on the RN10 and over 3100 m on the RD983 and RN12.

# 3. SPECTRAL ANALYSIS

## 3.1. Mathematical Tools

Spectral analysis provides powerful tools in signal processing, to describe the frequency content of a signal or a random process. It may use a finite set of data. In vehicle dynamics and pavement/vehicle interaction, the signal consists of the wheel or axle loads applied on the road, and measured by on board vehicle' instrumentation. We are interested in the eigenfrequencies of the vehicle and vehicle parts, but also in the frequency or wavelength content of the pavement profile, which induces the vertical motions of the vehicles. The spectral analysis helps to identify these characteristics, and to explain some signal amplification caused by frequency matching.

### 3.1.1. Fourier and Fast Fourier Transform

The Fourier Transform of an integrable function h(t) is defined by:

$$\phi(\omega) = \int_{-\infty}^{+\infty} h(t) e^{-i\omega t} dt$$

To compute the Fourier Transform, a numerical integration must be performed. That leads to an approximation called ‘Discrete Fourier Transform’. The ‘Fast Fourier Transform’ (FFT) is an efficient algorithm developed to compute the Digital Fourier Transform (Cooley & Tukey 1965).

### 3.1.2 Power Spectral Density (PSD)

For a random signal $X_t(w)$ written as a stationary time random process, the auto-correlation function *r(t,τ)* is:

$$r(t,\tau) = \text{cov}(X_t, X_{t+\tau}) = r(\tau)$$

The Power Spectral Density (PSD) of $X_t$ is then defined as the Fast Fourier Transform of *r(τ)*. Physically it gives the distribution of the energy of the signal (or the variance of the random process) as a function of the frequency. In case of wheel/axle impact forces or of road profiles, the theoretical signal is considered, as such a (stationary) random process, while the recorded signal is a sample path measured on a given section. The Fast Fourier Transform may be used for the estimation of the PSD (Welch 1967).

Before computing the PSD, a Hanning window was applied on the impact force signal to correct the non periodic effects. The PSD may be plotted as a frequency $f$ or a wavelength $\lambda$ function, as both are linked by the vehicle velocity: $V = f.\lambda$.

## 3.2. Spectral analysis of the pavement profiles

For each of the three test sites presented in section 2.1, the PSD of the pavement profile was calculated, and are plotted versus the wavelength in **Figure 2**. The main peak is located at 50, 55 and 65 m for the RN10, RN12 and RD983 respectively (Fig. 2(a)). The larger the area under the PSD curve, the greater the roughness. Details of these PSD are given for each road and wavelength under 20 m, which show some typical peaks at 18.8, 14.1 and 11.7 m for the RD983 (Fig. 2(c)) 4.3 and 3.2 m for the RN10 (Fig. 2(b)) and 14.8, 11.7, 9.2, 8.0 and 3.95 m for the RN12 (Fig. 2(d)). Additional peaks may be seen for the RN10 and RN12 at 1.8, 0.9 and 0.60 m, which correspond to the wheel perimeter of the APL and its two first harmonics; for the RD983 they almost disappear because of the very strong roughness of the profile which induces a much higher average level of the PSD.

## 3.3. Spectral analysis of the IKH trailer impact forces

According to the common validity criteria of a PSD which depends on the measuring length (Jacob & Dolcemascolo 1997), the PSD of the wheel and axle impact forces of the IKH trailer may be considered over 0.37, 0.56 and 0.74 Hz on the RN10 for 40, 60 and 80 km/hr respectively, and over 0.06 Hz on the other sites. This allows for the analyses of the lowest frequencies of the roll motions, at least for the highest velocity. The upper bound (around 80 Hz) is not critical, because the PSD are negligible over 30 Hz.

Two PSD were calculated for each case (site, suspension, load and speed):
- the PSD of the axle impact force (load), sum of both wheel loads, representative of the bounce and axle hop motions, and
- the PSD of the difference between the left and right wheel loads, representative of the roll motion.

Most of the PSD are presented for the heaviest axle load (80 kN) in **Figure 3**. At lower loads the impact forces are smaller and less aggressive. For the lowest load (25kN) the automatic load levelling valve of the air suspension was not functioning, while the dry friction of the steel suspension becomes dominant. Frequencies lower than 7 Hz were mainly considered, because the body eigenfrequencies given in section 2.2.2 were under this threshold; moreover the PSD amplitudes become much smaller - always under 0.1 kN²/Hz - over this threshold. The PSD of the axle loads (Fig. 3(a), 3(c) and 3(e)) are plotted in semi-logarithmic coordinates, because the peak amplitudes vary considerably from 0.2 to 48 kN²/Hz.

The main findings of this spectral analysis are:

- The body bounce with the steel suspension gives the highest peaks, as expected between 2.4 and 2.7 Hz, with their amplitudes quickly increasing with the pavement roughness (by a factor 2 from one site to another (80 km/hr), and by a factor 5 (40 km/hr)). The amplitudes are also increasing with the speed. Nevertheless, on the very smooth RN12 pavement, this bounce effect only gives the second largest peak.
- The second largest peaks generally correspond to the wheel perimeter (*p*) effect, at the frequency: $f = V/p$ , i.e. 3.4, 5.1 and 6.7 Hz for 40, 60 and 80 km/hr (small frequency shift may occur if the real speed is not accurately the targeted one). This results from wheel imbalance and tyre non-uniformity; this effect decreases when the speed increases, because the bounce motion becomes dominant.
- The body bounce with the air suspension only appears over 60 km/hr, at 1.8 Hz; under that speed, the load levelling valve cuts this motion, and only the wheel imbalance may be seen.
- When the differences between left and right wheel loads are considered, the body roll motion at a frequency (0.4 - 0.55 Hz) becomes the main effect on rough (RD983) and good (RN10) evenness, but the wheel imbalance effect is of the same magnitude on the very smooth road (RN12), or even higher at low speed; frequency matching is found between the roll motion at 0.44 Hz and the long wavelength unevenness at 50 m, on the RN10 at 80 km/hr. This increases the peak amplitude with the air suspension by a factor 3 compared to the second largest peaks.
- In both axle load and difference between left and right wheel load PSD, some lower peaks may be seen around 13.5 and 27 Hz for 80 km/hr, and around 20 Hz for 60 km/hr, with amplitudes between 0.015 and 0.1 kN²/Hz; these are due to the first and second harmonics of the wheel imbalance wavelength (app. 1.65 and 0.83 m).

The body bounce peak amplitude is 10 to more than 20 times smaller with the air suspension than with the steel suspension. This confirms the road friendliness of the air suspension in this case.

## 3.4. Spectral analysis of the NRC vehicle impact forces

Among the 91 passes of the NRC vehicle, those presented here were made in the 5-axle configuration (axle 4 was lifted) and a gross weight of 359 kN. This configuration was chosen as it was seen to be most representative of European heavy lorries. In addition, two passes at 250 and 173.9 kN were considered to check the influence of the axle load. Three speed levels (80, 50 and 30 km/hr) were analysed at the highest load, while only the two extreme speeds are considered for the other loads.

PSD’s were calculated for each wheel and axle load (PSD of right wheel and axle loads are presented in **Fig. 4**(a) to 4(f)), and for the difference between the left and right wheels for each axle (Fig. 4(g) and 4(h)). Most of the known eigenfrequencies of the vehicle were found, but with large variations in amplitude. In addition, these PSD were also analysed with a wavelength scale in abscissa. This presentation revealed a series of peaks at wavelengths independent of the speed. They are clearly related to wheel perimeters (imbalance) and several harmonics. The shapes of the PSD for wheel and axle loads are similar for each speed, with more or less the same peaks; only the roll effect is more important for wheels, while the axle hop is higher for axles.

The main findings of this analysis are:

- The body bounce motion around 1.6 Hz is the dominant effect at high speed (80 km/hr) and medium speed (50km/hr) for all axles, and above all for the tandem of the semi-trailer. The steering axle is almost not affected by the body bounce, because the semi-trailer carries most of the load, but is mainly affected by the pitch motions at 2.5 and 3 Hz. At 30 km/hr, the bounce motion is greatly attenuated by the air suspension.
- The body roll effect at frequencies lower than 0.8 Hz increases with respect to the other motions, when the speed decreases, since at 30 km/hr the body bounce becomes rather low; moreover some frequency matching occurs with the main road profile wavelength (50 m), which corresponds to 0.44, 0.27 and 0.17 Hz at 80, 50 and 30 km/hr.
- Axle 5 is the most sensitive to hop, at 11.5 Hz, with a peak heights close to 3 $kN^2/Hz$, and up to 12 $kN^2/Hz$ at 80 km/hr; the drive axle 3 has a hop motion around 8.3 Hz.
- The wheel imbalance induces a sine wave in the wheel forces, with wavelengths equal to the perimeters: 3.5 m, 3.3 m and 3.2 m for axles 1, 2-3 and 5-6 respectively. The corresponding frequencies are proportional to the speed, between 6.4 and 6.9 Hz at 80 km/hr, 4.0 and 4.3 Hz at 50 km/hr, and 2.4 to 2.6 Hz at 30 km/hr. The amplitude of this sine wave is rather constant with speed, and therefore its relative importance decreases at high speed. The three first harmonics also appear for the wheels of axles 2 to 6, at wavelengths of 1.65 and 1.6 m, 1.1 and 1.06 m, 0.83 and 0.8 m, and even the three next ones at 30 km/hr for axles 5 and 6, at 0.64, 0.53 and 0.46 m.
- Frequency matching greatly increases some motions, such as the axle 5 and 6 roll (17.5 Hz) matching the third wheel imbalance harmonics (0.8 m) at 50 km/hr, that amplifies this peak amplitude by a factor 13 to 15 compared to the same peak at 80 km/hr. The pitch motion on the steering axle is also amplified by a frequency matching with the wheel imbalance at 2.4 Hz, at 30 km/hr, with a factor 5 on the peak amplitude compared to the case at 50 km/hr.

**Figure 5** shows the PSD variations of the axle 5 impact force for three loads at velocities of 30 and 80 km/hr. The body motions are dominant for the heaviest load (76.4 kN), either the bounce at 80 km/hr or the roll at 30 km/hr. Axle hop became the main effect at lower loads, with a slight frequency shift to the left, from 11.5 to 10.5 and 9.5 Hz.

# 4. AMPLITUDE OF THE IMPACT FORCES

## 4.1. Definitions

The wheel Impact Factor (IF) is defined at any time or abscissa, such as the ratio of the dynamic impact force to the static load. For an axle or a vehicle, the IF is defined in the same way, the dynamic and static loads or weights being calculated as the sum of the axle/vehicle wheel loads. The maximum IF is the largest value computed along a sample path.

The Dynamic Load Coefficient (DLC) is the coefficient of variation of the dynamic force along a sample path; it is defined for a wheel, and extended to an axle or a vehicle. If the mean dynamic impact force (of a wheel, an axle or a lorry) along a sample path is equal to the static load (this is generally the case), then the DLC is the coefficient of variation of the IF.

The maximum IF (Max IF) gives an indication of the largest dynamic increments resulting from the vehicle motions, while the DLC measures the scattering of the dynamic loads around the static load. In order to complete the spectral analysis and to quantify the loads resulting from the pavement/vehicle interaction, these Max IF and DLC were analysed for both instrumented vehicles.

## 4.2. Results

**Figures 6 and 7** give the maximum IF's and DLC's for the instrumented axle of the IKH trailer (for each load, suspension and two speeds), as functions of the IRI on each site. DLC increases with the IRI, and for the RD983 it is often a factor of two greater than that of the RN12. DLC also increases with speed except on the smoothest evenness. The maximum IF also increases with the IRI. It was noticed that some values were slightly less on the RN10 than on the RN12, but this could be accounted for by the fact that different road lengths were considered (240 m on the RN10 instead of 3100 m on the other roads). Light axles generally have higher DLC and maximum IF's, except in case of 80 kN at 80 km/hr and steel suspension.

DLC's are always smaller with air suspension than with steel suspension for the same evenness, load and speed, but the efficiency of the air suspension is clearly better for high axle loads.

Table 6 gives the minimum IF's, maximum IF's and DLC's, relative to the gross weight for the NRC vehicle, for two load configurations on the RN10. DLC's and maximum IF's are smaller for a whole vehicle than for an axle, because of the averaging effect and load transfer by pitching from one axle to another. They both increase with speed. At low speed the DLC greatly decreases if the load increases, while DLC and maximum IF are rather independent of the load at high speed due to the adaptive suspension of the semi-trailer, which was designed to be efficient at high loads. Again the air suspension is clearly designed to be road friendly for loaded axles and vehicles.

**Table 6 - Maximum (Max), minimum (Min) IF's and DLC's of the NRC vehicle - RN10**

| | GW = 443 kN | | | GW = 240 kN | | |
|---|---|---|---|---|---|---|
| Speed (km/hr) | Min IF | Max IF | DLC (%) | Min IF | Max IF | DLC (%) |
| 80 | 0.92 | 1.10 | 3.76 | 0.92 | 1.12 | 3.50 |
| 30 | 0.98 | 1.04 | 0.83 | 0.92 | 1.05 | 2.52 |

## 5. CONCLUSIONS AND RECOMMENDATIONS

The investigations carried out in this study pointed out the great benefit of using instrumented vehicles for measuring the response of heavy vehicles travelling on roads and for analysing the vehicle/pavement interaction phenomena. Even if experiments may be conducted with instrumented pavements, using stain gauges or WIM sensors (Jacob & Dolcemascolo 1997), such an approach only provides axle loads on some discrete sections along the road, and therefore the complete history of the dynamic axle load along the road pavement is not measured.

With on board instrumented vehicles, recording their axle/wheel loads at high frequency sampling rate over long road lengths, the signal may be analysed in both frequency/wavelength and time/spatial domains. Spectral analysis provides powerful tools to point out the main eigenfrequencies of the vehicle motions, as well as some wavelengths linked to geometrical vehicle characteristics or the pavement profile.

Some important findings of this research were: (i) the importance of the wheel imbalance effect on the wheel and axle dynamic impact factors, especially at low speed and on smooth road profiles, where the body bounce and axle hop motions are low; (ii) air suspension reduces significantly the dynamic increments; this is mostly sensitive for the heaviest loads for which active valves were designed; this justifies the concept of road-friendly suspension; (iii) the pavement roughness has a great influence on the dynamic loads, with DLC's and IF's increasing by factors of 2 and 1.5 for an IRI of 0.8 (excellent profile) to 3.5 (poor profile) respectively. This leads to the conclusion that preventive maintenance should be undertaken, in order to avoid quick pavement deterioration, especially for the older pavements.

Frequency matching was found in some cases, between long pavement profile wavelengths (45 to 60 m) and low roll eigenfrequencies (0.2 to 0.8 Hz), between the wheel perimeter (imbalance) around 3.3 m and pitch eigenfrequencies (2.5 to 3 Hz) and between wheel perimeter harmonics (0.8 to 0.6 m) and axle roll eigenfrequencies (15.5 to 17.5 Hz). This phenomenon occurs for particular velocities, fitting some pavement or vehicle wavelengths to vehicle eigenfrequencies, which significantly increase the wheel/axle impact forces. Because of the great variability of pavement profiles encountered on existing roads, there is a limit of the practical recommendations that can be made. These are as follow:

(i) the driver should reduce speed temporarily when crossing some road sections. However, this would require on board instrumentation and driving assistance, such as expected in IVS (Intelligent Vehicle Systems);

(ii) the manufacturers and transport companies should carefully balance lorry wheels, such as already done for personal cars for safety reasons.

Such provisions, combined with the development of road friendly suspension, carefully designed and maintained, could reduce vertical dynamic vehicle motions, pavement wear, and increase vehicle comfort, safety and (fragile) goods safety during journeys.

Introduction

Content

# ACKNOWLEDGEMENT

This work was supported by the OECD/RTR programme. The DIVINE executive committee, the IR6 expert group, and all the contributors to the Element 5 are acknowledged. Special thanks are expressed to the IKH of Hanover University for its fruitful in-kind contribution.

# REFERENCES


Becher, H.0 (1991), *Design criteria for controlled suspensions of heavy vehicles*, PhD thesis, Institute of Automotive Engineering, University of Hanover, (in German).

Cooley, J.W and Tukey, J.W (1965), 'An algorithm for the machine calculation of complex Fourier series', *Math. of Computation*, vol.19, pp. 297-301, April.

Delanne, Y. (1992), 'L'analyseur de profil numérique', *Revue Générale des Routes et Aérodromes*, N°698, pp 64-68, juillet-août.

Gillespie, T.D (1992), 'Truck factors affecting dynamic loads and road damage', *Proceedings of the third International Symposium on Heavy Vehicle and Dimensions*, Heavy vehicles and roads - Technology, safety and policy, T. Telford, London, pp. 102-108.

Gyenes, L. and Mitchell, C.G.B (1992), 'The spatial repeatability of dynamic pavement loads caused by heavy goods vehicles', *Proceedings of the third International Symposium on Heavy Vehicle and Dimensions*, Heavy vehicles and roads - Technology, safety and policy, T. Telford, London, pp. 95-101.

Jacob, B. and Dolcemascolo, V. (1997), *Dynamic loading of pavements and spatial repeatability*, OECD/DIVINE project, Final report of Element 5, LCPC, Paris.

LeBlanc, P.A., Woodrooffe, J.H.F and Papagiannakis, A.T (1992), 'A comparison of the accuracy of two types of instrumentation for measuring vertical wheel load', *Proceedings of the third International Symposium on Heavy Vehicle and Dimensions*, Heavy vehicles and roads - Technology, safety and policy, T. Telford, London, pp. 86-94.

OECD, IR2 (1992), 'Dynamic Loading of Pavements', Road Transport Research Programme, final report, OECD, Paris.

OECD, IR6 (1997), 'DIVINE: Dynamic Interaction Vehicle - Infrastructure Experiment', final report, *in proceedings of the American, European and Asian-Pacific conferences*, Ottawa (June 23-25), Rotterdam (September 17-19), Melbourne (November 5-7), OECD, Paris.

Ullidtz, Y.H (1987), *Pavement Analysis. Developments in Civil Engineering*, 19, Elsevier.

Welch, P. (1967), 'The Use of Fast Fourier Transform for the Estimation of Power Spectra: a Method Based on Time Averaging Over Short Modified Periodograms', IEEE Trans Electroacoust., vol. AU-15, pp. 70-73, June.

Introduction Content

## AUHTOR BIOGRAPHIES

**Bernard JACOB**
Laboratoire Central des Ponts et Chaussées (LCPC)
58 bd Lefèbvre, 75015 Paris, France
tel: +33 1 40 43 53 12, fax: +33 1 40 43 54 98,
Email: jacob@lcpc.fr

A graduate of Ecole Polytechnique and Ecole Nationale des Ponts et Chaussées, started work as a research engineer at the SETRA. Since 1982 with the LCPC, first as head of the "Structural Behaviour and Safety" section and now in the Scientific and Technical Division. He has worked in the fields of actions on structures, probabilistic modeling, fatigue of steel bridges, traffic loads on bridges and weigh-in-motion (WIM) of road vehicles. He was involved in the Eurocode 1.3 (Traffic loads on road bridges) expert group, and then he became the leader of a national WIM project. He is now the chairman of the European COST323 action Management Committee (WIM) and coordinator of the European research project ‘WAVE’. He was also the leader of the Element 5 of the OECD/DIVINE project.

**Victor DOLCEMASCOLO**
Laboratoire Régional de l’Ouest Parisien (LROP)
12 rue Teisserenc de Bort, 78190 Trappes, France
tel: +33 1 34 82 12 42, fax: +33 1 30 50 83 69,
Email: lrop.vd@wanadoo.fr

A graduate in telecommunications from Ecole Nationale Supérieure des Télécommunications de Bretagne, master of science in microelectronics from university Joseph Fourier (Grenoble) and in applied physics from university of Metz, started work in 1992, as an engineer for the French Ministry of Transport with Laboratoire Régional de l’Ouest Parisien (LROP), in charge of road measuring devices. From 1994 to 1996, he was in charge of measurements and data analysis of the OECD/DIVINE project, Element 5. Since 1995, he has been in charge of research work in WIM of road vehicles, and he is also member of the COST 323 action and the ‘WAVE’ project.

Introduction Content

*Figure 1 - NRC instrumented lorry and IKH tractor and instrumented trailer*

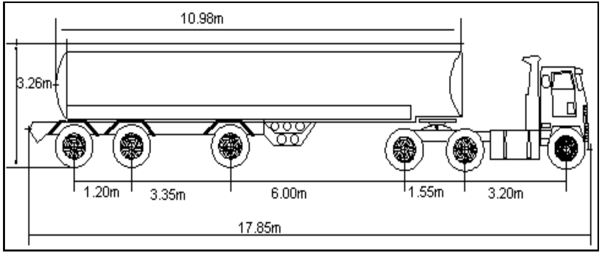



Fig. 1a - NRC vehicle

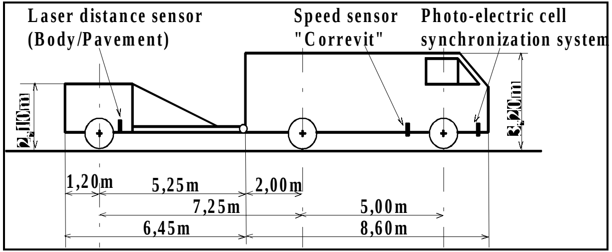



Fig. 1b - IKH tractor and trailer

Return to paper

Content

## *Figure 2 - PSD of the road profiles*

Fig. 2(a) - PSD of the three profiles (lw)

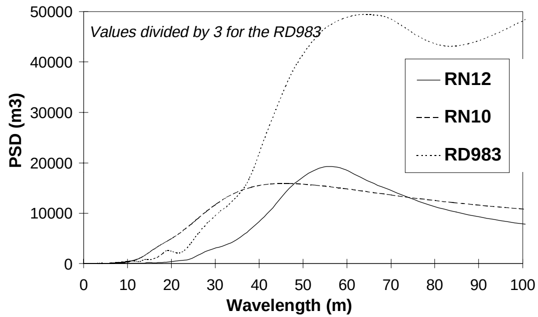



Fig. 2(b) - PSD of the RN10 profile (sw-mw)

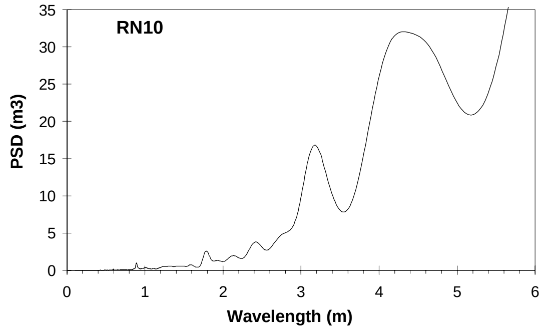



Fig. 2(c) - PSD of the RD983 profile (sw-mw)

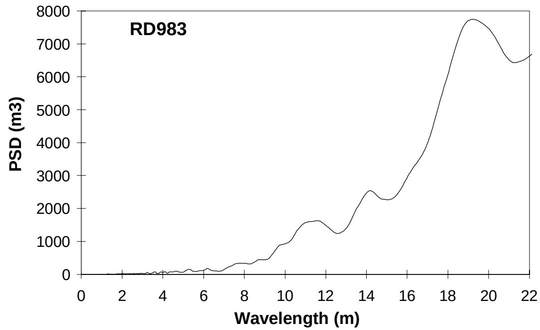
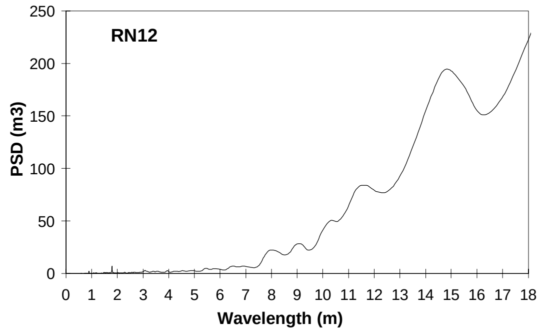



Fig. 2(d) - PSD of the RN12 profile (sw-mw)





Return to paper

Content

## *Figure 3 - PSD of the IKH trailer impact forces*

Fig. 3(a) - axle / RN12

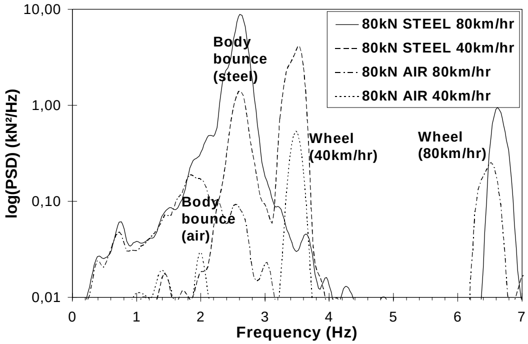



Fig. 3(b) - wheel difference / RN12

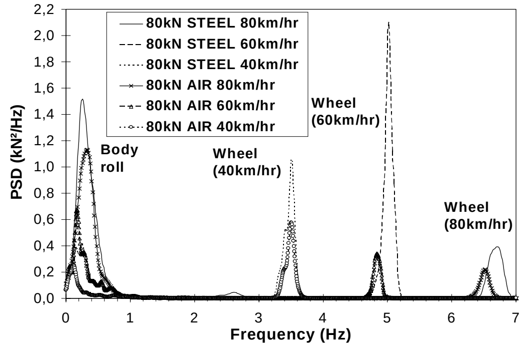



Fig. 3(c) - axle / RN10

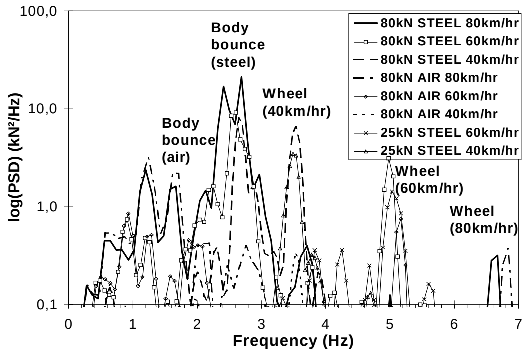



Fig. 3(d) - wheel difference / RN10

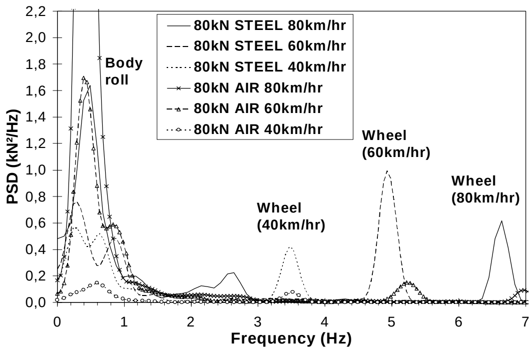



Fig. 3(e) - axle / RD983

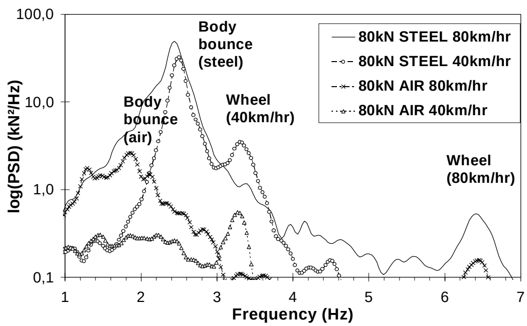
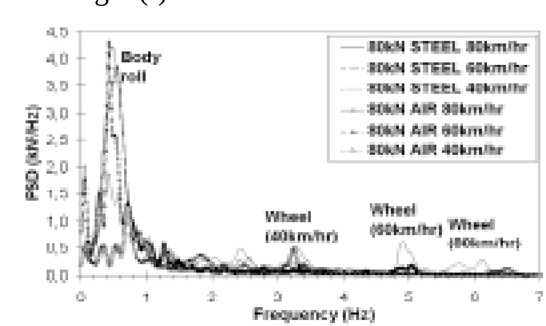



Fig. 3(f) - wheel difference / RD983




Return to paper

Content

*Figure 4 - PSD of the NRC vehicle wheel and axle impact forces*

Fig. 4(a)

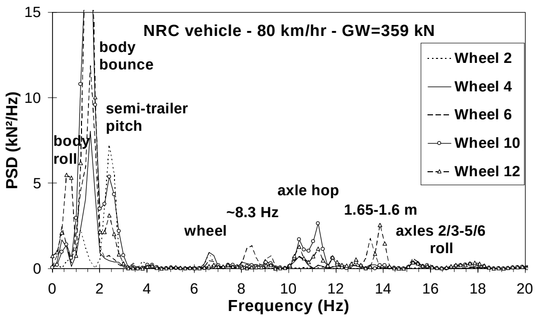



Fig. 4(b)

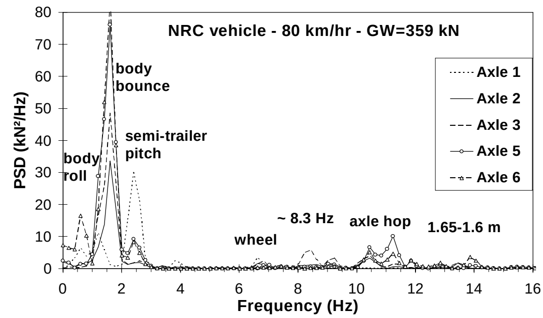



Fig. 4(c)

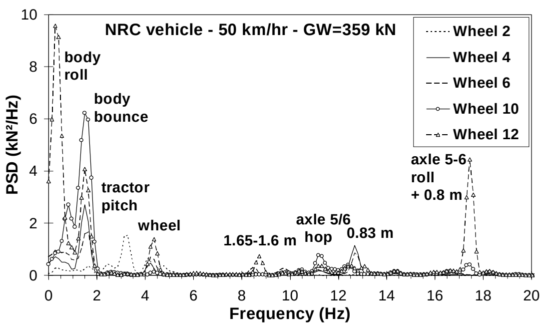



Fig. 4(d)

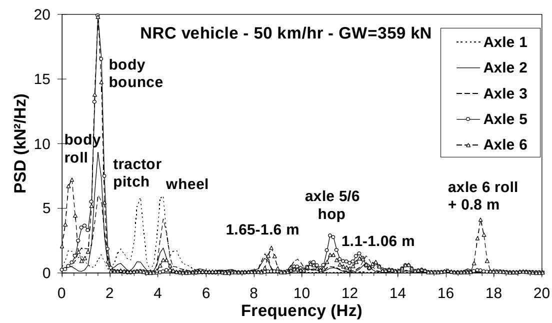



Fig. 4(e)

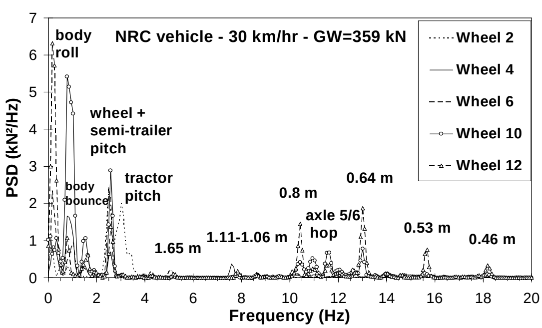



Fig. 4(f)

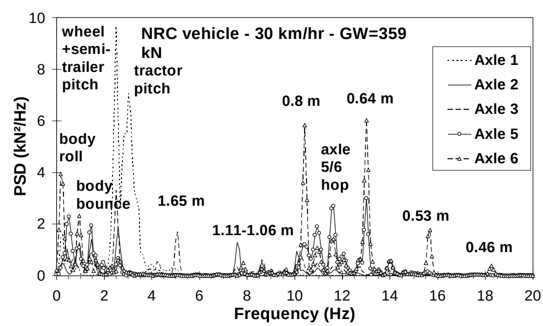



Fig. 4(g)

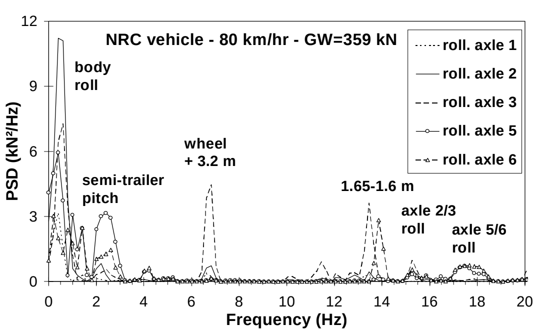
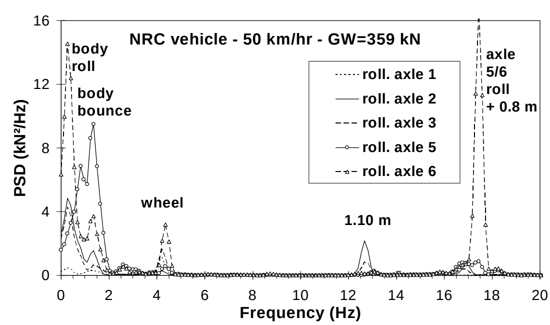


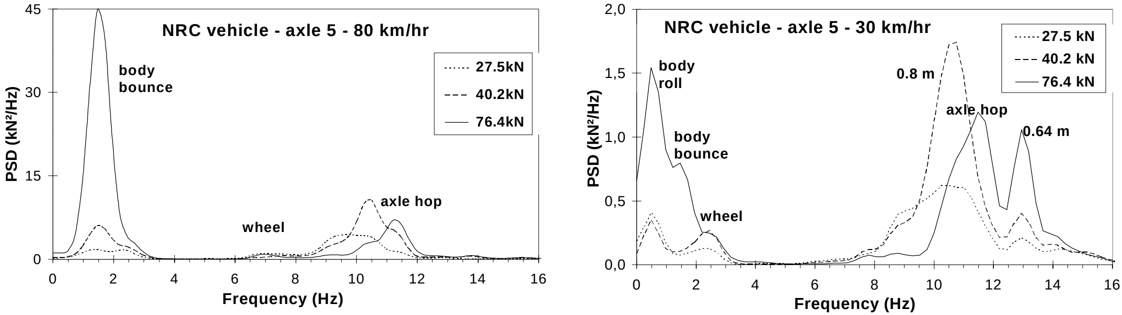

Fig. 4(h)




Return to paper

Content

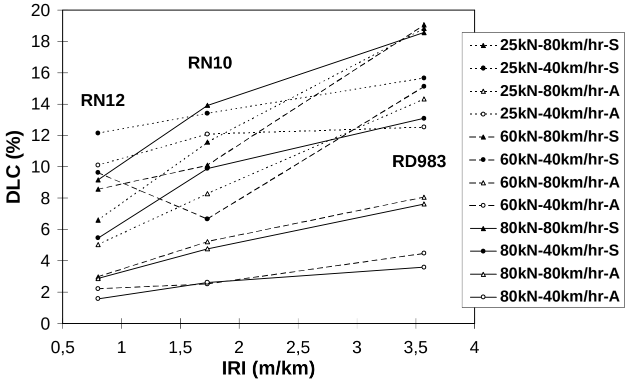
*Figure 5 - PDS of the axle 5 impact force versus load (NRC vehicle)*



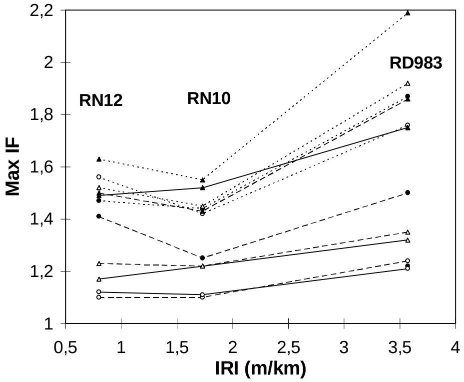

Return to paper

Content

## *Figure 6 - DLC versus IRI*




## *Figure 7 - Max IF versus IRI*




Return to paper

Content