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EXPERIMENTAL RESULTS OF FREE FIELD AND STRUCTURAL VIBRATIONS DUE TO UNDERGROUND RAILWAY TRAFFIC

P. Chatterjee [a], G. Degrande [a], S. Jacobs [a], J. Charlier [b], P. Bouvet [b] and D. Brassenx [c]

[a]*K.U.Leuven, Department of Civil Engineering, Kasteelpark Arenberg 40, B-3001 Heverlee, Belgium*

[b]*Vibratec, 28 Chemin du Petit Bois, F-69131 Ecully, France*

[c]*RATP, Département Environnement et Sécurité, 13 Rue Jules Valles, F-75547 Paris Cedex 11, France*

e-mail: pranesh.chatterjee@bwk.kuleuven.ac.be

Abstract

The present paper concentrates on the results of in situ vibration measurements performed within the frame of the EC-Growth Project CONVURT (”The control of vibration from underground rail traffic”) at the site of the Cité Universitaire campus in Paris on the RER B line of RATP between the stations of Cité Universitaire and Gentilly. Tests were carried out to determine the track and the soil characteristics, the transfer functions between the track and the free field and the track and the building, as well as the free field and the building response during the passage of a test train and service trains at variable speed.

INTRODUCTION

Underground trains create vibrations which are transmitted through the ground, resulting in vibrations and re-radiated noise in nearby buildings. The amplitude of vibrations depends on factors as the vehicle characteristics, the train speed, the rail and wheel roughness, the properties of the tunnel, the propagation of waves through the soil and the properties of the structures.
Within the frame of the EC-Growth project CONVURT (”The control of vibration from underground railway traffic”), a modular numerical prediction tool is developed to predict vibration and re-radiated noise in adjacent buildings from excitation due to metro trains in tunnels for both newly built and existing situations. The model will be validated by means of in situ experiments at the sites of Cité Universitaire in Paris and Regent’s Park in London.

The main objective of this paper is to describe the results of the in situ vibration measurements performed in May 2002 at two locations on the site of Cité Universitaire, Paris: the first is in the free field, while the second is in the student dormitory 'Maison du Mexique', a five-story reinforced concrete frame structure with foundations in close proximity of the tunnel.
Rail unevenness, rail receptance, sleeper receptance and wave decay along the rail have been measured independently to determine the dynamic characteristics of the track. A Spectral Analysis of Surface Waves (SASW) test has been performed to obtain the thickness and the dynamic characteristics of the shallow soil layers.
Vibrations have been measured on the track, on the tunnel invert, in the free field and in the building during the passage of service trains, as well as a test train at variable speed. Furthermore, transfer functions between the track and the free field and the building have been determined using a hammer impact on the rail head.
Results are presented in terms of time history and frequency content of the velocity and the acceleration, the variation of the peak particle velocity and the frequency content as a function of the train speed and the distance to the tunnel in the free field. Furthermore, it is demonstrated how the vibrations in the building are attenuated at the foundation level and amplified over the height of the building and on the eigenfrequencies of the floors and the walls. These experimental results are used to validate the numerical model, as demonstrated in an accompanying paper [4].

PARAMETER IDENTIFICATION

Tunnel and track characteristics. The metro tunnel on the line RER B at Cité Universitaire is a masonry cut-and-cover tunnel with two tracks at a shallow depth of about 9.3 m below the free surface and a width of 11.9 m (figure 1). The slab thickness is 0.6 m at the top and 0.4 m at the bottom, while the side wall thickness is 1.5 m.

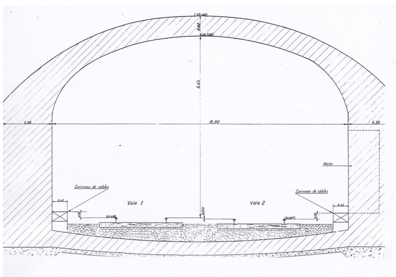


Fig. 1. Cross section of the metro tunnel on the line RER B of RATP at Cité Universitaire.

Two classical ballast tracks supported on mono-block concrete sleepers are running in the tunnel. The UIC60 rails are supported by grooved rubber pads with a thickness of 9 mm and are resting on mono-block concrete sleepers (VXP U61) with a mass of 200 kg. The sleeper distance is 0.6 m. The thickness of the ballast layer is 0.4 m.
The direct rail receptance, measured with a static pre-load and a small dynamic force amplitude, [1] shows a first resonance around 80-90 Hz, from which a ballast stiffness per unit area of $100\,\text{MN/m}^3$ and a loss factor of 0.80 can be estimated. The second resonance frequency around 600 Hz allows to derive a dynamic rail pad stiffness of about $375\,\text{MN/m}$ and a loss factor of 0.50. The pinned-pinned frequency of the rail is about 1200 Hz, which is a common value for tracks with a UIC60 rail and a sleeper distance of 0.60 m. Wave decay rates of the rail confirm the values of the track's natural frequencies.
Each sleeper has a length of 2.27 m, a width of 0.29 m and a thickness of 0.14 m. Modal analysis is performed to identify the first mode shapes and natural frequencies [1]. The first mode is a

transverse rocking mode at 65 Hz with a modal loss factor of about 0.60, while the first bending mode is identified at 110 Hz with a modal loss factor of about 0.30.

Rail and wheel roughness. Rail roughness has been measured by a measurement team of SNCF using the Muller BBM technique at two sections, over a length of 10 m at the free field site and a length of 3 m near the building. The range of wavelengths measured between 0.01 m and 0.25 m partially covers the range of wavelengths between 0.1 m and 1.0 m, that are relevant for ground borne vibrations.

The wheel roughness has been measured on the 8 wheels of two consecutive bogies, which are considered as the reference bogies on the test train, using LVDT sensors. Six parallel lines have been measured on each wheel. From a global point of view, the rail roughness is much higher than the wheel roughness in the wavelength domain of interest. During the test runs, 6 vertical accelerometers are mounted on the axle boxes, in order to assess the total wheel/rail roughness level for long wavelengths.

Characteristics of the rolling stock. The test train (type MI79) consists of four coaches. Each coach has two bogies with two axles. The front and the rear coaches have a length of 26.08 m. The length of an intermediate coach is 26.00 m. The total length of the test train is 104.16 m, while its mass is equal to 205000 kg. The bogie distance and the axle distance on a bogie are 18.5 m and 2.4 m, respectively, for all coaches.

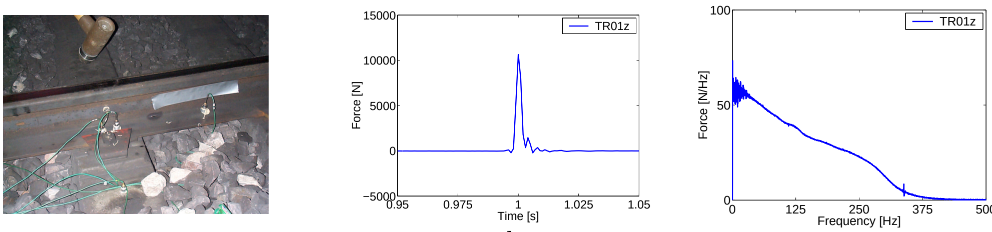
Prior to the in situ vibration measurements, modal analysis of the wheelset has been performed to determine the first natural frequencies and mode shapes of the axle that can influence the excitation at the contact point. The cross receptance between the axle box and the contact point with the rail has also been measured to validate the prediction of the contact force in the excitation model.

Dynamic soil characteristics. Historical borings show that the soil stratigraphy at the test site has four distinct layers. The top layer is 1.6 m thick fill material underlain by a 3.2 m thick Beauchamp sand layer. Below this, there is a stiffer layer of 7.8 m marl and gravel followed by layer of chalk.

A SASW test has been performed in order to determine the thickness and the dynamic characteristics of the shallow soil layers [5]. The tests have been performed on two measurement lines, one line perpendicular to the tunnel and one line parallel to the tunnel. The results demonstrate the presence of a thin layer of approximately 1.7 m and a shear wave velocity $C_s = 123\,\text{m/s}$, a stiffer layer with a thickness of 3.0 m and a shear wave velocity $C_s = 278\,\text{m/s}$ on top of a half-space with a shear wave velocity $C_s = 329\,\text{m/s}$.

IN SITU MEASUREMENTS IN THE TUNNEL AND IN THE FREE FIELD

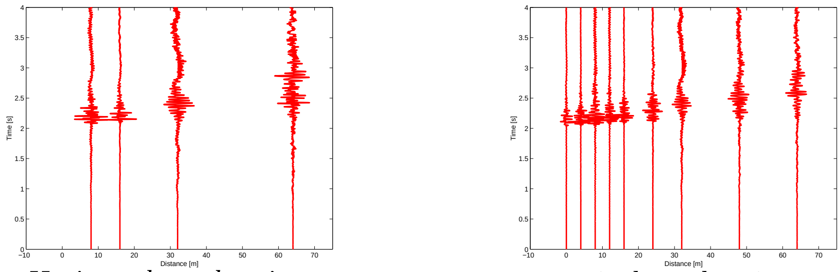
Transfer functions. Transfer functions between the track and the free field have been measured, using the excitation due to the impact of a large hammer ($m = 5.3\,\text{kg}$) on the rail head (figure 2a) of the high rail of track 1 which is the left track in the direction from Cité Universitaire to Gentilly [3]. Figures 2b and 2c show the time history and frequency content of the impact force, as measured with a load cell.



a. *b.* *c.*

Fig. 2. (a) Impact hammer, and (b) time history and (c) frequency content of the impact force.

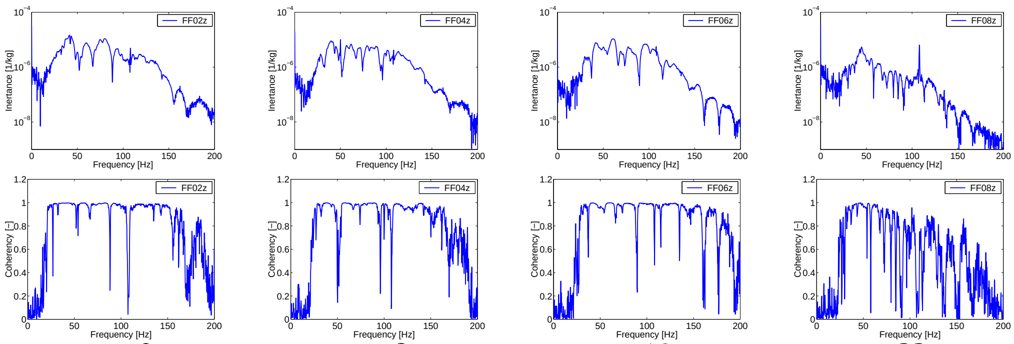
Horizontal and vertical accelerations are measured with 13 accelerometers on a line in the x-direction perpendicular to the tunnel at distances varying between -16 m and + 64 m. Two additional vertical accelerations are measured in 2 points that are located symmetrically along the axis of the tunnel at 16 m from the reference section. Figure 3 shows the time history of the free field horizontal and vertical accelerations as a function of the distance perpendicular to the tunnel for a hammer impact on the left rail of track 1. The function values of these seismograms have been rescaled so that the dispersive nature of the wave propagation can better be appreciated. On the contrary, the attenuation of the waves with increasing distance to the track, due to material and radiation damping in the soil, is no longer visible.



Horizontal acceleration. *Vertical acceleration.*

Fig. 3. Time history of the free field (a) horizontal and (b) vertical accelerations as a function of the distance to the tunnel.

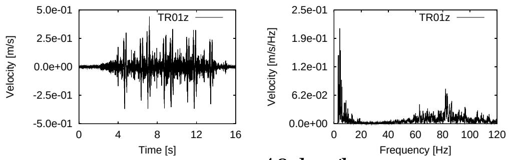
Inertance (or receptance) for all channels in the free field is derived from the average auto-power spectra of the acceleration and the impact force, and allows to identify the transfer functions between the track and the free field. The coherency gives an indication of the data quality in the frequency range of interest. Figure 4 shows the vertical inertance and the corresponding coherency at 4 points in the free field on a line perpendicular to the tunnel.



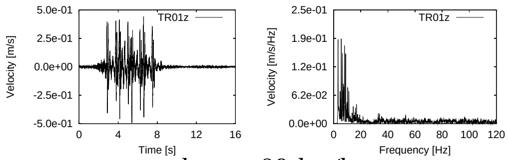
x = 0 m. *x = 8 m.* *x = 16 m.* *x = 32 m.*

Fig. 4. Inertance (top) and coherency (bottom) of the vertical acceleration at (a) x = 0 m, (b) x = 8 m, (c) x = 16 m and (d) x = 32 m from the tunnel.

Passage of a test train at variable speed. Vibration measurements have also been performed on the track, on the tunnel invert and in the free field due to the passage of a four carriage test train at variable speed, between 40 and 80 km/h on the track in the south-bound direction towards Gentilly [2]. The measurement setup is similar to that for the transfer functions.
Figure 5 shows the time history and frequency content of the vertical velocity of the rail above a sleeper for the passage of the test train at speed of 40 and 80 km/h, respectively. The passage of all axles can clearly be observed. At 40 km/h, the bogie passage frequency is $f_b = v/L_b =$



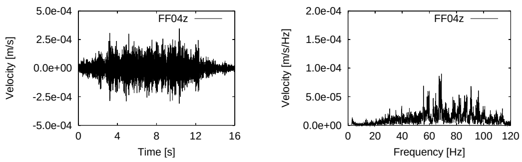
a. $v = 40$ *km/h.*



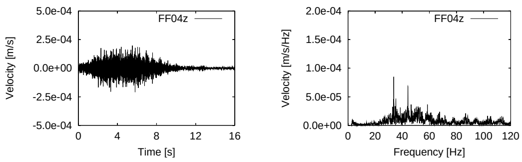
b. $v = 80$ *km/h.*

Fig. 5. Time history and frequency content of the vertical velocity of the rail at a sleeper position during the passage of a test train at a speed (a) $v = 40$ km/h and (b) $v = 80$ km/h.

0.606 Hz, while the axle passage frequency is equal to $f_a = v/L_a = 4.67$ Hz. Figure 6 shows the time history and frequency content of the vertical velocity at 8 m from the longitudinal axis of the tunnel during the passage of the test train on track 1 at 40 and 80 km/h. Similar results are shown in figure 7 at a distance of 32 m from the tunnel. The passage of individual axles can no longer be distinguished, even in the near field at 8 m. The peak particle velocity (PPV) at 8 m from the tunnel is about 0.3 mm/s and only weakly depends on the speed of the train. At 32 m from the tunnel, the PPV is about 0.1 mm/s. The frequency content is situated between 0 and 100 Hz at 8 m and shifts to lower values upto 60 Hz at 32 m from the tunnel. The excitation in this frequency range is mainly due to dynamic excitation as the wheels travel on an uneven rail.

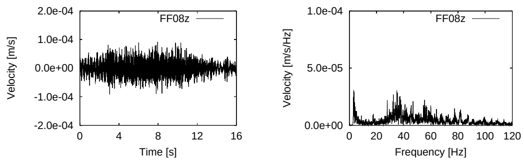


a. $v = 40$ *km/h.*

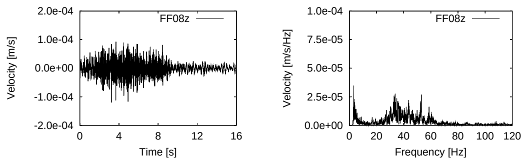


b. $v = 80$ *km/h.*

Fig. 6. Time history (left) and frequency content (right) of the free field vertical velocity at 8 m from the longitudinal axis of the tunnel during the passage of a test train.



a. $v = 40$ *km/h.*



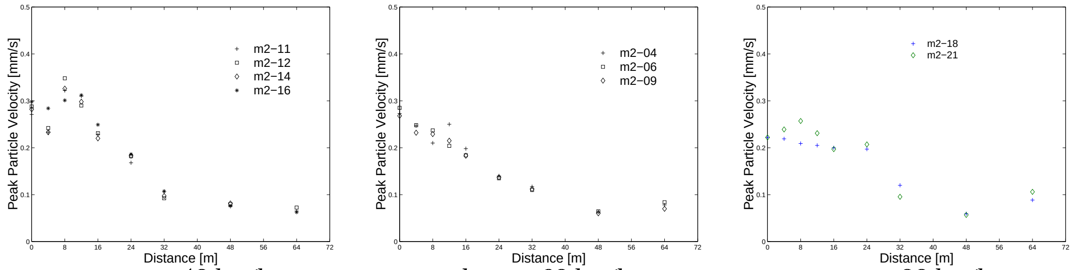
b. $v = 80$ *km/h.*

Fig. 7. Time history (left) and frequency content (right) of the free field vertical velocity at 32 m from the longitudinal axis of the tunnel during the passage of a test train.

Figure 8 shows the variation of the vertical PPV in the free field as a function of the distance to the tunnel for different passages of the test train at a speed of 40 km/h and 80 km/h. The amplitude of vertical vibrations decrease for increasing distance to the tunnel due to material and radiation damping in the soil. Although the number of train passages is too low to apply a statistical analysis, the variation of the response for different passages at the same train speed is moderate. In the range of train speeds considered, the PPV appears to be independent of the train speed.

IN SITU MEASUREMENTS IN THE TUNNEL AND IN THE BUILDING

Vibration measurements have been performed on the track, on the tunnel invert, in the free field and also at basement and at different floor levels of the 5-storey building ’Maison du Mexique’



a. $v = 40$ *km/h.* *b.* $v = 60$ *km/h.* *c.* $v = 80$ *km/h.*

Fig. 8. Vertical PPV as a function of the distance from the longitudinal axis of the tunnel for different passages of the test train at a speed (a) $v = 40$ km/h, (b) $v = 60$ km/h, and (c) $v = 80$ km/h.

due to the passage of service trains at variable speed [6].

Experimental setup. 25 accelerometers and 2 microphones are placed in the free field and in the building. The position of the accelerometers in the building is shown in figure 9.

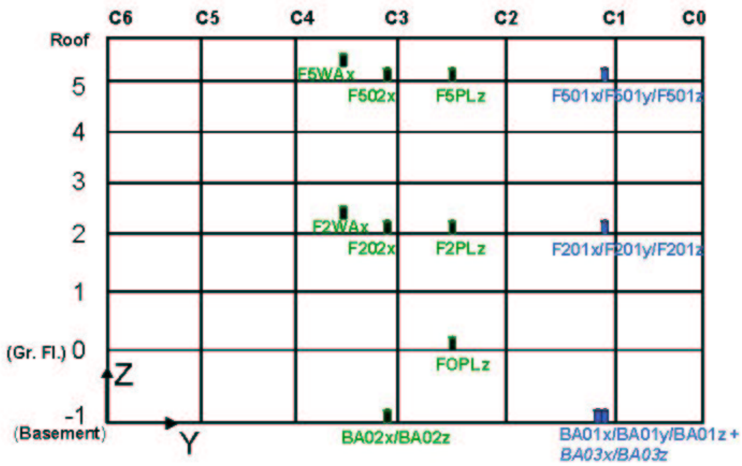
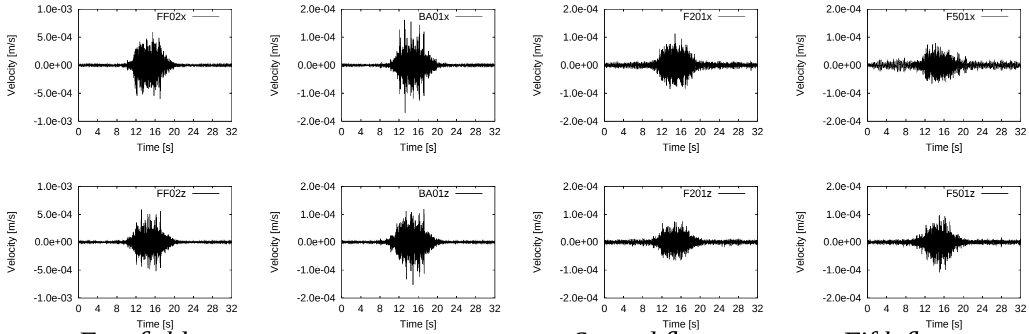


Fig. 9. Location of the measurement points in the building.

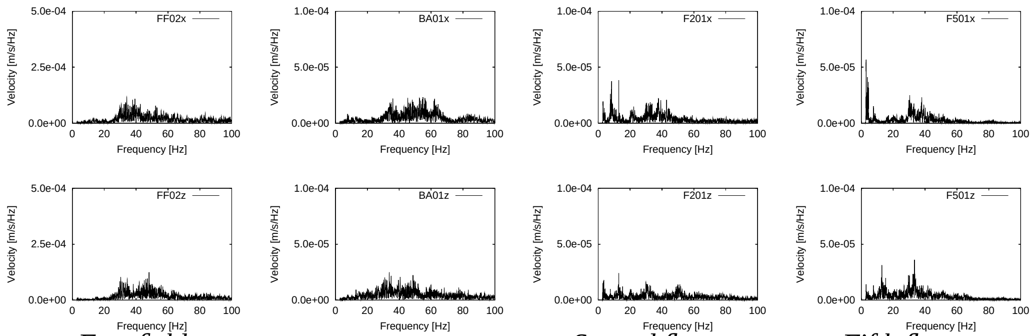
Passage of service trains. Figure 10 and 11 show the time history and the frequency content of the response in the free field and the building during the passage of a service train with 4 carriages at 71.72 km/h in directions perpendicular (x) to the tunnel and in the vertical direction (z). Figure 10 shows that the identification of the bogies or the axles is possible in the free field and in the basement but not on other floors of the building. The PPV in the vertical direction on the free field (FF02z) equals 0.583 mm/s. The response in the basement of the building is generally less than in the free field due to attenuation in the soil and dynamic soil-structure interaction effects. The PPV in the x-direction on the second floor (F201x) equals 0.113 mm/s and on the fifth floor (F501x) is 0.079 mm/s. There is a small decrease of the horizontal vibration amplitudes in stiff points over the height of the building. The vertical PPV on the second floor (F201z) equals 0.074 mm/s and is smaller than the PPV in the basement; this value slightly increases to 0.108 mm/s (F501z) on the fifth floor.

Figure 11 shows that in the free field, the frequency content is mainly situated between 20 and 60 Hz. The frequency content of the second and fifth floors show an amplification at frequencies of about 2 Hz, which correspond to the lateral bending frequencies of the building. These values have been confirmed by finite element analysis.



Free field. *Basement.* *Second floor.* *Fifth floor.*

Fig. 10. Time history of the response in the free field and the building during the passage of a service train at 71.72 km/h in x (top) and z (bottom) directions.



Free field. *Basement.* *Second floor.* *Fifth floor.*

Fig. 11. Frequency content of the response in the free field and the building during the passage of a service train at 71.72 km/h in x (top) and z (bottom) directions.

Figure 12 shows the time history and the frequency content of the responses recorded on the slabs and walls at ground floor and fifth floor. The frequency content of the response of the slab on the ground floor is dominant around 50-60 Hz, which is much higher than the resonance frequencies around 15 Hz that appear on the slabs of the second and the fifth floors. This may partly be explained by a possible higher stiffness of the slab on the ground floor.

CONCLUSION

From the various types of in-situ measurements performed on the RER B line, RATP, Cité Universitaire campus, Paris, the following conclusions can be drawn. The PPV decreases due to increasing distance from the tunnel and only weakly depends on the speed of the train. Both the horizontal and vertical vibrations have the same order of magnitude and both components decrease for increasing distance to the tunnel due to material and radiation damping in the soil.

ACKNOWLEDGEMENTS

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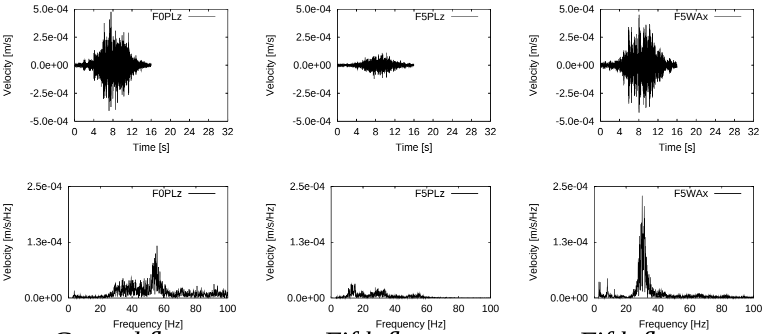

Ground floor. (F0PLz) *Fifth floor. (F5PLz)* *Fifth floor. (F5WAx)*

Fig. 12. Time history (top) and frequency content (bottom) of the response on the slabs of the ground floor (left) and the fifth floor (centre) and on the wall of the fifth floor (right) during the passage of a service train at 71.72 km/h.

way traffic”). The financial support of the European Community is gratefully acknowledged. In situ vibration measurements have been performed in collaboration with Vibratec and RATP.

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