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A HYBRID TWO-STEP APPROACH FOR EVALUATING THE IMPACT OF LOCAL RAIL DEFECT ON BUILDING VIBRATION

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With the development of light rail transit in urban areas, the effect of railway vibrations on buildings and people inside buildings is a growing problem. In particular, urban transit commonly generates large vibration levels at rail discontinuities, and thus this paper presents a 2-stage numerical-experimental vibration prediction methodology. The first step is purely numerical and focuses on the vehicle-track dynamics by analysing the effect of local defects at the rail surface during train passage. A multibody vehicle model and a flexible two-dimensional track are coupled using Herzian contact theory, which includes the geometry of the studied defect. The results obtained capture the interaction between the railway vehicle and the track, which serves as input for the second step. The latter uses experimental source transfer mobilities obtained on-site. This offers a way to accurately evaluate the soil-structure interaction which occurs in a complex medium such as the ground in urban areas. Structural response is then calculated by combining the two approaches. An illustrative example is presented, where the effect of various rail defects in the tram Brussels network is analysed. It is shown that it is possible to quantify vibration levels on light rail transit lines, where tramway networks interact with local rail defects and where railway ground vibration are problematic.

Keywords: building vibration, ground wave propagation, wheel/rail contact, singular defect, tram

1. Introduction

Compared to road network, modern tram and metro networks represent an interesting modal transfer and they significantly alleviate traffic congestion and pollution, especially in urban area. However, they are subject to some drawbacks, particularly problems related to vibration [1]. During these last decades, important studies were undertaken in order to reduce the vibration impacts: e.g. using floating slab solution [2], using wave barriers [3] or isolating buildings [4].

To do this, a physical model offers a way of predicting ground-borne vibrations in existing or new situations. A large amount of research has been done in modelling of railway-induced ground vibrations. Several deterministic and probabilistic models have been emerged during the last three decades [5–9]. However, the use of prediction scheme is subject to two major drawbacks.

- Complexity of modelling soil/building subsystem due to the lack of information: some configuration information in dense cities (modified soil composition due to human activities, drain connected to the city sewer, complex and coupled foundations, ...) is poorly available and thus difficult to take into account in prediction models.
- Uncertainty of soil parameters: the simplified hypotheses adopted in some prediction models induce a certain unawareness of models and parameters.

One solution to overcome these drawbacks is to combine empirical relationships with numerical data, as recently proposed by Auersch [10], Verbraken et al. [11] or Kuo et al. [12]. All these research works are based on the use of transfer mobility functions.

The objective of this paper is to explore new insights in terms of prediction scheme by proposing a hybrid numerical/experimental assessment dedicated to the urban area. The problem statement is described by analysing the different phenomena in vibration generation between a track with continuous irregularity and a track with a single localized defect. The developed model is then presented with an illustrative case from Brussels, focusing on the effect of local defects at various locations inside Brussels region.

2. Prediction tool

The proposed hybrid tool works in two steps. The first step is purely numerical and based on the dynamic simulation between the vehicle and the track, using a prediction model illustrated in Figure 1. It is derived from the model of Zhai and Sun [13] and consists of a classical multibody approach for the vehicle coupled to a finite element/lumped mass model for the track and the foundation. The track is defined by a rail modelled using an Euler–Bernoulli beam, discretely supported by the sleepers. The degrees of freedom of the vehicle are in the same plane as the track. The flexible rail is described using the finite element method. The sleepers have a lumped mass with a regular spacing between the sleepers. Viscoelastic properties are considered for the railpads and ballast, characterised by springs and dampers. The track lies on the foundation represented by a coupled lumped mass (CLM) model. The system is described by its mass, damping, and stiffness matrices built from its mechanical and geometrical properties. This offers a way to accurately predict the track response in low frequencies were the foundation plays an important role with non-negligible motion and a stronger coupling [14].

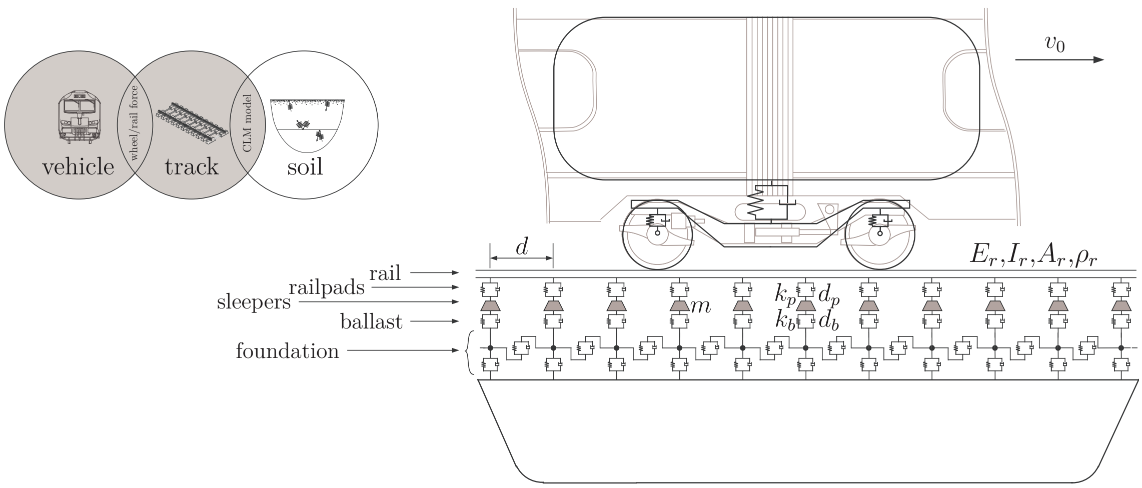


Figure 1: Step 1: Vehicle/track/foundation numerical simulation [15].

The simulation of the vehicle/track/foundation system is computed in the time domain, with the help of a home-made C++ library called *EasyDyn* [16]. As an alternative to a Winkler's foundation, CLM model has been developed for track/soil coupling [17]. As the name suggests, this model takes into account the coupling between foundations, here representing the contact soil area supporting the sleeper through the ballast.

The wheel/rail contact forces are calculated and saved

$$F_{\text{wheel/rail},i} \quad = \quad K_{Hz} \left(z_{\text{wheel,i}} - z_{\text{rail}}(x_j) - h_{\text{defect}} \right)^{3/2} . \tag{1}$$

where $z_{\text{wheel,i}}$ is the vertical position of the wheel and $z_{\text{rail}}(x_j)$ the vertical displacement at the rail at coordinate x_j. K_{Hz} is the Hertz's coefficient. These forces act at the defect location and are saved during the simulation. They are used to define force density

$$L_F \quad = \quad 10 \log_{10} \left(\sum_i \text{DFT} \left[F_{\text{wheel/rail},i} \right] \right) \tag{2}$$

to characterize the excitation forces generated by the interaction of the vehicle with the local defect, defined by the analytical function h_{defect}. In this case, the discrete Fourier transform (DFT) is used to calculate the frequency content of each wheel/rail contact force. This method offers an accurate way to estimate the wheel/rail forces, because they can only be accurately obtained if track flexibility is taken into account in the prediction scheme [18].

This imposes some conditions on the second step. The basis of this step is the measurement of a single source transfer mobility function between various points i on a system (Figure 2). This function gives, as its name suggests, the dynamic transfer characteristics between two points of the system — the soil velocity response $v_i(t)$ and the force $f(t)$ acting at the track surface (at the location of the local defect) — and yields the track/soil dynamic response in the frequency domain (obtained using the DFT):

$$M_{ij}(f) = \frac{V_i(f)}{F(f)} \tag{3}$$

where

$$V_i(f) = \text{DFT}(v_i(t)) \tag{4}$$
$$F(f) = \text{DFT}(f(t)). \tag{5}$$

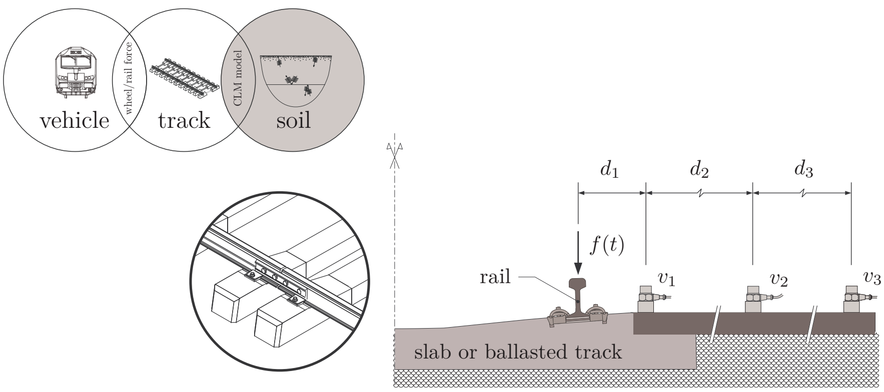


Figure 2: Step 2: Experiments in the track/soil/structure area.

As the study is dedicated to low speed and to the dynamic effect of local defects, one point transfer mobility remains sufficient to evaluate the vibratory effect of the ground wave propagation. This case is truly applicable to urban environment. This is why combined track/soil transfer mobilities are used, duplicating the track contribution to the response. Using soil transfer mobilities (without the track) requires for the consideration of more excitation points (every track support reaction close the the local defect).

Finally, the wheel/rail forces defined in Eq. (1) and saved during the first calculation step are combined with the mobility transfer function obtained from Eq. (3). The vibration level is thus obtained by multiplying these two parameters, or by summing these in a decibel scale

$$L_V = L_F + 10\log_{10}(M_{ij}(f)) \; . \tag{6}$$

An inverse discrete Fourier transform is then used to obtain the equivalent time histories.

3. Selected sites

Experimental data from a total of 14 test locations, designated site 1 to site 14, across the Brussels Region, were examined (Figure 3). The sites consisted of both slab and ballasted tracks and covered a significant percentage of the Brussels area.

Figure 3: Geographical map showing test site locations in Brussels Region.

A drop weight device was used to excite the rail at the local defect location (at this stage, detailed information about the defect was not necessary since the proposed method can analysed any type and size of defect). An integrated electronic piezoelectric (IEPE) sensor was fixed on top of the mass for measuring the impact force. Piezoelectric accelerometers were fixed on structures by cementing them to the test surface. As vibration velocities were expected to be analysed in this study, acceleration time histories were converted into their equivalent velocity components. Analogue signal conditioners with amplifier were used for this purpose. For all sites, vertical component vibration signals were recorded. At least, one sensor was placed at the tram site edge and one sensor at the building foundation. Except for sites 2 and 9, an additional sensor was also fixed on the edge of the sidewalk. Configuration of each site may differ according to the track configuration: sites 1 and 2 consisted of ballasted tracks with concrete sleepers and elastic railpads, sites 3 to 6 were designed by ballasted tracks with azobe sleepers, sites 7 and 8 were defined as elastic track (resting on resilient material), site 9 was a floating slab track and sites 10 to 14 were represented as a concrete slab track. Sites 10–14 were selected in the same railroad, in order to efficiently compare the effect of building behaviour on structural vibration response.

Figures 4 presents the calculated transfer mobility functions for the 14 sites. The dynamic excitation generated within the track is both filtered and dampened by the soil as it propagates. This

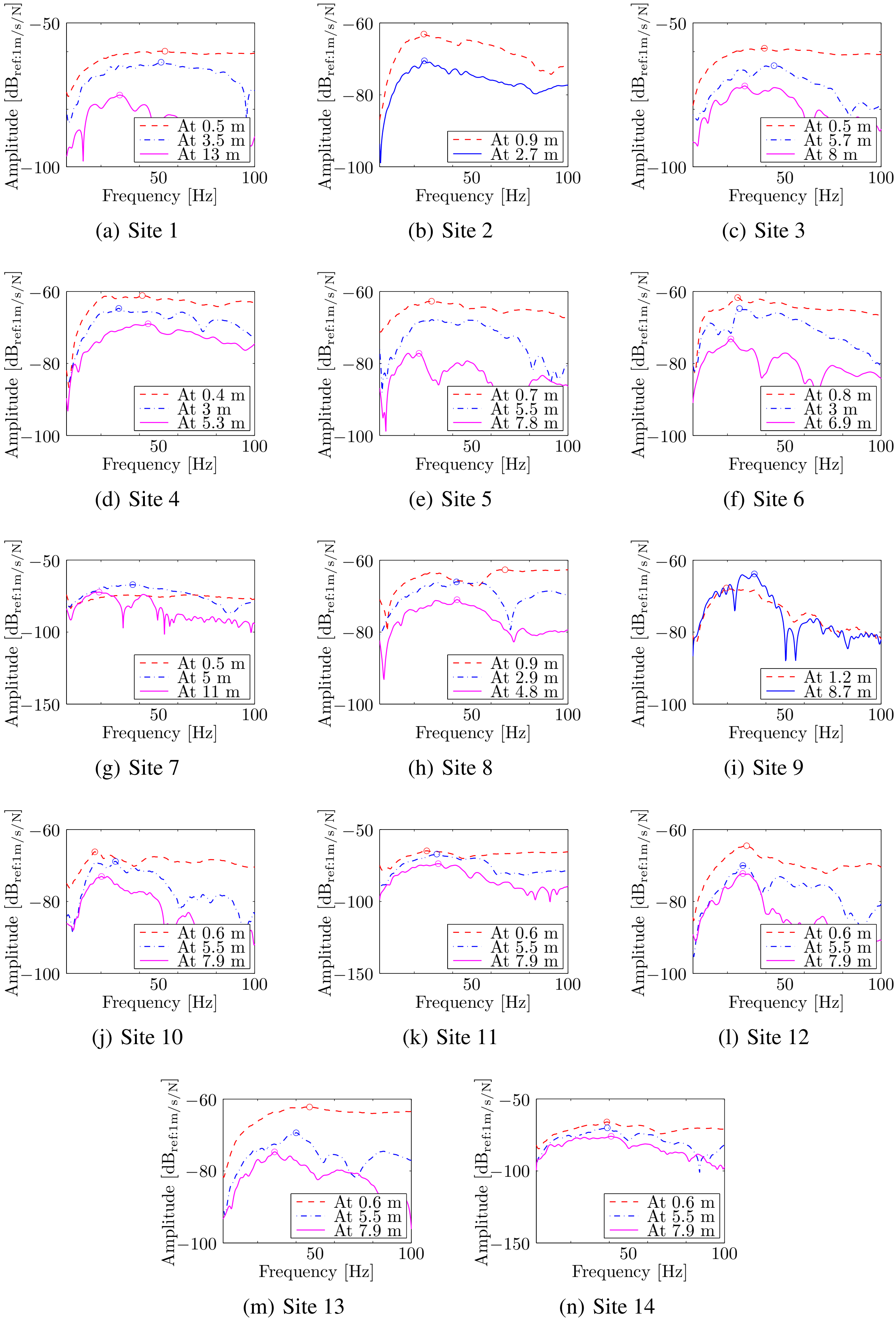


Figure 4: Overview of all the recorded mobility transfer functions for all the 14 sites in Brussels Region and for all the locations.

shows an attenuation with the distance in all the studied frequency range: between track and building foundations, a difference of almost $10\,\mathrm{dB}$ is observable. The efficiency of the track type can be evaluated: the track installation has a great influence of the vibratory impact on neighbour buildings. By comparing the different transfer mobilities, it appears that slab tracks generally presented a better vibration isolation than classic ballasted tracks. The only site with floating slab (site 9) caused a very low attenuation but it is difficult to draw accurate outcomes since only two measurement points were used. Other findings can be found in [19].

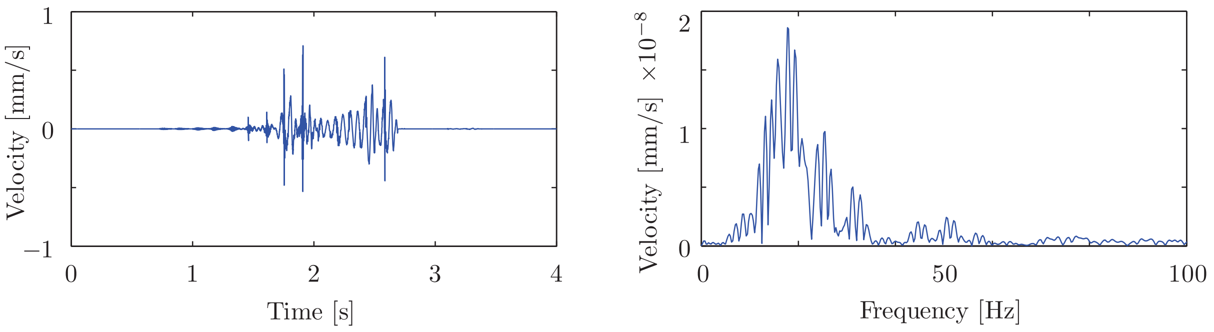
4. Results

The whole model was used to predict vibrations induced by the passing of tram T2006. This was motivated by the several complaints against by this kind of tram circulating in Brussels [8]. No tram pass-by was recorded during the test and only transfer mobility functions were available. The studied local defect was geometrically defined as a step-up function with a height h of $1\,\mathrm{mm}$. Taking into account the tram wheel radius R_{wheel}, the analytical function related to the defect in Eq. (1) can be defined as [18]

$$h_{\mathrm{defect}}(x) = \begin{cases} \sqrt{R_{\mathrm{wheel}}^2 - (x - x_0 - l_0)^2} + h - R_{\mathrm{wheel}} & \text{if } x_0 < x < x_0 + l_0 \\ h & \text{if } x > x_0 + l_0 \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

where $l_0 = \sqrt{h\,(2\,R_{\mathrm{wheel}} - h)}$ is the location of the defect contact locasized at coordinate x_0 and x the coordinate of wheel centre.

Figure 5 shows the ground vibration results for site 6 when the tram runs on the defect. The vehicle speed is constant and equal to $40\,\mathrm{km/h}$. The response is calculated at the building foundation. Figure 5(a) plots the time history, showing that the passing of each wheel over a specific defect generates a different vibration signature (both in shape and level). The frequency content plotted in Figure 5(b) shows that the high amplitude concerns the frequency range 10 to $30\,\mathrm{Hz}$ where the main vehicle's vibration modes dominate the spectrum with a maximum peak around $16\,\mathrm{Hz}$ corresponding to the vehicle's bogie bounce mode [20].



(a) Time history

(b) Frequency content

Figure 5: Vibration velocity predicted at $6.9\,\mathrm{m}$ from the track, (site 6) for a tram T2006 running at $40\,\mathrm{km/h}$ on stepwise joint (step-up function) of height $h = 1\,\mathrm{mm}$.

Figure 6 shows the peak particle velocities ($PPVs$) at the building locations as a function of the studied sites and the tram speed. Each site is studied for a constant tram speed (in the speed range 20–$80\,\mathrm{km/h}$). It appears that some sites present elevated vibrations and the general tendency is that the PPV level increases with the vehicle speed more or less different according to the site type.

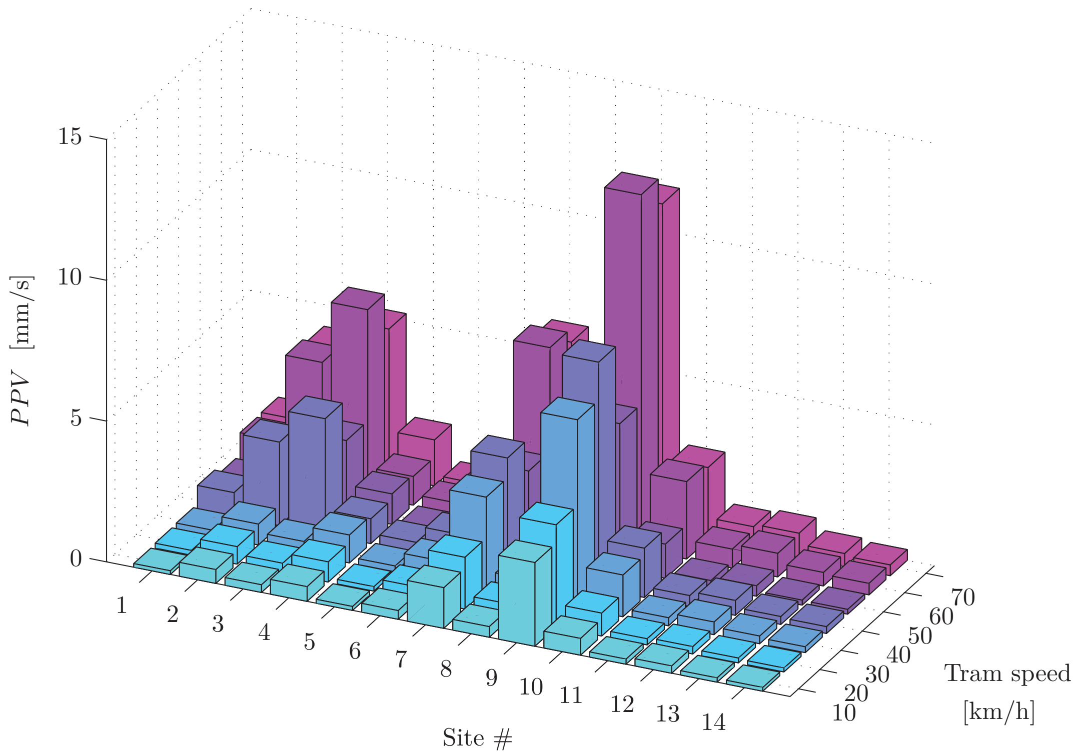


Figure 6: Predicted PPV as a function of speed for a tram T2006 running on a step-up joint ($h = 1\,\mathrm{mm}$) and for all the studied sites.

5. Conclusion

The methodology proposed in this paper used a hybrid approach combined experimental results for the track/soil subsystem with a numerical prediction of the wheel/rail forces acting on localized defects on rail surface. With a single measured transfer function, it was possible to predict the vibration generated by the passing of a train on a local defect, including the complex behaviour of track of ground systems. Within this way, 14 sites around the city of Brussels were analysed. It was shown that several studied sites presented high level vibrations, showing that the problems of local rail defects as potential sources of vibration and the complex path of vibration transmissions need to be studied as a whole. It was also proved that the point transfer mobility remains a useful tool to assess the vibration control problems relating to light rapid transit system operations. The use of a numerical model for estimating the effect of a localised defect offers new insight of railway-induced ground vibration assessment.

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