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An Experimental Methodology for the Assessment of Ground-Borne Vibrations due to Railway Vehicles

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Abstract

This paper shows the procedure and setup used for assessing the impact of a railway vehicle on the infrastructure in terms of ground-borne vibration. The proposed methodology relies on the definition of the so-called Force Density Level (FDL) proposed by the US Federal Transit Administration (FTA). To compute the FDL, vibration levels at different locations should be measured. The contribution associated with the dynamic behaviour of the ground should be removed, and this has been done by proposing impact tests carried out using a dedicated machine designed for this purpose. Results show that the FDL is almost independent of the measured line used for the computation up to 80 Hz, while some differences occur at higher frequencies. Additionally, for the considered vehicle (a modern articulated tramcar), the dependence on speed is investigated, showing no clear trend.

Keywords: ground-borne vibration, force density level, falling mass, impact test, tramways, line source transfer mobility.

1 Introduction

The rapid expansion of urban rail transport systems necessitates increased attention from municipalities regarding the issues of noise and vibration related to the operations of railway vehicles. In particular, the vibrations generated by the wheel/rail interaction may significantly disturb people living in areas close to the railway lines. To mitigate the issues of noise and vibration, it is often required to assess the impact of specific vehicle and track design choices or to develop appropriate mitigation measures. Various methodologies have been developed over the last decade. One of the most widely used is the calculation procedure proposed by the US Federal Transit Administration (FTA). This approach allows to compute the overall vibration level induced by a pass-by rail vehicle in a specific receiver position as the sum of two contributions. The first one is solely related to the vehicle characteristics and the dynamics of the train/track interaction, which is called Force Density Level (FDL). The second contribution is given by the dynamics of the site, which is included through the Line Source Transfer Mobility (LSTM). The description of this procedure can be found in [1] and has been verified through numerical simulations in [2]. Analytical expressions are derived for the force density and for the line source transfer mobility of the FTA procedure. The derivation of these expressions is verified using a coupled finite element-boundary element method. The formulation proposed in [1] can also be used to predict surface vibration levels generated by a railway at grade through hybrid formulations, combining numerical and experimental analyses, as proposed in [3]. The ground-borne vibration assessment based on the FDL requires the estimation of the line transfer mobility of the site. This can be computed numerically or by combining a series of point source transfer mobilities obtained through impact tests. The impact test can be performed by adopting an instrumented impact hammer or through dedicated setups involving a falling mass, such as the one proposed in [4], [5]. A comprehensive experimental characterisation of the procedure adopted to estimate the line transfer mobility is presented in [6]. The influence of the number and the location of the impact points on the line transfer mobility is investigated. A comparison between the line transfer mobility estimated experimentally and the one obtained numerically is also carried out.

This paper shows the procedure and the setup used for assessing the impact of a railway vehicle on the infrastructure in terms of ground-borne vibration. In Section 2, a brief overview of the formulation adopted to estimate the FDL is given. The falling mass setup adopted to estimate the LSTM is described in Section 3. Line tests are presented in Section 4. The point source transfer mobilities obtained through the falling mass setup are compared to the ones obtained adopting an impact hammer. The LSTM obtained with the falling mass method at two distances from the track are shown. The vibration levels generated by a modern tramcar running at different speeds and considering different distances are analysed. The FDL at different tramcar speeds are estimated. A comparison between the FDL obtained through vibration measurements at two different distances from the track is carried out. Finally, conclusive comments are given.

2 Estimation Procedure of Force Density Level

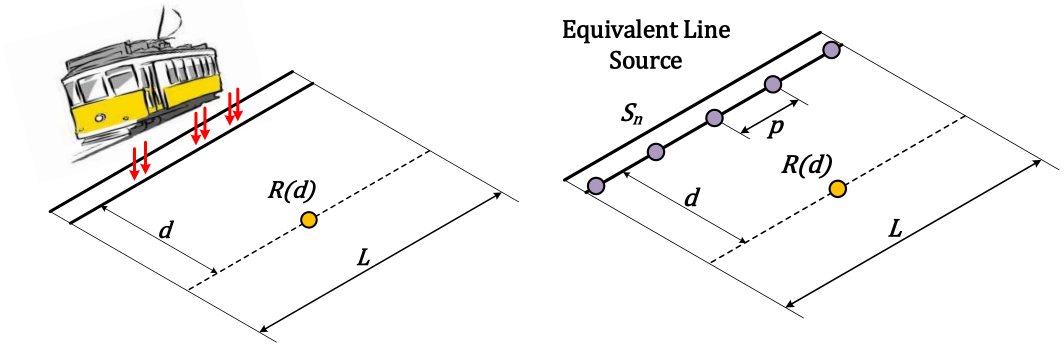
The estimation of the FDL is carried out through an empirical method outlined in the Transit Noise and Vibration Impact Assessment Manual by the US Federal Transit Administration (FTA) [1]. The procedure can be employed in different ways. It was developed to allow the use of vibration data collected at one location to predict the vibration levels at a different site where the geologic conditions may be completely different. The estimation of FDL is also suitable to compare different vehicles or to assess the impact of specific change in the vehicle characteristics.

The transfer mobility between a line source acting on the railway line and a receiver at a defined distance on the line, measured at an existing transit system, is used to normalize the ground-borne vibration data measured during the vehicle's passage at the same location to remove the effect of the geology. The normalized vibration data is referred to as the Force Density. Thus, the Force Density Level (FDL) can be expressed in dB as:

$$FDL = L_v - LSTM \tag{1}$$

where L_v is the ground-borne vibration velocity level generated by the vehicle at a receiver, while $LSTM$ is the Line Source Transfer Mobility between a line source acting on the rail and the receiver. The first can be directly measured by performing a pass-by test, while the LSTM can be obtained by combining different Point Source Transfer Mobilities (PSTM) from impact tests at the measurement site. The mathematical derivation of Equation (1) is illustrated in the following section to define the relationship between the line source and the point source transfer mobilities.

2.1 Line Source Transfer Mobility



(a) (b)

Figure 1: Calculation of the LSTM. (a) Real scenario and (b) schematic representation of the vehicle as a series of point load (line source).

The real scenario is represented in Figure 1a, where the moving contact forces at each wheel-rail interface contribute to the vibration velocity perceived by a Receiver $R(d)$ positioned at a defined distance d from the line. The moving contact forces generated during the train/track interaction are a series of moving point sources distributed over the track. The distance between the point load sources is defined by the distance between consecutive wheelsets (Figure 1b). This series of load can be approximated as an equivalent line source with a total length equal to that of the vehicle. The LSTM is defined as the vibration velocity at the Receiver $R(d)$ induced by a line source with unit amplitude. The LSTM is so a dynamic property of the site under analysis.

It is estimated by combining different Point Source Transfer Mobilities ($Y_n(f)$), i.e. the vibration velocity at the Receiver $R(d)$ due to a point source S_n at a defined position on the track:

$$Y_n(f) = \frac{v_n(f)}{S_n(f)} \tag{2}$$

where $v_n(f)$ is the vibration velocity at the receiver and $S_n(f)$ is the concentrated force. In the following, a number N of point sources equally distributed with a spacing p over the reference length L are considered. This reasonably approximates the loading condition induced by the contacts between the wheels and the rails [6].

The mean square value of the vibration velocity $\left(v_{RMS,n}^k\right)^2$ due to the source S_n in the k-th frequency band can be obtained as:

$$\left(v_{RMS,n}^k\right)^2 = \int_{f_{1,k}}^{f_{2,k}} PSD_n(f)|Y_n(f)|^2 df \tag{3}$$

where $PSD_n(f)$ is the power spectral density of the load S_n, while $f_{1,k}$ and $f_{2,k}$ are the lower and upper boundaries of the k-th frequency band, respectively.

By defining the average square value of the point source transfer mobility (related to the source S_n) in the k-th frequency band $\left|\bar{Y}_{n,k}\right|^2$ as:

$$\left|\bar{Y}_{n,k}\right|^2 = \frac{1}{f_{2,k} - f_{1,k}} \int_{f_{1,k}}^{f_{2,k}} |Y_n(f)|^2 df \tag{4}$$

The mean square value of the vibration velocity is approximately according to:

$$\left(v_{RMS,n}^k\right)^2 \approx \left|\bar{Y}_{n,k}\right|^2 \int_{f_{1,k}}^{f_{2,k}} PSD_n(f) df \tag{5}$$

Under the hypothesis that all the load sources are uncorrelated and generate the same power spectral density $PSD(f)$, the mean square value of the vibration velocity

$\left(v_{RMS,line}^{k}\right)^{2}$ generated by the N sources is obtained by summing up the contribution of each source:

$$\left(v_{RMS,line}^{k}\right)^{2}=\sum_{n=1}^{N}\left|\bar{Y}_{n,k}\right|^{2}\int_{f_{1,k}}^{f_{2,k}}PSD(f)df=\sum_{n=1}^{N}\left|\bar{Y}_{n,k}\right|^{2}F_{RMS,k}^{2} \tag{6}$$

where $F_{RMS,k}^{2}$ is the mean square value of the source, i.e. the wheel-rail contact force in the k-th frequency band.

The mean square value of the force density (i.e. force strength per unit length) in the k-th frequency band is defined as:

$$F_{d,k}^{2}=\frac{N}{L}F_{RMS,k}^{2} \tag{7}$$

Finally, by substituting Equation (7) into Equation (6) the following relationship is obtained:

$$\left(v_{RMS,line}^{k}\right)^{2}=F_{d,k}^{2}\frac{L}{N}\sum_{n=1}^{N}\left|\bar{Y}_{n,k}\right|^{2}=F_{d,k}^{2}\left(p\sum_{n=1}^{N}\left|\bar{Y}_{n,k}\right|^{2}\right) \tag{8}$$

Equation (1) is derived by expressing Equation (8) in dB, where:

$$L_{v,k}=10\log_{10}\left(\left(v_{RMS,line}^{k}\right)^{2}\right) \tag{9}$$

$$FDL_{k}=10\log_{10}\left(F_{d,k}^{2}\right) \tag{10}$$

$$LSTM_{k}=10\log_{10}\left(p\sum_{n=1}^{N}\left|\bar{Y}_{n,k}\right|^{2}\right) \tag{11}$$

A common method to estimate the LSTM of a site is to perform impact tests varying the receiver position. This allows to compute a set of PSTMs, which are combined to estimate the LSTM of the site.

3 Falling Mass Experimental Setup

The impact tests required to estimate the LSTM consist of exciting the railhead with an impulse force and measuring the ground response at defined positions. An ideal impulse is an impact of infinitesimal duration that introduces the same amount of energy across all frequencies. Real impacts have finite durations, thereby limiting the upper bound of the frequency range that can be excited.

An approximation of the impulse force can be applied to the system in two different ways. The first method involves the usage of an impact hammer equipped with a load cell to measure the applied force. The advantages of this excitation method include the direct measurement of the input force and the ease of performing tests. However, the amount of energy that can be introduced into the system is limited (the peak force is in the range of 20 kN).

This drawback can be overcome by exciting the railhead with a falling mass. A weight with a calibrated mass is dropped onto the railhead from a specified height. This second solution is preferred for two main reasons. Firstly, it introduces a greater amount of energy into the system than the impact hammer, thereby causing higher vibration amplitudes and enabling the ground response to be measured at greater distances from the excitation point. Secondly, the impacts generated by the falling mass are more repeatable than the ones from an impact hammer. This is because, when using the impact hammer, the position of the excitation point and the magnitude of the impulse depend on the operator's skill.

To implement this, a falling mass setup has been designed based on the machine used in [5]. The falling mass machine is depicted in Figure 2a, with an aluminum frame serving as a guide for the falling of the mass (Figure 2b). The falling mass is positioned at the desired height using a lifting system employing an electromagnet (indicated by the red arrow in Figure 2b) connected to a steel cable. A pulley system suspends the falling mass at the desired height. When the power supply to the electromagnet is switched off, the falling mass falls over the railhead, guided by pins within the sockets in the vertical profiles (indicated by the green arrow in Figure 2b).

The falling mass features a modular design comprising multiple parts, as illustrated in Figure 2c. The head is the component that impacts the rail. Above the head, there is a primary mass to which secondary masses can be added to increase the overall weight. At the top of the assembly is positioned the lifter, that is connected to the electromagnet. A 4 mm thick rubber layer is placed between the head and the primary mass to reduce the possibility of multiple impacts. In the upcoming tests, the dropping weight is utilized in its minimum mass configuration, i.e., without secondary masses. The mass of the head is 10.2 kg, while the mass of the assembly comprising the primary mass and the lifter is 28.5 kg. From now on, this assembly will be referred to as “Mass”.

The falling mass method has the drawback that the impact force cannot be measured directly. It is estimated from acceleration measurements. Since the rubber element dynamically decouples the Head and the Mass, piezoelectric accelerometers (full range 2000 g) are positioned over the Head, inside the falling mass (marked in red in Figure 2c), while the second is installed on the top of the lifter (marked in green in Figure 2c) to measure the acceleration of the Mass. The impact force can be estimated as:

$$F_{impact} = m_h a_h + m_m a_m \tag{12}$$

where m_h and m_m represent the mass of the Head and the Mass, respectively, while a_h and a_m are the corresponding accelerations.

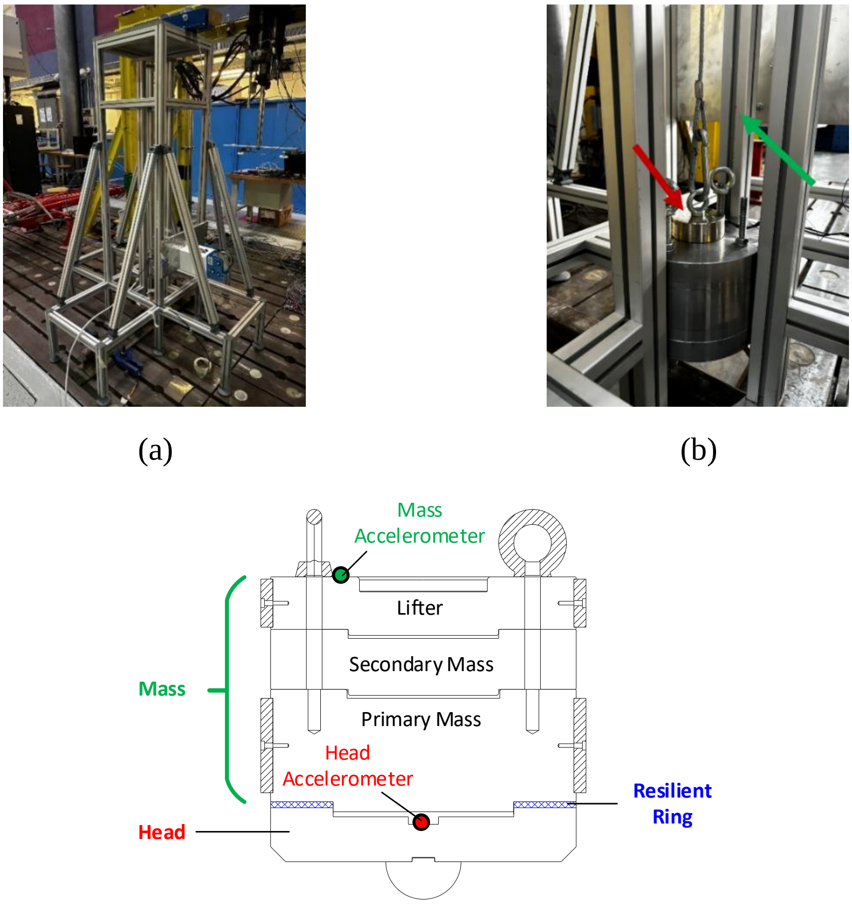

(a)
(b)
(c)

Figure 2: Overview of the falling mass setup. (a) Falling mass machine, (b) detail of the falling mass and guiding frame and (c) drawing of the falling mass cross-section.

4 Line Tests

The procedure described in section 2 is used to experimentally estimate the FDL of a modern articulated tramcar. It is made up of three bogies and its length *L* is 28 m. The testing site is characterized by two long straight tracks running in parallel. The tramway is flanked by a park where the sensors to measure the ground response are installed to get the free field response of the soil surrounding the track, limiting the impact of the nearby buildings on wave propagation. The track system in the measurement section consists in a slab track system adopting Vignole rails.

A first test campaign is used to characterize the dynamics of the testing site in terms of LSTM, while the ground vibrations induced by a series of vehicle passages are measured in a second test session to estimate their FDL.

4.1 Dynamic Characterisation of the Testing Site

Impact tests are carried out with the dropping weight setup in the selected testing site to measure the PSTMs for estimating the LSTM. According to the FTA testing procedure [1], two different measurement setups can be alternatively used. The first is represented in Figure 1b, in which the rail is excited in several positions within the measurement section, and the vibration velocity response is measured by using a single sensor located at the midpoint of the measurement section at a defined distance from the line. The alternative setup the rail is excited at the midpoint of the measurement section and multiple sensors are placed along the measurement section at a defined distance from the line. The two options can be considered equivalent under the hypotheses of uniform soil and linear behaviour of the system. Due to the limited time available for the test and the difficulty of moving the falling mass setup, the second option is used.

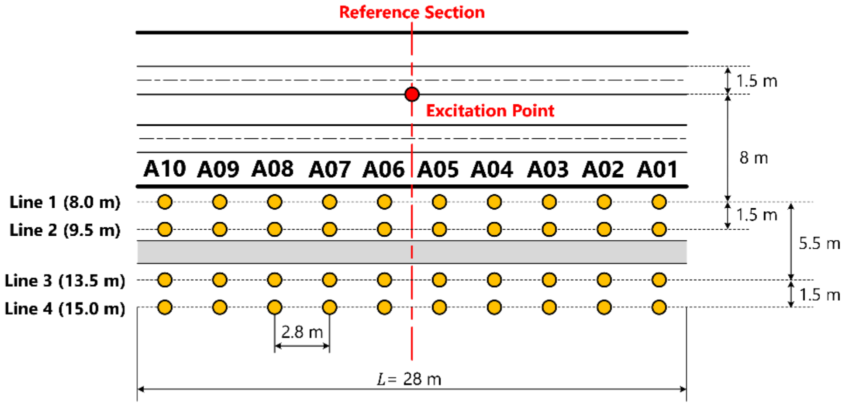


Figure 3: Measurement setup for the dynamic characterisation of the testing site.

The scheme of the adopted setup is represented in Figure 3. The falling mass setup is positioned at the excitation point marked in red and ten equally spaced seismic accelerometers (full range 0.5 g) are used to measure the ground vibration on four lines parallel to the track at 8 m, 9.5 m, 13.5 m, and 15 m. The distance between Line 1 and Line 2 is equal to the wheelbase of the tested vehicle (1.5 m, track gauge of 1445 mm). The same applies to Line 3 and Line 4. The length *L* of the measurement section is equal to 28 m (approximate length of the tested vehicle) and thus the spacing between the sensors is equal to 2.8 m. A sampling frequency of 25 kHz is used for data acquisition. Twenty impacts with the falling mass are repeated for each line, as specified in the FTA technical report [1].

Referring to the setup in Figure 3, the PSTMs measured by accelerometer 1 (A01) and 5 (A05) on Line 1 obtained with the Falling mass are compared with the corresponding ones measured by exciting the rail with the impact hammer. They are expressed in dB (reference 10^{-6} m/s/N) in one-third octave bands from 5 Hz to 250 Hz. These sensors are selected because A01 is the farthest (as A 10) from the excitation point, while A05 is the nearest (as A06).

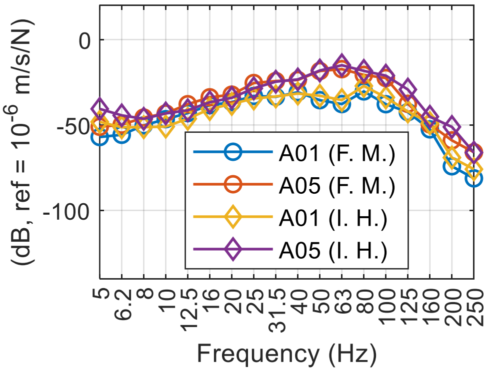


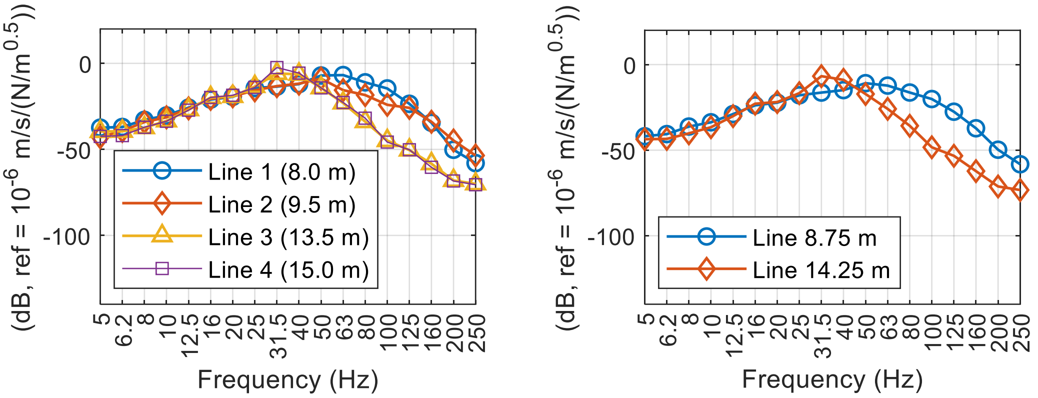
Figure 4: PSTMs measured by A01 and A05 on Line 1, obtained with the Falling Mass (F. M.) and the Impact Hammer (I. H.).

The PSTMs measured with the falling mass (F. M.) are represented with circular markers, while those measured with the impact hammer (I. H.) are shown with diamond markers. The curves show good agreement between the two excitation methodologies, except in the frequency bands below 8 Hz. A difference of about 10 dB is present in the 5 Hz one-third octave band for both A01 and A05, which reduces to 5 dB in the 6.2 Hz frequency band. This difference may be due to two main causes. The first cause may be associated with a non-linear behaviour of the system. Since the magnitude of the impact force differs significantly between the two excitation methodologies, non-linearities in the track and soil structures may cause different responses in the low-frequency range. The second cause is the high sensitivity of seismic accelerometers. Disturbances, such as movements by the operators performing the test, are detected by the accelerometers. The higher force applied with the falling mass results in a much higher vibration magnitude than that caused by such disturbances. Conversely, the vibration levels caused by the impact hammer are much lower, so even minor disturbances may affect the measurements, especially in the low-frequency range.

The Line Source Transfer Mobilities related to the four lines in Figure 3 are calculated by combining the PSTMs according to Equation (11). They are shown in Figure 5a. The LSTMs of Line 1 and Line 2 are almost superimposed because the distance between the two measurement lines is low (1.5 m). The small differences are attributable to the non-uniformity of the soil. Similar considerations apply to the LSTMs of Line 3 and Line 4.

Railway vehicles apply contact forces on both rails and the equivalent line source must contains the combined effect of the two sides. According to [7], this condition can be experimentally replicated in two ways. The first is to perform the impact tests exciting both the rails simultaneously, while the second option is to excite the two rails separately and the PSTMs with a point source at both the rails is calculated by superimposing half of the PSTMs obtained by exciting a single rail at a time.

The second option is used in the presented testing procedure because the first one requires using a tool to spread the impact force of the falling mass on both rails and its effect on the measurements should be considered. Due to the limited time available for the tests, only the rail highlighted in Figure 3 is excited. Consequently, the response to the combined excitation, which is assumed as a line source acting at the track centreline, is approximated as the sum of half the responses at the two lines separated by the wheelbase of the vehicle, i.e., combining Line 1 with Line 2 and Line 3 with Line 4. The resulting LSTM is referred to as the average LSTM. Two average LSTMs are computed. The first LSTM is calculated between the track and a receiver placed 8.75 meters from the line. The second LSTM is computed with the receiver positioned 14.25 meters from the line. The average LSTMs are shown in Figure 5b.



(a) (b)

Figure 5: (a) LSTMs related to the four measurement lines and (b) average LSTMs.

4.2 Experimental Estimation of Force Density Level

The experimental estimation of the FDL is carried out starting from vibration measurements induced by the passage of the analysed vehicle. The setup employed for the pass-by tests is shown in Figure 6. The track used for the tests and the travelling direction are marked in red.

The ground vibration velocity due to the vehicle passage is measured by placing seismic accelerometers in correspondence of the section marked as *reference section* in both Figure 3 and Figure 6. The accelerometers are positioned at 8.75 m and 14.25 m from the track centreline. These distances are the same adopted to estimate the average LSTMs (see Section 4.1). The measurements on the two lines are performed simultaneously. The pass-by tests are conducted at 10, 30 and 50 km/h. The vibration velocity data is processed according to [7].

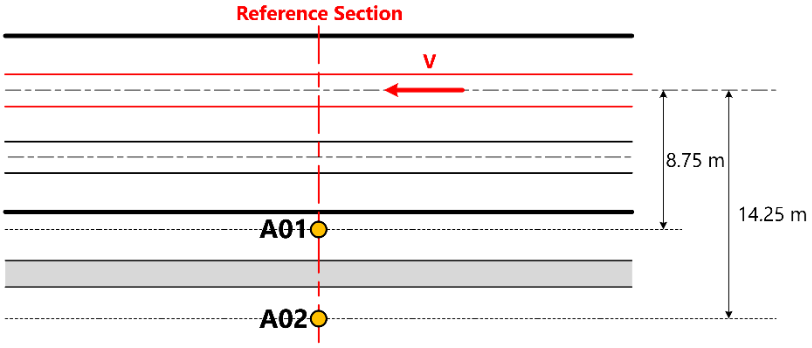


Figure 6: Measurement setup for the pass-by tests for estimating the FDL.

As an example, the vibration velocity induced at 8.75 m and 14.25 m by the vehicle running at 10 km/h is shown in Figure 7, while the average LSTM at the same distance is shown in Figure 5b. As for the LSTM, the vibration velocities are expressed in dB units in one-third octave bands. The ground-borne vibration velocity levels (L_v) as a function of the distance show a similar trend of LSTMs. This can be a confirmation that the estimation procedure of the LSTM is satisfactory since the measured L_v contains also the effect of the dynamic of the testing site.

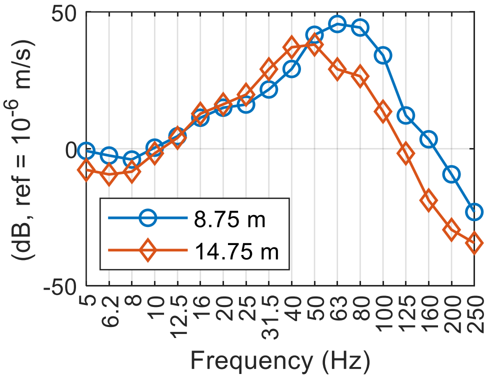
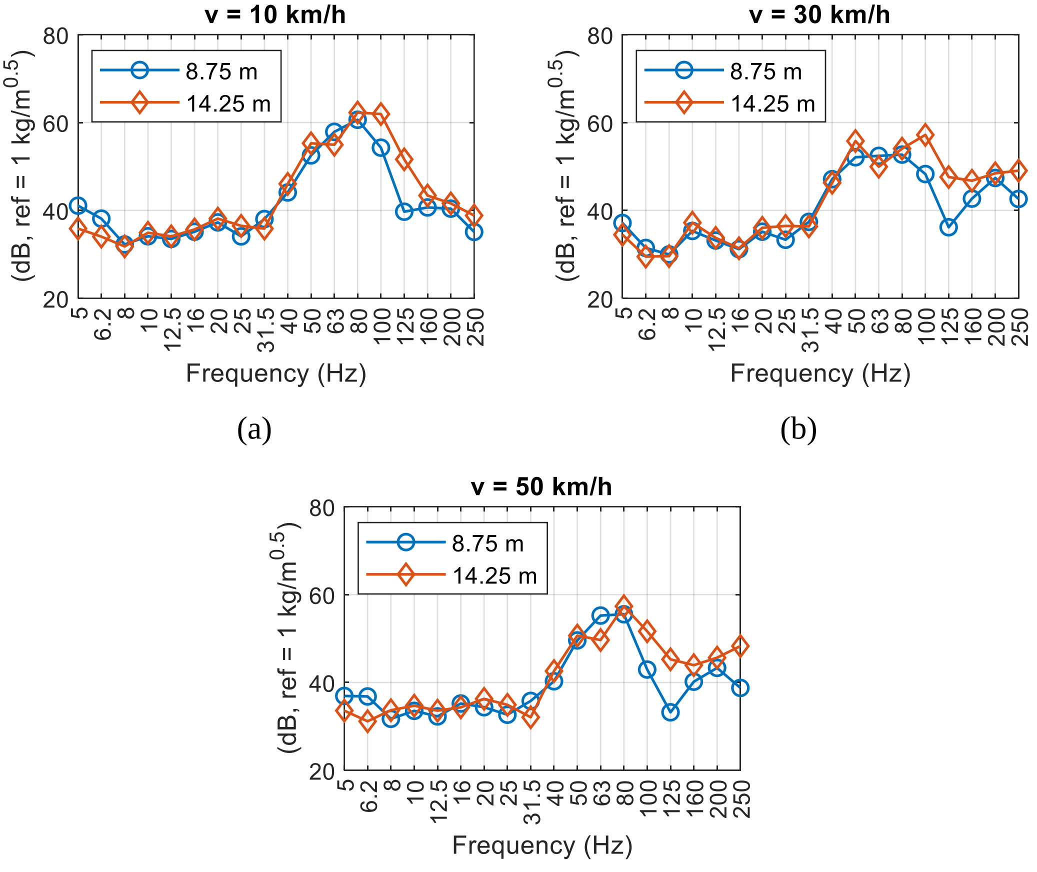


Figure 7 Ground vibration velocity levels (L_v) measured at 8.75 m and 14.25 m by the vehicle running at 10 km/h

The estimation of the FDL is achieved by normalising the L_v induced by the vehicle passage with respect to the LSTM of the testing site according to Equation (1). The estimated FDL at the different running speeds by using the data relative to the considered lines are shown in Figure 8. No clear trend with respect to the running speed is observed: Similar results are obtained in [8], [9]. However, other studies show a strong dependence with the speed [10]. A good agreement between the FDL estimated considering the lines at 8.75 m and 14.25 m is observed up to the 80 Hz one-third octave band, regardless the running speed. This confirm that the FDL is independent from the distance from the track, since it describes the force per unit distance applied by the vehicle on the track. However, differences are present in the higher frequency bands. This difference may be related to the fact that at higher frequencies the assumptions behind the calculation of the LSTM, i.e. linearity and uniformity of the soil, are no more valid, since the response becomes more and more dependent to the local dynamic characteristics of the position where the sensors are located.



(a)

(b)

(c)

Figure 8: FDLs estimated considering the lines at 8.75 m and 14.25 m from the track centreline. (a) At 10 km/h, (b) 30 km/h and (c) 50 km/h.

5 Conclusions

The force density level is an index representing the performance of a railway vehicle in terms of generated ground-borne vibrations. It can be empirically estimated by normalising the vibration velocity at a receiver caused by the passage of the vehicle with the dynamic characteristics of the testing site in terms of line source transfer mobility at the receiver.

In the present work, the force density level of an articulated tramcar is estimated by performing an experimental campaign on a track section characterised by a long straight track.

The line source transfer mobility of the testing site is estimated by combining point source transfer mobility measured by performing impact tests employing a dedicated falling mass setup. The rail is excited using a calibrated falling mass. This excitation methodology offers the advantages of higher repeatability in the generated impact and greater energy introduced into the system compared to a standard impact hammer. The impact force is estimated from acceleration measurements recorded by sensors mounted on the falling mass. The accuracy in the force estimation procedure is verified by comparing the point source transfer mobilities obtained with the falling mass with the ones measured by exciting the rail with an impact hammer.

After the line source transfer mobilities at defined distances from the track are obtained, pass-by tests are performed to measure the ground-vibration velocity levels generated by a modern tramcar running at different speeds. The force density level is estimated following the procedure provided by US Federal Transit Administration.

The force density levels estimated at different distances from the line show a good agreement up to 80 Hz. Some differences in the force densities at higher frequencies may be related to the local dynamic characteristics of the soil in the location where the sensors are installed to estimate the line source transfer mobility of the measurement site. The results confirm that the setup developed is suitable for empirically estimating rail vehicles' force density level. The methodology can be employed to characterise the vibration induced by specific vehicles or to quantitatively assess the performance of mitigation measures aimed at reducing the generated ground-borne vibrations.

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