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Ground-borne noise and vibration: classification of railway vehicles based on a track-independent vehicle indicator

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Abstract. Within the SILVARSTAR project, a track-independent vehicle indicator (TVI) is proposed that can be used to identify railway vehicles which generate low ground-borne vibration and noise levels. The proposed TVI is based on applying a frequency weighting to the force density, which may be obtained at a site from the measured ground vibration velocity levels due to train passages and the measured line source transfer mobility. Two different formulations of TVI are proposed; one related to ground-borne vibration and the other to ground-borne noise. Each TVI is a single number quantity, defined as a sum over all frequency bands of the frequency-weighted force density levels. The proposed performance classification of different vehicles can be achieved by comparing the relative differences of their TVIs. A series of test cases is used to demonstrate the calculation of the TVIs and the TVI-based classification of different vehicles at the same site. Although the values of the TVIs for each vehicle may vary due to the different modelling approaches and detail, or due to the limited knowledge of the input parameters used for the target site, the TVI-based classification of different vehicles is found to be insensitive to this model and parameter uncertainty.

1. Introduction

The SILVARSTAR project [1] aims to provide the railway community with proven software tools and methodologies to assess the ground-borne noise and vibration environmental impact of railway traffic at a system level. One of the objectives of the SILVARSTAR project is to propose a track-independent vehicle indicator that can be used to identify ground-borne noise and vibration friendly vehicle designs and condition.

For classifying the ground-borne vibration and noise performance of a vehicle it is not possible to use directly the measured emission levels as these are strongly dependent on the track and ground properties, so that measurements at different sites cannot be directly compared. Therefore, to compare the ground-borne noise and vibration performance of different vehicles, it is desirable to define a vehicle indicator that is track independent. Nelson and Saurenman [2] proposed an indirect method based on an equivalent force density that was later adopted in several empirical procedures of ground-borne vibration prediction from railways (e.g. [3], [4]). The force density represents the source (force) strength at the wheel/rail interface and can be determined from the measured ground vibration velocity levels due to

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train passages and the measured line source transfer mobility. Unlike the vibration levels during train passages, the force density is relatively independent of the track and ground properties and the distance from the track at which it is calculated [5], and hence it is suitable to be used as a basis for the classification of railway vehicles.

Within the SILVARSTAR project, having as a starting point the force density that is determined from the measured or predicted vibration response, two different formulations of TVI are presented; one related to ground-borne vibration and the other to ground-borne noise. They are both based on applying a frequency weighting to the measured force density and they represent the overall vibration or noise levels in a nominal (reference) building on a nominal soil.

A series of test cases is devised to demonstrate the calculation of the TVIs of different vehicles at the same site and the TVI-based classification which is achieved by comparing their TVIs. To replicate practical situations, the TVIs for each vehicle are calculated from force density levels obtained by numerical models. The simulations are performed using generic models of passenger and freight trains and the most important parameters of the vehicle that affect ground vibration and noise are investigated: wheel unevenness, unsprung mass, primary and secondary suspension stiffness, train speed, the number of axles per unit length and the axle spacing.

2. Track-independent vehicle indicator formulation

The measured force density $\mathrm{L_F^{exp}}(\mathbf{X},\mathbf{x}_1)$ at a site can be obtained from the measured vibration velocity levels $\mathrm{L_v^{exp}}(\mathbf{x}_1)$ in one-third octave bands at a receiver distance $\mathbf{x}_1$ for a train passage and the measured line source transfer mobility $\mathrm{TM_L^{exp}}(\mathbf{X},\mathbf{x}_1)$ to this location as

$$\mathrm{L_F^{exp}}(\mathbf{X},\mathbf{x}_1)=\mathrm{L_v^{exp}}(\mathbf{x}_1)-\mathrm{TM_L^{exp}}(\mathbf{X},\mathbf{x}_1) \quad (1)$$

where $\mathbf{X}$ are the excitation positions along the line source. Alternatively, equivalent numerical or hybrid force density results can also be determined using predicted vibration velocity levels $\mathrm{L_v^{num}}(\mathbf{x}_1)$ and/or predicted line source transfer mobilities $\mathrm{TM_L^{num}}(\mathbf{X},\mathbf{x}_1)$.

The two formulations of the proposed TVI are defined as a sum over all one-third octave frequency bands n_f of a frequency-weighted force density $\mathrm{L_F^{exp}}(\mathbf{X},\mathbf{x}_1)$:

$$\mathrm{TVI_i}=10\log_{10}\sum_{k=1}^{n_\mathrm{f}} 10^{\frac{\mathrm{L_F^{exp}}(\mathbf{X},\mathbf{x}_1)+\mathrm{W}_{\mathrm{F},i}}{10}} \quad (2)$$

where the weighting function $\mathrm{W_{F,i}}$ for i=1 is related to ground-borne vibration and for i=2 is related to ground-borne noise, as described below.

3. Weighting functions

Different weighting functions are used for vibration, which is dominated by lower frequencies, and noise, which is dominated by higher frequencies. For vibration, the weighting function $\mathrm{W_{F,1}}$ is defined to give an estimate of the vibration spectrum in nominal conditions. The weighting function is formed from:

- a line source transfer mobility $\mathrm{TM_L}(\mathbf{X},\mathbf{x}_{\mathrm{rec}})$ (in dB ref. 1 $\frac{\mathrm{m/s}}{\mathrm{N}/\sqrt{\mathrm{m}}}$) for a nominal ballasted track on a reference soil and at the defined receiver distance $\mathbf{x}_{\mathrm{rec}}$=16 m,
- the building coupling function between the vibration at the ground and the vibration of the floor in the building $\mathrm{C_b^{vib}}(\mathbf{x}_{\mathrm{rec}},\mathbf{x}_\mathrm{b})$ for a chosen nominal building, and
- the $\mathrm{W_m}$ weighting curve based on human perception of vibration according to ISO2631-2:2003.

The line source transfer mobility $\mathrm{TM_L}(\mathbf{X},\mathbf{x}_{\mathrm{rec}})$ and the building coupling function $\mathrm{C_b^{vib}}$ are selected from the SILVARSTAR database [6] for a standard ballasted track on medium stiffness soil and for the situation of the ground floor of a tall building with concrete floors.

Combining these expressions for the vibration TVI in Eq. (2), and considering the measured force density $\mathrm{L_F^{exp}}(\mathbf{X},\mathbf{x}_1)$ expressed in dB ref. 1 $\mathrm{N}/\sqrt{\mathrm{m}}$, the weighting function $\mathrm{W_{F,1}}$ is obtained as:

$$W_{F,1}=TM_L(\mathbf{X},\mathbf{x}_{rec})+C_b^{vib}+W_m \tag{3}$$

in $dB(W_m)$ ref. $5\cdot10^{-8}$ $m^{3/2}s^{-1}N^{-1}$. TVI_1 is expressed in $dB(W_m)$ ref $5\cdot10^{-8}$ m/s. The proposed weighting function $W_{F,1}$ for vibration is defined in the frequency range 1-80 Hz and is shown in Figure 1(a).

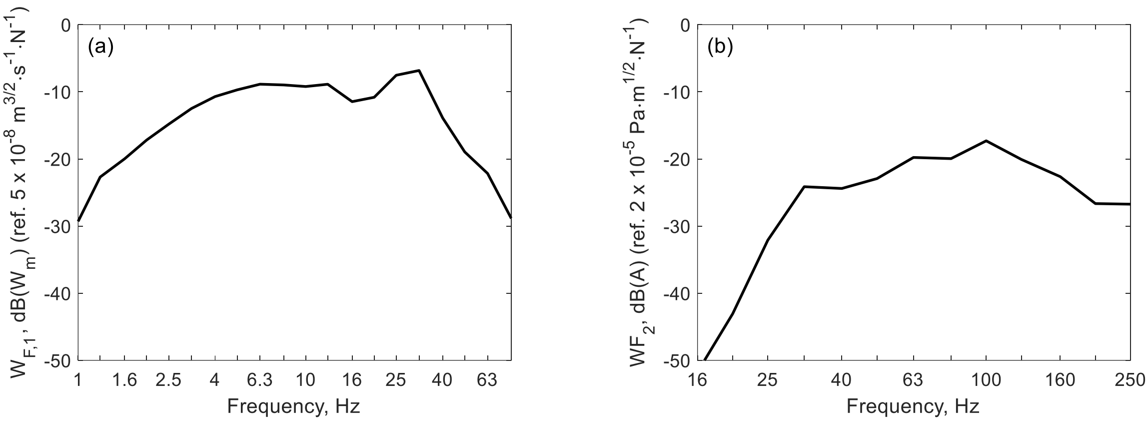

Figure 1. (a) $W_{F,1}$ for ground-borne vibration and (b) $W_{F,2}$ for ground-borne noise.

For the case of ground-borne noise, the weighting function $W_{F,2}$ is defined from:

- the line source transfer mobility $TM_L(\mathbf{X},\mathbf{x}_{rec})$ (in dB ref. 1 $\frac{m/s}{N/\sqrt{m}}$) as above,
- the building coupling function between the vibration at the ground and the noise inside the nominal building $C_b^{noise}(\mathbf{x}_{rec},\mathbf{x}_b)$ for a chosen nominal building, and
- the standard A-weighting curve W_A for human acoustic perception.

The line source transfer mobility $TM_L(\mathbf{X},\mathbf{x}_{rec})$ is computed for the nominal track-soil case at $\mathbf{x}_{rec}$=16 m, identical to that used for $W_{F,1}$. The building coupling function C_b^{noise} is again selected for the situation of the ground floor of a tall building with concrete floors, but including an additional correction term C_{b4} to consider the noise level in a room; $C_b^{noise}=C_b^{vib}+C_{b4}$ [6]. These terms are expressed in dB and applied to a vibration level spectrum in dB ref. $5\cdot10^{-8}$ m/s.

Combining these expressions, for the noise TVI from Eq. (2) and considering the measured force density $L_F^{exp}(\mathbf{X},\mathbf{x}_1)$ expressed in dB ref. 1 N/$\sqrt{m}$, the weighting function $W_{F,2}$ is given as:

$$W_{F,2}=TM_L(\mathbf{X},\mathbf{x}_{rec})+C_b^{noise}+W_A \tag{4}$$

in dB(A) ref. $2\cdot10^{-5}$ Pa $\sqrt{m}$ N^{-1}. TVI_2 is expressed in dB(A) ref. $2\cdot10^{-5}$ Pa. Figure 1(b) shows the proposed weighting function $W_{F,2}$ for the case of ground-borne noise.

4. Vehicle indicator for different rolling stock

The most important parameters of a railway vehicle that affect ground vibration are the unsprung mass, the primary and secondary suspension stiffness and the wheel unevenness and out-of-roundness [7]-[10]. These parameters affect the force density $L_F^{exp}(\mathbf{X},\mathbf{x}_1)$ and consequently the TVI. Additionally, the number of axles per unit length affects the vibration level and the axle spacing can influence the shape of the spectrum. The static vehicle load influences only the response to quasi-static loading, which is generally much smaller than that due to dynamic loading except at low frequencies for receivers close to the track [11], [12]. Based on that, a series of test cases is devised to demonstrate the calculation of the TVI, both for ground-borne vibration and for noise, involving different vehicles at the same site.

In the test cases the measured force density $L_F^{exp}(\mathbf{X},\mathbf{x}_1)$ needed for the calculation of the TVIs in Eq. (2) is replaced by the force densities calculated using the advanced numerical model TRAFFIC [13]. The main parameters used to model the trains are given in Table 1 and those used for the tracks are given in Table 2. The site conditions selected for the study are those of a medium stiffness soil with S-wave velocity 200 m/s, P-wave velocity 400 m/s, density 1800 kg/m^3 and damping ratio of 0.025. The combined track-wheel unevenness used in the simulations is shown in Figure 2. The location $\mathbf{x}_1$ used for the calculation of the force density $L_F^{TR}(\mathbf{X},\mathbf{x}_1)$ is selected as 16 m from the track.

Table 1. Vehicle properties.

Parameter	IC	Freight
Car mass	32000 kg	90000 kg
Vehicle length	23 m	15.8 m
Bogie mass	5000 kg	2100 kg
Bogie distance	17 m	9 m
Wheelset mass	1200 kg	1400 kg
Axle distance	2.5 m	1.8 m
Primary suspension stiffness (per axle)	2 MN/m	5 MN/m
Primary suspension viscous damping (per axle)	40 kN·s/m	40 kN·s/m
Secondary suspension stiffness (per bogie)	0.5 MN/m	100 MN/m
Secondary suspension viscous damping (per bogie)	31.6 kN·s/m	20 kN·s/m

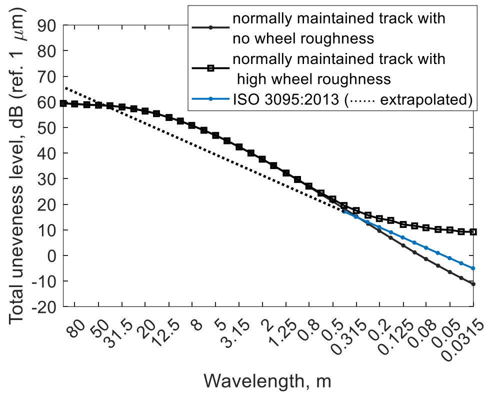

Figure 2. Total track and wheel unevenness spectra and ISO 3095:2013 limit curve (extrapolated to long wavelengths).

Table 2. Track properties.

	Ballasted track		Slab track	
Rail	Bending stiffness	6.4 MNm^2	Bending stiffness	6.4 MNm^2
	Mass per unit length	60 kg/m	Mass per unit length	60 kg/m
	Damping loss factor	0.01	Damping loss factor	0.01
	Track gauge	1.5 m	Track gauge	1.5 m
Railpad	Stiffness (per pad)	150 MN/m	Rail fastener stiffness	120 MN/m
	Damping loss factor	0.3	Rail pad damping loss factor	0.15
	Rail fastener spacing	0.6 m	Rail fastener spacing	0.6 m
Sleeper/ slab/ ballast	Sleeper mass	325 kg	Slab mass per unit length	3720 kg/m
	Sleeper length	2.6 m		
	Sleeper width	0.25 m	Slab width	3.4 m
	Sleeper height	0.2 m		
	Ballast mass per unit length	1485 kg/m	Slab mass moment of inertia	3086 kg·m
	Ballast stiffness per sleeper	500 MN/m	Slab bending stiffness	233 MN·m^2
	Ballast damping loss factor	0.15	Slab damping loss factor	0.015
	Ballast height	0.3 m		
	Ballast top width	3.0 m	Slab torsional stiffness	3086 kg·m
	Ballast bottom width	3.6 m		

Table 3 lists the six cases devised to demonstrate the TVI calculation and in Figure 3(a) the one-third octave force densities $L_F^{TR}(\mathbf{X},\mathbf{x}_1)$ obtained for these cases are shown. The reference train T1 has the generic Intercity (IC) properties listed in Table 1. Unless otherwise stated, the same properties are used in the other cases. For the case with high wheel roughness, T2, the total track/wheel unevenness is shown in Figure 2 and is the combination of the track unevenness for normally maintained ballasted track based on measurements [6] with a measured high wheel roughness reported in [14]. For the case of the freight train T6, the properties of the vehicles are given in Table 1. All vehicles are modelled as 10-DOF systems, except for the articulated train T4 that for simplicity is modelled as a series of 1-DOF systems representing the individual wheelsets. The vehicle compliance magnitudes for trains T1, T3, T4 and T6 are shown in Figure 3(b). Trains T2 and T5 have the same vehicle compliance as train T1 since the change of the wheel unevenness or train speed do not affect the vehicle compliance.

The force densities from Figure 3(a) are weighted and summed to give the values of the TVI, which are given in Table 3. The relative differences ΔTVI between the TVIs calculated for trains T2 to T6 and T1 are also given. The proposed performance classification of different vehicles can be achieved by comparing these relative differences of the TVIs.

Table 3. Vehicle indicator rolling stock cases and results.

		Vibration		Noise	
Case	Train parameters involved (changes in brackets)	TVI_1	ΔTVI_1	TVI_2	ΔTVI_2
T1	Conventional IC train running at 100 km/h	51.6	-	46.1	-
T2	High wheel roughness (Figure 2)	51.9	0.3	48.1	2.0
T3	Wheelset mass (1800 kg)	55.5	3.9	48.0	1.9
T4	Articulated IC (vehicle length 18.7 m, axle distance 3 m)	48.4	-3.2	44.6	-1.5
T5	Train speed (120 km/h)	53.1	1.5	48.3	2.2
T6	Freight train (Table 2)	60.9	9.3	48.0	1.9

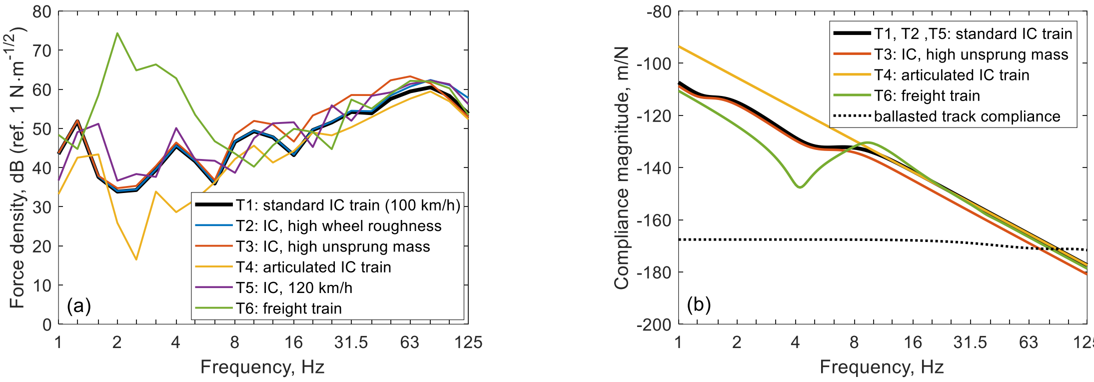

Figure 3. (a) Force densities $L_F^{TR}(\mathbf{X},\mathbf{x}_1)$ in dB (ref. 1 $N/\sqrt{m}$) for the six train test cases obtained using TRAFFIC and (b) vehicle compliance in dB (ref 1 m/N) for trains T1, T3, T4 and T6.

In the force density levels shown in Figure 3(a), the effect of the high wheel roughness of train T2 is limited to the high frequency range, above about 50 Hz, and is proportional to the increase of the total roughness in the corresponding wavelengths as shown in Figure 2. At lower speeds, lower frequency ranges would also be affected and the effect of wheel roughness on ground-borne noise would be larger.

The higher wheelset mass of train T3 compared with the standard IC train T1 increases the force density levels in the frequency range 8-63 Hz due to the lower vehicle compliance of T3 compared with T1 as shown in Figure 3(b). The maximum difference in the force density levels is about 5 dB for the 50 Hz frequency band. Above 63 Hz the vehicle compliance of both train types becomes lower than the track compliance and thus its effect on the force density reduces.

For the articulated train T4 the force density levels shown in Figure 3(a) are lower than for the standard IC train T1 in almost all frequency bands. The difference is less than about 4 dB in the frequency bands above 8 Hz and is caused by the reduction of the number of axles for the articulated IC train. At lower frequencies, the difference can be up to almost 20 dB (i.e. at the 2.5 Hz frequency band), mainly due to the higher vehicle compliance of train T4; there are also differences in the peaks and dips due to the different axle spacing. However, the vehicle compliance used for T4 is not representative below 8 Hz because it is based on a 1-DOF model whereas other trains are based on 10-DOF models.

A small increase of the force density levels in Figure 3(a) occurs when the speed is increased from 100 km/h (T1) to 120 km/h (T5). This is because, for a given frequency, the excitation is caused by unevenness with a longer wavelength that has a higher amplitude (Figure 2).

For the freight train T6, the force density levels in Figure 3(a) are significantly higher than for the standard IC train T1 below 8 Hz. This is caused mainly by the lower vehicle compliance at these frequencies due to the very stiff secondary suspension assumed for the freight train T6 (see Table 1).

Figure 4 shows the weighted force densities, $L_F^{TR}(\mathbf{x}_1)+W_{F,i}$, representing the ground-borne vibration and noise spectra, for the six trains listed in Table 3. For the vibration-weighted levels in Figure 4(a), the highest levels occur for frequencies between 20 and 63 Hz for all train cases apart from the freight train T6. For the noise weighting function in Figure 4(b), the highest levels occur for frequencies above 50 Hz. The train with the highest unsprung mass T3 shows the highest vibration and noise levels between 20 and 63 Hz which results in TVI_1 that is 4 dB higher than the standard IC train T1 and TVI_2 that is 2 dB higher (see Table 3). For the freight train T6, high vibration levels are obtained in the 2-8 Hz frequency bands and lead to the highest TVI_1, which is about 9 dB higher than train T1. This is due to the high force density levels as seen in Figure 3(a) caused by the very stiff secondary suspension stiffness. The increase in train speed from T1 to T5, increases the vibration and noise levels due to the higher unevenness experienced and leads to an increase of 1.5 dB in TVI_1 and 2 dB in TVI_2. The increased wheel unevenness of train case T2 affects the force density levels above about 50 Hz, but has negligible effect on TVI_1 due to the low weighting values applied at these frequencies. However, it increases the noise spectrum and leads to a 2 dB increase in the TVI_2. For both noise and vibration, the articulated train T4 with a lower axle density has the lowest spectrum, leading to a reduction of about 3 dB in TVI_1 and 1.5 dB in TVI_2. The freight train T6 also has a higher axle density than the passenger trains due to having shorter vehicles and this leads also to a small increase in the calculated vibration and noise levels and contributes to both TVIs.

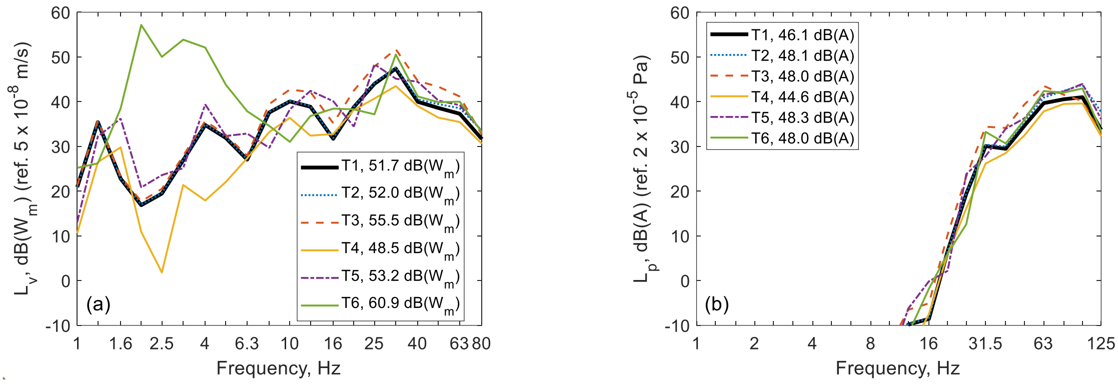

Figure 4. Weighted force density spectra (a) $L_F^{exp}(\mathbf{x}_1)+W_{F,1}$ for vibration and (b) $L_F^{exp}(\mathbf{x}_1)+W_{F,2}$ for noise based on force densities calculated with the TRAFFIC for the six train cases.

5. Vehicle indicator based on numerical modelling

In some practical situations the measured force densities at a site are not available. Instead, it is possible to predict the force density levels by using numerical modelling. The force density levels can be predicted by using numerical or hybrid calculations using a predicted or measured line source transfer mobility $TM_L(\mathbf{X},\mathbf{x}_1)$ and a predicted or measured vibration velocity level $L_v(\mathbf{x}_1)$. When available, they can also be calculated by numerical predictions of the dynamic wheel-rail interaction forces.

However, different modelling assumptions and detail (model uncertainty) may give different results for the predicted force densities and consequently the TVIs. In the following, the TVIs for the six train cases T1 to T6 of Table 3 are calculated using force densities obtained from three different modelling situations: (i) TRAFFIC line source transfer mobility and vibration velocity levels (as in Section 4); (ii) MOTIV [15] line source transfer mobility and vibration velocity levels and (iii) the line source transfer mobility and vibration velocity levels calculated with the prototype model developed within the SILVARSTAR project. It should be noted that models (i) and (ii) use the same 10-DOF vehicle model (except for case T4 in TRAFFIC that is modelled with 1-DOF systems per axle) and their main differences are in the modelling of the track-soil interface. The SILVARSTAR model (iii) differs from the other models, TRAFFIC and MOTIV, in both the vehicle (3-DOF systems per axle) and in the track-soil subsystem. The site conditions selected for the track-soil subsystem in the models are the same as

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in Section 4. The force density levels calculated from the three models (not shown here) are similar, although in individual frequency bands there are differences of several dB. These differences between the model outputs are mainly due to the different vehicle modelling detail (at low frequencies) and due to the different kinematic assumptions at the track-soil system.

Table 4 reports the values of the vibration TVI_1 and noise TVI_2 using the weighted force densities predicted from the different model outputs from TRAFFIC, MOTIV and SILVASTAR. The differences ΔTVI between the TVIs calculated for trains T2 to T6 and T1 are also given. The values of the TVIs calculated with the three different model outputs can vary by more than 3 dB. Nonetheless, for each of the train cases, the level differences ΔTVI are similar for each of the models, with differences of less than 1 dB. This means that the ground-borne vibration and noise performance of different vehicles can be assessed by comparing the relative difference of their TVIs, with the resulting classification being insensitive to the model assumptions used.

Table 4. Vehicle indicator predicted with different models.

Case	Vibration						Noise					
	TRAFFIC		MOTIV		SILVARSTAR		TRAFFIC		MOTIV		SILVARSTAR	
	TVI_1	ΔTVI_1	TVI_1	ΔTVI_1	TVI_1	ΔTVI_1	TVI_2	ΔTVI_2	TVI_2	ΔTVI_2	TVI_2	ΔTVI_2
T1	51.6	-	51.0	-	53.5	-	46.1	-	46.2	-	48.1	-
T2	51.9	0.3	51.2	0.2	53.7	0.2	48.1	2.0	48.5	2.3	50.5	2.4
T3	55.5	3.9	54.9	3.9	57.4	3.9	48.0	1.9	47.3	1.1	50.1	2.0
T4	48.4	-3.2	47.8	-3.2	51.1	-2.4	44.6	-1.5	44.9	-0.9	45.9	-2.2
T5	53.1	1.5	52.8	1.8	55.6	2.1	48.3	2.2	48.8	2.6	50.3	2.2
T6	60.9	9.3	61.3	10.3	63.1	9.6	48.0	1.9	47.4	1.2	49.8	1.7

6. Vehicle indicator robustness

Compared with the ground vibration levels during train passages, the force density shows less dependency on the track and ground properties [5] and hence on the site selected for the measurement of the force densities. Nevertheless, relatively small changes of the force density levels in the critically weighted frequency bands may affect the magnitude of the estimated TVIs. This section investigates the robustness of the proposed TVIs when using measured force densities obtained from different sites, and also when performing numerical calculations for the prediction of the force density at a target site where not all the input parameters are known (parametric uncertainty).

Five representative situations are considered for the calculation of the TVIs for the six vehicle cases T1 to T6 of Table 3. The force density that is used to determine the TVIs has been predicted for test sites with different conditions. The reference site S1 corresponds to a ballasted track on a medium stiffness soil with the same properties as the previous sections. The other test sites considered differ from the reference site S1 as follows: S2 has a track with softer rail pads (40 MN/m instead of 150 MN/m); S3 has the slab track of Table 2 instead of the ballasted track; S4 has softer soil with S-wave velocity 100 m/s and P-wave velocity 200 m/s; S5 has stiffer soil with S-wave velocity 400 m/s and P-wave velocity 800 m/s; and S6 has the same conditions as the reference site but the force density is calculated at 12 m from the track instead of 16 m. All the calculations of the force densities in this section are performed using the vibration velocity levels of the train passages and the line source transfer mobilities obtained with the SILVARSTAR vibration prediction tool.

Figure 5(a) shows the force density levels $L_F^{num}(\mathbf{X},\mathbf{x}_1)$ of train T1 calculated with the SILVARSTAR tool for the reference site and the five variant sites. The corresponding vibration velocity levels $L_V^{num}(\mathbf{x}_1)$ due to the passage of the train T1 are given in Figure 5(b). Large differences are present in the velocity levels, especially where a change in the transmission path has occurred (different soil stiffnesses or different distance from the track) and can affect the whole frequency range. However, when these results are converted to force densities the differences are much smaller and limited to higher frequencies.

The site differences affect the force density levels above about 30 Hz, with the more notable effects occurring for large changes in the track parameters, such as changing the rail fastener stiffness or the track type. For these two situations, differences up to about 4 dB are found in the frequency range up to 63 Hz which is critical for ground-borne vibration and up to about 10 dB in the frequency range 63-125 Hz which is important for ground-borne noise. Similar differences in dB can be seen in the vibration velocity levels shown in Figure 5(b) for these two situations.

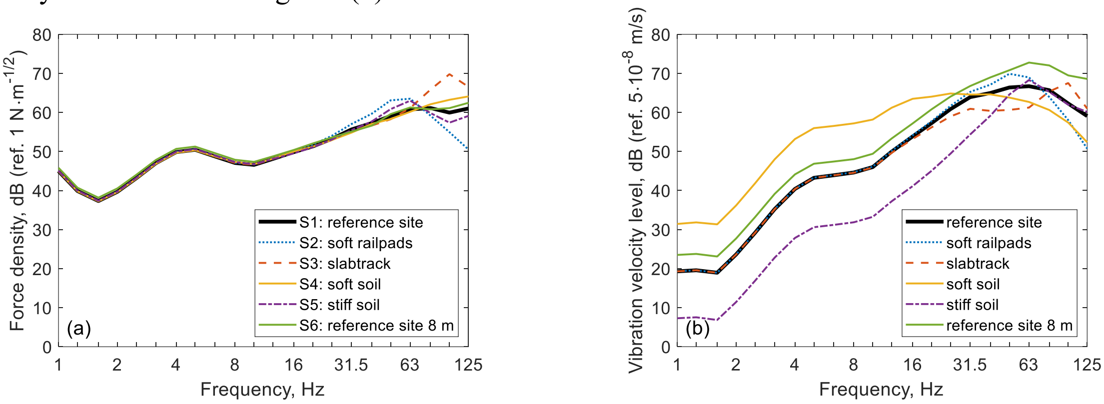

Figure 5. (a) Force density and (b) vibration velocity levels of generic IC train T1 at different sites.

Table 5. Vibration and noise vehicle indicator predicted at different test sites.

	Vibration TVI_1 and ΔTVI_1						Noise TVI_2 and ΔTVI_2					
Site	T1	T2-T1	T3-T1	T4-T1	T5-T1	T6-T1	T1	T2-T1	T3-T1	T4-T1	T5-T1	T6-T1
S1	53.5	0.2	3.9	-2.4	2.1	9.6	48.1	2.4	2.0	-2.4	2.2	1.7
S2	54.8	0.2	4.5	-2.4	2.1	8.7	47.4	1.3	1.2	-2.3	2.2	1.4
S3	53.4	0.3	3.8	-2.3	2.1	9.7	54.5	2.8	1.9	-2.4	2.3	2.0
S4	53.2	0.2	3.5	-2.4	2.0	9.5	49.9	2.8	2.0	-1.9	2.3	0.7
S5	53.7	0.2	4.1	-2.5	2.0	9.6	47.7	2.0	2.7	-2.4	2.2	2.0
S6	53.7	0.2	3.7	-2.3	2.0	9.6	48.8	2.5	1.9	-2.1	2.2	1.3

The differences in the weighted force density levels between the different site conditions (not shown here) will affect ground-borne vibration and noise levels inside the building and consequently the vibration and noise TVIs. Table 5 reports the values of the vibration TVI_1 and noise TVI_2 for train T1 as well as the relative differences between all the other trains T2 to T6 and case T1 using the force densities obtained from the different sites.

When the site conditions change, the values of the TVIs in Table 5 are affected. Nonetheless, the differences between the values of TVI_1 for different trains are consistent between the various site conditions; the largest variations are found for T3-T1 and T6-T1 with a range of up to 1 dB. This means that the classification of the vehicle vibration performance based on the proposed TVI is generally not sensitive to changes in the test site conditions for which the force density is obtained. For the noise TVI results, the differences between the different train cases show greater variation when changing the site conditions; ranges of 1.5 dB are found for T2-T1, T3-T1 and T6-T1. Consequently, the classification of the vehicle performance based on the proposed noise TVI would be less reliable when using force densities measured at significantly different sites. The consistency of the results could be improved by applying transposition to the force density estimates so that they correspond to the reference site.

7. Representativeness of vehicle indicator

The weighting functions used in the proposed vehicle indicators are chosen to represent a nominal track, ground and building. Here, it is assessed whether the TVIs are representative of the changes in vibration and ground-borne noise that will occur when changing from one vehicle type to another, even when the track, ground, building and receiver distance do not correspond to the chosen nominal conditions.

The ground-borne vibration and noise levels have been calculated for the six different train cases T1 to T6 of Table 3 for a range of different site conditions (soil, track, building distance and building type).

These are expressed as the overall vibration level in dB(W_m) ref. $5 \cdot 10^{-8}$ m/s and the overall ground-borne noise level in dB(A) ref. $2 \cdot 10^{-5}$ Pa, calculated by combining the same force densities with different line source transfer mobilities $\mathrm{TM_L}(\mathbf{X},\mathbf{x}_{rec})$ and building correction factors C_b^{vib} and C_b^{noise} determined using the SILVARSTAR vibration prediction tool.

The overall vibration and noise levels for train case T1 and the difference in the overall levels between each train type and train type T1 are given in Table 6 for six different site situations. Results are shown for (W1) the reference site case (used in Section 3) and five variations: (W2) different track stiffness (about 70% softer rail pads); (W3) different track type (slab track instead of ballasted track), (W4) softer soil with the wave velocities halved, (W5) stiffer soil with the wave velocities doubled, and (W6) different building type (small building with concrete floors instead of tall building). The results are also shown for two other receiver distances $\mathbf{x}_{rec}$, 8 m and 32 m to consider the potential differences between an urban site and a suburban site.

Table 6. Overall W_m-weighted vibration level and overall A-weighted noise level for train T1 and differences of other trains relative to T1 (in dB ref. 1) at different sites.

		Vibration level						Noise level					
Site	$\mathbf{x}_{rec}$	T1	T2-T1	T3-T1	T4-T1	T5-T1	T6-T1	T1	T2-T1	T3-T1	T4-T1	T5-T1	T6-T1
W1	8 m	57.0	0.2	3.9	-2.5	2.0	9.3	54.5	2.6	1.7	-2.5	2.2	1.5
	16 m	53.5	0.2	3.9	-2.4	2.1	9.6	48.1	2.4	2.0	-2.4	2.2	1.7
	32 m	49.0	0.1	3.6	-2.5	2.0	10.8	37.4	1.7	3.0	-2.3	2.3	2.1
W2	8 m	56.8	0.2	3.8	-2.5	2.0	9.5	56.4	3.2	1.2	-2.4	2.3	1.3
	16 m	53.5	0.2	3.8	-2.5	2.0	9.6	48.7	2.7	1.8	-2.4	2.3	1.6
	32 m	49.0	0.1	3.6	-2.4	2.0	10.8	38.1	1.8	2.7	-2.4	2.2	2.0
W3	8 m	54.2	0.1	3.4	-2.5	1.9	11.7	48.9	2.9	1.5	-2.4	2.3	1.4
	16 m	51.8	0.1	3.5	-2.5	1.9	11.0	43.4	2.6	2.0	-2.4	2.3	1.7
	32 m	48.1	0.1	3.4	-2.5	1.9	11.6	33.5	1.5	3.2	-2.3	2.3	2.2
W4	8 m	64.5	0.1	2.8	-2.5	1.8	13.6	54.7	2.6	1.7	-2.5	2.2	1.5
	16 m	61.1	0.1	2.6	-2.4	1.8	14.1	43.0	1.6	3.2	-2.3	2.3	2.2
	32 m	57.4	0.0	1.9	-2.5	1.6	14.9	29.1	0.6	4.1	-2.4	2.2	2.5
W5	8 m	48.4	0.6	3.8	-2.4	2.1	6.8	53.3	3.0	1.3	-2.4	2.3	1.4
	16 m	45.4	0.6	3.9	-2.4	2.1	6.6	49.3	2.8	1.4	-2.4	2.3	1.4
	32 m	41.6	0.4	4.0	-2.4	2.1	6.8	42.1	2.4	1.8	-2.4	2.2	1.6
W6	8 m	62.3	0.2	3.9	-2.5	2.0	9.2	60.5	2.8	1.5	-2.5	2.2	1.4
	16 m	58.8	0.2	3.9	-2.5	2.1	9.4	53.9	2.6	1.9	-2.4	2.3	1.7
	32 m	54.2	0.1	3.6	-2.5	2.0	10.6	42.9	1.8	2.9	-2.3	2.3	2.1

Considering the differences between the vibration levels for each train relative to train T1 in Table 6, the results are consistent for the three receiver distances $\mathbf{x}_{rec}$. Moreover, these results are consistent between sites W1, W2, W3 and W6 that have the same soil type. The insensitivity of the classification of the train types to the distance of the receiver, the track stiffness and track type mean that the proposed vibration TVI is representative of the changes in vibration that will occur when changing from one vehicle type to another across a range of situations.

Larger variations between the results in Table 6 occur for different soil stiffness (sites W4 and W5). This is because changes to the soil stiffness affect the line source transfer mobility $\mathrm{TM_L}(\mathbf{X},\mathbf{x}_{rec})$ differently in different frequency bands; an increase in soil stiffness reduces the vibration levels at low frequency more than at high frequency. This particularly affects the case of the freight train T6; for the stiff soil the high levels below 8 Hz become about 8 dB less prominent in the calculated vibration levels inside the building than for a soft soil. For the other trains the effect of the soil stiffness is much smaller.

For the noise levels, the differences in Table 6 between the levels for each train relative to train T1 seem to be sensitive to some extent to the receiver distance $\mathbf{x}_{rec}$ and, for some train cases, to the soil stiffness. However, the chosen compromise of a medium receiver distance (16 m) and a medium soil stiffness seems to be the most representative to consider the changes in ground-borne noise that will occur when changing from one vehicle type to another.

8. Conclusions

Two different track-independent vehicle indicators were proposed, one representative of ground-borne vibration and the other of ground-borne noise. The TVIs represent the overall vibration and noise levels in a nominal building on a nominal soil. To demonstrate their use, they were calculated for several types of train using the force densities at the same site. The TVIs for each vehicle were calculated from force density levels obtained by the TRAFFIC and the MOTIV models and the SILVARSTAR prediction tool. The simulations were performed using generic models of passenger and freight trains and changes in the most important vehicle parameters that affect ground vibration and noise were investigated: wheel unevenness, unsprung mass, primary and secondary suspension stiffness, train speed, number of axles per unit length and axle spacing. Although the TVI values for each vehicle may vary in some cases by more than 3 dB due to the different modelling approaches and detail, the TVI-based classification of different vehicles is insensitive (less than 1 dB) to the model uncertainty.

The vibration vehicle indicator is generally robust to changes in site conditions for which the force density is calculated. Similar changes in the vibration TVI between the train types were found for different sites, within a range of 1 dB. For the noise TVI, in some cases, the variations are slightly greater, with ranges of up to 1.5 dB.

The vibration and noise levels are considered at different sites and in different buildings. The relative changes in the TVIs are shown to be representative of the changes in vibration and ground-borne noise that will occur when changing from one vehicle type to another, even when the track, ground, building and receiver distance do not correspond to the chosen nominal conditions.

References

[1] https://silvarstar.eu/ (last accessed 30 March 2023).
[2] Nelson J T and Saurenman H J 1987 *Transp Res Rec*, **1143** 26–35.
[3] International Organization for Standardization 2005 *ISO 14837-1:2005*.
[4] Hanson C E, Ross J C and Towers D A 2012 *Technical Report DOT/FRA/ORD-12/15* U.S. Department of Transportation, Federal Railroad Administration, Office of Railroad Policy and Development.
[5] Verbraken H 2013 Prediction of railway induced vibration by means of numerical, empirical, and hybrid methods. PhD thesis, Department of Civil Engineering, KU Leuven.
[6] Thompson D J, Ntotsios E, Degrande G, Lombaert G, Herremans G, Alexiou T, Reumers P, Nélain B, Barcet S, Bouvet P, Fröhling B and Nuber 2022 *SILVARSTAR Deliverable D2.1*.
[7] Mirza A, Frid A, Nielsen J C O and Jones C J C 2010 *Proc. 10th Int. Workshop on Railway Noise*, Nagahama, Japan. *Notes Numer Fluid Mech* **118** 259-66.
[8] Nielsen J C O, Mirza A, Cervello S, Huber P, Müller R, Nélain B and Ruest P 2015 *Int J Rail Transp* **3** (1):17-39.
[9] Colaço A, Costa P A and Connolly D P 2016 *Struct Infrastructure Eng* **12** (5):517-34.
[10] Nielsen J C O, Nélain B, Müller R, Frid A, Mirza A 2012 *RIVAS (SCP0-GA-2010-265754), Deliverable D5.2.*
[11] Sheng X, Jones C J C and Thompson D J 2003 *J Sound Vib* **267** 621-35.
[12] Lombaert G and Degrande G 2009 J Sound Vib **319** (3-5):1036–1066.
[13] Lombaert G, François S and Degrande G 2012 *User's Guide Traffic 5.2 Report BWM-2012-10* Department of Civil Engineering, KU Leuven.
[14] Gratacos P and Mora P 2013 *RIVAS (SCP0-GA-2010-265754) Deliverable D2.4*.
[15] Ntotsios E, Thompson D J and Hussein M F M 2017 *J Sound Vib* **402**:142–163.