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A track-independent vehicle indicator for ground-borne noise and vibration emission classification

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ABSTRACT

Ground vibration from railways is increasingly recognised as a source of annoyance to lineside residents. However, in contrast to airborne noise, there are no standard test procedures to quantify the vibration emission of trains. This is compounded by the fact that measurements of vibration are highly sensitive to the properties of the test site. Here, to help overcome this, a 'track-independent vehicle indicator' (TVI) is proposed that can be used to classify railway vehicles in terms of their ground-borne noise and vibration emission. Two different formulations of TVI are proposed, one related to feelable ground-borne vibration and the other to ground-borne noise. The proposed TVIs are based on the force density at the railhead, which may be obtained indirectly from measured ground vibration due to train passages together with a measured line source transfer mobility at the test site. Corresponding frequency weightings are defined to mimic the sensitivity of human response to ground vibration or ground-borne noise. Each TVI is a single number quantity, defined as a sum over all relevant frequency bands of the frequency-weighted force densities. The proposed performance classification of different vehicles can be achieved by comparing the relative differences of their TVIs. The force density is chosen as the basis of the TVIs because, in contrast to the vibration levels, it is relatively independent of the test site. Nevertheless, some restrictions should be applied to the site to avoid undue influence from the track or ground properties. A transposition procedure can also be used to convert results to a standard situation to reduce this influence. A series of test cases is used to demonstrate the potential of the TVIs to classify railway vehicles in terms of their ground-borne vibration and noise emission.

Introduction

Train-induced ground vibration is increasingly recognised as a source of annoyance to lineside residents [1]. Vibration transmitted through the ground can affect people through whole-body 'feelable' vibration as well as through ground-borne noise radiated inside buildings. However, in contrast to airborne noise, there is much less standardisation of test procedures to quantify the vibration emission of trains.

Since 2002 the noise emission from new and refurbished rolling stock has been controlled via the European Technical Specifications for Interoperability, initially introduced for high-speed rolling stock and later extended to conventional passenger and freight vehicles [2]. As the noise emission is strongly influenced by the track design as well as the vehicle, a standard test procedure has been developed that aims to minimise the influence of the track by defining limit curves for the track decay rate and the rail roughness [3]. The noise measured under these standardised conditions at the reference microphone position is used in the certification of vehicles. The introduction of the TSIs and the subsequent tightening of limit values, especially for freight vehicles, is seen as an effective means of gradually eliminating noisy wagons. The aim of the current study is to propose an equivalent measurement quantity and procedure that can be used to classify the vibration emission of railway vehicles. This must take account of the fact that measurements of vibration are sensitive to the properties of the track and ground at the test site [1,4,5].

The design and condition of railway vehicles can have an important influence on ground-borne noise and vibration. This is clear from measurement campaigns at particular sites where mixed traffic operates [6,7], but also from the results of parametric studies performed using prediction models for a range of vehicle parameters [8–10]. These

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studies have shown that the most important parameters of the vehicle affecting ground vibration are the wheel unevenness and out-of-roundness [6,7], the unsprung mass of the wheelsets and the primary suspension stiffness [8]. Additionally, the number of axles per unit length affects the average vibration level and the axle spacing can influence the shape of the spectrum [9,10], although their effect is relatively small. The vehicle weight 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].

The above studies have shown that, although there are limited opportunities in the design of rolling stock to minimise their ground-borne noise and vibration emission, it is possible to identify vehicles which have beneficial properties in terms of the generation of ground-borne noise and vibration. However, ground vibration levels are strongly dependent on both the track and ground properties and the receiver condition [1,4,5], so 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 quantity that is independent of both the track and ground at the test site. Recently, a procedure for characterizing and predicting a railway vibration emission quantity that can be used at different sites with different train traffic, track system or ground type was proposed in [13]. This is based on a source-receiver mobility approach, in which the vehicle-track system is considered as the source and the ground as the receiver and can be based on measured or numerically calculated practical quantities. Some initial results were presented, which showed that further research and experimental work is needed to overcome certain limitations when sites with different soil conditions are involved.

The aim of this paper is to propose a track-independent vehicle indicator (TVI) that can be used to characterise railway vehicles in terms of their ground-borne noise and vibration emission. The basis of the proposed indicator is the concept of force density, as used in the Detailed Vibration Assessment of the United States Federal Railroad Administration (FRA) and Federal Transit Administration (FTA) [14,15]. The procedure used to obtain the force density from vibration measurements is first recalled in Section '**Measurement of force density**'. In Section '**Definition of track-independent vehicle indicator**', two different formulations of the TVI are presented, one related to feelable vibration and the other to ground-borne noise. They are both based on applying a frequency weighting to the measured force density. The proposed frequency weightings are derived and presented in detail.

A series of test cases is devised in Section '**Examples of vehicle indicator for different rolling stock**' to demonstrate the calculation of the TVIs of different vehicles at the same site. For this demonstration, numerical models are used to simulate practical measurements of the force density, from which the TVIs for each vehicle are calculated. The simulations are performed using generic models of passenger and freight trains. Changes to the most important parameters of the vehicle that affect ground-borne vibration and noise are investigated: wheel design and condition, unsprung mass, primary and secondary suspension stiffness, train speed, the number of axles per unit length and the axle spacing.

Ideally, the TVI should be representative of the relative performance of different vehicles, irrespective of the site conditions. This is investigated in Sections '**Vehicle indicator robustness**' and '**Representativeness of vehicle indicators**', using numerical simulations of ground-borne noise and vibration from the different vehicles considered when varying the properties of the track, the ground or the building as well as the receiver distance.

Measurement of force density

Nelson and Saurenman [16] introduced an empirical prediction procedure for ground-borne vibration based on the concept of an equivalent force density. This approach has been adopted, for example, in the FRA/FTA approach [14,15]. The procedure also conforms to the general framework subsequently recommended in ISO 14837-1:2005 [17] in which the magnitude of ground-borne vibration $A(f)$, typically a root mean square (rms) velocity in one-third octave bands f, is divided into source, propagation, and receiver terms as

$$A(f) = S(f)P(f)R(f) \tag{1}$$

where $S(f)$ is a source term that represents the excitation at the wheel/rail interface, $P(f)$ describes the propagation path and $R(f)$ characterises the receiver, i.e., the building. The FRA/FTA approach [15,16] is similar to this but is expressed in decibels for each one-third octave frequency band as

$$L_v(\mathbf{x}_b) = L_F(\mathbf{X}) + L_{Y_L}(\mathbf{X}, \mathbf{x}_r) + C_T(\mathbf{x}_r, \mathbf{x}_b) \tag{2}$$

where L_v is velocity level at the location $\mathbf{x}_b$ inside the building. The source term is given by an rms force density, denoted by F, or in decibels by L_F. F has units $\text{N}/\sqrt{\text{m}}$ and represents the source by a line of incoherent forces applied on the track or on the ground surface adjacent to the alignment. The corresponding propagation term, here denoted by Y_L, is called the line source transfer mobility and has units $(\text{m/s})/(\text{N}/\sqrt{\text{m}})$. It gives the velocity at a receiver point $\mathbf{x}_r$ on the ground due to a unit force density applied along the line at $\mathbf{X}$ (Fig. 1). Hence, the rms velocity v at $\mathbf{x}_r$ in frequency band f is expressed as

$$v(\mathbf{x}_r) = F(\mathbf{X})Y_L(\mathbf{X}, \mathbf{x}_r) \tag{3}$$

The third term $C_T(\mathbf{x}_r, \mathbf{x}_b)$ in Eq. (2) is the receiver term or the building's vibration transmissibility (or coupling loss); it can be computed as a combination of adjustment factors to account for soil-structure interaction at foundation level and attenuation and amplification within the building, see Fig. 1. It is the ratio of the measured velocity at receiver $\mathbf{x}_b$ inside the building to the velocity at the ground position $\mathbf{x}_r$ (usually adjacent to the building).

The line source transfer mobility can be determined by combining a series of n_s point source transfer mobilities Y for excitation at positions $\mathbf{X}$ distributed over a length L along the track alignment. The line source transfer mobility is then given by

$$Y_L(\mathbf{X}, \mathbf{x}_r) = \sqrt{\frac{L}{n_s} \sum_{k=1}^{n_s} |Y(\mathrm{X}_k, \mathbf{x}_r)|^2} \tag{4}$$

The line source transfer mobility can be defined for excitation at points $\mathbf{X}$ on the track or, for the case of a new railway that has not yet been built, at locations on the soil surface close to the future track alignment.

In contrast to the line source transfer mobility and the building coupling loss factor, the force density cannot be measured directly so an indirect method is used, by measuring (i) the vibration on the ground surface at the positions $\mathbf{x}_r$ during train passages and (ii) the corresponding line source transfer mobility at the test site. Rearranging Eq. (2) and omitting the building coupling loss term (or using Eq. (3) in reverse) gives a method of determining the equivalent force density level L_F due to a train passage as

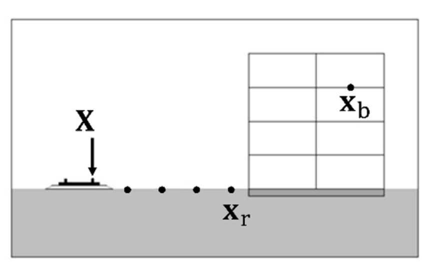

Fig. 1. Position of the source and receiver points for the FRA/FTA procedure when the railway is present.

$$L_F(\mathbf{X},\mathbf{x}_r) = L_v(\mathbf{x}_r) - L_{Y_L}(\mathbf{X},\mathbf{x}_r) \tag{5}$$

Such an empirical approach for the calculation of the excitation term has the advantage that it accounts directly for unknown soil properties in the ground transfer functions. Whereas the vibration levels during train passages can vary significantly due to variations in track and ground properties, the force density shows much smaller variations [18]. Due to factors such as the Doppler effect in the ground and variations in the soil properties, the force density depends on the receiver distance $\mathbf{x}_r$ used in its evaluation. Nevertheless, as shown in [18–20], it is not strongly dependent on the receiver distance. For these reasons, it is considered to be suitable for use as the basis for the classification of railway vehicles.

Definition of track-independent vehicle indicator

Railway-induced ground-borne vibration inside a building is perceived by humans as whole-body motion at frequencies 2 to 80 Hz, and as low-frequency rumbling noise at audible frequencies approximately in the range 20 to 250 Hz [1,4]. For this reason, two slightly different formulations of TVI are proposed, one related to each phenomenon. In both cases, the starting point is the indirectly measured force density $L_F(\mathbf{X},\mathbf{x}_r)$, determined from the vibration response at a location $\mathbf{x}_r$ using Eq. (5). Each proposed TVI is a single number quantity in dB, defined as a sum over all frequency bands from $l_{f,i}$ to $n_{f,i}$ of a frequency-weighted force density

$$\mathrm{TVI}_i = 10\log_{10}\sum_{k=l_{f,i}}^{n_{f,i}} 10^{\frac{L_F^{(k)}(\mathbf{X},\mathbf{x}_r)+\mathrm{W}_{F,i}^{(k)}}{10}} \tag{6}$$

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. The corresponding frequency ranges $l_{f,i}$ to $n_{f,i}$ contain the frequency bands between 2 Hz and 80 Hz for $\mathrm{W}_{F,1}$ and between 20 Hz and 250 Hz for $\mathrm{W}_{F,2}$. The performance classification of different vehicles can be achieved by comparing the relative differences of their TVIs.

The weighting functions $\mathrm{W}_{F,i}$ applied to the force density are defined to give an approximate estimate of the spectrum shape of the vibration or noise in a nominal building at a distance $\mathbf{x}_r$ from a reference track on a nominal ground. The ground in this reference situation is represented by a line source transfer mobility $L_{Y_L}(\mathbf{X},\mathbf{x}_r)$ obtained using Eq. (4) with a set of point source transfer mobilities $Y(\mathrm{X}_k,\mathbf{x}_r)$ that are determined numerically with the semi-analytical prediction model MOTIV [5,21,22]. In MOTIV, the track and tunnel are modelled as an infinitely long structure, whereas the ground is modelled as a linear, layered and infinite soil medium. Damping is introduced in the soil as rate independent using a damping loss factor, an assumption commonly used in soil dynamics in the low frequency ranges and which corresponds well with measurements [23–25].

The receiver distance $\mathbf{x}_r$ used for determining the weighting function is chosen to be 16 m from the track, which is a typical distance from a railway to the nearest building in a suburban area. The nominal track properties used for these calculations are given in Table 1. The soil is assumed to have a medium stiffness with a shear (S-) wave speed of 200 m/s and a compressional (P-) wave speed of 400 m/s. The density of the soil is 1800 kg/m^3 and the hysteretic damping loss factor is 0.05 (equivalent to a damping ratio of 0.025).

Ground-borne vibration

For the case of ground-borne vibration, the weighting function $\mathrm{W}_{F,1}$ is formed by:

(i) the line source transfer mobility $L_{Y_L}(\mathbf{X},\mathbf{x}_r)$ for a reference track on the nominal soil and at the receiver distance $\mathbf{x}_r$ as described above,

Table 1
Properties of the nominal ballasted track.

Rail UIC60	Bending stiffness	6.4 MN m^2
	Mass per unit length	60 kg/m
	Damping loss factor	0.01
	Track gauge	1.435 m
Rail pad	Stiffness	150 MN/m
	Damping loss factor	0.3
Sleeper	Mass	325 kg
	Spacing	0.6 m
	Length	2.6 m
	Width	0.25 m
	Height	0.2 m
Ballast	Mass per unit length	1485 kg/m
	Stiffness per sleeper	500 MN/m
	Damping loss factor	0.15
	Height	0.3 m
	Top width	3.0 m
	Bottom width	3.6 m

(ii) a building coupling function $C_T^{\mathrm{vib}}(\mathbf{x}_r,\mathbf{x}_b)$ between the vibration at the ground surface and the vibration of the floor and/or walls in the building for a chosen nominal building, and

(iii) the W_m acceleration weighting curve based on human perception of vibration according to ISO2631-2:2003 [26], but converted to apply to a velocity spectrum.

The selected building coupling function C_T^{vib} corresponds to the mid-span of the ground floor of a tall building with concrete floors, taken from the experimental database reported in the SILVARSTAR project [27]. Although the vibration level will vary with height within a building, it can be assumed [14] that the spectrum shape will not be greatly affected and thus the weighting function will not change. These expressions are combined and smoothed by applying a running average over three adjacent frequency bands. The weighting function is finally normalised to a maximum value of 0 dB, as shown in Fig. 2(a).

Ground-borne noise

In a similar way, for the case of ground-borne noise, the weighting function $\mathrm{W}_{F,2}$ is formed by:

(i) the line source transfer mobility $L_{Y_L}(\mathbf{X},\mathbf{x}_r)$ for a reference track on the nominal soil and at the defined receiver distance $\mathbf{x}_r$, as above,

(ii) a building coupling function $C_T^{\mathrm{noise}}(\mathbf{x}_r,\mathbf{x}_b)$ between the vibration at the ground and the noise inside a room in the nominal building and

(iii) the standard A-weighting curve W_A for human acoustic perception

The building coupling function C_T^{noise} is selected similarly from the experimental database reported in the SILVARSTAR project [27]. It comprises C_T^{vib} and an additional term that represents the relation between the mid-span floor vibration level and the noise level in a room. The A-weighting is applied afterwards as in [27]. These expressions are combined, smoothed and normalised in the same way as for $\mathrm{W}_{F,1}$. The values of $\mathrm{W}_{F,2}$ are shown in Fig. 2(b).

Examples of vehicle indicator for different rolling stock

A series of test cases is presented to demonstrate the calculation of the two TVIs, for ground-borne vibration and for noise, involving different vehicles at the same site. In these test cases the force density

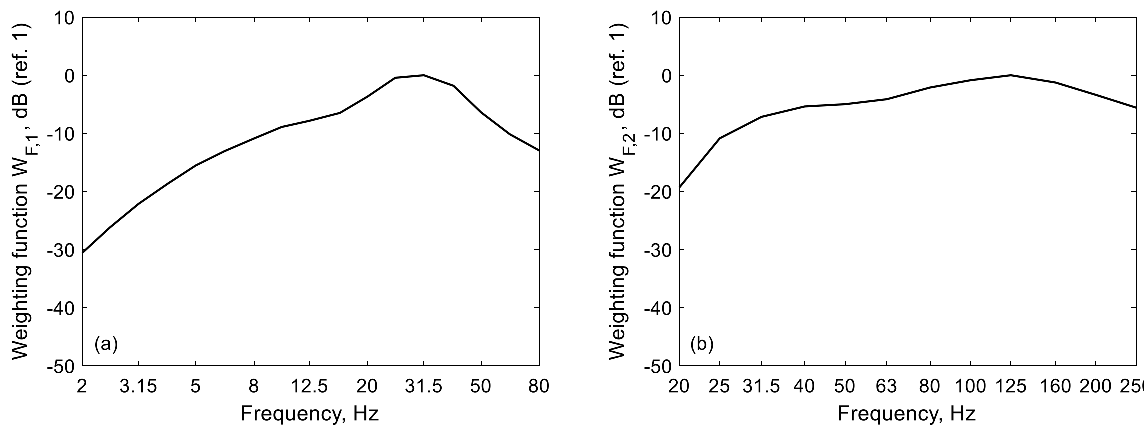

Fig. 2. Proposed weighting functions. (a) $W_{F,1}$ in the 2–80 Hz one-third octave bands related to ground-borne vibration, (b) $W_{F,2}$ in the 20–250 Hz one-third octave bands related to ground-borne noise.

$L_F(\mathbf{X}, \mathbf{x}_r)$ needed for the calculation of the TVIs in Eq. (6) is obtained using the advanced semi-analytical model MOTIV [5,21,22], which is used to simulate measurements.

Train cases

For the calculation of the TVIs for different trains, the following parameters are considered: wheel unevenness, type of train and its characteristics (unsprung mass, wheel design, suspension stiffness and axle spacing) and train speed. These parameters affect the force density $L_F(\mathbf{X}, \mathbf{x}_r)$ and consequently the TVI due to their effect on the dynamic axle loads. The response location $\mathbf{x}_r$ used for the calculation of the force density $L_F(\mathbf{X}, \mathbf{x}_r)$ in MOTIV is selected as 16 m from the track. The site conditions are those of a ballasted track with the parameters given in Table 1 and a medium-stiffness soil with a shear wave speed of 200 m/s, compressional wave speed of 400 m/s, density 1800 $\mathrm{kg/m^3}$ and hysteretic damping loss factor of 0.05. These track and ground parameters were previously used in Section '**Definition of track-independent vehicle indicator**' for the calculation of the nominal line source transfer mobility used in the definition of the proposed weighting functions. The sensitivity to other track and ground properties is considered in Section '**Vehicle indicator robustness**'.

Table 2 lists the eight train cases used to demonstrate the TVI calculation. The reference train T1 has vehicle properties of a generic InterCity (IC) train, reported in Table 3. Unless otherwise stated in Table 2, the same properties are used in the other cases. All train models consist of four identical vehicles that are modelled as 10-degree-of-freedom (DOF) systems [5], except for the train with resilient wheels T4 which includes one more DOF per wheelset to represent the wheel tyre. A linearized Hertzian contact spring is included between each wheel and the rail, although for the frequency range of ground-borne noise and vibration, inclusion of the contact spring does not influence the total response significantly. Train T6 uses a different primary suspension design using a viscoelastic type of damping (modelled as a Maxwell element instead of the typical viscous damper). For the freight train, T8, the properties of the vehicles are given in Table 3.

Table 2
Vehicle indicator rolling stock cases. Parameters correspond to those of T1 unless otherwise stated.

	Train case	Train parameters involved
T1	Reference train	Conventional IC train (see Table 3); running at 100 km/h; low wheel roughness.
T2	Higher wheel roughness	High wheel roughness (see Fig. 3).
T3	Higher wheelset unsprung mass	1800 kg per axle
T4	Resilient wheels	Wheel centre/axle mass 940 kg; tyre mass 260 kg (per axle). Stiffness 450 MN/m; viscoelastic damping 200 kN•s/m.
T5	Increased train speed	120 km/h.
T6	Modified primary suspension	Stiffness 1.5 MN/m; viscoelastic damping 60 kN•s/m in series with stiffness 3 MN/m (Maxwell element).
T7	Modified axle spacing	Articulated IC (vehicle length 18.7 m, bogie wheelbase 3 m).
T8	Freight train	See Table 3.

Table 3
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 centre distance	17 m	9 m
Wheelset mass	1200 kg	1400 kg
Bogie wheelbase	2.5 m	1.8 m
Contact stiffness (per wheel)	1.13 GN/m	1.45 GN/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 car end)	0.5 MN/m	100 MN/m
Secondary suspension viscous damping (per car end)	31.6 kN•s/m	20 kN•s/m

The combined track/wheel unevenness that is used is shown in Fig. 3 in the form of one-third octave band spectra. The limit curve from ISO 3095:2013 [3] is shown for comparison; this is also extrapolated to long wavelengths. These spectra are based on the track unevenness for normally maintained ballasted track, as included in the SILVARSTAR experimentally-based database [27]. For most cases the wheel unevenness is assumed to be much smaller than this, but for the case with high wheel roughness, T2, a measured wheel roughness spectrum reported in the RIVAS project is added to the track unevenness [28].

Force densities

The simulated measurements of one-third octave band force densities $L_F(\mathbf{X}, \mathbf{x}_r)$, obtained with the MOTIV model for the eight train cases of Table 2, are shown in Fig. 4. Fig. 4(a) shows the cases T1 – T4 that are related to changes in the condition and design of the wheel and wheelset; the other cases T5 – T8 are related to the vehicle and bogie design and are shown in Fig. 4(b).

To assist in interpreting these force densities, the magnitude of the

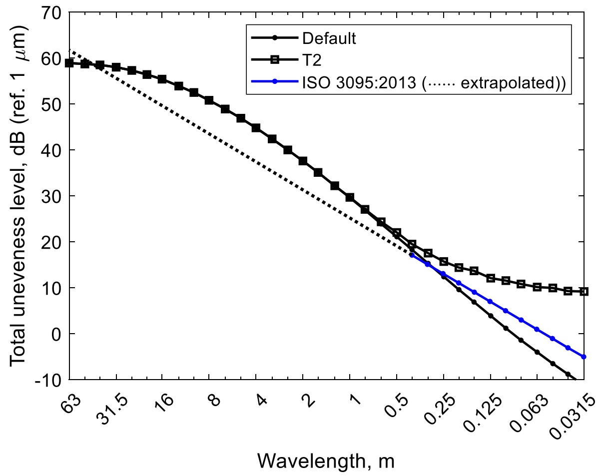

Fig. 3. Total track and wheel unevenness spectra and ISO 3095:2013 limit curve [3] (extrapolated to long wavelengths).

point receptance (displacement due to a unit harmonic load, also known as compliance) at the first wheelset of each train type is shown in Fig. 5. The track point receptance is shown for comparison. The frequency at which this crosses the vehicle receptance, at around 80–100 Hz, can be identified as the P2 resonance. Train cases T2 and T5 have the same vehicle receptance as train T1 since the change of the wheel unevenness and the change of the train speed do not affect the vehicle receptance.

Since the force densities shown in Fig. 4 are calculated using responses at 16 m from the track, the quasi-static component of vibration on the total vibration levels of all train cases has attenuated significantly and does not affect the force density levels except below 2 Hz. The subsequent peaks and dips in the spectrum are caused by the vehicle and axle passing frequencies present in the dynamic excitation.

The high wheel roughness of train case T2 only affects the force density levels above about 50 Hz. At lower speeds, lower frequency ranges would also be affected and the effect of wheel roughness on ground-borne noise would be greater. The higher wheelset mass of train case T3 increases the force density levels in the frequency range 8 – 63 Hz due to the lower vehicle receptance. A lower vehicle receptance produces higher force density levels below the P2 resonance frequency. The maximum difference in the force density levels is about 5 dB at the 40 Hz and 50 Hz frequency bands.

The resilient wheels of train T4 affect the force density below 6.3 Hz and above 31.5 Hz. Between these frequencies, the vehicle receptance is similar to that of train T1 which results in equal force density levels. In the range 2 – 6.3 Hz the force density of train T4 is higher than train T1 by up to about 7 dB due to differences in the wheelset receptance magnitude and phase (the latter is not shown here) of the two trains. Below 2 Hz, the force density is dominated by the quasi-static response,

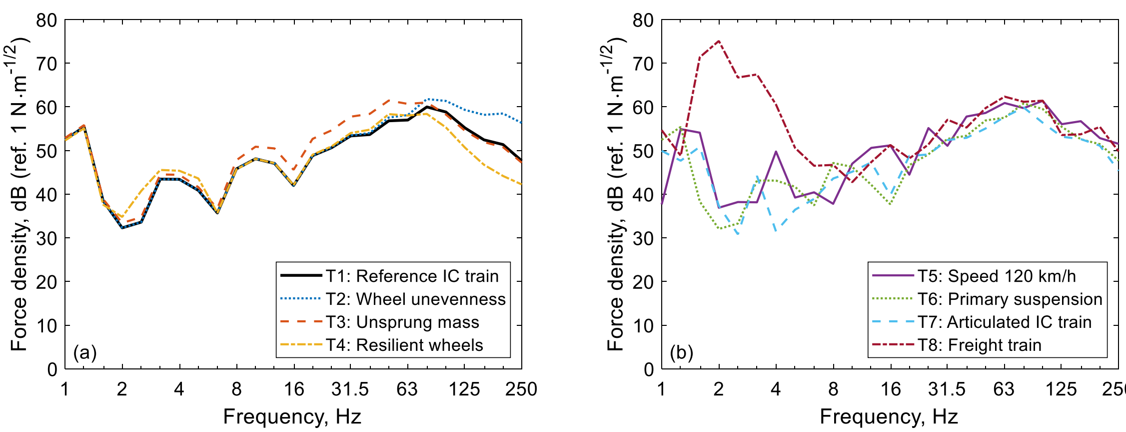

Fig. 4. One-third octave force density levels $L_F(\mathbf{X}, \mathbf{x}_r)$ in dB (ref. 1 N/$\sqrt{\text{m}}$) for the eight train test cases obtained using the MOTIV model. (a) Train cases T1, T2, T3 and T4; (b) train cases T5, T6, T7 and T8.

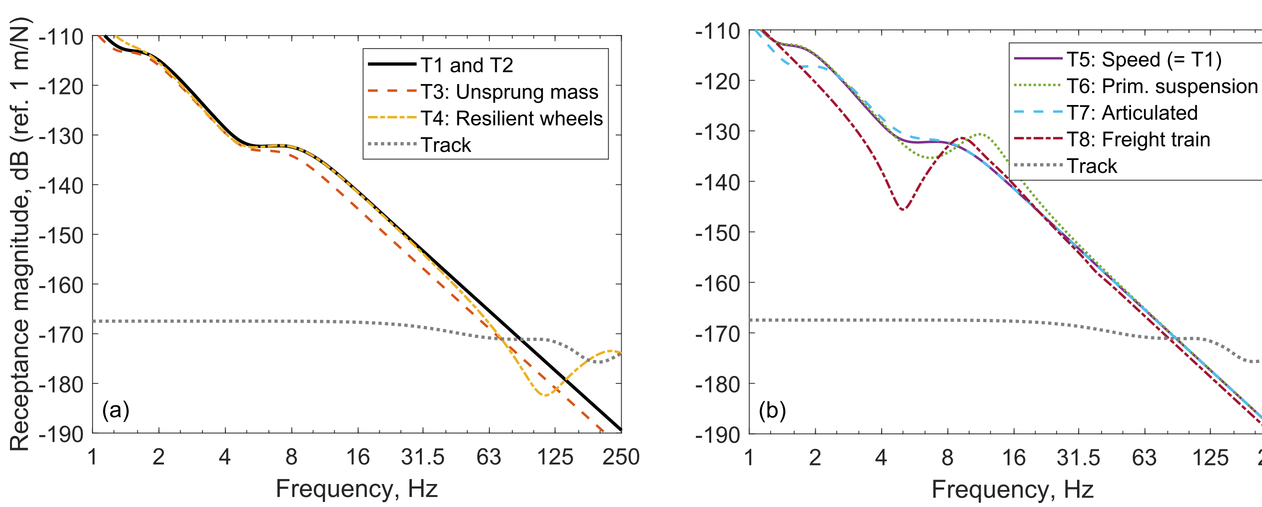

Fig. 5. Vehicle and track receptance (narrow band) in dB (ref 1 m/N) for the eight train test cases obtained using the MOTIV model. (a) Train cases T1, T2, T3 and T4; (b) train cases T5, T6, T7 and T8.

as mentioned earlier. Between 31.5 Hz and 63 Hz, train T4 again shows higher force density levels than train T1, with a maximum difference of about 1.5 dB at 50 Hz. Above 63 Hz, the force density levels become lower than those of train T1 as the P2 resonance of train T4 is around 70 Hz.

The force density levels are increased when the train speed is increased from 100 km/h (T1) to 120 km/h (T5) due to the shift in frequency content of the unevenness spectrum. The modified primary suspension of train T6 affects the vehicle receptance in the frequency range 5 – 40 Hz and in turn the force density. The maximum difference is about 5 dB in the 12.5 Hz frequency band.

For the articulated train case T7 the force density levels shown in Fig. 4(b) are lower than for the standard IC train case T1 in almost all frequency bands although the receptances are similar. The difference in force density is less than about 3 dB above 8 Hz and is caused by the reduction of the number of axles. At lower frequencies there are differences in the peaks and dips due to the different axle spacing. For the freight train T8, the force density levels are significantly higher than for the other trains below 8 Hz. This is caused by the lower wheelset receptance in these frequency bands due to the very stiff secondary suspension assumed for the freight train T8.

Weighted force densities and TVIs

Figs. 6 and 7 show the result of applying the frequency weightings $W_{F,i}$ to the force densities from Fig. 4 for the eight trains considered. These quantities show the frequency content of the weighted force densities that will be summed to give the TVIs. For the vibration-weighted levels in Fig. 6, the highest levels occur between 25 and 63 Hz, whereas for the noise-weighted levels in Fig. 7, the highest levels occur between 50 and 160 Hz. The weighted force densities from Figs. 6 and 7 are summed (Eq. (6)) to give the values of the TVIs. These are listed in Table 4. The differences between the TVIs calculated for train cases T2 to T8 and reference train T1 are also given.

From the results for T2, T3 and T4, both TVIs are affected by the changes in wheel condition and wheelset design. The increased wheel unevenness of train case T2 mainly affects the force density levels above about 50 Hz and so has negligible effect on TVI_1 due to the low weighting values applied at these frequencies. However, it leads to a 3 dB increase in TVI_2 (the highest value of TVI_2 of all cases). Train T3 with the higher unsprung mass shows the highest force density levels between 20 and 50 Hz, which results in a TVI_1 that is more than 4 dB higher than the standard IC train T1 and a TVI_2 that is about 1.5 dB higher than T1. This is the highest value of TVI_1 of all the train cases. The resilient wheels of train T4 give an increase of about 0.5 dB in TVI_1, but they reduce the spectrum above 50 Hz and lead to a reduction of about 2 dB in TVI_2.

The increase in train speed (T5) leads to an increase of 2 dB in both indicators. The primary suspension stiffness and design of train T6 has the smallest effect on the calculated TVIs, with differences of 0.5 dB compared with train T1. This is because the differences in the vehicle receptance and the force density levels are mainly concentrated in the frequency range 5–20 Hz where both weightings $W_{F,1}$ and $W_{F,2}$ have relatively low values (see Fig. 2).

The articulated train T7, with its lower axle density, yields a reduction of 1 dB in both indicators. Conversely, the freight train T8 has a higher axle density than the passenger trains due to having shorter vehicles and this leads to a small increase in both TVIs. Additionally, high force density levels are obtained in the frequency bands 2–8 Hz which lead to a value of TVI_1 which is about 3 dB higher than train T1.

Vehicle indicator robustness

Compared with the ground vibration levels during train passages, the force density is much less dependent on the track and ground properties [18–20] and hence on the site selected for the measurement. Nevertheless, relatively small changes of the force density levels in the critically weighted frequency bands may affect the magnitude of the estimated TVIs. This subsection investigates the robustness of the proposed TVIs when using force densities obtained from different sites.

To investigate the robustness of the TVI to changes in site properties, the measurement of the force densities is simulated for eight additional test sites, labelled S2 to S9, and compared with the reference site used in Section '**Examples of vehicle indicator for different rolling stock**' (labelled S1). For each site the TVIs are calculated by weighting the measured force densities for the eight vehicle cases listed in Table 2 with the weighting functions proposed in Section '**Definition of track-independent vehicle indicator**'. The test sites S2 to S9 differ from the reference site in the following ways:

(i) S2: track with softer rail fasteners (40 MN/m instead of 150 MN/m),
(ii) S3: track with ballast layer that is softer (250 MN/m instead of 500 MN/m) and heavier (2000 kg/m instead of 1485 kg/m),
(iii) S4: the slab track of Table 5 instead of the ballasted track of Table 1,
(iv) S5: softer soil with S-wave speed of 100 m/s and P-wave speed of 200 m/s,
(v) S6: stiffer soil with S-wave speed of 400 m/s and P-wave speed of 800 m/s,
(vi) S7 soil with damping loss factor of 0.1 (higher than the reference site S1),

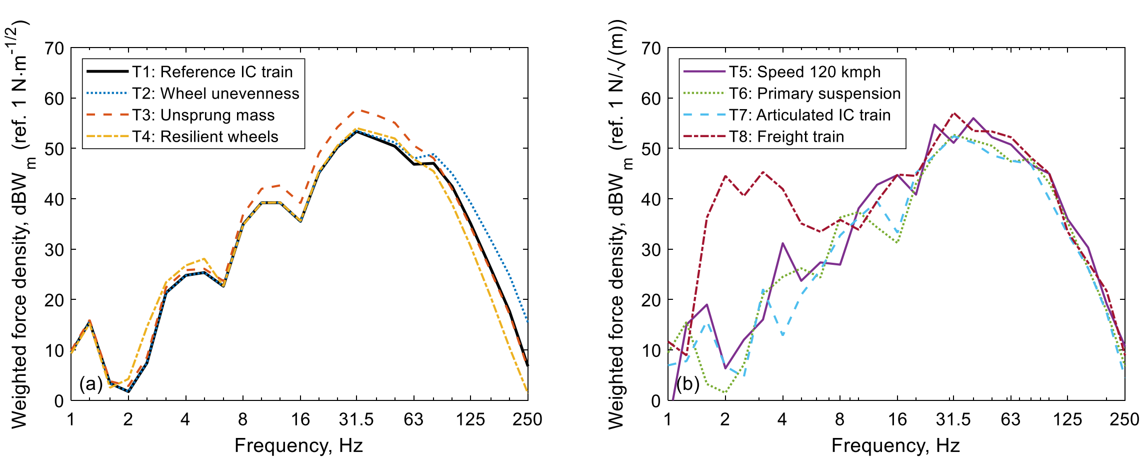

Fig. 6. Weighted force density spectra $L_F(\mathbf{X}, \mathbf{x}_r) + W_{F,1}$ for vibration. (a) Train cases T1, T2, T3 and T4; (b) train cases T5, T6, T7 and T8.

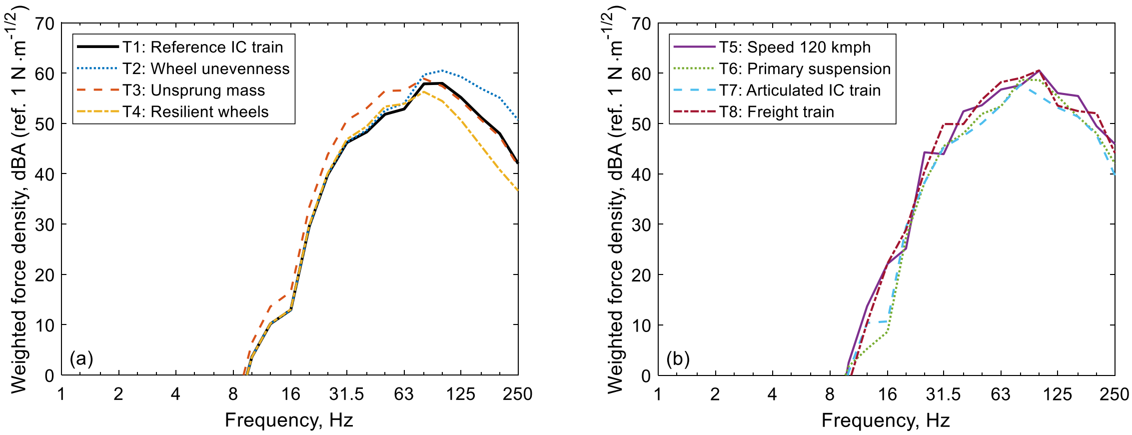

Fig. 7. Weighted force density spectra $L_F(\mathbf{X},\mathbf{x}_r) + \mathrm{W}_{F,2}$ for noise. (a) Train cases T1, T2, T3 and T4; (b) train cases T5, T6, T7 and T8.

Table 4
TVI_1, TVI_2 and differences relative to train T1.

Train case	TVI_1 dB ref. 1 $\mathrm{N}/\sqrt{\mathrm{m}}$	TVI_1 difference vs T1, dB ref. 1	TVI_2 dB ref. 1 $\mathrm{N}/\sqrt{\mathrm{m}}$	TVI_2 difference vs T1, dB ref. 1
T1, reference train	58.7		63.5	
T2, high wheel roughness	59.1	0.4	66.4	2.9
T3, high unsprung mass	62.9	4.2	64.8	1.3
T4, resilient wheels	59.4	0.7	61.7	−1.8
T5, change in train speed	60.9	2.2	65.5	2.0
T6, primary suspension	58.2	−0.5	64.0	0.5
T7, change in axle spacing	57.8	−0.9	62.5	−1.0
T8, freight train	61.7	3.0	65.7	2.2

Table 5
Properties of the slab track.

Rail UIC60	Bending stiffness	6.4 MN m^2
	Mass per unit length	60 kg/m
	Damping loss factor	0.01
	Track gauge	1.435 m
Rail fastener	Stiffness	120 MN/m
	Damping loss factor	0.15
	Spacing	0.65 m
Slab	Width	3.4 m
	Mass per unit length	3720 kg/m
	Bending stiffness	233 MNm^2
	Damping loss factor	0.015

(vii) S8 layered soil with a 2 m thick top layer with S-wave speed of 100 m/s and P-wave speed of 200 m/s on top of a halfspace with S-wave speed of 400 m/s and P-wave speed of 800 m/s, and
(viii) S9: the same site conditions as the reference site S1, but with the force density calculated using a distance from the track of 8 m instead of 16 m.

All the other site properties are identical to the properties of the site S1 and are given in Section '**Examples of vehicle indicator for different rolling stock**'. The force densities are obtained from Eq. (5) using the vibration velocity levels of the train passages $L_v(\mathbf{x}_r)$ and the line source transfer mobilities $L_{Y_L}(\mathbf{X},\mathbf{x}_r)$ obtained with the MOTIV model.

It is assumed that all the sites have the same track unevenness. It is recognised that, in practice, in any measurement of vibration or force density, the result will be sensitive to the combined wheel and track unevenness. A test site with high levels of track unevenness would lead to unrepresentable values of TVI, which would not be a true characterisation of the vehicle performance. It is recommended, therefore, to use a procedure similar to that adopted for acoustic tests in ISO 3095 [3], in which the track unevenness spectrum at the test site is controlled to ensure that it lies below a specified limit spectrum.

For greater precision, a transposition method can be considered, in which corrections are applied to the force density estimates so that they correspond to a reference site. In particular, differences in track unevenness relative to a reference situation can be applied as corrections to the corresponding force densities. However, it is important that the TVI captures the influence of high values of wheel unevenness, as this is a parameter representing the condition of the vehicle under test (e.g. train T2). Thus, while it is desirable to use a transposition procedure to remove the influence of track unevenness, care is needed in situations where the wheel unevenness is prominent. As it is usually impractical to measure the wheel unevenness, it is not feasible to allow for this directly in making any transposition. In practice, as seen in Fig. 3, the unevenness of the wheel is generally lower than that of the track except at short wavelengths. This suggests that the track unevenness must be kept below the specified limit spectrum for wavelengths shorter than 0.5 m, but that a transposition procedure could be applied for longer wavelength unevenness.

Fig. 8 shows the force density levels of train T1 at the eight different sites. The corresponding vibration velocity levels $L_v(\mathbf{x}_r)$(at $\mathbf{x}_r = 16$ m for sites S1 to S8 and $\mathbf{x}_r = 8$ m for site S9) due to the passage of the train T1 are given in Fig. 9. Large differences are present in the velocity levels, especially where a change in the transmission path has occurred (different soil stiffnesses in cases S5 and S6, soil damping in case S7, soil stratification S8, or different distance from the track in case S9) and this can affect the whole frequency range. However, when these results are converted to force densities the differences are much smaller and limited mainly 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 (S2), the ballast stiffness and mass properties (S3) or the track type (S4). For these three situations, differences up to about 2.5 dB are found in the frequency range 20 – 63 Hz which is critical for ground-borne vibration and up to about 12 dB in the frequency range 100 –160 Hz which is important for ground-borne noise. Similar differences in dB can be seen in the

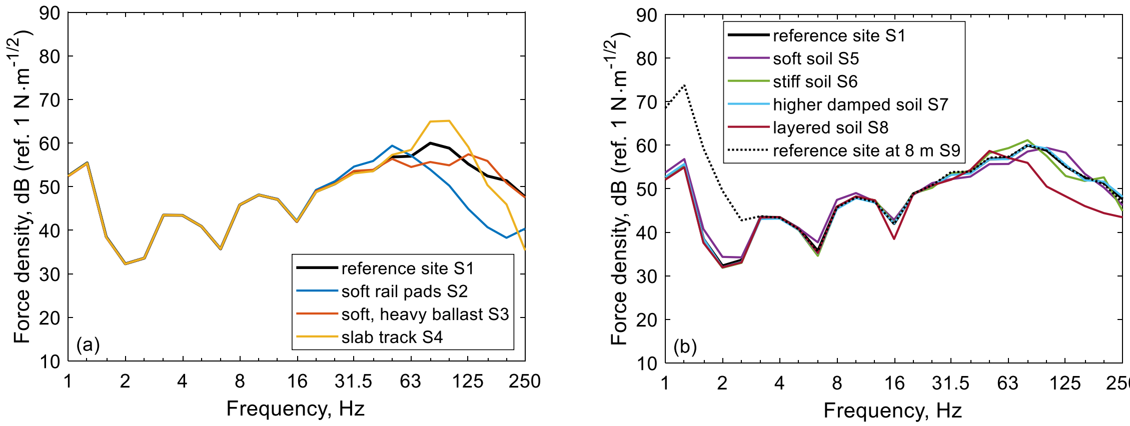

Fig. 8. Force density of generic IC train T1 at different sites. (a) Sites S1, S2, S3 and S4; (b) Sites S1, S5, S6, S7, S8 and S9.

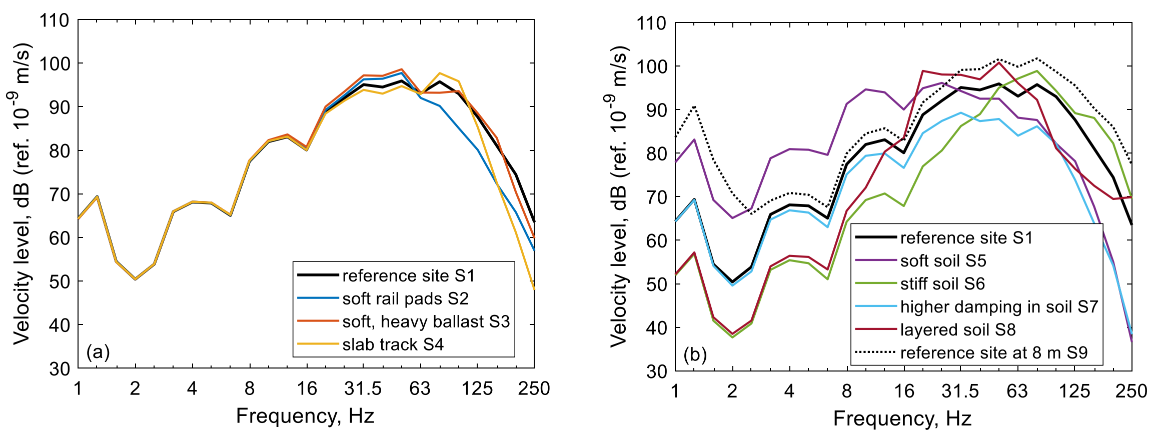

Fig. 9. Vibration velocity levels of generic IC train T1 at different sites. (a) Sites S1, S2, S3 and S4; (b) Sites S1, S5, S6, S7, S8 and S9.

vibration velocity levels shown in Fig. 9 for these three situations. For sites S5, S6, S7 and S8, the large change in soil stiffness, damping, or soil stratification results in differences in velocity levels of more than ± 10 dB, but despite this the force density levels are affected by less than 3 dB for sites S5, S6 and S7; site S8 shows higher variation (up to about 8 dB) at frequencies above 80 Hz. For site S9, with the receiver distance of 8 m, the response to quasi-static excitation is much higher, which affects the force density levels below 3 Hz, but at higher frequencies the force density is unaffected.

In Tables 6 and 7 the values of the two TVIs are listed for train T1, as well as the relative differences between all the other trains and case T1 using the force densities obtained from the different sites. When the site conditions change, the values of the TVIs are affected. TVI_1 for train T1 varies in a range of around ± 1 dB whereas TVI_2 can vary by up to ± 4 dB for changes in the track properties and soil layering, and less than ± 0.5 dB for changes in the soil stiffness, damping, or receiver distance. Similar variations are found for the TVIs of the other trains T2 to T8 (not shown here). 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 with a range of up to 0.8 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 TVI_2, the differences between the different train cases show greater variation when changing the site conditions. Ranges of up to 2 dB are found when changing the track properties, whereas changes in the soil properties yield ranges of only up to 0.5 dB. Consequently, the classification of the vehicle performance based on the proposed noise TVI would be slightly less reliable when using force densities measured at sites with significantly different track properties.

The results in this section have shown that the proposed TVI-based classification is generally not very sensitive to changes in the test site

Table 6
TVI_1 for vibration in dB ref. 1 N/$\sqrt{m}$ at different sites for train case T1 and differences of train cases T2-T8 relative to train T1.

	T1	T2–T1	T3–T1	T4–T1	T5–T1	T6–T1	T7–T1	T8–T1
S1: Reference site	58.7	0.4	4.2	0.7	2.2	−0.5	−0.9	3.0
S2: Soft rail pads, reference soil	59.9	0.4	4.5	0.6	2.3	−0.1	−0.9	3.2
S3: Soft, heavier ballast reference soil	58.4	0.4	4.2	0.7	2.3	−0.5	−0.9	3.0
S4: Slab track, reference soil	59.3	0.7	4.4	0.7	2.0	−0.2	−0.7	3.0
S5: Reference track, soft soil	59.3	0.4	3.8	0.7	2.0	−0.5	−1.1	3.2
S6: Reference track, stiff soil	58.0	0.5	4.6	0.8	2.2	−0.4	−0.6	2.8
S7: Reference track, high soil damping	58.6	0.4	4.2	0.7	2.2	−0.5	−0.9	2.9
S8: Reference track, layered soil	58.7	0.4	4.1	0.5	2.1	−0.1	−1.0	3.0
S9: Reference site at 8 m	58.7	0.4	4.2	0.7	2.2	−0.5	−0.9	3.0

Table 7
TVI_2 for noise in dB ref. 1 $N/\sqrt{m}$ at different sites for train case T1 and differences of train cases T2–T8 relative to train T1.

	T1	T2–T1	T3–T1	T4–T1	T5–T1	T6–T1	T7–T1	T8–T1
S1: Reference site	63.5	2.9	1.3	−1.8	2.0	0.5	−1.0	2.2
S2: Soft rail pads, reference soil	59.7	1.6	2.2	−0.5	2.4	0.7	−0.5	3.3
S3: Soft, heavier ballast reference soil	62.5	3.6	1.2	−2.0	2.2	0.2	−1.1	1.8
S4: Slab track, reference soil	67.8	2.5	0.7	−2.5	1.6	1.2	−1.3	2.0
S5: Reference track, soft soil	63.7	3.1	1.2	−1.9	2.0	0.4	−1.4	2.3
S6: Reference track, stiff soil	63.8	2.6	1.7	−1.6	1.8	0.7	−0.9	2.5
S7: Reference track, high soil damping	63.6	2.9	1.3	−1.8	1.9	0.5	−1.1	2.3
S8: Reference track, layered soil	60.0	2.4	1.6	−1.3	2.0	0.6	−0.8	2.6
S9: Reference site at 8 m	63.5	2.9	1.3	−1.8	2.0	0.5	−1.0	2.2

conditions for which the force density is obtained. Nonetheless, to increase the consistency of the TVI-based classification when using force densities measured at significantly different sites it is often desirable to base the calculation of the TVIs on a reference situation by applying a transposition method, similar to the methods proposed in [29,30], to the force density estimates so that they correspond to a reference site. This can be performed by using measurements or numerical models to predict the differences in the vibration level for sites with known different characteristics (i.e., soil stiffness, track type) and applying these differences as correction factors to the measured vibration spectrum. In such a prediction scheme based on the force density, transposition from site A to site B will depend on (i) identifying the force density through measurements at site A, and (ii) applying correction terms, estimated either from measurements or predictions, to determine the force density that applies at site B that will be used with the proposed weighting to predict the TVIs.

Representativeness of vehicle indicators

The weighting functions introduced in Section '**Definition of track-independent vehicle indicator**', that are used in determining the proposed vehicle indicators, are chosen to represent a nominal track, ground, and building. Here, it is assessed to what extent the TVIs are representative of the *relative* changes in vibration and ground-borne noise that will occur when changing from one vehicle type to another, even when the ground, track, building and receiver distance do not correspond to the chosen nominal conditions. The purpose is to demonstrate whether the TVI-based classification of different vehicles that has been determined at a specific test site is representative of sites with significantly different conditions.

The vibration and noise levels are calculated for the eight different train cases T1 to T8 of Table 2 for a range of different site conditions (soil, track, building distance, building type and measurement conditions) using the MOTIV model and applying different building correction factors C_T^{vib} and C_T^{noise} for vibration and noise respectively. These are calculated, not by weighting the force densities as in the previous section, but by applying C_T^{vib} and C_T^{noise} directly on the predicted ground vibration levels $L_v(\mathbf{x}_r)$. They are expressed in dB ref. 10^{-9} m/s for vibration and in dB ref. $2 \bullet 10^{-5}$ Pa for noise. The overall vibration and noise levels are calculated as the sum over all frequency bands between 2 Hz and 80 Hz for vibration and between 20 Hz and 250 Hz for noise, after applying the W_m weighting [26] (converted to apply to a velocity spectrum) and A weighting curves respectively.

The difference in the overall vibration and noise levels between each train type and train type T1 are given in Figs. 10 and 11 for the eight different sites. Results are shown for the reference site V1 (presented in Section '**Examples of vehicle indicator for different rolling stock**') and nine alternatives:

– V2 that has a different rail fastener stiffness (softer rail fasteners 40 MN/m instead of 150 MN/m; similar to site S2 in Section '**Vehicle indicator robustness**'),

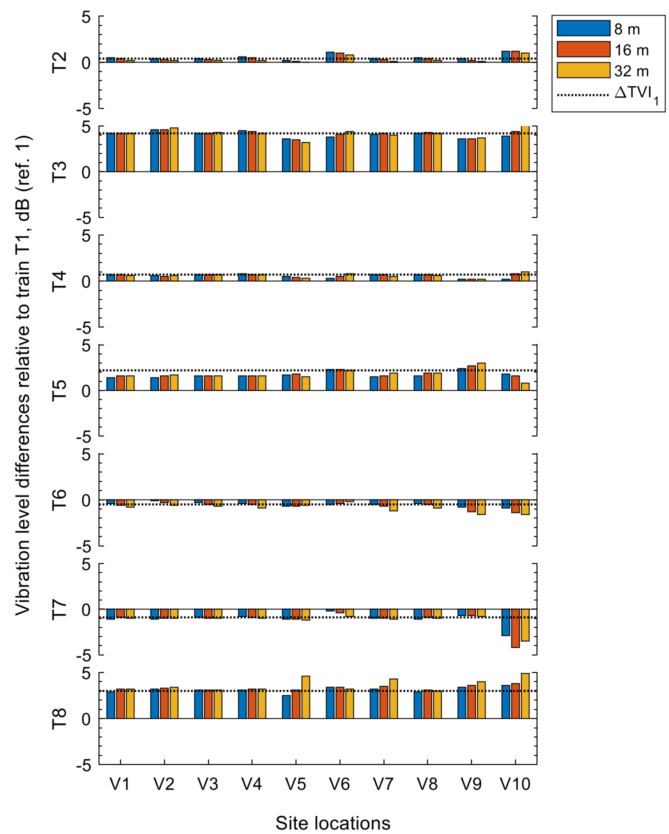

Fig. 10. Comparisons in dB ref. 1 of the differences relative to train T1 between the overall vibration levels at 8 m, 16 m, 32 m and the proposed TVI_1 for different site conditions V1 to V10.

– V3 that has different ballast properties (softer with 250 MN/m instead of 500 MN/m and heavier with 2000 kg/m instead of 1485 kg/m; similar to site S3 in Section '**Vehicle indicator robustness**')
– V4 that has a different track type (slab track instead of ballasted track with properties given in Table 5; similar to site S4 in Section '**Vehicle indicator robustness**'),
– V5 that has softer soil with the wave velocities halved (similar to site S5 in Section '**Vehicle indicator robustness**'),
– V6 that has stiffer soil with the wave velocities doubled (similar to site S6 in Section '**Vehicle indicator robustness**'),
– V7 that has a soil with higher damping (similar to site S7 in Section '**Vehicle indicator robustness**'),
– V8 that has a different building type (small building with concrete floors instead of tall building from [27]),
– V9 that has a different building type (house with wooden floors instead of tall building from [27]),
– V10 the track is located in a 0.25 m thick concrete tunnel at 10 m depth (tunnel external radius is 3 m),

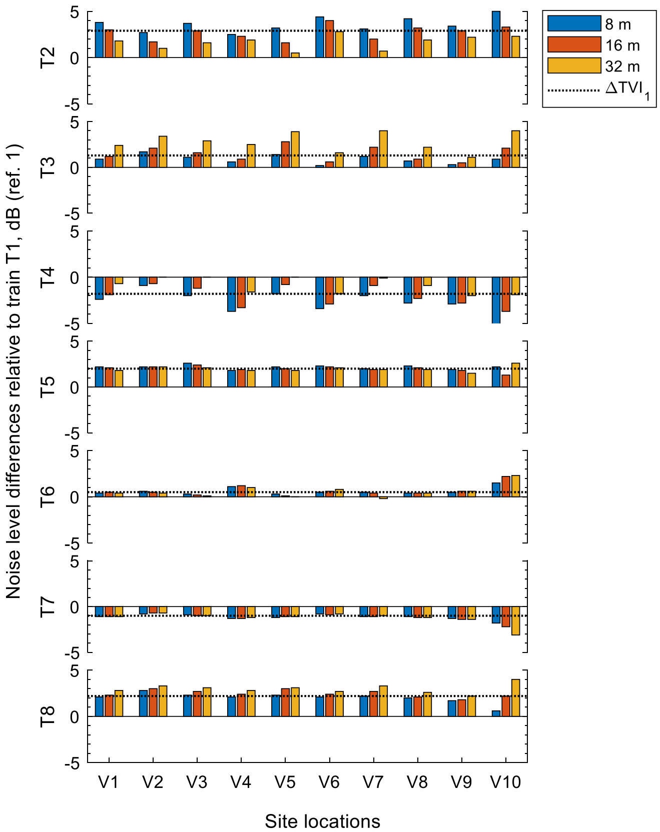

Fig. 11. Comparisons in dB ref. 1 of the differences relative to train T1 between the overall noise levels at x_r = 8 m, 16 m, 32 m and the proposed TVI_2 for different site conditions V1 to V10.

The results are also shown for two other receiver distances x_r, 8 m and 32 m to consider the potential differences between an urban site and a suburban site. For comparison, in Figs. 10 and 11, the differences in vibration TVI_1 and noise TVI_2 relative to train T1 calculated in Section '**Examples of vehicle indicator for different rolling stock**' are also shown as dotted lines. It should be noted that due to the running average smoothing applied to the TVI weighting functions, the differences obtained between the overall vibration and noise levels of site V1 at x_r = 16 m do not match exactly the differences of the TVIs.

The vibration velocity levels for train T1 calculated for site V1 at x_r = 16 m and x_r = 32 m and those calculated for the tunnel site V10 are shown in Fig. 12. The ground vibration levels at x_r = 16 m for the reference train T1 for sites V1 to V7 correspond to the results shown in Fig. 9 for sites S1–S7. Sites V8 and V9 have the same ground response as site V1 since their differences are in the building type.

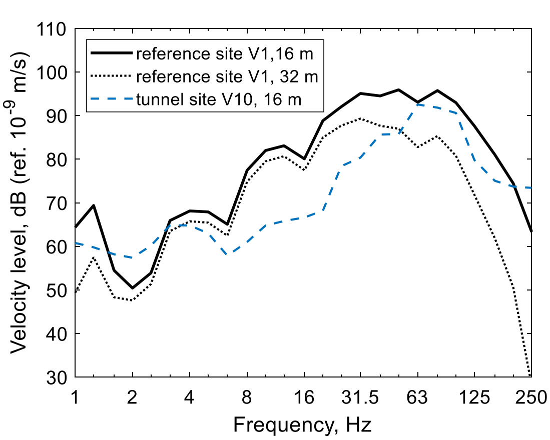

Fig. 12. Vibration velocity levels of generic IC train T1 for site V1, at 16 m and 32 m from the track, and for site V10 at the ground surface 16 m from the tunnel centre.

Considering the differences between the overall vibration levels for each train relative to train T1 in Fig. 10, the results are relatively consistent for the three receiver distances x_r. Moreover, these results are consistent between most of the sites, with the highest variations shown for the tunnel site V10. When comparing the overall vibration differences with the differences in vibration TVI_1 relative to train T1, it can be seen that the differences in TVI_1 are representative of the changes in vibration levels that will occur when changing from one vehicle type to another across a range of situations.

For the differences in overall noise levels for each train relative to train T1, shown in Fig. 11, larger variations are found between the results at different receiver distances x_r. This variation with receiver distance is higher (up to about 3 dB) when comparing trains T2, T3, and T4 with train T1 and seems to be relatively consistent for all site locations V1 to V10. However, the chosen receiver distance (16 m) used for the calculation of the noise indicator TVI_2 seems to be a good compromise.

Conclusions

Two different 'track-independent vehicle indicators' were proposed, one representative of ground-borne vibration and the other of ground-borne noise. The proposed TVIs are based on applying a frequency weighting to a measured force density to represent the overall vibration and noise levels in a nominal building on a nominal soil. Although the measurement of line source transfer mobilities and of the vibration during train passages, that are used for the indirect calculation of the force density, involves a significant measurement effort, this characterisation of the test site can form part of a standardised measurement method for assessing the vibration emission of rolling stock. To demonstrate the use of the TVIs, they were calculated for several types of train using force densities calculated from ground vibration predictions at a specific site using the MOTIV model. 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, resilient wheels, primary and secondary suspension stiffness, train speed, number of axles per unit length and axle spacing. The results showed that the TVI values for each vehicle may vary in some cases by more than 5 dB due to the differences on the vehicle parameters and the proposed performance classification of different vehicles can be achieved by comparing these relative differences of their TVIs.

The vibration vehicle indicator is generally robust to changes in site conditions at which the force density is obtained. Similar changes in the vibration TVI between the train types were found for different sites, within a range of 0.8 dB. For the noise TVI, in some cases, the variations are slightly greater, with ranges of up to 2 dB when changing the track properties. Thus, in specifying a test site for standardised measurements, it is more important to define the track properties than the ground properties. To eliminate the effect of the track unevenness, and to increase the reliability of the TVI-based classification when using force densities measured at significantly different sites, use of a transposition of vibration data was proposed.

The ground borne vibration and noise levels were considered at different sites and in different buildings. The relative changes in the TVIs were 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. Therefore, the results of the vehicle classification presented in this study can be used as a reference example of the ground-borne noise and vibration variation due to typical mixed train traffic on a railway line.

The main practical application of the proposed TVIs is that they allow the characterisation of railway vehicles in terms of their ground-borne noise and vibration emission independently of both the track and ground at a test site. The results presented here were based on simulations using numerical models; however, future studies that involve field measurement data are needed to evaluate the practicality of this approach and of similar approaches proposed in the literature.

CRediT authorship contribution statement

E. Ntotsios: Conceptualization, Data curation, Writing – original draft, Investigation, Validation, Formal analysis. **D.J. Thompson:** Conceptualization, Funding acquisition, Data curation, Writing – review & editing, Methodology. **P. Reumers:** Data curation, Investigation, Validation. **G. Degrande:** Funding acquisition, Writing – review & editing, Methodology. **P. Bouvet:** Project administration. **B. Nélain:** Data curation, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data published in this article are openly available from the University of Southampton repository at https://doi.org/10.5258/SOTON/D2965.

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