RAILWAY INDUCED **VIBRATION**

State of the art report

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Content

Executive summary

In modern daily life, people are exposed to many types of vibration. The vibration is often accepted as obvious and no cause for concern, for example when driving a car or when riding in a lift. In some cases, vibration originating from sources outside the house may be felt inside dwellings. This applies for example to heavy road traffic, trams and railway lines, both on surface lines and in tunnels. This vibration is typically observed as a gentle trembling of the house, usually of the floor people are standing on. The vibration itself can generate a rumbling sound, caused by the vibrating building radiating sound into the rooms (known as structure-borne sound). Secondary noise, i.e. rattling of loose doors, pottery, etc., can further amplify the audible noise or make it more noticeable.

Whether or not the vibration can be perceived depends on many factors, including distance to the source, speed and type of the traffic, quality of the road or track, type and build-up of the ground, and the construction of the building itself. Modifications performed in the soil (modification of the sewer network, for example) or even in adjacent buildings can give rise to an increase of vibration or ground-borne noise. Contrary to popular belief, **vibration caused by passing trains is far too weak to cause even cosmetic damage[1] to buildings**. Nevertheless, residents affected by vibration may experience annoyance and could thus voice concern. The degree to which the vibration sensation is masked by audible noise can also play a role, as well as the personal sensitivity.

Railway-induced vibration was first noticed and labelled an issue in relation to underground train lines. It is only in recent times that the vibration from surface lines is getting more attention. Vibration is usually accompanied by ground-borne noise. The relative significance of these two phenomena depends mainly on the soil type. In countries with stiff soils, e.g. solid rock, ground-borne noise is generally more important than vibration, and dominant vibration frequencies are higher (i.e. around 50 Hz). In countries with soft soil such as clay or peat, vibration may be more important than ground-borne noise and dominant vibration frequencies are lower (around 5 Hz). This difference in soil type is an important factor affecting the performance and selection of mitigation measures.

For railways, vibration is most often generated by the contact between the train wheel and the railway track. The vibration then travels from the track, through the ground and into the building foundation. Generally, the strength of ground vibration reduces as one moves away from the track. However, the strength of vibration may increase when moving up floors inside the building due to resonances of the building structure.

There are a number of mitigation measures available that can be applied to either the track or the vehicle. Because local factors (terrain, construction of individual buildings, space etc.) have a strong influence, the effectiveness of these measures can differ greatly from case to case. The prediction of

1. Cosmetic damage is damage that does not affect the structural integrity of the building.

vibration levels is thus a complex process and often involves a large degree of uncertainty. In some cases, especially existing situations, the cost of mitigation may be prohibitively expensive. In assessing vibration and designing mitigation, expert judgement is required.

Guidelines for acceptable levels of vibration vary from country to country. The impact on residents depends strongly on individual and local circumstances. Therefore, any values mentioned in this report should be interpreted with great care.

For new situations (railway lines or residential and other property development), it may be required to assess vibration and propose mitigation measures in the environmental impact assessment. For existing situations, most countries do not have a legal obligation for railway companies to assess and mitigate vibration. However, railways take residents' concerns seriously and, where appropriate, will support an assessment and consider mitigation measures.

The present report reflects the state of the art, which is mainly based on the experience of the European rail-operating community, publications from academia and consultancy, the results of the collaborative research projects RIVAS and Cargovibes, and the work of standardisation committees, insofar as it has been published.

1. Introduction to vibration

The present document is a state-of-the-art report about railway vibration (including re-radiated noise, see 1.1 below) and its environmental aspects. Furthermore, it addresses ground-borne noise as an effect of vibration being transmitted through the ground. The aim of this report is to inform a range of stakeholders about this complex theme. The target audience includes non-expert but interested readers (members of the public who encounter noise and vibration from railways), but also public authorities involved in railway vibration issues, representatives of railway companies and vibration specialists.

Guidance to readers

Most of the chapters start with a box of text to explain the matter at hand in a non-scientific way. These are then followed by a more detailed and in-depth discussion of rail vibration intended for vibration specialists. A list of references is included at the end of this report. In the text, reference to specific background or source is indicated by the symbol [ ]. However, the list also includes more general references.

In modern daily life, people are exposed to many types of vibration. Typical examples include vibration from car engines experienced whilst driving, vibration perceived through the hand when using a food processor in the kitchen, whole-body vibration commonly experienced when standing close to a washing machine. For railway vibration, a whole-body vibration is often experienced by waiting passengers on a station's platform.

Basically, any type of rotating machinery will cause vibration. This vibration can be transmitted through the structure of a building and then perceived in other rooms, away from the source. Often, the perception is a mixture of acoustic sensations (sound) and dynamic sensation (vibration). In many cases, the vibration is accepted as being obvious and of no cause for concern, for example when driving a car (vibration from the unevenness of the road surface are transferred through the tyres, the car body and the seats; vibration from the engine is transferred through the mounting of the engine and the vehicle structure), or when riding in a lift.

In some cases, vibration originating from sources outside the house may be felt inside dwellings. This applies for example to construction work like pile driving, heavy road traffic, trams and railway lines, both on surface lines and in tunnels. Whether or not the vibration can be perceived depends on many factors, including distance to the source, speed and type of the traffic, quality of the road or track, surface line or tunnel, type and build-up of the ground, the way the building is supported by its foundation and the construction of the building itself. In addition, the degree to which the vibration sensation is masked by audible noise can play a role, as well as the individual sensitivity of the person exposed.

Railway vibration is typically observed as a gentle shaking or trembling of the house, usually of the floor people are standing on. The shaking of the construction can be sensed with the hand, the feet or indeed the whole body. It feels as if the construction is trembling slightly. In addition to the movement, often a weak rumbling sound is observed, caused by the vibrating building construction radiating sound into the rooms (known as ground-borne noise). In addition to ground-borne noise, audible sound may be augmented by rattling of loose doors, pottery, glassware in cupboards, etc.

For railways, the vibration is most often generated by the contact between the train wheel and the railway track. The vibration then travels from the track, through the ground and into the building foundation. Generally (but not always!) the strength of ground vibration reduces as one moves away from the track. However, the strength of vibration may increase when moving up inside the building due to resonances of the building structure.

In all but the most extreme situations, vibration caused by passing trains is far too weak to cause damage to buildings. Nevertheless, such harmless vibration may be noticed by people and may cause annoyance or concern.

Annoyance and concern are usually experienced with more emphasis whenever a change to an existing situation occurs. In many countries, an impact assessment is required only in combination with a spatial planning procedure. This is required in the case of a new or significantly upgraded railway line. The latter expressions refer to substantial physical changes of the track layout.

In these cases, an assessment of vibration impact may be required as a part of the associated Environmental Impact Assessment. Guidance or accepted practice for appropriate vibration targets or thresholds vary from country to country; these may be set for an absolute level of vibration or for an increase due to the planned upgrade.

In exceptional cases (e.g. Switzerland), environmental legislation also covers vibration from operations on existing railway lines, but this is not usually the case. Regardless of the regulatory situation, infrastructure managers may receive complaints about vibration due to current rail operations. In some cases (e.g. in Norway), a measurement would be carried out – normally on a voluntary basis[2] - to assess the vibration magnitude. In Sweden, measurements are carried out in cases where it cannot be guaranteed that the estimated level is below the guideline level. Such measurements are preferably done on the foundation, outside the building (to avoid having to enter the property). The application of mitigation measures to existing lines or buildings is often expensive – and can be prohibitively so. In some situations, it remains unclear as to how successful the measures were, for example because the original estimate without mitigation was inaccurate in the first place.

When limits extend to existing situations, infrastructure managers may be obliged to take action when the traffic changes, e.g. after a speed increase or a change of vehicle type.

A special case is the planning or construction of new developments in the vicinity of existing railway lines or tunnels. In such cases, the party developing the property is normally responsible for ensuring compliance with the appropriate vibration limits. If considered necessary, measures to reduce vibration can be applied to the building foundation and are normally a feasible option during the design phase.

2. In theory, based on the environmental health protection act in Norway, the health authorities might deem measurements to be necessary, and the railway infrastructure manager would have to comply.

1.1 More detailed introduction

The present report deals with ground-borne vibration (i.e. originating in the ground and travelling through the ground), generated by running trains, both on surface lines and in tunnels, and its impact on persons in buildings close to the track. It is important to distinguish this subject from other, related subjects like air-borne noise, ground-borne noise, low frequency noise and structure-borne noise.

The different adjectives may be confusing, as they may refer to either the transmission medium or the generation medium, as well as to the sensory impact that they cause.

Sound is what a healthy human being can hear, and consists of longitudinal compression waves (air particles vibrating parallel to the propagation) in air, with frequencies between roughly 20 and 20,000 Hz. Ultrasound (frequency above 20,000 Hz) is not relevant to this report. Infrasound (frequency below 20 Hz) cannot usually be heard, but is often associated with vibrating structures.

At these low frequencies, it is sometimes difficult to recognise which of the sensory systems is at stake: feeling vibration or hearing sound.

Noise is unwanted **sound**.

Low frequency noise is noise at the lower end of the frequency scale. Salford University defines it as sound with frequencies between 20 and 160 Hz. Some researchers (e.g. Brigitta Berglund of Stockholm University), however, include infrasound, as some individuals are able to detect air-borne sound with frequencies lower than 20 Hz. Low frequency noise is an issue of growing concern in relation to e.g. wind farms, and is sometimes mentioned in cases where ground-borne noise is identified.

Air-borne noise consists of the progressive vibration of air particles in the form of sound waves propagating at a speed of 344 m/s (in normal circumstances). It is sound that is mainly transmitted through air, e.g. in a personal conversation where one person represents the source and another person the listener, as opposed to structure and ground-borne noise (see below).

Structure-borne noise, which is mainly transmitted through a solid structure such as brick, steel, wood, concrete, stone etc. In solid structures, most of the energy is transmitted in the form of bending waves, with different propagation velocity than sound in air. However, before it reaches our ear, the vibrating solid structure radiates noise into a space such as a room. The amount of radiated noise depends on the strength of the vibration and the radiation efficiency of the structure. Finally, the vibrating air reaches our ear as sound.

Ground-borne noise is a special case of structure-borne noise, where the vibration travels through the ground. Usually it excites the building, travels through the building structure (as vibration) and is radiated into a room (exciting the adjacent air) where it is observed as ground-borne noise.

Often, a vibrating structure may excite the adjacent air and thus radiate sound into a half space such as a room. If the structure was excited by air-borne noise, then the resulting noise in the room is sometimes indicated as **re-radiated noise.**

In slightly more complex terms, and according to relevant standards, the following definitions apply:

1. *Ground-borne vibration* (which is the most commonly perceived kind of "vibration") is generated by the interaction between train and track (and subsoil). The vibration is transmitted through the ground and may reach the foundation of a building. The building responds to the vibration; vibration is transmitted through the building structure, and may be observed as perceivable vibration of the floor. Ground-borne vibration is associated with a frequency range of roughly between 1 and 100 Hz.

2. *Ground-borne railway noise* is defined in ISO 14837-1: ("Mechanical vibration – Ground-borne noise and vibration arising from rail systems – Part 1, General Guidance") as *"noise generated inside a building by ground-borne vibration generated from the pass-by of a vehicle on rail".* It applies to both heavy and light rail. Ground-borne noise excludes direct air-borne noise. Note that ground-borne noise is sometimes referred to as re-radiated noise, structure-borne noise (see 4) and solid-borne noise (according to ISO 14837). Ground-borne noise is the term used in this report. Its frequency range is roughly between 20 and 250 Hz.

3. *Air-borne railway noise* is generated by the wheel rail contact and the additional equipment (e.g. traction, ventilation and air conditioning) on board the train. For high-speed traffic, aerodynamic noise may be relevant, which is usually generated at protruding elements of the train body, such as the bogies, the pantographs, and the inter-coach gaps. For surface lines, the noise is radiated by the train and the track, travels through the air and may reach a building, where it is transmitted through the façades. It may reach a resident staying inside the building, who will notice it as audible noise. In the propagation paths, there are numerous phenomena attenuating the noise, for instance the distance between the source and the resident and the sound insulation of the façade. Air-borne noise can be in the full audio range between 20 and 20,000 Hz. Obviously, for tunnel lines, air-borne noise is not relevant.

4. *Structure-borne noise* occurs as a result of the vibration in the building structure. Structure-borne noise is also addressed as re-radiated noise (see 5 below). It is observed as audible noise, usually with a strong low frequency content (therefore sometimes addressed as low frequency noise). Even for a trained listener, it is difficult to distinguish audible structure-borne noise from sensible vibration, as the two are usually occurring in combination. In this report, we will prefer ground-borne noise as the term to indicate this phenomenon. Like ground-borne noise, structure-borne noise is found between 20 and 250 Hz.

5. *Re-radiated noise* (re-radiated either as ground-borne noise or structure-borne noise) occurs as a result of vibration and is observed as audible noise. This is also addressed as structure-borne noise. In this report, we will use ground-borne noise as the preferred term.

6. *Secondary effects*: A particular kind of re-radiated noise refers to the rattling of pottery or the trembling of doors as a result of vibration in the building structure.

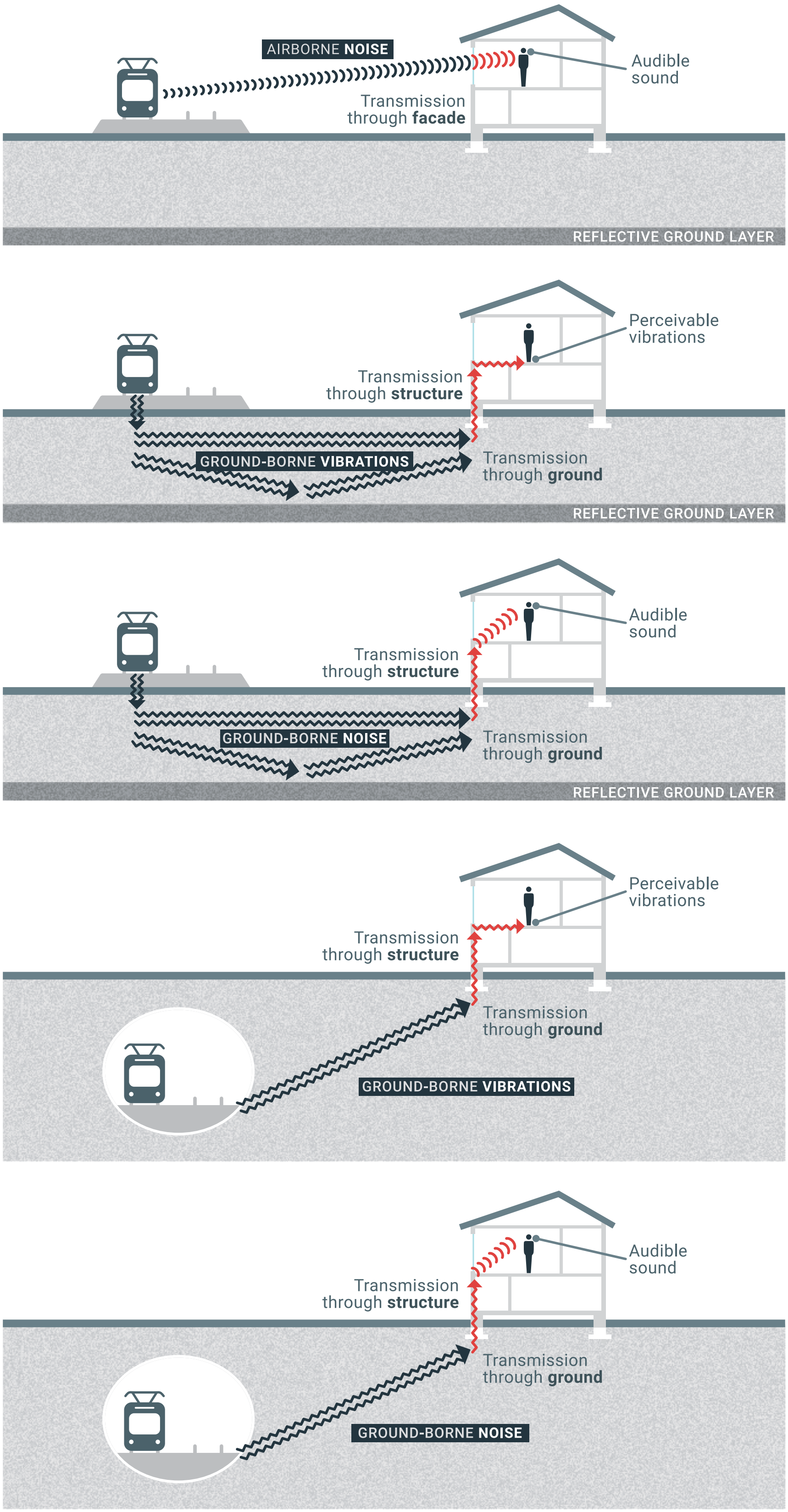
7. *Low frequency noise* is audible noise within a frequency range from 20 to 160 Hz. It can emerge from any source (not only vibration) but due to its significant low frequency content it requires different indicators (e.g. dB(C) instead of dB(A)). Low frequency noise is often difficult to measure and it can be very difficult to determine the source and transmission path (is it direct air-borne noise, ground-borne noise, secondary noise or a combination?). In some situations, normal audible noise can mask low frequency noise, making it harder to detect. However, in combination with ground-borne vibration, low frequency noise may be more easily noticeable. Particularly for underground train lines, low frequency noise can be a clear indication of the pass by of a rail vehicle.

The efficient control of environmental noise and vibration requires a good understanding of the different generation mechanisms and transmission paths. If these are not adequately separated during the analysis, then any subsequent proposals for mitigation may have limited results. As with sound, the most efficient way to control vibration is usually at the source.

1.2 Variability

This document presents characteristics of vibration caused by rail traffic. The relevance and representability of these characteristics is highly dependent on the local situation. Particularly the properties of the soil affect the vibration that may or may not excite adjacent buildings. The variability of these properties is significant, particularly between areas with typical soft soil (as in the Netherlands or in the south of Sweden) and areas with stiffer soil (as in mountainous areas in Switzerland). The variability particularly affects the relevant range of frequencies of the resulting vibration and the effectiveness of mitigation measures. In soft ground, the frequency range of vibration is lower and – generally speaking – measures in the track are less effective. In stiff grounds, the frequencies are higher, ground-borne noise is more relevant than vibration, and measures in the track may be more effective.

These topics will be discussed in more detail in the chapters below.



Graph 1. The different generating mechanisms and transmission paths of air-borne noise (not applicable for underground line), ground-borne vibration and ground-borne noise.

1.3 Sources of vibration

1.3.1 Source description

In our everyday life, we frequently experience vibration from many different sources. For instance, when riding a car or a bike, our body is subject to significant vibration levels. Some sources are known for the distinct characteristic of their vibration and noise, for example:

- earthquakes above a certain magnitude
- pile driving or sheet driving for construction work
- air conditioning equipment mounted on light weight roofs
- washing machines on light weight floors
- road or rail traffic passing
- neighbours slamming doors
- footsteps from upstairs neighbours

Rail traffic is only one of many different sources of vibration, and certainly not the one source which causes the highest vibration levels.

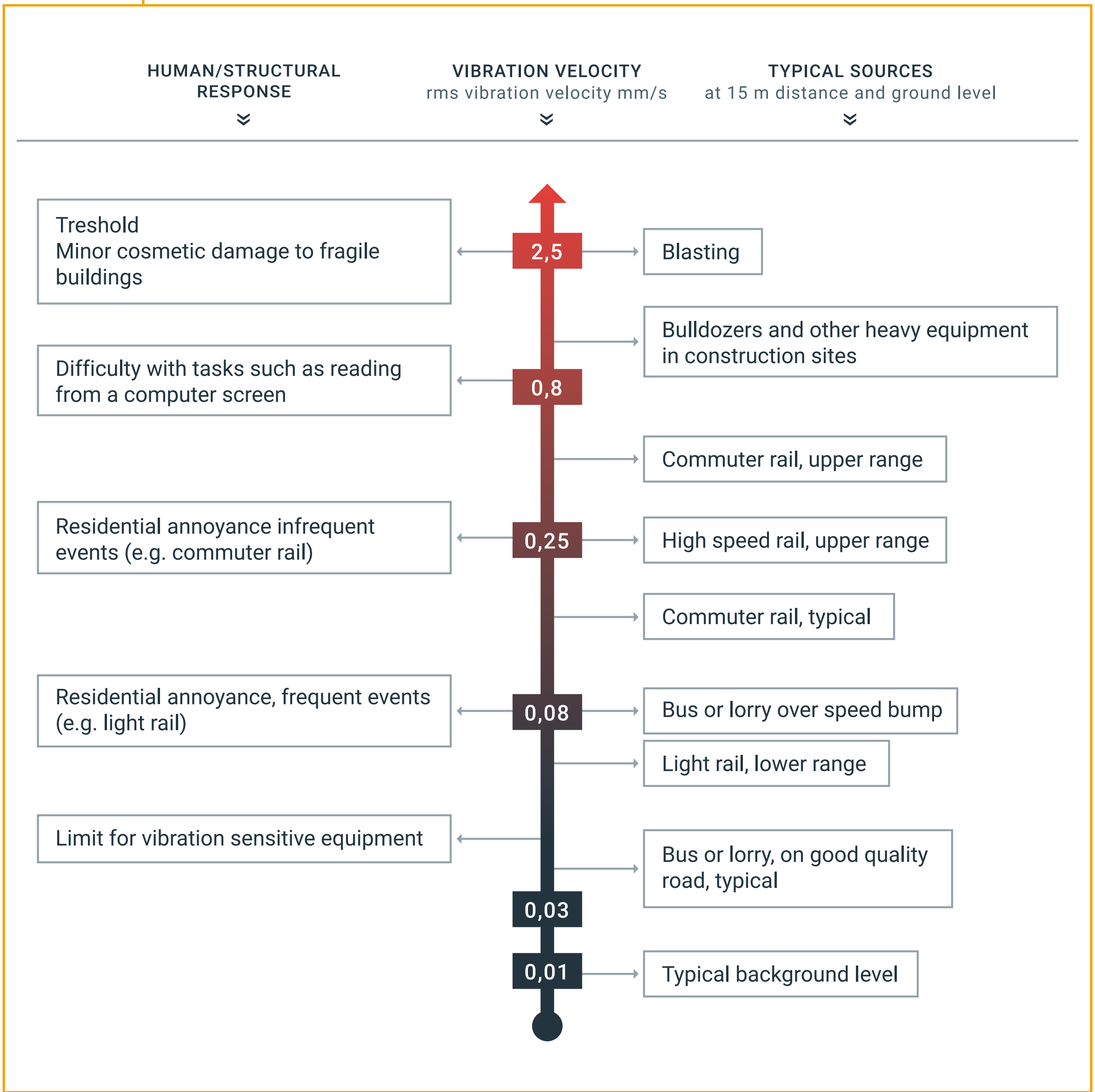
The sensitivity of humans to vibration covers a large range of amplitudes. Unlike sound sources, which are always radiating their energy into air, vibration sources are located such that the source has to move a solid body. The ability of a solid body to move when subjected to a dynamic force is called mechanical mobility (unit m/Ns). The mobility of a solid surface carrying a vibration source depends on the mass and the stiffness (compressibility) of that surface and on the frequency of the vibration. This means that the same source of vibration, say a washing machine, when mounted on a light floor, will cause higher levels of vibration in that floor than if it were mounted on a massive concrete floor.

The characterisation of the strength of a source of vibration requires three parameters, i.e. the blocked force[3], the free velocity and the mobility of the "receiving" medium to which the source is connected. This is more complex than the characterisation of a sound source, which usually only requires assessing the sound intensity (sound pressure level) at a given distance (in the free field) of the source. The simplicity is caused by the fact that most of the time the "receiving" medium is ambient air.

A ranking of vibration sources according to their strength therefore inherently assumes a typical mechanical mobility (i.e. a typical solid surface supporting that source), a typical frequency range, a typical distance to an observation point, and a typical attenuation of the vibration over distance. The latter depends on the type of soil, the layers, and the frequency range of interest. And to make things even more complex, the observation often takes place inside a building, for example on the floor. For the vibration energy to arrive at that floor, the behaviour of the building with specific resonances may cause amplifications of the vibration of up to 15 times the incident vibration strength.

3. The parameter "blocked force" describes the force on a mass with a fixed position.

With all this in mind, the following figures present a range of different sources of vibration with an indication of the vibration strengths caused at the receiver position (usually inside a dwelling at typical distance). Note that there are many different units and indicators applied to describe vibration (see chapter 2). In the current report, unless explicitly stated otherwise, we will use the root mean square (rms) value of the vibration velocity in mm/s, in three directions (i.e. vertical, horizontal and perpendicular to the track, and horizontal and parallel to the track).



Graph 2. Typical sources of vibration with their typical strength. Adaptation from FTA-VA-90-1003-06, May 2006, transit noise and vibration impact assessment.

Table A.1 — Ranges of structural response for various sources

Vibration source	Frequency range[a] Hz	Amplitude range µm	Particle velocity range mm/s	Particle acceleration range m/s^2	Time characteristic
Traffic road, rail, ground-borne	1 to 100	1 to 200	0,2 to 50	0,02 to 1	C[b]/T[c]
Blasting vibration ground-borne	1 to 300	100 to 2 500	0,2 to 100	0,02 to 50	T
Air over pressure	1 to 40	1 to 30	0,2 to 3	0,02 to 0,5	T
Pile driving ground-borne	1 to 100	10 to 50	0,2 to 100	0,02 to 2	T
Machinery outside ground-borne	1 to 100	10 to 1 000	0,2 to 100	0,02 to 1	C/T
Machinery inside	1 to 300	1 to 100	0,2 to 30	0,02 to 1	C/T
Human activities inside	0,1 to 30	5 to 500	0,2 to 20	0,02 to 0,2	T
Earthquakes	0,1 to 30	10 to 10^5	0,2 to 400	0,02 to 20	T
Wind	0,1 to 10	10 to 10^5	—	—	T
Acoustic (inside)	5 to 500	—	—	—	C/T

NOTE 1 The ranges quoted are extreme, but they still indicate the values which may be experienced and which may have to be measured (see also Note 2). Extreme ranges of displacement amplitudes and frequencies have not been used to derive particle velocities and accelerations. Values lower than 0,2 mm/s can also be considered. For building security and human annoyance, these values may be insignificant, but for sensitive equipments they are significant.

NOTE 2 Vibration values within the given ranges may cause concern. There are no standards which cover all varieties of structures, conditions and durations of exposure, but many national codes associate the threshold of visible (or otherwise noticeable) effects with peak particle velocities at the foundation of a structure of more than a few millimetres per second. A significant damage is linked to peak particle velocities of several hundred millimetres per second. Vibration levels below the threshold of human perception may be of concern in delicate and industrial processes.

[a] Ranges quoted refer to the response of structures and structural elements to a particular type of excitation and are indicative only.

[b] Continuous.

[c] Transient.

Graph 3. Extract from ISO 4866:2010 Mechanical vibration and shock — Vibration of fixed structures — Guidelines for the measurement of vibration and evaluation of their effects on structures.

Some observations with respect to the levels of vibration affecting buildings considered by ISO 4866:2010 Table A.1 (presented in Graph 3 above):

- As indicated in NOTE 1, the table shows extreme values. There is a wide variability in vibration levels considered by the standard, which include the extremes for each source.
- For traffic, including rail, the range of vibration velocity is more than a factor of 250 due to the range of influencing factors such as vehicle type, speed, track quality, subsoil dynamic stiffness, ground damping, distance from the source, amplification of the building structure or frequency.
- Railway transport is at the lower end of the scale of vibration sources considered by the standard.
- Railway transport may cause annoyance.
- Transport vibration is well below the level at which minor damage to buildings occurs. This however does not apply to vibration related to the construction of rail related structures like tunnels, viaducts, etc. The piling needed for this work may cause higher levels of vibration, which may represent a source of damage to adjacent houses.

The longest distances where vibration can be perceived (VDI3837) in residential buildings, and are likely to exceed DIN 4150-2 limits ("indicative values for new lines"[4]) are as follows:

- Freight lines, extremely soft ground, timber floors and ceilings: 200 m
- Railway: 60 m
- Tram: 40 m
- Underground, city railway, tram: 50 m

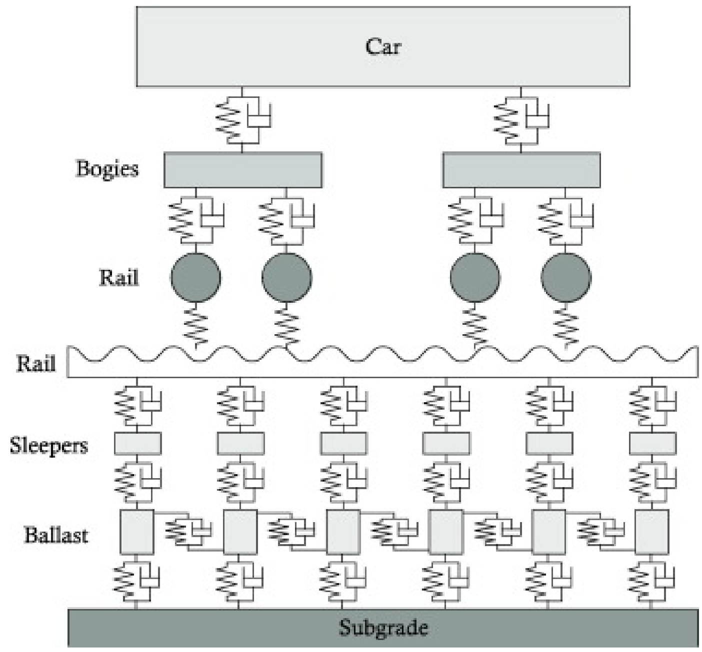
These references confirm that

- Railway traffic usually causes vibration in the ground.
- This vibration travels through the ground and may reach residential buildings.
- When the building is close enough to the railway track, the vibration may in some cases be strong enough for people to notice it.
- Many different factors affect the strength of the vibration, the main factors being the frequency of the vibration, the soil properties and the dynamic behaviour of the building.
- If the vibration is strong enough, and occurs regularly over a long period, people inside buildings may feel annoyed or could be disturbed in their sleep. The individual sensitivity to vibration is an important factor determining the risk to be annoyed or sleep disturbed.
- Ground-borne vibration is almost always accompanied by ground-borne noise, which can be heard by people inside buildings.

1.3.2 Generating mechanisms of rail vibration

A train moving along a track generates vibration in both the wheels and the track. The vibration of the wheel depends on the system above the wheel, i.e. the bogie and its springs and dampers, as well as the load of the vehicle. The vibration of the rail depends on the system below the rail, i.e. the track, the subsoil and soil. Since neither the wheel nor rail surfaces are perfectly smooth, the train wheel in effect runs across a series of "peaks" and "troughs" and thus is forced to move in a vertical direction. The track is not entirely stiff and so also moves vertically and in turn this excites the rail pad and sleeper. In addition, the rail may be supported at discrete points (the sleepers) whereas it can vibrate freely between these fixation points. The sleepers in turn are held in place by the ballast bed. However, the subsoil under the ballast bed is often composed of different layers (inhomogeneous) and so the elasticity of the soil may vary along the track. Thus, the vehicle and track together with the track substructure and the soil interact with each other and vibrate in many different resonant frequencies. The response of the individual elements (wheel, rail, sleeper, soil, etc.) depends on the overall connected system. Exactly how an individual element will respond for a given situation can be very difficult to predict, mainly because the properties of all the different influencing factors are generally not known.

4. It is assumed that this applies to conventional speed railways only. For high-speed, the distances may be somewhat larger.



Graph 4. Schematic of the dynamic system of rail car, bogies, wheels, rails, sleepers and ballast on the subsoil [1].

Vibration originates from the unevenness of either one (or both) of two surfaces in rolling contact with each other (wheel and rail). This unevenness can be inherent to the surface (corrugation on a railhead) or due to variation in the support stiffness (e.g. hanging sleepers or soft spots in the subsoil of the track). Due to this unevenness, a dynamic force is applied to the two bodies which then respond with movement (they vibrate). They will be more responsive to this excitation at their eigenfrequencies (resonance frequencies) where the mobility (ability to move) is relatively high, even though there is always some damping.

Both the train and the track represent a complex structure, responding to dynamic forces as resonating bodies. This means that some excitation frequencies "fit" the bogie, so that the bogie, when excited, will vibrate strongly and almost without damping. Other frequencies "fit" the track so that either the sleepers or the rails will respond strongly and almost without damping. The vehicle track system may withstand excitation of yet other frequencies, because they do not fit the response of the system. A model for the vibration of the vehicle and the track is presented for example in reference [2].

All in all, the source of vibration is a complicated interactive system, which makes it very difficult to accurately predict the generation of vibration, mainly because it is difficult to know all the relevant parameters with sufficient certainty.

Six vibration-generating mechanisms can be distinguished:

- *Quasi-static excitation*, also known as the "moving load". This is the static force of the mass of the train moving along the track at the speed of the train. This causes movement in the ground which at some distance from the track can be observed as a (very) low frequency vibration. In normal circumstances, this quasi-static excitation is of little relevance for feelable vibration.
- *Dynamic excitation*, which in turn can have four different causes:
  - *Parametric excitation*, usually caused by iterative track variations like rail fixations and sleepers, with a spacing of approximately 60 cm (wavelengths of excitation of the wheel at the fixed points is 60 cm). Spatial variation of the soil impedance may also cause parametric excitation. The first mode (as shown in Table 1) is usually the strongest; higher harmonics (smaller wavelengths) are much weaker. Other sources of parametric excitation, but with lower frequencies, may be inter axle spacing, inter bogie spacing or inter vehicle spacing.
  - *Unevenness of the track*, with wavelengths between 0.1 and sometimes 10 metres (in contrast to the shorter wavelengths between 0.1 and 100 mm which are relevant to noise). The unevenness may originate from variations in the track alignment, which can sometimes be due to variations in the subsoil or ballast bed (causing hanging sleepers) and which are generally removed when tamping the ballast.
  - *Rail corrugation*, with wavelengths between 0.01 and 0.05 m, which occurs due to periodic wear of the running surface on the rail head.
  - *Track singularities* at the wheel rail contact such as uneven joints, switches and turnouts, crossings, etc.
  - *Unevenness of the wheel surface*, generally indicated as wheel out of roundness (low frequency) or wheel roughness (higher frequency). Wheel roughness causes broad band vibration, whereas polygonisation[5] causes a modular behaviour. The longest wavelength is equal to the wheel circumference which is normally around 2.9 metres. Wheel flats are an extreme example of unevenness and are normally removed by maintenance.

Note that the above listing refers to surface lines as well as underground lines.

The frequencies of the vibration that result from the above mechanisms depend on the speed of the train. The following table presents the frequency range for each of the generating mechanisms at speeds of 40, 80 and 160 kph. For high-speed traffic, higher speeds may apply, which are not shown in the table.

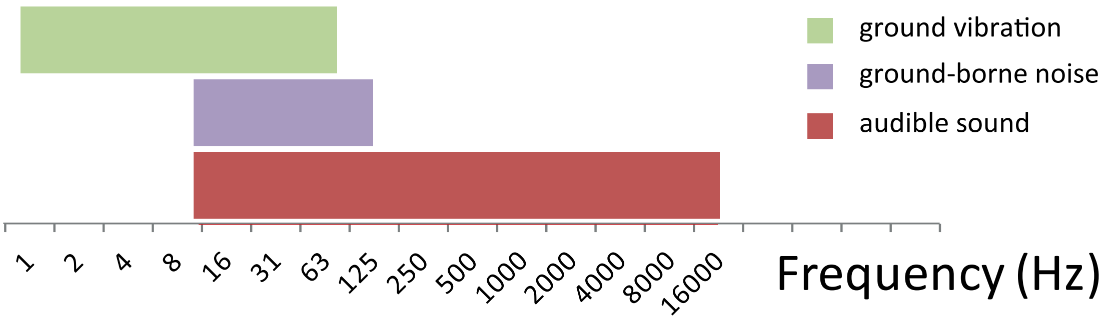
5. According to M. Küsel et al [Lecture Notes in Applied Mechanics Volume 6] polygonisation is a wavy wear pattern on the tread of railway wheels.

Vehicle Speed	40 kph	80 kph	160 kph
Moving load (axle spacing approx. 1.8 m)	3 Hz	5 Hz	11 Hz
Track unevenness	≥ 1 Hz ≤ 100 Hz	≥ 2 Hz ≤ 200 Hz	≥ 4 Hz ≤ 400 Hz
Rail corrugation	Approx. 500 Hz	Approx. 1000 Hz	Approx. 2000 Hz
Wheel unevenness	≥ 4 Hz	≥ 8 Hz	≥ 15 Hz
Wheel polygonisation (here assuming a wavelength of 0.1 m)	Approx. 100 Hz	Approx. 200 Hz	Approx. 400 Hz
Inter bogie spacing (assuming approx. 8 m)	Approx. 1 Hz	Approx. 3 Hz	Approx. 5 Hz
Sleeper spacing (0.6 m)	Multitudes of 16 Hz	Multitudes of 32 Hz	Multitudes of 64 Hz

Table 1. Frequency of typical vibration for each of the generating mechanisms, depending on train speed (indicative only). Most relevant mechanisms are indicated by the green boxes.

For ground-borne vibration, the relevant frequency range is defined in ISO 14837 Mechanical vibration – ground-borne noise and vibration arising from rail systems – as the range between 1 and 80 Hz. The table indicates which of the generating mechanisms may be most relevant (colour).

The following Graph 5 presents the frequency ranges of interest for ground-borne vibration, ground-borne noise and audible noise in general.



Graph 5. Frequency ranges for audible sound, feelable ground-borne vibration and ground-borne noise.

The graph shows that there is a frequency range where all three phenomena are relevant, roughly between 15 and 80 Hz. In this range, it can be difficult to distinguish one from the other, and the perception of one might be influenced by the presence of another. There might be either a masking effect (sometimes vibration is suddenly noticed after the installation of a sound barrier) as well as a cumulative effect (vibration is perceived as stronger when accompanied by audible sound or low frequency sound).

1.4 Freight trains and passenger trains

It is often stated that freight trains cause more frequent and greater magnitude vibration than passenger trains. The conclusion is greatly confirmed for example in reference [3]. While this is generally found to be true, people's assumption of freight trains being heavier than passenger trains is not always correct. Loaded passenger trains often have similar axle load to loaded freight trains. There are a number of other factors which are more likely to explain why freight trains can generate stronger vibration:

- A freight wagon usually has a single suspension system, this means the full weight of the wagon and its load will become the "excitation mass" which determines the strength of the vibration. Passenger trains have double suspension, which basically makes the wheelset (with much lower mass) the excitation mass (we speak of the "unsprung mass" of the wheelset). Like freight wagons, most locomotives have single suspension as well, and on top of that heavy axles with gear boxes and sometimes partly even electric motors included in the unsprung mass.
- Freight trains are typically longer than passenger trains, which may lead to a longer exposure time for the observer.
- The wheel maintenance for freight trains is not as strict as for passenger trains, so it is to be expected that more wheel defects are found in freight trains than in passenger trains. Wheel irregularities can be a significant cause of vibration.
- Freight trains usually have lower speed than passenger trains. This might be interpreted as an advantage, resulting in lower vibration strength, particularly in parametric excitation (see 1.3.2). However, in some cases it may well be that at lower speed, the generated vibration shows a better "fit" to the resonances of building structures or track structure. This could result in higher vibration strengths rather than lower.
- Freight trains often run during the night when people's sensitivity to vibration/ ground-borne noise can be higher.

1.5 High-speed trains

High-speed trains may cause ground-borne vibration and ground-borne noise in adjacent buildings. From table 1 it can be derived, that the dominant frequencies will shift to a range above approx. 10 Hz when the train speed increases to 300 km/h or more. High-speed lines usually have high quality (dedicated) track and rolling stock. Thanks to this quality level, the generation of vibration is often less than at conventional speed traffic.

In very soft ground, the speed of the propagating ground vibration may be in the same order as the train speed. Around this "critical speed" trans-Rayleigh waves may act as the equivalent of a sonic boom. This phenomenon was described at the beginning of this century, for example by Krylov and by Madshus [4, 5]. The occurrence of high levels of vibration from these trans-Rayleigh waves is a relatively rare situation. This phenomenon is well understood [6] and can be mitigated by appropriate design and construction techniques.

Where this could occur, measures such as soil strengthening or bridging over soft ground can be used to ensure there is no adverse effect on train operations, damage to the infrastructure nor impact on nearby people and wildlife. This "critical speed" phenomenon is not addressed further in the present report.

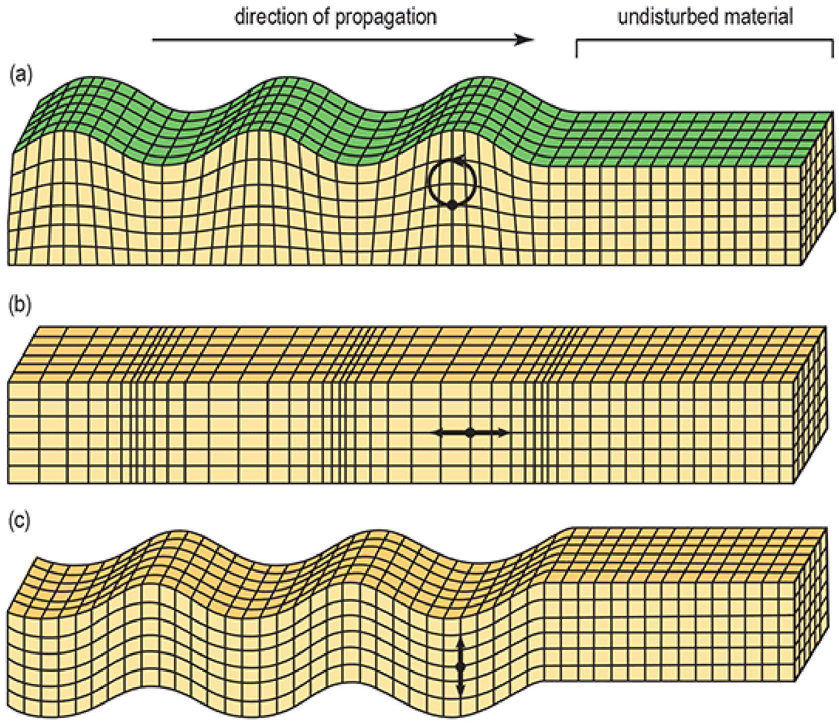
1.6 Transmission through the ground

The vibration generated by rail traffic on surface lines is transmitted through the track bed into the soil. There the vibration propagates in the form of waves travelling through the ground. Some of these waves run on the surface of the soil, more or less like water waves. Other wave forms travel through the deep ground, rather like sound waves.

For tunnel lines, the vibration is transmitted from the track to the wall of the tunnel, which excites the surrounding soil. From the tunnel, vibration propagates to the surface, where it propagates further in the form of surface waves. Some of the energy is reflected by deeper layers, which usually are stiffer than the surface layers. The propagation of these waves, especially their speed, is influenced by the ground properties, in particular the density and stiffness, as well as the water table and the reflections mentioned previously. The ground is typically not a homogeneous medium; there are considerable differences between layers which may include sand, clay, rock and ground water. Predicting ground propagation of vibration requires a detailed knowledge of the soil layers and their properties. Part 32 of ISO 14837 [7] presents appropriate measurement methods.

Vibration travels through the ground in three wave forms (see Graph 6); arrows indicate particle motion for each wave type.

The surface waves (Rayleigh waves) are the most relevant for the excitation of buildings. In the ideal case of a homogenous ground P- and S-waves propagate in all directions away from the source. They are therefore significantly attenuated, both by geometrical spread and by the damping of the ground. Rayleigh waves are not subject to the same geometrical spread because they are surface waves.



Graph 6. The three main wave forms in the ground association with the transmission of ground vibration [8].

- Top figure (a): Rayleigh waves. These occur at the surface of the soil only, comparable to waves in water. Particles move in the direction of the propagation as well as perpendicular to the propagation. The propagation velocity is somewhat lower than that of shear waves (typically 10% slower). Like shear waves, Rayleigh waves are dispersive, meaning that the velocity of propagation depends on the frequency. For tunnel lines, Rayleigh waves are arising from P-waves (b) and shear waves (c) reaching the surface.
- Middle figure (b): P-waves (primary or pressure waves). These are longitudinal waves with relatively high propagation velocity and long wave lengths. These waves propagate mainly downward into the medium, or radially in the case of underground tunnels. The propagation velocity depends on the density of the ground, with higher velocities occurring for higher densities. A typical velocity range is between 800 m/s for an average stiff soil up to 1500 m/s for a water saturated soil.
- Bottom figure (c): S-waves (shear waves). These are transversal waves, usually directed obliquely into the medium, with shorter wavelengths than P-waves, and velocities ranging from roughly 30 to 500 m/s. Shear waves are dispersive, which means that different frequencies propagate with different speeds.

Due to geometrical spread and damping, vibration amplitudes are likely to decrease with increasing distance from the source but this is not always the case. This is due to the influence of the different wave forms and the fact that this attenuation is frequency dependent and is more significant for the higher frequencies. At larger distances, the low frequencies therefore dominate. This is an important consideration when designing mitigation measures and interpreting measurements. If a mitigation measure is effective for higher frequencies at a measurement location close to the track, it may not be effective at larger distance.

In [3], the main dynamic properties of the soil are identified. Their numerical value was measured at seven different sites in Europe. The parameters and their spread are presented in the following table.

Parameter	Max value	Min value
Speed of shear wave in surface layer	275 m/s	50 m/s
Speed of compression wave	1761 m/s	286 m/s
Damping factor shear wave	0.08	0.02
Damping factor compression wave	0.08	0.02
Density	2000 kg/m^3	1100 kg/m^3

Table 2. Minimum and maximum measured value of the characteristic soil parameters for seven sites in Europe [3].

The table shows that there are large differences between soil types throughout Europe. The survey included sites with very soft soils in Sweden and The Netherlands, and sites with very stiff soils e.g. in Spain. This underlines the relevance of thoroughly assessing the values of these parameters as an input for any prediction.

Typically for surface lines, vibration waves travel in the ground down to a depth of up to 20 metres, depending on the stiffness of the ground and the wavelength under concern. Often this implies that mitigation measures in the ground (e.g. a trench) have to go down to an equivalent depth. For tunnel lines, the waves travel from the tunnel wall to the surface. Typically, the top ground layer is soft, whereas at 5-10 metres depth there may be a stiffer layer. This layer works as a reflector and mitigation measures should therefore go at least as deep as about 75% of the depth of this reflective layer. Ground water has an impact on the reflection of waves as well. As the level of ground water may change with season, so can the wave propagation.

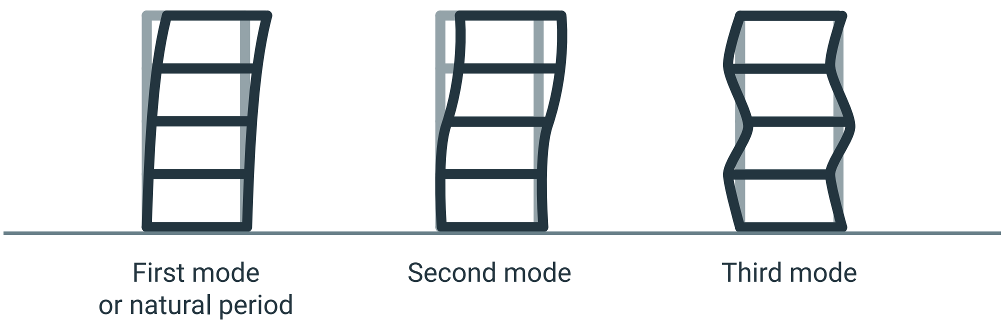
These are only a few of the factors that affect the transmission of vibration through the ground, the most significant being the inhomogeneous build-up of the soil. This implies that it requires a detailed and laborious survey of the soil to model and predict vibration transmission.

In case of an underground railway (or metro), the tunnel itself can radiate vibration in any direction. The preferable route of radiation may depend on the cross-sectional shape of the tunnel. Vibration radiated upward can easily excite foundations of buildings and from there run up to the building floors. Higher vibration can reach buildings when the tunnel alignment is directly below the buildings, compared to alignments running under street axes. Obviously, mitigation measures in the ground (e.g. a trench) cannot be implemented for underground railways because they would need to be at least as deep as the tunnel. Similar to at-grade railways, boundaries between soil layers (or also the water table) can partially reflect vibration waves, but with the important difference that the boundary can be above the railway (not below) and hence vibration can travel very far from the railway and reach receivers that may not even suspect the railway tunnel as a source of incoming vibration. Railway tunnels are usually built in urban areas where the transmission medium (soil) hosts many underground services (sewage, water, electricity, etc.) which may alter the normal radiation of vibration waves. Also, it may happen that a part of the tunnel touches a part of a building foundation. This constitutes a rigid bridge for vibration transmission and hence shall be avoided as far as possible in tunnel design and construction. The same can happen when soil concreting or stiffening techniques are used.

1.7 Vibration inside a building

A small part of the vibration emitted into the ground by the running train may reach the foundation of nearby buildings. Depending on the type of foundation the building may react to the excitation so that vibration is transmitted through the structure. Note that vibration in buildings may be both parallel to the floor (i.e. in a horizontal plane) and perpendicular to the floor (i.e. vertical). In buildings, the base plate or foundation shows little response while the ground floor and higher floors may tremble slightly. Wooden floors in particular are susceptible to low frequency vibration. In multi-storey buildings, there may be an amplification of the vibration going from the ground floor to higher floors. The assessment of the vibration strength usually takes place either at the foundation or at the centre of higher floors because the highest vibration strength on a floor is typically observed in its centre.

Ground-borne vibration can reach foundations of buildings close to the track. For buildings at larger distances, the vibration is usually damped sufficiently so that the vibration at the foundations is not noticeable. However, a vibrating foundation excites the building, which responds by vibrating at various resonant frequencies. The frequency and strength of the resonances are highly dependent on the building structure and materials. Measurements have shown an amplification of foundation vibration to floor vibration by between 1x and approximately 15x. This should be considered when mitigation measures for railway lines are discussed. In the case of a large urban area with many different building types, it can be very difficult to assess and guarantee compliance with limit values for all buildings, when the amplifications are so different (and unknown).



Graph 7. Theoretical resonances of a building structure, first three modes with low frequencies (1 to 5 Hz, amplitude highly exaggerated). Higher modes result from the resonance of the floor spans [9].

1.8 Ground-borne noise in buildings

The vibrating foundation causes vibration in the building structure. Depending on the mass and damping of stiffness of the floors and walls, the frequency of vibration may be in the audio range. In that case, the vibrating wall and floor panels generate audible noise in the rooms of the building. In the relevant frequency range, wavelengths may be such that an amplification occurs in these rooms (standing waves). The phenomena described cause ground-borne noise, noticeable to the residents in the building, perhaps even more so than the vibration itself.

The occurrence of ground-borne noise thus depends both on the frequency content of the ground vibration that reaches the foundation, on the transmission in the building structure, and on the acoustic properties of the receiver room. A prediction method is presented in reference [7].

2. Descriptors, indicators and standards

2.1 Descriptors

In different countries, there is a wide range of different indicators for the perceived strength of vibration. The amplitude of the vibration may be described by either its peak or maximum value or by the average (rms)[6] value of either the velocity or acceleration. Some indicators may account for the number of trains passing during a given period of time. Most indicators apply a frequency weighting curve which is designed to account for the fact that people are more sensitive to some frequencies than to others. There are ways to balance the contribution from vibration in vertical or horizontal direction. For transient events like trains passing, the indicator is intended to reflect the maximum amplitude during the passage. Some countries use a vibration "level" or "dose", sometimes expressed in decibels, whereas others use a vibration velocity in m/s or a dimensionless "vibration value". Correspondingly, there are important and significant differences in the relevant limit or target values. For this reason, great care should be taken when comparing different limit values and exposure values. A comprehensive overview of different descriptors and target values is presented in the RIVAS publication, "Review of existing standards, regulations and guidelines, as well as laboratory and field studies concerning human exposure to vibration" (see [10] and [11]).

A major standardisation effort is being made, with the objective of producing one comprehensive ISO standard, namely ISO 14837, which in the end will include 35 parts defining different elements. So far three parts have been published (see [12], [13] and [14]).

Most countries do not have a comprehensive legal framework to limit or reduce vibration from rail traffic (i.e. prevention and obligation to apply measures in case a limit is exceeded). However, many countries apply directives, guidelines and recommendations which may have an almost similar status under the influence of a growing precedence. Often in these regulations, reference is made to a range of standards, either international (ISO or CEN) or national (DIN, VDI, BS, UNI, Ö-Norm etc.). One of the most widely used standards is the German DIN4150-2, which at the time of writing is under revision. The ISO standard 14837, referenced in the text block above, may become the most relevant reference once more parts have been published. Table 3 lists the most commonly used indicators for vibration strength and a comprehensive overview of relevant standards is provided in reference [10]. Usually the value of the indicator is to be assessed at a location inside the building where the vibration has its highest value, e.g. floor mid span. Often the assessment has to be carried out in three directions; the relevant value might be either the highest or the average of these three directions.

6. RMS or root mean square refers to the most common mathematical method to derive the effective value of a quantity that varies over time.

Quantity	Reference	Symbol	Unit
rms weighted acceleration		a_{eff}	m/s^2
rms vibration velocity		v_{eff}	m/s
Maximum rms vibration velocity		$v_{eff,max}$	m/s
Maximum rms vibration velocity level		VdB	dB[7]
Vibration dose value	BS6472	VDV	$m/s^{1.75}$ [8]
Particle velocity	BS7385	pvth	m/s
Maximum transient vibration value (running rms)	ISO 2631		
Vibration dose value	ISO 2631	VDV	$m/s^{1.75}$ [9]
Maximum acceleration	Ö Norm S 9012	E_{max}	m/s^2
Risk of exceeding a limit value by 5%	NS 8176	$V_{w,95}$	mm/s
Mean equivalent acceleration	Ö Norm S 9012	E_r	m/s^2
Maximum weighted rms acceleration level	UNI 9614	L_{aW}	dB re 10^{-6} m/s^2
Maximum weighted rms velocity level	SS 460 4861	L_{vW}	mm/s
Unweighted vibration level	ISO 14837, Part 31	$L_{vs, max}$ L_{veq}	dB (reference unknown), to be published by the end of 2017
Maximum weighted vibration strength	DIN 4150	KB_{Fmax}	-
Mean vibration strength	DIN 4150	KB_{FTr}	-

Table 3. Examples of different quantities used to describe the strength of a vibration.

The various quantities differ in a range of aspects:

- The frequency weighting curve may differ or may even be disregarded;
- Some quantities account for vibration only in the direction with the highest amplitude, others include all three directions, and
- Some indicators focus on the maximum value, whereas others focus more on the average value.

In conclusion, the table shows that it is difficult, if not impossible, to compare or even to translate vibration strengths from one quantity into another. An effort to give guidelines for this translation was made in the Cargovibes project. In most indicators, the traffic plays a significant role as well.

7. Note that in some indicators a reference value of the logarithm is used of 10^{-6} inch/sec. This means that these levels are 28 dB lower than the dB velocity levels with reference 10^{-9} m/sec.
8. Note the different exponent of this quantity.
9. Note the different exponent of this quantity.

If one wants to compare different indicators and target values, the vibration velocity rms value in mm/s, possibly averaged over a series of pass-bys, is probably the best basis, as this is a familiar quantity in most countries. As mentioned before, we will use the rms mm/s velocity value in the present report unless stated otherwise.

In addition to the list of indicators for vibration impacts referenced in Table 3, there may be dedicated indicators for railway-induced ground-borne noise. In draft ISO 14837, $L_{pAs,max}$ (the A weighted maximum sound pressure level with time constant slow) is suggested as the best indicator to predict the impact of ground-borne noise. With respect to the impact of low frequency noise, the difference between the C-weighted and A-weighted sound pressure level may be used as an indicator.

Currently, the difference in indicators and reference quantities does not represent a problem to the rail infra managers in different countries. In future, a call for harmonisation may arise, with the corresponding benchmarking. Then it will become important to account for these differences.

2.2 Maximum or average levels?

No matter which of the above indicators is applied, it should reflect the feeling of the residents, or if that is not possible it should be easy to explain to them. Residents feel more familiar with maximum values during the pass-by of a train, but the long-term effects – like annoyance – are probably better predicted with an indicator that takes account of the number of pass-bys over time. This is similar to what happens with noise levels of train traffic, where residents ask for assessment of the maximum levels, whereas the long-term equivalent is the best predictor for annoyance.

For vibration, different standards apply different indicators and different methods to assess the numerical value of the indicator. The assessment of vibration according to DIN 4150 includes both, i.e. the maximum vibration (KB_{Fmax}) of a single train as well as the influence of the number of train pass-bys over a period (e.g. night or day) KB_{Ftr}. So does the combination of $L_{vs,\ max}$ and L_{veq} as suggested in the draft ISO 14837.

If only the maximum vibration is assessed, the outcome will not reflect the number of trains passing. In current impact studies, the result of a planned significant renewal is often an increase in the number of trains. However, the maximum vibration may remain the same as it is determined by a single train. In cases where the indicator value does not change in spite of the increasing number of trains, some residents may consider the assessment to be unfair.

Other indicators known as “equivalent levels” or “equivalent velocities or accelerations” represent an average level (leaving out periods in between train passages) and are sensitive to increases in traffic volume. However, basing the assessment on the average level of vibration will reduce the influence of the most noticeable trains. For this approach, some residents may object on the basis that they are most affected by the trains causing the highest levels of vibration.

Some guidelines set criteria both for the maximum strength and the equivalent strength of the vibration. Similar to the effects of noise, the long-term average exposure would be a better indicator for predicting long-term effects like annoyance, whereas the average level of an event would better predict instantaneous effects such as sleep disturbance. A well-balanced indicator may be a number representing the highest 5% of vibration events.

3. Assessment

3.1 Legal obligations

In very few countries there is a legal framework which obliges vibration levels to be kept within specified limits. On the other hand, many countries maintain a framework that requires an assessment of vibration following a significant change to the railway. This normally applies where there is a change to railway infrastructure such as:

- A new track is planned in an existing environment close to a living area; or
- An existing track is significantly altered leading to more tracks or tracks closer to the residential properties.

In addition, some countries require an assessment following a change to the operation of rail vehicles on existing tracks such as:

- Increases in train speed, traffic volume or axle loads on existing tracks,
- Introduction of freight trains on lines where only passenger trains currently operate.

Yet another case is when a new residential area (or other sensitive development) is being planned close to an existing railway. In these cases, it is usually the developer or planning authority that is responsible for the impact assessment. The latter case is therefore not addressed further in this report, but it should be clear that the railway cannot usually be held responsible for vibration affecting the new developments.

In all these cases, an assessment of the expected vibration levels inside nearby buildings has to be carried out. The following sections present the methods to be applied for this assessment.

In most countries, there is no legal obligation to assess existing exposure to vibration. An assessment would be carried out merely to investigate whether a complaint would be justified or not. If vibration levels are assessed in existing situations, this would only very seldom lead to mitigation measures. This is due to the fact that it is almost impossible, in existing situations, to take effective measures at reasonable cost (see chapter 6).

On an EU level, however, Directive (EU) 2016/797 of the European Parliament and of the Council of 11 May 2016 on the interoperability of the rail system within the European Union, annex III (essential requirements), paragraph 1.4.5 (environmental protection) states that “operation of the rail system must not give rise to an inadmissible level of ground vibration for the activities and areas close to the infrastructure and in a normal state of maintenance”.

3.2 Direct measurement

In existing situations, the vibration can be assessed by direct measurements at the sensitive location, i.e. in the middle of a vibrating floor inside a relevant number of buildings along the track. This is often the starting point for an extrapolation carried out to predict the impact of future changes. The standards mentioned in the previous chapter – particularly ISO 14837-1 – provide guidelines on how these measurements should be executed and analysed. Still, such measurements must be carried out with great care and preferably by accredited organisations with expert staff in this field, in order to avoid errors and confusion.

The main objectives when planning a measurement are to determine:

- A reliable estimate of the present and possibly future situation. Note that any assessment of a future situation, particularly regarding the choice of mitigation measures, but also the expected impact on buildings and people in buildings, has to be based on detailed simulative calculation (e.g. finite element modelling).
- A representative comparison with the applicable limit value and/or with the situation existing before the change.
- A reliable advice on possible mitigation measures to be carried out.

As minimum, the following points should be considered:

- In the case of an urban area with many different properties, there should be sufficient measurement locations to allow a representative assessment for all affected buildings (see previous chapter).
- It should be ensured that extraneous sources (doors slamming, people walking, etc.) have not compromised the measured vibration signal.
- Have the measurements been continued long enough to give a reliable average or maximum value? A reliable average requires a sufficient number of train pass-bys for every relevant train category (typically at least 10) and for each period of the day (day, evening and night; this should be feasible with un-manned monitoring equipment). Preferably a statistical analysis should be carried out on the results to demonstrate that the resulting value is significant, accurate and certain.
- Has the rail traffic during the measurement been monitored and registered in terms of numbers of vehicles, vehicle type and speed? Sometimes this information can be acquired from the infrastructure manager.
- Has the sensor been placed adequately, i.e. well-fixed to the surface and at an appropriate location?

3.3 Prediction of vibration for changes to existing railways

A (re-)assessment of vibration can be required where significant changes are proposed to either the track geometry (e.g. an additional track closer to existing properties and new switches and crossings) or rail traffic. Changes in traffic might include the introduction of a different vehicle type (e.g. freight traffic on a formerly passenger line), an increase in speed, or night traffic on a track previously limited to daytime traffic. To some extent, these cases can be assessed through interpolation or extrapolation of measurement results collected for the existing situation.

Where there will be a change in distance due to relocation of an existing track or addition of a new track, the assessment would normally require a series of vibration measurements at different distances from the track in order to derive the distance attenuation. Within certain limits, this approach should allow a reasonably reliable prediction (assuming there to be no changes other than distance). Care should be taken if applying the distance dependency to other sites, as this is highly dependent on the type and composition of the ground layers at each site.

For a given frequency and without damping of the soil, the vibration velocity is reduced with the square root of the distance between a point source and the receiver. The vibrating train-track system is between a point source and a line source. This is based on the equation suggested by Galitsin as early as 1912 [15].

Site-specific and frequency-specific damping factors can be derived by fitting the ‘Barkan curve’ (which describes Galitsin’s equation) to the measured values taken over a range of distances. This process should be repeated over a range of different frequencies relevant to the assessment. Typical damping values could give an additional attenuation of up to 10%. All these values are highly indicative, as they depend on the frequency, the type of waves and the direction of the vibration involved.

A different approach to assessing the soil characteristics is presented in [16].

For changes of vehicle speed, the relationship between vibration strength and speed can be assessed by measurements of individual trains passing at a range of different speeds (the speed should be recorded separately, e.g. by radar or sensors in the track). Note that the relationship between speed and resulting vibration is complex and depends on many factors including the type of rolling stock (freight, long distance, suburban etc.) and its technical condition (especially condition of wheels etc.), the technical condition of railway infrastructure (type of sleepers, condition of rails etc.) and also the composition of the ground (type and layers of soil, clay, rock, etc). It is therefore difficult to make a general statement about how changes in vehicle speed will affect the strength of any resulting vibration. This notion is confirmed for example by research carried out by the Polish infrastructure manager PKP PLK. For each individual situation, a relationship can be established and then interpolated for speeds between the measured values. Extrapolation outside the measured range should be interpreted with care, particularly in the case of large relative increases, because changes in speed cause changes in amplitude and excitation frequency at the same time.

A prediction model, possibly validated with different measurements at site, is suggested for example in reference [7].

3.4 Prediction of vibration for new railways or new properties

There are two basic types of new situations:

- A new property development being planned next to an existing railway
- A new railway line being planned next to existing vibration sensitive properties (e.g. an urban area)

For a new property development (e.g. dwellings), it is considered to be the responsibility of the developer or planning authority to assess the vibration expected inside the building. The railway infrastructure manager has no responsibility for the resulting vibration level. However, sometimes the rail infra manager may take part in the assessment, e.g. by supplying data on the traffic and the track.

On behalf of the developer, measurements can be carried out on the planned location of the future building using a sensor mounted on a pole or ground spike inserted into the soil. Various national and other standards provide guidance on how these measurements must be carried out and analysed. It is possible to include mitigation measures as part of the building construction, but this should be considered at an early stage of the building design (see chapter 5).

In the case of new railway track, accurate predictions based purely on calculations present a major challenge because of the large effort required to collect the appropriate input data. This applies both to the source data and the propagation data. For the source (the train running on the track), average data from previous measurements on similar track, similar subsoil and with similar rolling stock could be used, also to validate source model predictions. However, substantial deviations may arise locally due to, inter alia, differences in rail pad stiffness, track evenness, subsoil dynamic properties, track irregularities and singularities. For the propagation, in particular the damping of different wave types in the soil, soil sounding data can be used to compare the site under concern with previous sites that have been measured. Assuming these data can be gathered with sufficient precision, a numerical method, for example a Finite Element Approach or a Boundary Element Approach, would be appropriate. These are academic types of modelling which require substantial knowledge and experience. Alternatively, a measurement at the specific site can be organised, where an artificial source, for example a shaker or a large mass is used to excite the ground at the location where the track will be constructed and vibration levels are measured over a range of distances. Even with this elaborate method, one has to consider variability in the soil properties along the length of track. In the RIVAS project [17], measurements taken at 100m intervals parallel to a length of track showed significant differences even though both track and soil appeared to be identical at all locations.

For underground railways, vibration shakers are preferable to mass-dropping. Vibroshakers are machines with oscillating masses, which provide a controlled and repeatable dynamic input. The vibration energy induced into a tunnel structure by vibroshakers is much higher than mass-dropping and hence the effects can be measured also at larger distances. The machines can be used to validate the calculations of transmission loss between source and receiver on site.

Currently, there are several initiatives to improve prediction models both for the source and the propagation, aiming at a better reliability and higher efficiency of the prediction. Nevertheless, it is helpful to develop and apply a standard approach on how to define and manage uncertainties from measurement/prediction [17, 18].

4. Impact of vibration

Depending on the strength of the signal, ground-borne vibration may have different types of impact. For example: vibration at low strength may not be noticed at all by any person. In that case we say that the vibration is below the threshold of perception (feelable vibration). Ground-borne noise however is almost always present and noticeable.

At greater vibration strengths, people can feel vibration, either with the whole body when standing, sitting or lying, or with their hands. When a vibration is noticed, especially when the source is unknown, this may cause concern or anxiety.

One common concern is that the vibration may cause damage to the property. This is discussed for example in British Standard BS 5228:2009 Code of practice for noise and vibration control on construction and open sites, which states: "*Vibration nuisance is frequently associated with the assumption that, if vibration can be felt, then damage is inevitable; however, considerably greater levels of vibration are required to cause damage to buildings and structures (see, for example, British Standard BS 7385-2) or to cause computers and similar electronic equipment to malfunction. Vibration transmitted from site activities to the neighbourhood can, therefore, cause anxiety as well.*"

The above statement unconditionally applies to railways; there are few credible reports where railway vibration can be considered the possible cause of damage to properties. In these cases, the damage was only cosmetic, i.e. damage that does not affect the structural integrity of the building but can nevertheless be observed, e.g. as minor cracks. There are a few cases in Sweden and one in Belgium where more significant damage was attributed to railway vibration. In France, damage was found in old barrier-guard houses – only a few metres away from the track. In these situations, the recorded levels of vibration were so high (over 5 mm/s) that more than cosmetic damage to the property was plausible. However, for the Swedish case, in none of the properties could the observed cracks be assigned to railway vibration with certainty. The Belgian case was an extreme situation where the building was only three metres from the track. Given the vibration strength occurring with rail traffic, there is no risk at all of serious damage being caused to buildings, which are at reasonable distance (50 metres or more) from the track.

Nevertheless, vibration of much lower strength resulting from rail traffic may be perceivable in properties close to the track. When exposed to this vibration for a long time, this can cause annoyance for some residents and the more sensitive ones may be disturbed in their sleep. These are the cases that the railways are working to avoid, provided that cost-effective solutions are indeed available.

Ground-borne noise can have similar effects on residents. However, mitigation is often more complex, especially compared to air-borne noise. Moreover, it is often a point of discussion whether or not the usual limit values for noise should apply to ground-borne noise.

Another effect is disturbance or damage to sensitive equipment such as highly sensitive weighing equipment, electronic microscopes and MRI instruments.

4.1 Damage to buildings

Damage to buildings due to ground-borne vibration is often feared, but it almost never occurs in practice. Minor cosmetic damage due to settlement of the subsoil may occur during construction work for new railway lines. Even in that case, the settlement has nothing to do with the traffic but could be caused by drainage of water, for example. One approach to this is often that the company responsible for the construction commissions an expert report on the condition of the buildings before the work starts. If cracks or other cosmetic damage occur that can be attributed to the construction work, the builder will be liable for the cost of repair. This applies for instance to pile- and sheet-driving activities.

For properties close to railways, there are many cases with minor cosmetic damage (small cracks) that are attributed to railways by the residents. In these cases, there are often many more credible causes (settlement due to fatigue caused by natural aging of building materials, moisture, weather, temperature variations including freezing of the soil, doors slamming, poor building quality, ground water extraction) but it is virtually impossible to assign the damage to any of these potential causes with certainty. Infrastructure managers are often faced with this problem and when the cause cannot be defined with certainty, the suspicion of the public remains.

The vibration strengths that are reported in typical cases of minor cosmetic damage to buildings (for example due to pile driving) are in the order of more than 5.0 mm/s. (maximum value). This far exceeds the vibration caused by trains (typically between 0.1 and 0.6 mm/s average). The challenge here lies in better communication with the residents and providing credible reassurance that there is virtually no risk of more than minor cosmetic damage and absolutely no risk of serious damage to their properties due to vibration from passing trains, as long as the building is of reasonable quality and at reasonable distance from the track. See reference [19] on the concern of property damage.

4.2 Human perception of vibration

4.2.1 Threshold of perception

Scientists broadly agree that there is a threshold of perception for whole body vibration. Below this threshold, vibration is generally not perceived and impact on human beings is then considered to be none. This threshold, expressed as the rms value, lies at a vibration strength of approximately 1 mm/s at 1 Hz and 0.1 mm/s at 10 Hz and higher (ISO 2631, see Graph 8). Alterations of sleep rhythm and sleep depth are reported in reference [20] for amplitudes of vibration as low as 0.4 mm/s (this is a frequency weighted rms value). Cardiovascular reactions are reported in reference [20] for amplitudes from 0.3 mm/s.

One should however note that differences between individuals may occur, depending on the personal sensitivity and many other “circumstantial” aspects. **The values mentioned in this chapter should therefore be interpreted with great care.**

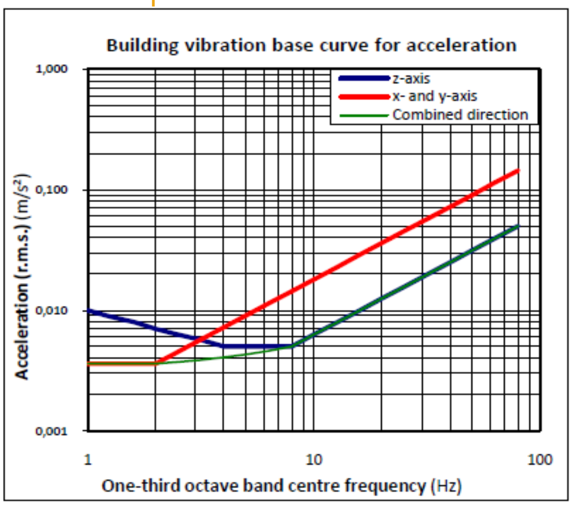
In ISO 2631-1:1997, the absolute threshold of perception of weighted vertical vibration is stated to be round 0.015 m/s². This represents the median highest magnitude of acceleration at which the acceleration can be just detected by "alert, fit persons". In terms of KB value (DIN 4150) the threshold is set at 0.1 (compares to mm/s, although the KB value is officially dimensionless).

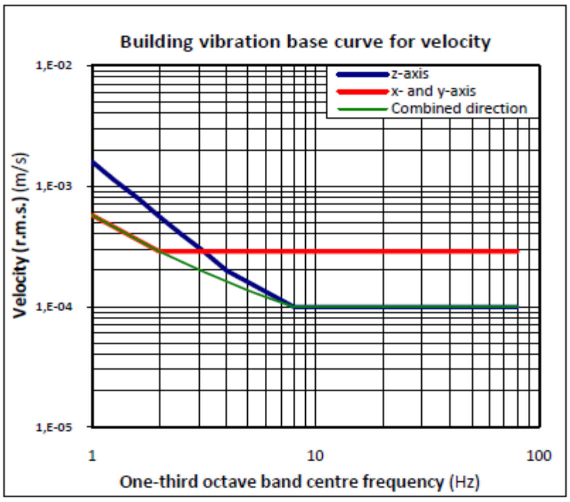
A representation of the response to vibration with different values is given in the following table from reference [10]. The values in the column mentioning KB values could be interpreted as equal to a rms mm/s value.

Weighted maximum vibration velocity (KB values)	Perception
0.1	Threshold of perception, just noticeable
0.2	Weakly noticeable
0.4	Noticeable
0.8	Awakening threshold, clearly noticeable
1.6	Strongly noticeable
6.3	Very strongly noticeable

Table 4. Perception of vibration according to DIN, after reference [21].

In ISO 2631-2:1989 this approach is elaborated on somewhat further in so-called base curves, where the threshold is related to the frequency of the vibration. With a vibration strength below these base curves, no adverse comments, sensations or complaints have been reported. Note that the ISO 2631 curves differentiate for vertical (blue lines) and horizontal vibration (red lines).





Graph 8. Building vibration base curves for just noticeable vibration expressed as acceleration (left-hand curve) or velocity (right-hand curve) for vertical and horizontal direction separately, as well as for the combined directions. After ISO 2631-2: 1989.

The value of vrms ≤ 0.1 mm/s can be considered a safe value; when we can be certain that the vibration strength is under this value, we do not need to consider what the exact level is and options for mitigation can be disregarded. Together with an estimated source strength and an estimated propagation reduction (and possibly a building amplification), the value can be used to define a zone on both sides of the track beyond which a more thorough investigation is not required.

4.2.2 Perception of differences

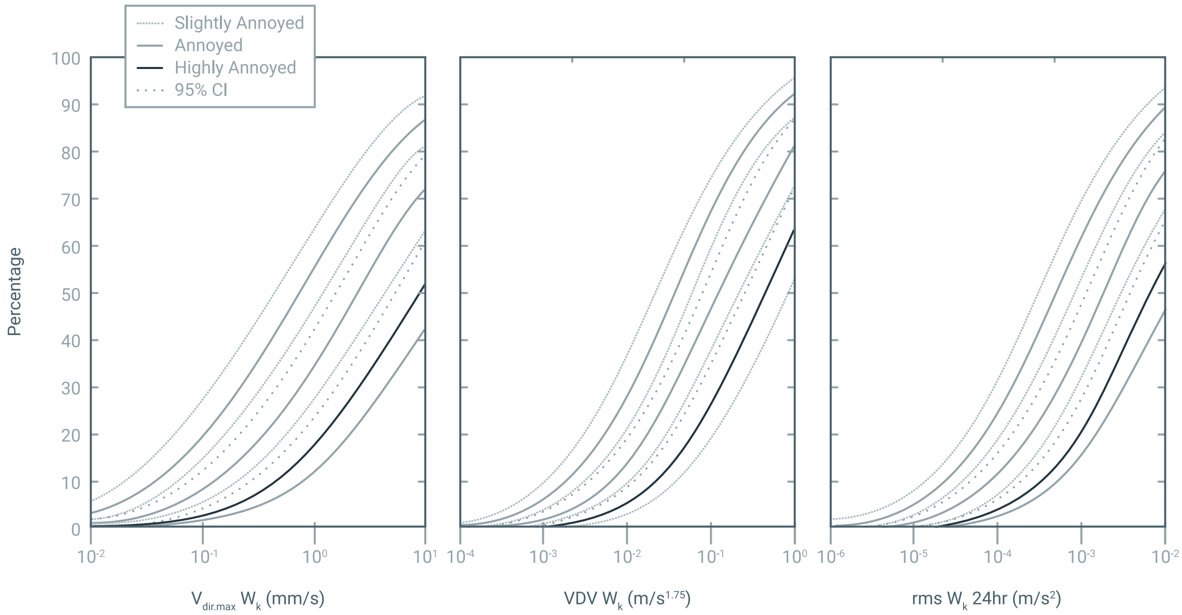
In most sensory systems of the human body, there is the ability to sense increases or reductions of the stimulus. Not only can our eyes detect light, but they can also detect which of two different sources emits more light. Not only can our ears detect sound, but they can also detect an increase in sound due to more traffic. In noise, the smallest increment that a healthy human being can detect is (by definition) a 1 dB step. Such a step corresponds to a 12% increase in sound pressure and a 25% increase in sound intensity. Since the decibel is a relative indicator, it means that the relation between the increment detected and the absolute starting value is constant. This is Weber's Law, which states that the ratio of the increment threshold to the background intensity is a constant.

This has been applied by various researchers to the perception of vibration, and was proven to be globally true. Different researchers ([23], [24], [25]) however arrive at different constants. In some national guidelines (Switzerland, The Netherlands), increments in rms velocity of 25 to 40% are applied as "not noticeable" or "insignificant" respectively and therefore no mitigation is required in cases where the vibration increase is less than 25 or 40%. Obviously, this consideration can only be used once and "creeping" levels must be managed appropriately. It must be emphasised that some studies have also found increments much smaller than the aforementioned 25%, i.e. 8 - 10% [26].

4.3 Annoyance

4.3.1 Vibration

Long-term (i.e. several years') exposure to noticeable vibration may lead to annoyance within a small percentage of the people exposed. The higher the exposure, the larger the percentage of people that will report to be annoyed or even highly annoyed. Recently, in a project called Cargovibes, a meta-analysis [27] was carried out of a range of dose response relation assessments, based on various field studies (total of more than 4,000 respondents). The following curves represent the results of this meta-analysis.

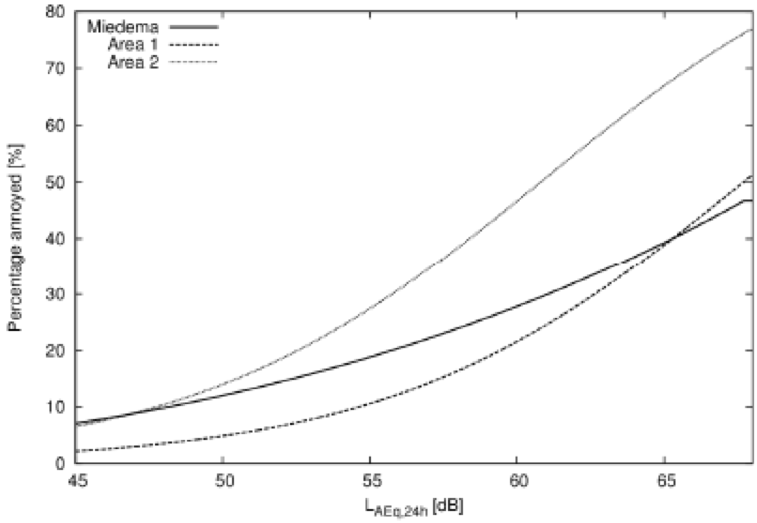


Graph 9. Exposure response curves following from a meta-analysis (total 4129 exposure and response data) carried out in Cargovibes [27]. The left-hand curve shows percentages of slightly annoyed, annoyed and highly annoyed residents as a function of the maximum weighted vibration velocity in mm/s.

The left-hand curve shows that at a threshold value of $v_{dir,max}$= 0.01 mm/s the percentage of annoyed residents is close to zero. At $v_{dir,max}$= 0.4 mm/s (the higher range of realistic levels for rail traffic) the percentage goes up to a value between 0% and 5% for highly annoyed, and up to approximately 15% for annoyed.

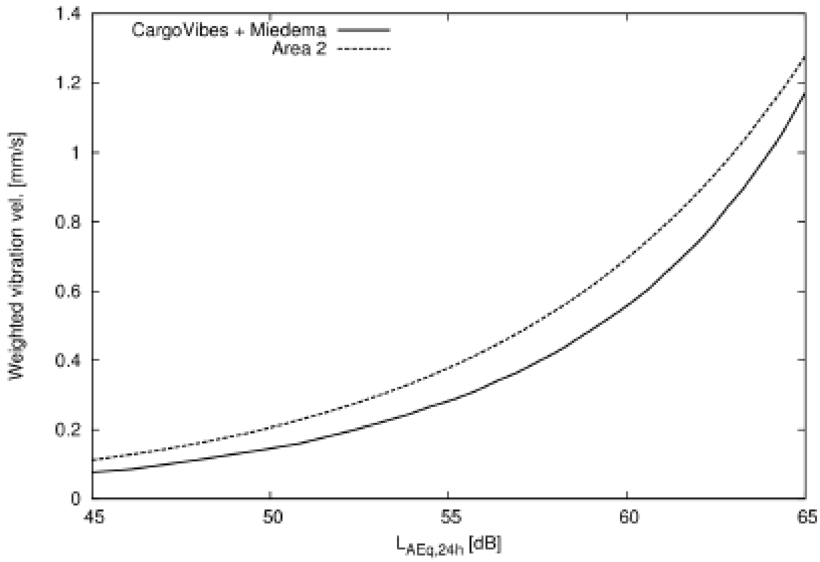
In a recent field study in The Netherlands [28] by the Dutch National Environment and Health Agency, much higher percentages were found. In that case the exposure was estimated through calculation, with all the uncertainties as mentioned in the present report. The reason for the differences between Cargovibes and the Dutch study could not be explained.

A recent Swedish study [29] compared noise and vibration exposure causing comparable annoyance rates. Graph 10 presents the dose response curves for two areas, compared to the curves from the EU position paper on dose response [30] (referred to as "Miedema" in the graph). In area 1, the residents are exposed only to noise, in area 2 the exposure is to both noise and vibration. The presence of vibration causes a higher response.



Graph 10. Dose response relations for traffic noise in Europe (solid line, according to [30]), exposure to railway noise (lower dashed line, according to [29]) and exposure to noise and vibration (upper dashed line, according to [29]).

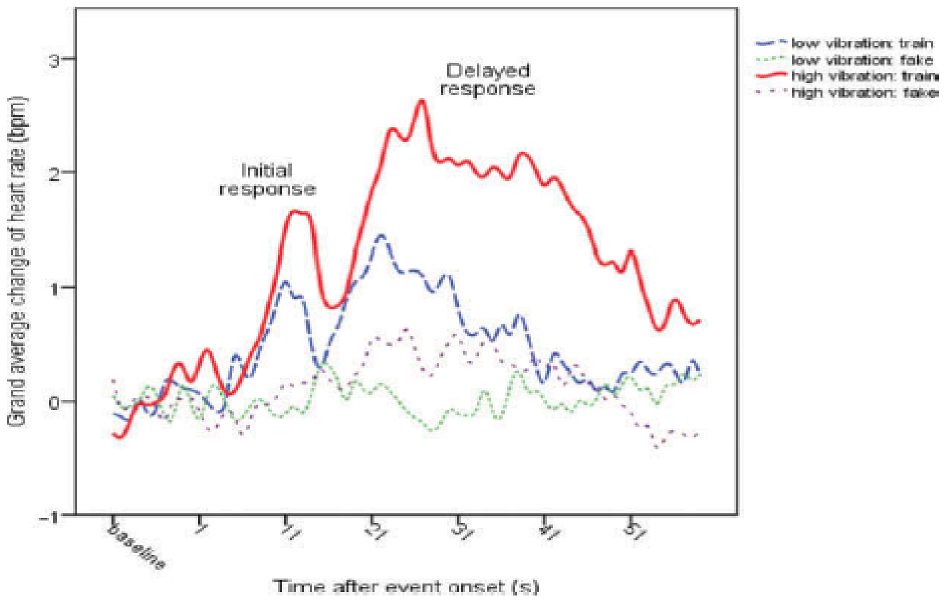
The study derives a curve for "equal annoyance" due to noise or vibration, which is presented in Graph 11.



Graph 11. Equal annoyance for exposure to noise (horizontal axis) and vibration only (vertical axis) [29].

Graph 11 shows that a vibration velocity of 0.1 mm/s is comparable to a rather low noise level of 45 dB, which is likely to be suggested as a night time noise level. A noise level of 55 dB (a candidate for a European noise limit) causes annoyance comparable to a vibration velocity of around 0.3 mm/s.

For night-time vibration, sleep disturbance was investigated among others in reference [17]. The studies often refer to laboratory experiments with very low numbers of test individuals. Also, different studies show very different results. As an example, the following Graph 12 shows the change of heart rate resulting from events during sleep, with either "low" (0.7 mm/s which is not low at all compared to vibration recorded in practice) or "high" vibration (1.4 mm/s) levels. The graph shows a clear, although somewhat delayed effect at high vibration, and almost no effect at low vibration. The Swedish sleep study indicates 0.3 mm/s (frequency weighted rms value) maximum amplitude for alterations in the sleep rhythm. Some studies indicate 0.4 mm/s (frequency-weighted rms value) as a physiological threshold for sleep reactions.



Graph 12. Heart rate change during sleep following freight train pass-bys with "low" (blue curve, 0.7 mm/s) and "high" (red curve, 1.4 mm/s) vibration strength. The levels applied here are hardly ever found in practice [3].

Summarising, in extreme situations rail traffic may cause vibration strengths of up to 0.8 mm/s rms (measured on the foundation of one of the buildings close to the track and depending on soil foundation condition, distance and frequency). Above about 0.1 to 0.3 mm/s annoyance may occur. An effect on sleep can be observed above about 0.3 mm/s rms.

4.3.2 Ground-borne noise

The exposure to ground-borne noise is located inside dwellings. The acceptable level can be derived from legal limits for environmental noise, which are usually in the order of 35 to 40 dB(A) equivalent during daytime and about 25 to 30 dB(A) during night time. These limits are used for determining the façade insulation as well as the maximum noise caused by appliances inside the building. The limit values can be used for ground-borne noise. Due to the low noise character, A-weighting reduces the levels to very low values. For underground trains passing dwellings, maximum (not equivalent) ground-borne noise levels of 25 to 30 dB(A) have been applied in some cases. For the assessment of ground-borne noise, sometimes a C-weighting is used.

4.4 Complaints

Complaints can occur in existing situations or where a change has taken place. It is important to have a first estimate of whether or not the complaint is due to any impact of the rail traffic and, if so, whether or not vibration could be the actual cause for complaint. Complaints often refer to noise and vibration at the same time, although complaints about noise are much more frequent than about vibration. For example, in Sweden the number of registered complaints about noise is about 8 times higher than the number of complaints about vibration.

Most countries do not maintain an obligation to mitigate only because of complaints. Some infrastructure managers maintain a standard procedure to react to complaints, which in case of suspected impact of vibration may even include a measurement. For a proposed procedure of handling complaints, see paragraph 7.4.

5. Targets and action levels

In general, the railways recognise that noticeable vibration may occur in buildings close to the track as a result of rail traffic. In the previous chapters, we have seen that there are still many different questions when it comes to predicting and assessing vibration, and to a lesser extent regarding the impact of vibration. Also, the responsibilities are not always clearly identified.

Finally, as we will see in chapter 6, mitigation measures are often very costly and their efficiency is not ascertained. Nevertheless, many railway operators have recognised this impact of their operations and are pro-actively working with stakeholders to mitigate the impact of vibration. They thus intend to give confidence to residents that their interests are being managed consciously.

In the case of new and significantly altered lines, mitigation of excessive vibration is part of the impact assessment. Possible mitigation costs are carried by the project, often funded by the public. It may thus be necessary to involve a number of government bodies to ensure that a sensible balance is found between costs and benefits of mitigation measures.

Target values are defined or suggested in most of the guidelines on rail vibration. Without the ambition to be complete, the following list presents some examples of guidelines on rail vibration.

5.1 German standards DIN 4150 and DIN 45669-1

These two German standards are widely used in Europe. They describe the methods of signal processing (DIN 45 669-1) and measurements. DIN 4150-1 defines the measurement and prediction method for the prescribed indicators. DIN 4150-2 (which is currently under revision) focuses on the impact on human beings, whereas DIN 4150-3 is focusing on the effects on buildings. The standard gives criteria for the levels to be assessed.

5.2 RIVAS project

In the RIVAS project, target values were defined for both vibration and ground-borne noise. The values are summarised in the following table, quoted from reference [31]. The table distinguishes a green zone and a yellow zone. In the latter zone, special attention is required and measures should be included if feasible.

Descriptors	Targets (green zone)		Targets (yellow zone upper limits)	
	Velocity	Acceleration	Velocity	Acceleration
Max (slow, W_m) vibration $Lv_{w.Smax}$ ref. 5 10^{-8} m/s →	0.10 mm/s 66 dB	3.6 mm/s^2	0.30 mm/s 76 dB	10.8 mm/s^2
Eq. (24h, W_m) vibration $Lv_{w.eq.24h}$ ref. 5 10^{-8} m/s →	0.028 mm/s 55 dB	1.0 mm/s^2	0.084 mm/s 65 dB	3.0 mm/s^2
Max (slow, A) GBN	38 dB (A)		48 dB (A)	
Eq. (24h, A) GBN	32 dB (A)		42 dB (A)	

Graph 13. Target values for vibration (max values first row, equivalent values second row) and ground-borne noise (max and equivalent, third and fourth row respectively) [31].

5.3 United States of America, Federal Transport Administration, Transit Noise and Vibration Impact Assessment. FTA-VA-90-1003-06, May 2006

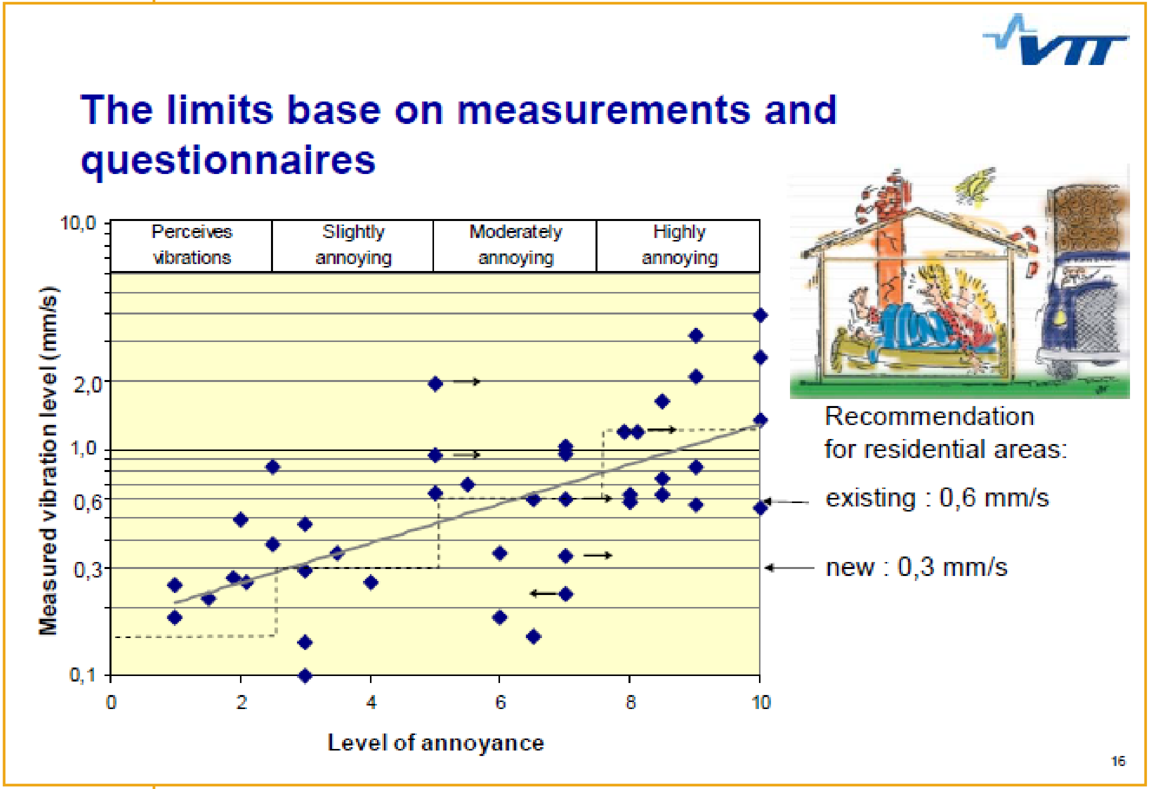
This guidance manual [16] presents descriptors for rail induced vibration as well as their impact and presents criteria for three levels of sensitivity of areas in the proximity of railways. The criteria are given in three classes of traffic frequency (frequent events, occasional events and infrequent events). The document presents a range of methods and approaches, allowing detailed analyses of different situations. The document specifies, for different cases, minimum distances to comply with in order to be certain that given criteria are not exceeded. These extend up to a distance of 200 m from the track. A screening process is presented, which permits an assessment of the complexity of new projects. A simplified prediction method considers characteristics of the vehicle and the track (“adjustments”). Another prediction method assesses the so-called line transfer mobility based on a range of measurements and translates the results to the project site.

5.4 Railway Association of Canada / Federation of Canadian Municipalities: Guidelines for New Developments in Proximity to Railway Operations, May 2013

These guidelines recommend that an impact study covering 75m on both sides of the track be carried out by a qualified expert. A range of recommendations is given on how to assess vibration levels by measurement and computation. Mitigation measures are described in reasonable detail. This refers mainly to measures in the propagation path and at the foundation of the house.

5.5 Finnish guidelines on Traffic Vibration in Planning of Land Use (VTT)

The following graph illustrates how recommended vibration limits for residential areas were deduced from measurements gathered during a field survey.



Graph 14. Illustration of recommended limit values derived from field survey and measurements (source: presentation by VTT).

5.6 BS 6472, Evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz)

This standard defines two indicators: Vibration Dose Value and Peak acceleration, the latter being more suitable for the evaluation of blasting vibration. It also presents frequency weighting curves for three directions and defines measurement methods. A range of base curves for different vibration levels in buildings are established to provide an indication of when to expect annoyance or even complaints from residents.

6. Mitigation measures

Similar to the approach with air-borne noise, mitigation measures can control the vibration at the source, in the propagation path and at the receiver. For vibration, the source is considered to include the wheel, track and subsoil, whereas the propagation paths encompass all paths between the subsoil below the track and the foundation of the building. The receiver thus encompasses all propagation paths from the ground near the building foundation through the building's structure.

A range of mitigation methods are presented below, together with an indication of their cost and effectiveness. Note that the effectiveness of most measures is highly frequency-dependent: what might work in one frequency range will not work in a different frequency range.

Many of these measures have been investigated in laboratories, using scale models and computer simulation. A number of measures applied to the track have been tested in the field. However, for surface lines, there is relatively little real-world experience or test data from measures applied to the propagation path. Therefore, there is little proven technology with respect to vibration mitigation in the transmission path.

In general, track measures mitigating vibration represent a major interference both with the track itself and with the traffic using it. For most track related measures, it is virtually impossible to install them into a track that is in service. The installation of some measures would require an almost complete renewal of the track, including possibly ballast, sleepers, rail pads and rails. This can only be carried out when the track is taken out of service for a substantial period of time. Similarly, improving the foundation or the stiffness of floors would represent a huge impact on the occupants of a building. Residents would have to move out of the premises for some days or weeks.

Therefore, when discussing options, we distinguish between new lines and retrofitting existing lines.

6.1 Mitigation approaches

In the following sections, examples of mitigation measures are given. Wherever relevant, the feasibility of installation in existing situations is discussed. For each example, cost is compared with effectiveness, in as far as information is available. Two sources of information were used (here referred to as A and B for better comparison in the following paragraphs):

- Reference A: A list of mitigation options with cost and effectiveness from the RENVIB project (RENVIB Annex A, date not known but around 1995)
- Reference B: The Measure Catalogue for Railway Vibration, produced by Grontmij for ProRail (2016).

The effectiveness is expressed in dB as insertion loss, i.e. the difference in vibration (or ground-borne noise if explicitly mentioned) between the situation with the measure applied and the situation before the application.

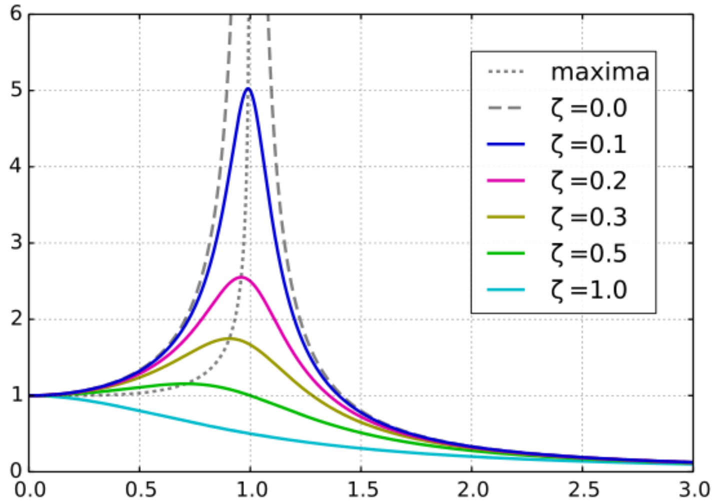
Please note that both cost and effectiveness are to be seen as indicative, as they are highly dependent on the actual situation. Also, the numbers for cost may refer to investment cost only (including or excluding installation), where it would be preferable to present life-cycle cost (including maintenance, etc.). Compared to measures to mitigate noise, the vibration related measures are much more expensive.

When selecting an appropriate way of mitigation, a distinction should be made between tunnel lines and surface lines. In tunnels, in general the options to control vibration at source are manifold (at least for new lines), whereas the options in surface lines are more limited. On the other hand, measures in tunnels tend to be expensive.

We have indicated the effectiveness where available. It should be emphasised that measures may be focused on vibration, ground-borne noise or even audible noise. Each of those phenomena has its own typical frequency range. An effective measure for ground-borne noise may not be effective at all for vibration or even counter-productive, and vice versa. The frequency range of interest should always be assessed and measures be dimensioned such that they are indeed effective in this range.

Most of the mitigation methods are based on the combination and modification of mass spring systems. Note that most mass spring systems show a frequency response that, in its simplest form, looks like Graph 15 below:

- there is a resonant frequency where amplification occurs, subject to damping of the system,
- below the resonant frequency, there is little amplification or attenuation,
- significant attenuation occurs only above the resonant frequency.



Graph 15. Simplified frequency behaviour of a single mass spring system with different damping factors ζ. The main reduction is around the resonant frequency. The reduction is smaller, but at a wider range of frequencies, when the damping factor increases (source: Wikipedia).

6.2 Measures at the vehicle

The combination of a rail vehicle and a track represents a complex dynamic system, built up of masses, springs and dampers. Vibration originates mostly from the wheel-rail contact. The response of each element in the system depends on how it is coupled to other elements, damping and its resonant frequency.

Any interference in the vehicle track system changes the excitation, but whether or not this is effective at the receiver point depends on the distance, the frequency and the stiffness of the soil in between. A reliable prediction of the effectiveness of a modification of either the vehicle or the track requires dynamic models combining vehicle, track system and ground (or tunnel + ground). These models should be 2D minimum, field-calibrated and should be used to extrapolate field measurements; such models consider the train as a line of uncorrelated forces and lead to estimating the line of uncorrelated forces applied to the ground (or the tunnel + ground) in a new situation; this quantity can be also measured and corresponds to the line transfer mobility defined in FTA document and mentioned in section 5.3.

In soft ground and at low frequencies, the heavy mass of the vehicle vibrating on the bogie often represents the dominant source. But in stiff soils and at higher frequencies (including ground-borne noise), the wheel out of roundness and the unsprung mass of a single wheel are often the dominant excitation mechanisms.

RIVAS report D5.5 [32] considers mitigation measures for the vehicle. The main potential for vibration control and mitigation can be found in the following points:

- *Improving wheel roundness:*

  Wheel out of roundness is one of the main causes of excessive vibration. This can be treated through good maintenance of the wheels.

- *Reduction of the unsprung mass:*

  This can be achieved, for new locomotives and multiple units, by improving the suspension of the drive system. Lower levels of vibration are associated with vehicles which have secondary suspension or a smaller wheel diameter, although the benefit will be limited to the higher frequency range (above approximately 20 Hz).

Reference A estimates the effect as 2-12 dB for both vibration and ground-borne noise, with no cost indication. Reference B does not mention this measure.

Own estimate:

A cost estimate for the above measures could not be assessed in a general sense. Obviously, for a vehicle-related measure to be effective, many vehicles will have to be treated. The overall vibration reduction of some of these measures, or a combination of all of them, could reach 10 dB, depending on the reference situation.

6.3 Measures in the track

6.3.1 Track alignment and track singularities

Track defects such as “hanging sleepers” and malfunctioning ballast can be a source of vibration. Good track condition is important to control vibration. In the H2S project in Britain it was found that good track alignment can provide a 10dB reduction for ground-borne noise for speeds at 320 kph [33]. In track design, discontinuities like track joints and switches or turnouts should be located away from very vibration- or noise-sensitive locations whenever possible. Regular tamping – including complete renewal of the ballast – and track levelling up to complete track renewal may improve situations with soft underground. Once a ballasted track is in good condition with good track alignment, additional measures applied to this track (see below) will only achieve minor improvement for vibration. They may still be effective for ground-borne noise.

Reference A estimates the effect at 0 - 2 dB for vibration (no information for ground-borne noise) and does not present a cost estimate).

Reference B estimates the effect at maximum 6 dB, an additional effect of another 6 dB for tamping and does not present a cost estimate either.

Own estimate:
The (additional) cost of an improved or intensified type of maintenance can be difficult to calculate as it depends on local circumstances. The effect of regular maintenance is estimated to be up to 10dB. In cases where the track is already in good condition, the benefits for vibration would be small, however.

6.3.2 Resilient and vibration-isolating rail fasteners

Resilient rail fasteners were proposed a long time ago, in the famous “Cologne Egg”. This concept has been improved over the years and is still on the market. However, it is suitable for light rail only.

Building on the ideas of the Cologne Egg, other designs have been developed, such as the two examples by Pandrol Vanguard and ORTEC GmbH, respectively, shown in Graph 16. In these systems, the rail is supported by resilient blocks fitting in the web of the rail.

Graph 16. Two examples of resilient rail fasteners (left © Pandrol, right © ORTEC GmbH). The rail is supported at the web by rubber wedges.

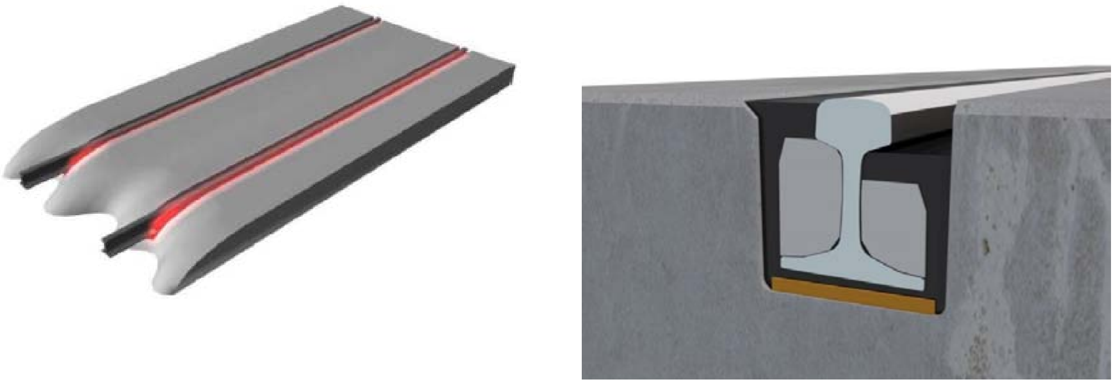
Recent application of this system in the Thameslink project in London showed reductions of 13 dB A-weighted ground-borne noise [34]. The expected effectiveness for vibration would be lower.

Reference A mentions no information on the effect for vibration and an effect of 0 - 6 dB for ground-borne noise and the cost at 350 - 700 euros per metre of track (single track), including track renewal.

Reference B estimate the effect at up to 13 dB and does not mention the cost but contrary to Reference A limits the application to new track.

6.3.3 Embedded rail

In the embedded rail system, the rail is continuously supported on a longitudinal resilient mat and is embedded in a concrete slab with a wedge on either side to keep the rail in place.



Graph 17. Example of an embedded rail support in a concrete slab (right: Edilon Sedra; source: Wikipedia).

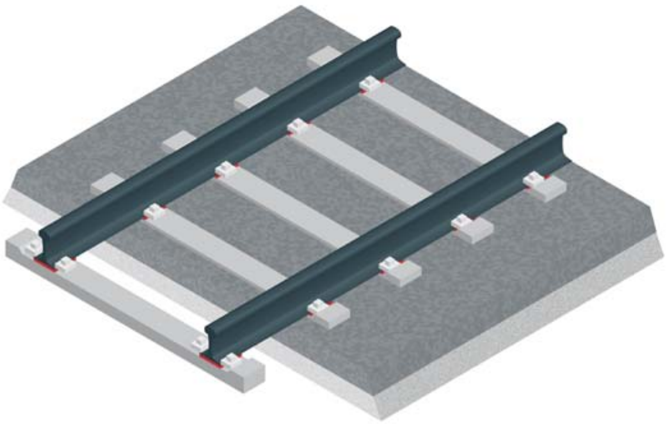
The system has been applied in short sections of heavy rail track (mainly for testing) and in operational tracks of light rail and trams. With a proper choice of the stiffness of the supporting mat, it may be effective for ground-borne noise reduction (limited effect for vibration).

Reference A estimates the effect at 2.5 dB for both vibration and ground-borne noise and does not mention the cost.

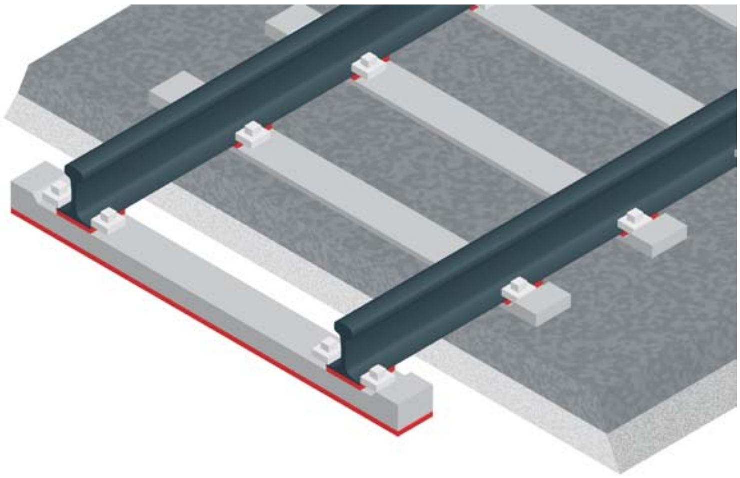
Reference B does not mention this measure.

6.3.4 Under-Sleeper Pads

For ballasted tracks in surface lines, under-sleeper pads (USP) are a possible solution. Under-sleeper pads are sometimes used to protect the ballast and thus also extend the intervals between maintenance. To reduce vibration, we are looking for under-sleeper pads with low dynamic stiffness (typically below 100 MN/m) and a small ratio between static and dynamic stiffness (typically below 1.2). The limitations of this requirement lead to materials that can reduce vibration in the higher frequency region (above approximately 30 Hz). At lower frequencies, an amplification of the vibration strength is to be expected. For situations where the higher frequencies represent a problem (e.g. very close to the track), the use of under-sleeper pads may be useful. Different sources mention cost in the range of 100 up to 900 euros per metre of single track [10].



Graph 18. Schematic of regular ballasted track.



Graph 19. Under-sleeper pad for vibration reduction and ballast protection.

Graph 20. Sleepers with blue under-sleeper pads (© Getzner Werkstoffe GmbH).

Requirements for under-sleeper pads have been defined in EN 16730:2016-09: “Railway applications - Track - Concrete sleepers and bearers with Under-Sleeper Pads” [36]. Also, there is a UIC International Railway Solution (IRS) including the findings of the UIC project USP in Track, currently pending approval before publication.

Possible optimisations of under-sleeper pads were described in RIVAS report D3.13 [37]. They are, however, limited to ballasted track and surface lines, although some measures may be effective in tunnel applications.

For straight ballasted track, the report proposes soft under-sleeper pads combined with either heavy sleepers, or alternatively very soft rail fastening systems. Reductions of 8 - 20 dB were measured in a field test. The additional reduction applies to 1/3 octave bands with frequencies between 80 and 100 Hz. The cost (probably investment including installation) is reported to amount to up to 90 euros per metre of single track for new lines (under-sleeper pads with standard sleeper; not the optimised product) and up to 250 euros per metre for upgraded lines reference [37]. For very soft rail fastening systems, the costs are comparable. The insertion loss applies to a frequency range down to 50 Hz, i.e. for ground-borne noise.

Reference A mentions an effect of 2 - 6 dB (for ground-borne noise only) with a cost of 60 - 100 euros per metre of track.

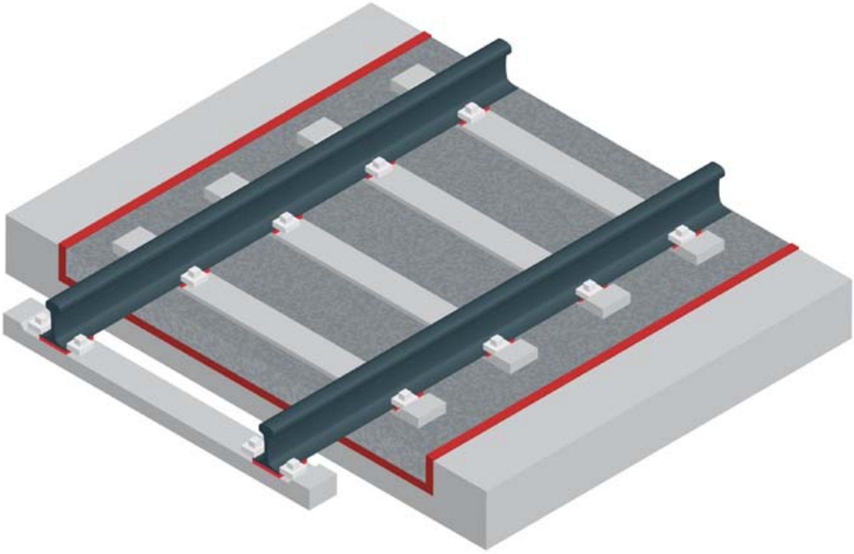
Reference B mentions up to 20 dB effect (probably for ground-borne noise only) and 750 - 900 euros per metre of track.

It has been demonstrated that the use of under-sleeper pads, although reducing ground-borne vibration, sometimes increases air-borne noise radiating from the sleepers and the rails. Therefore, installation of under-sleeper pads should be carried out with great care when surface railways are close to residential buildings.

6.3.5 Ballast mats for ballasted track in tunnels and troughs of surface lines

Ballasted track is applied in tunnels mainly to prevent changes in track dynamics from the open track to the underground track. When in contact with the concrete wall of the tunnel, the ballast tends to be pulverised. Under-ballast mats are thus used to protect the ballast. With a slightly different specification (lower stiffness), the ballast mats may also reduce the transfer of vibration into the tunnel wall. Despite sometimes severe conditions (moisture), there is good experience with respect to the life cycle of ballast mats in tunnels [38].

Under-ballast mats may also be applied in surface lines where the track runs in a trough (see photo below).



Graph 21. Under-ballast mat in a concrete trough or in a tunnel.

Graph 22. Example of an under-ballast mat in a trough, here for a light rail track in Munich, Germany (© Calenberg Ingenieure).

The stiffness of the mat is crucial: some very soft mats which protect the ballast may well lead to resonances in a critical frequency domain, and thus to amplified vibration at the receiver. For a well-dimensioned mat, the reduction may be up to 5 dB at low frequencies (approximately 20 Hz). Much higher values have been mentioned for higher frequencies. The cost of these measures is difficult to estimate. For existing lines, the cost associated with closing the line, removing and replacing the track and ballast are likely to be dominant and dependent on local circumstances.

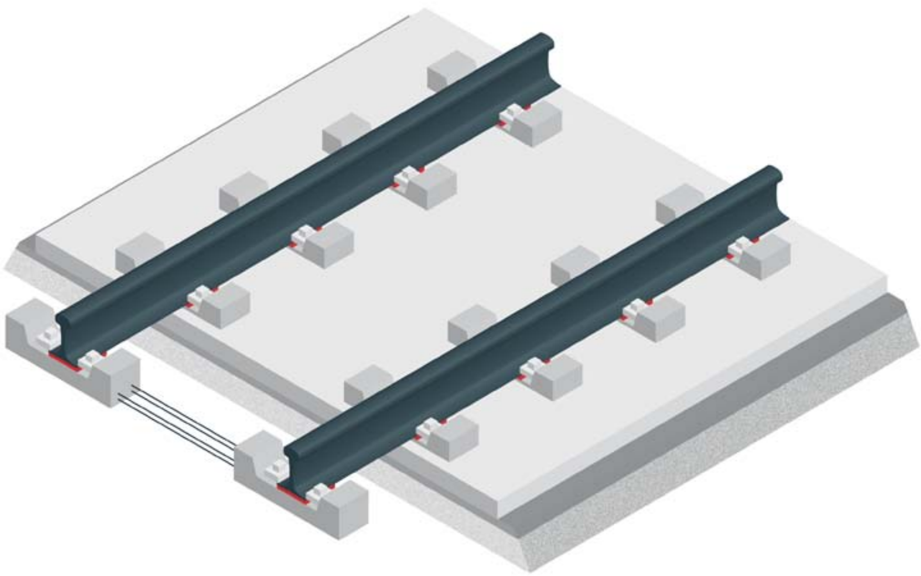
Reference A mentions 0 - 3 dB for vibration and 6 - 14 dB for ground-borne noise, with cost of 900 - 3000 euros per metre track (depending on whether the track is new or has to be renewed for the installation of the mats).

Reference B mentions 5 - 15 dB and does not mention the cost.

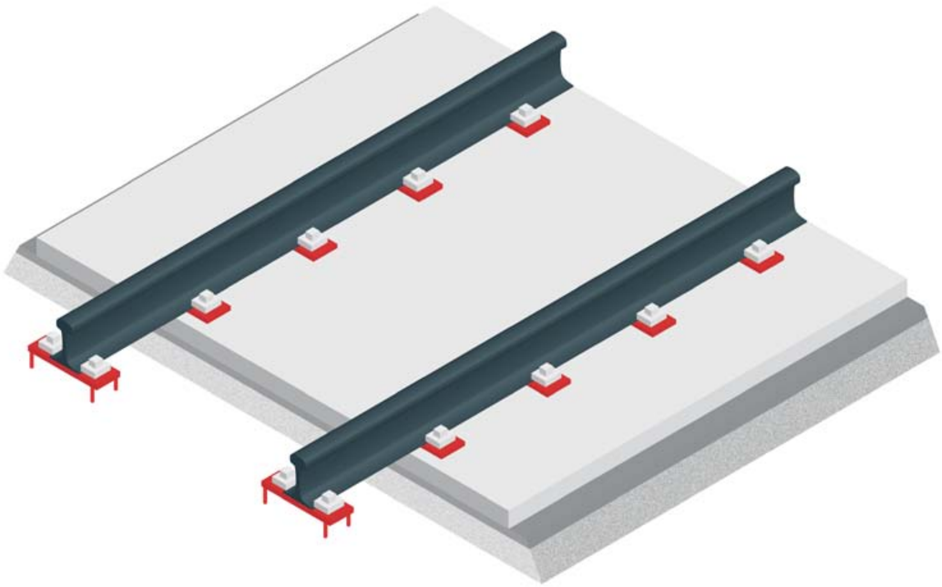
Similar to the under-sleeper pads, a EuroNorm is planned to be published shortly concerning the under-ballast mats and there is also a UIC Leaflet 719-1 entitled “Recommendations for the use of under-ballast mats” (2011) [39].

6.3.6 Slab track in surface lines

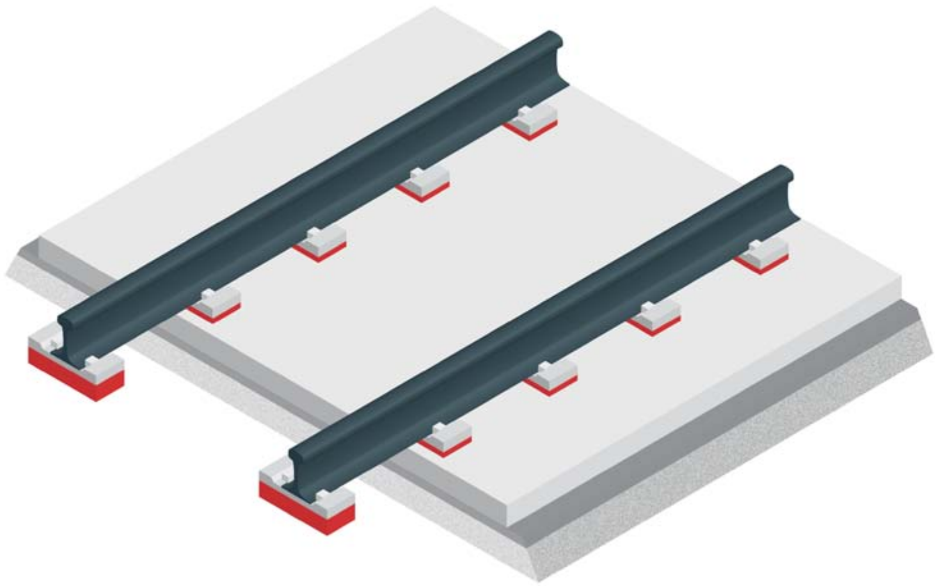
Non-ballasted “slab track” has been applied in some of the high-speed lines to save maintenance costs. For slab track, various options exist to reduce vibration and ground-borne noise. These are illustrated below in Graphs 23 to 26.



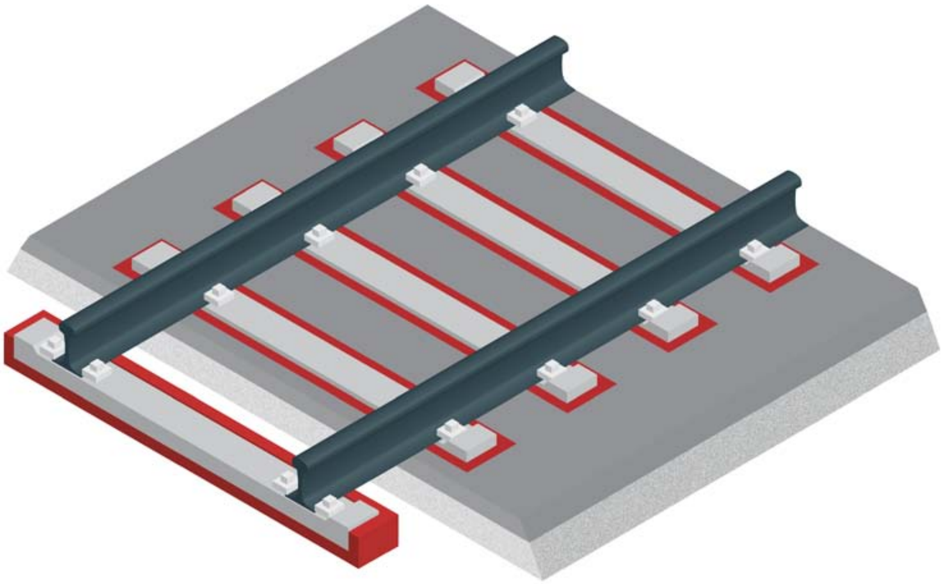
Graph 23. Non-ballasted track, with the rails being fixed in fixation blocks that are mounted on a concrete continuous slab (Rheda system).



Graph 24. Slab track with resilient base plates.



Graph 25. Slab track with booted sleeper.



Graph 26. Slab track lost in the subsoil, with under-sleeper mat to make it into a floating slab.

Under-sleeper mats can serve as a simpler and cheaper alternative to the floating slab track (see 6.3.7 below). In this case, every sleeper is supported by a mat, embedded in the slab. The mat is usually encased, together with the sleeper, in a rubber boot. For a much easier installation, the sleeper is commonly manufactured as two concrete blocks. A Swiss supplier proposes a 30% wider and 50% higher block, mounted onto a resilient mat, with similar or better efficiency than the sleeper mat in ballast. The effectiveness for ground-borne noise is expected to be good, but for vibration the effectiveness is probably limited.

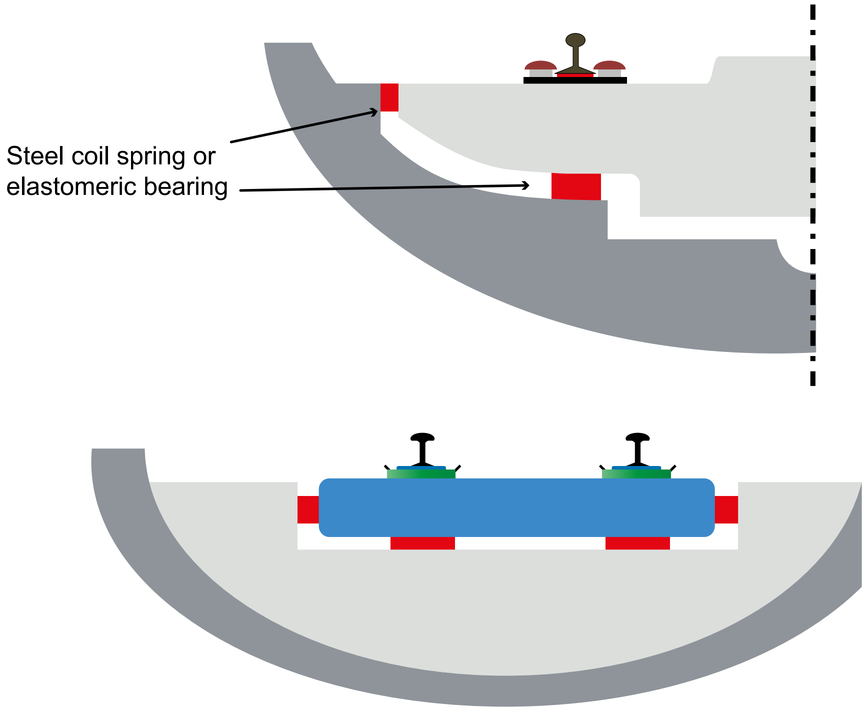
The additional cost of either of the measures presented above is relatively modest when compared to the total investment for a new slab track system. Generally, the vibration performance of a slab track line is already good to excellent, but further improvements could be achieved with the above measures if necessary.

Reference A mentions 0 -6 dB for vibration and an adverse effect for ground-borne noise, with 350 to 700 euros of cost per metre track.

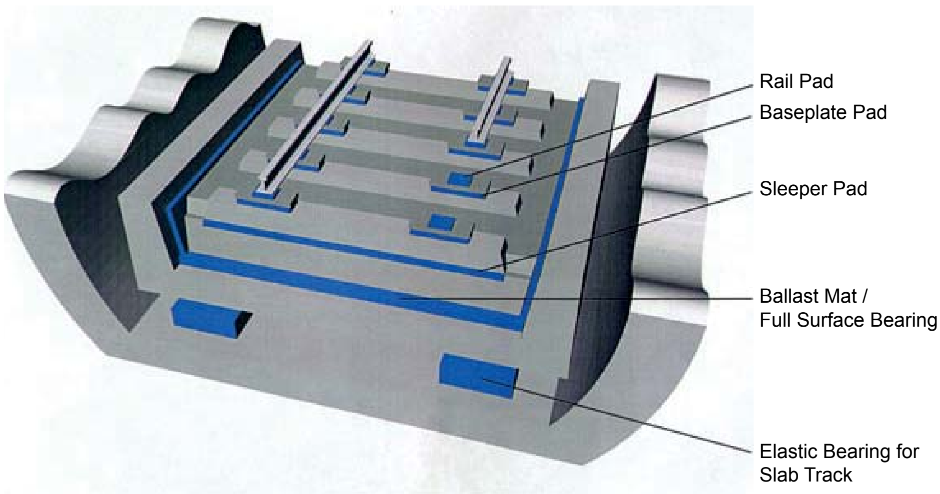
Reference B mentions 15 dB and a cost of 6,500 to 8,400 euros per metre track.

6.3.7 Floating slab track (mass spring) in tunnels

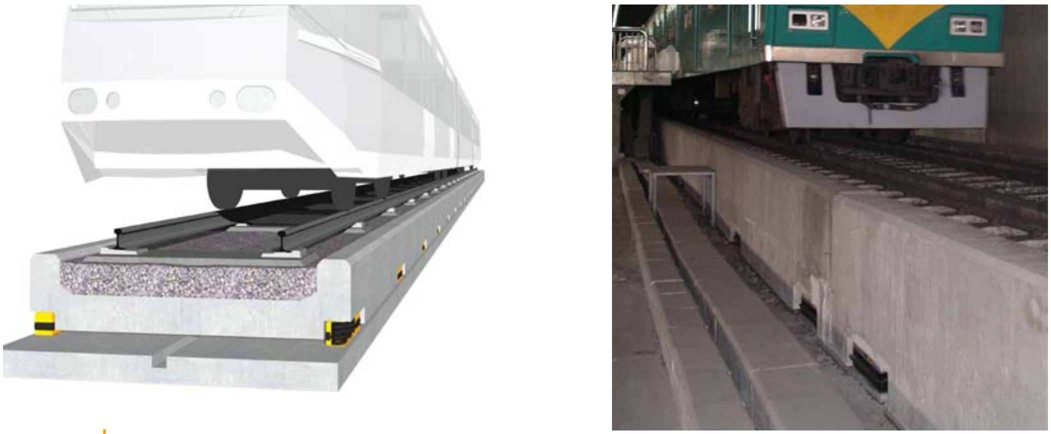
In tunnel sections, slab track is more common than in surface lines. The options to improve the performance of a tunnel line with slab track are good. The conditions allow an exact design of the performance within the desired frequency range. This is achieved by introducing a simple mass spring system, represented by the slab and its suspension [40].



Graph 27. Floating slab in cylindrical tunnels. The mass of the slab including train and the spring rate of the bearing determine the resonance frequency of the single mass spring system.



Graph 28. Slab track floating on elastomeric layers. © Getzner Werkstoffe GmbH.



Graph 29. Schematic of a mass spring system on steel coils (left) and real-life installation in a tunnel at Puchon Station, Korea. © GERB Vibration Control Systems.

The cost of this solution is mainly determined by the additional tunnel space required by the slab and springs. This widens the tunnel diameter, which will increase the cost substantially. The effectiveness of this measure is expected to be large, up to 20 dB. With good tuning, the measure will be applicable to very low frequencies, i.e. both ground-borne noise and vibration will be reduced.

As the ratio of the mass of the train relative to the mass of the slab is an important factor for the effectiveness of the system, the effect may be different for different types of rolling stock.

Floating slab tracks may have very high costs of renewal. After some years, elastomers can lose their mechanical properties and hence need to be replaced. Degradation of elastomers is faster than of the concrete mass borne by the elastomers. Being underneath the concrete slab, their replacement can be very difficult, sometimes impossible, to the point that slab demolishing is the only solution. Obviously, this is not the case with steel springs.

Reference A estimates the effect at 14 - 20 dB for vibration and 20 - 26 dB for ground-borne noise, with a cost of 2000 - 3500 euros per metre of track.

Reference B estimates the effect at up to 10 dB and the cost at 3500 - 4500 euros per metre of track.

Because of high initial costs and high renewal costs, floating slab tracks should be just ultimate solutions, to be adopted only when it is demonstrated that all the other alternatives would fail.

6.3.8 Column stabilisation

A solution for soft ground directly under the track is column stabilisation. Concrete columns are inserted into the ground down to a stiffer layer. The columns can be inserted either by pile drivers or by the so-called jet grouting technique [41], where fluid concrete is inserted under pressure into a bore hole. Alternatively, lime cement columns can be used in soils which contain a sufficient amount of water, such as clay soils.

The technique has been applied successfully in Sweden, where reductions of vertical vibration up to 45% were achieved at distances up to 60 metres from the track.

Graph 30. Jet grouting of piles/columns under an existing railway to compensate for very soft ground. © Hayward Baker, Inc., photographer: Jeffrey Hill.

Neither reference A nor reference B mentions this measure.

6.3.9 Suitability for retrofitting

Of the measures presented in section 6.3, only improving track alignment/removing track singularities (6.3.1), under-sleeper pads (6.3.4) as well as column stabilisation (6.3.8) are really suitable for retrofitting an existing track. The cost of installing any of the other measures with a track in operation would be enormous, with the only exception of minor adjustments in rail fastening elasticity, such as softer rail pads or softer base plate pads. However, the potential performance achieved by these cannot be significant.

6.4 Measures in the transmission path

Measures in the transmission path are suitable for surface lines, where surface waves are the main contributor to the excitation of sensitive buildings. For underground lines and buildings above them, the measures would not be effective. For buildings with a large horizontal distance to the tunnel, some effect may be achieved.

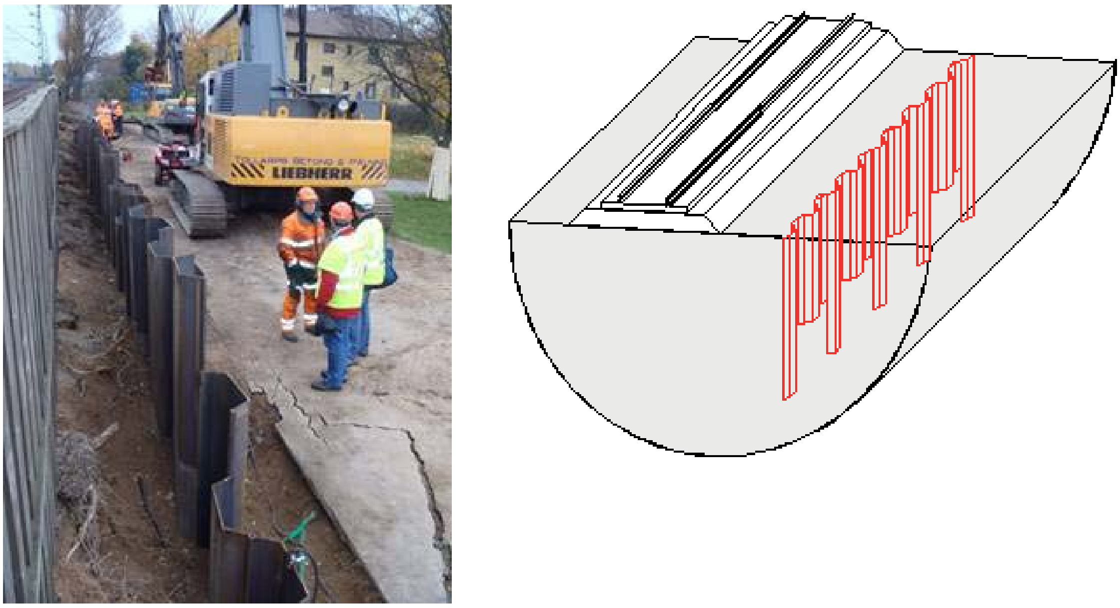
Dynamic models taking into account the ground layers and their dynamic properties should be used to quantify/predict the effect of mitigation measures in the propagation path. They should be 2D 1/2 minimum, having their input data field measured (see [17]), should be field calibrated and be used to extrapolate field measurements.

Mitigation measures in the propagation path between track and adjacent buildings aim to act as a barrier for the propagating waves. In the soil, a barrier can be achieved by introducing a material that deviates drastically from the surrounding soil by its density and/or stiffness. Such a material can be:

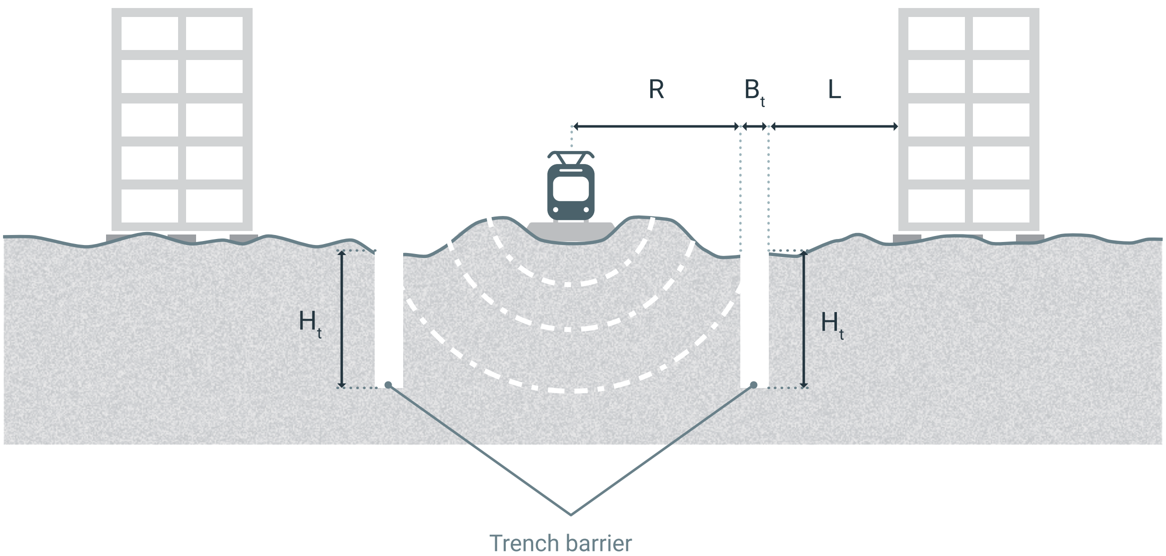
- an elastic mat, for example an under-ballast mat, provided that its stiffness differs sufficiently from the surrounding soil
- air (in the case of a trench) – which is very light compared to the surrounding soil

- water (in the case of a ditch) – also much lighter than the soil
- concrete (in the case of a "wave impeding block") – heavier and stiffer than the soil, where the soil is relatively soft and light.

Comparable to the concrete barrier is a technique called sheet piling. Steel sheet piles are driven into the soil close to each other to build a "sheet" of steel.



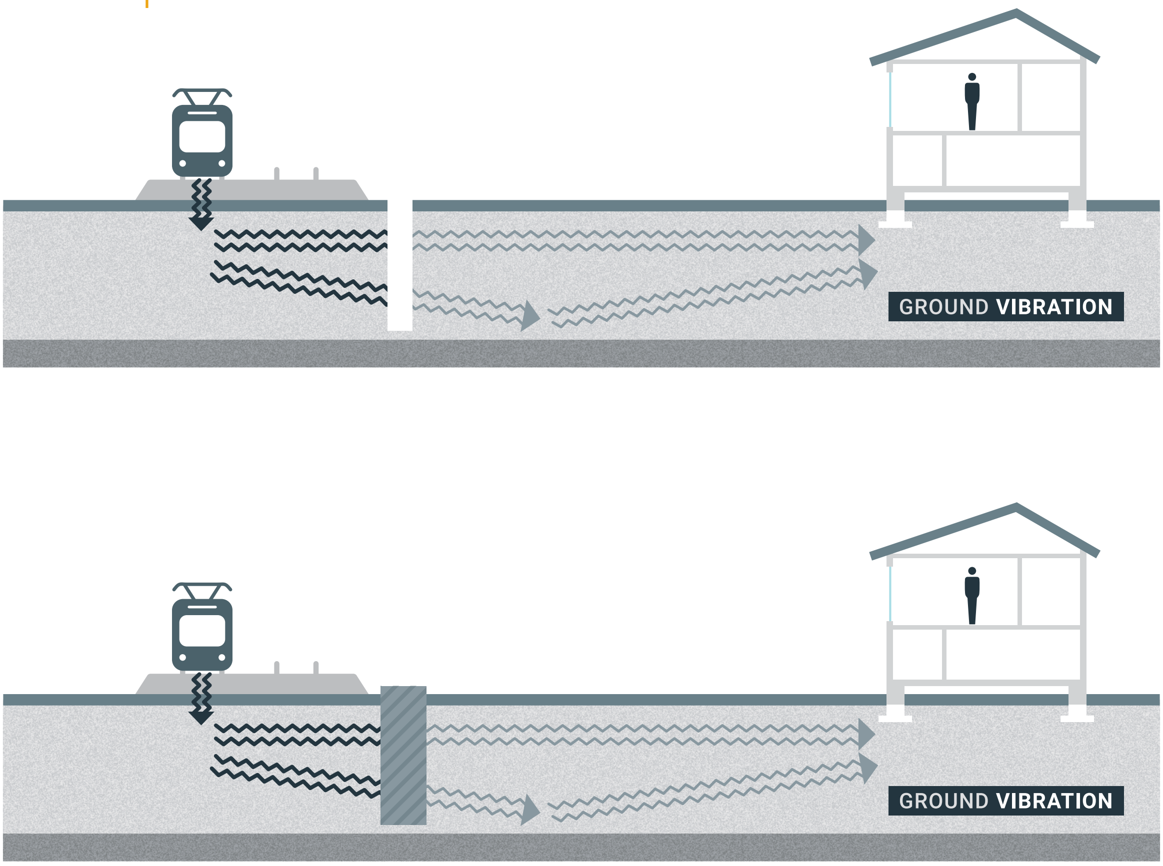
Graph 31. Construction of a sheet piling wall (left) and diagram of the construction of the wall (right). © Trafikverket.



Graph 32. Example of a trench barrier – here for model calculation of its efficiency [42].

Similar to noise barriers in the open air, the vibration waves tend to bend around the edge of the barrier. This means that the barrier must be deep enough to interfere with the vibration waves which reflect against the deep, stiff ground. Depending on the local circumstances, the barriers are typically 5 to 10 metres deep. In addition, in view of the long wave lengths of low frequency waves, the depth of the barrier should be in the order of 75% of that wavelength (reference [43] states “greater than 60% the Rayleigh wavelength at the most relevant frequency”), which often results in a similar requirement (up to an unrealistic 20 metres of depth). Where the layer of soft soil is not very deep, the depth of the barrier can be reduced.

Trenches and wave impeding blocks have been investigated in computer models and found to be effective [44, 45]. However, since this mitigation measure is very expensive and can be difficult to maintain, only very few cases have actually been implemented. Trench barriers thus cannot be considered a proven technology. For water ditches, sometimes not deeper than some 2 - 5 metres, an effectiveness of up to 3 dB was found (from various measurements in The Netherlands).



Graph 33. Schematic representation of a trench (upper graph) and a wave impeding block (lower graph).

Graph 34. Example of a water-filled ditch along the track. (© Paul de Vos).

All of the above measures are usually feasible even for existing lines, provided that there is sufficient space between track and any adjacent building. The presence of underground cables and pipes (or other uncertainties in the soil) may represent a considerable cost.

Reference A mentions 0 - 2 dB for filled trenches and 2 - 6 dB for unfilled trenches, both for vibration and for ground-borne noise. The cost is estimated at 33,000 to 66,000 euros per trench for a single building.

Reference B estimates the effect at up to 14 dB and the cost up to 2,000 euros per metre length and per metre depth.

6.5 Measures at the receiver

For the planning authority or the rail infrastructure manager, it is difficult to implement measures at the receiver. Since upgrading existing buildings is often prohibitively expensive, measures to improve vibration reduction in buildings already have to be implemented during its design and construction. Furthermore, such measures require the collaboration of the owner, sometimes even for taking measurements, depending on local law.

Four different types of measures are worth mentioning:

- Introducing a vertical elastic layer around the foundation (vertical parts and base of the foundation) of the building. This would inhibit vibration waves to affect the foundation. It would act as a protective shell around the foundation, provided that the shell is deep enough to prevent deep waves to reach the foundation. The effectiveness and cost depend highly on the situation.

  Reference A estimates the effect at 2 - 6 dB for ground-borne noise only and the cost at 17,000 to 34,000 euros per building.

  Reference B does not mention this measure.

- For newly built sensitive buildings, a resilient bearing can be introduced in the foundation. This is a standard approach for new builds over underground lines. The bearing usually consists of steel coil springs or elastomeric bearings. These bearings can be replaced in time if necessary. Even though the costs will be considerable, this measure can in principle be applied to existing buildings as well, provided that the existing foundation is suitable.

Reference A estimates the effect at 20 - 26 dB both for vibration and ground-borne noise and the cost at 65,000 - 330,000 euros per building (new buildings only).

Reference B estimates the effect at up to 20 dB and the cost between 10,000 and 100,000 euros per building (new buildings only).

- Stiffening the ground floor by means of piles (only for one-storey buildings) can reduce the vibration by a factor of up to two, although it may be difficult to implement in existing situations.
- In buildings with wooden floors, the stiffness of the floor can be substantially improved by inserting additional beams to support the floor. This kind of measure can be expensive.

  Reference A estimates the effect at 2 - 6 dB for vibration and adverse effects for ground-borne noise, with a cost of 65,000 - 130,000 euros per building.

  Reference B estimates the effect at up to 20 dB and the cost from 20,000 to 80,000 euros per dwelling.

Graph 35. Example of elastic bearing in building foundation (source: CDM Group)

The options mentioned here usually represent a substantial interference in existing residential buildings. For new constructions, however, resilient bearings have been proven to be very effective in mitigating/preventing vibration.

6.6 Comparison of measures

There is a high degree of uncertainty surrounding the data on cost and effectiveness of the mitigation measures presented above. Often the measures are described in scientific studies or suppliers' brochures, but data on practical cases is lacking. Even so, the following comparison should provide a point of reference to indicate which options offer the best value for money. Investment options are often compared solely based on their expected investment cost, which may be very high. This poses a risk of leading to the wrong conclusions. If a technical installation has to be replaced every 10 years, this would make this option less attractive than an option which stays for 50 years. Similarly, if a measure can be installed on the exact location of the hot spot (e.g. a concrete barrier in the soil), it would be less costly than a measure which would have to be installed on an entire line (e.g. any vehicle-related measure). Finally, if a measure could give rise to a shorter life cycle of the track or the rail, i.e. the frequency of renewal would go up substantially, this would represent a very significant cost increase.

As explained several times in the previous sections, the same mitigation measure may be very effective in one situation, but could be not effective at all (or even counter-productive) in other situations. For reasons of readability, this fact is ignored in the following section.

The fact that some mitigation measures are not yet completely understood or that they have not yet been applied in practice is also ignored. The indications on cost and benefit therefore show considerable margins of uncertainty.

We have produced four graphs:

- one for measures that are feasible in newly planned tunnel situations only,
- one for newly planned surface lines,
- one for measures that could be applied in existing tunnel situations, and
- one for existing surface lines.

The four graphs indicate the expected effectiveness as a percentage of the rms vibration velocity that could be reduced by the particular measure, including a range of uncertainty. It should be emphasised that we assume a proper design of the measure, based on a thorough and complete collection of necessary data to carry out the design work.

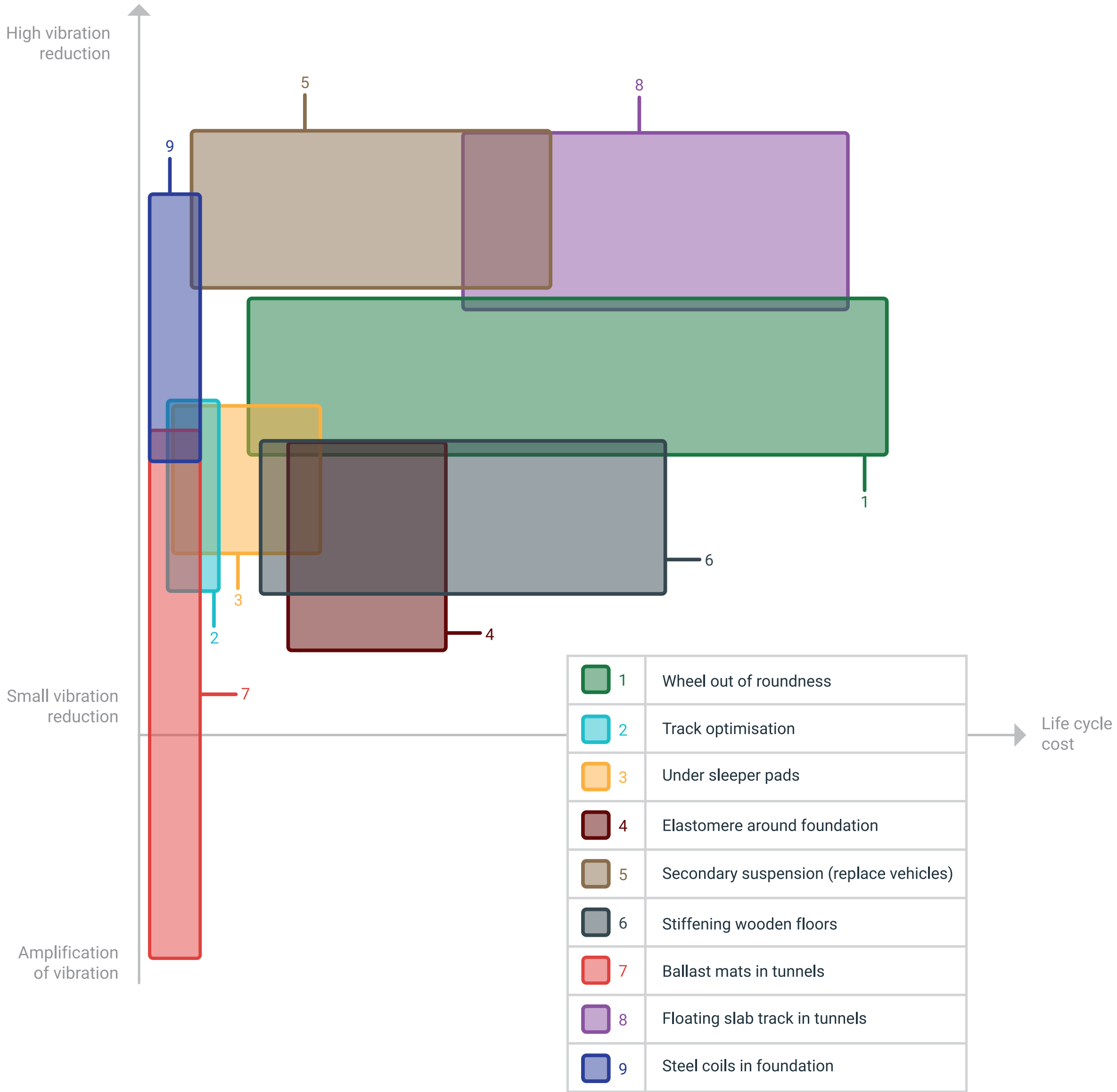
In many cases, an engineering estimate was used to assess the effectiveness, as very little data is available from real cases. This applies even more strongly to the cost. Here we estimated the expected investment cost for the measure, adding to that the cost of installation. The total cost thus derived was divided by the expected number of years before a replacement would be necessary, thus arriving at a simplified yearly life-cycle cost value. Depreciation and collateral benefits, which are likely to arise with some mitigation measures, were ignored.

In addition to this, we have used the following assumptions:

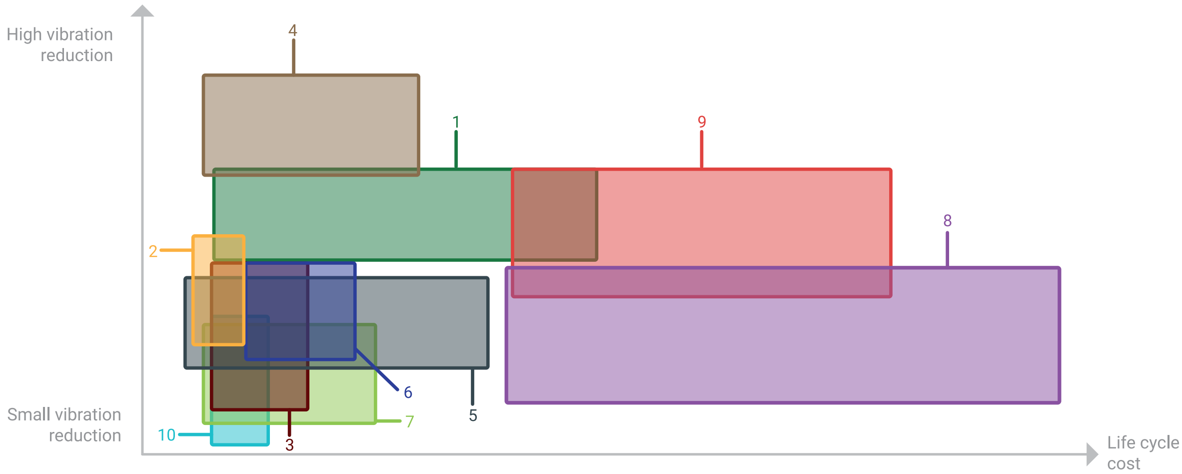
1. We consider one single hot spot of residential area along a two-track rail link. The length of the track causing potentially high vibration levels is assumed to be 500 m long.
2. In case of vehicle related measures, we consider an entire line, with 3,000 vehicles running on it, that may need to be treated/replaced in the context of this measure. In our assumption, this would apply to some of the freight vehicles and all locomotives. On the length of this line, we assume 20 hot spots. We consider the life cycle of a vehicle to be 50 years. The life-cycle costs are assessed per year and per hot spot.

   Note: This situation is rather unrealistic. Measures to the vehicle could apply in closed networks (e.g. an urban mass transport network). For freight traffic, many different vehicles (many more than 3,000) would use the same link and probably all of them would have to be modified.
3. For wheel flat monitoring and reprofiling, we have assumed an annual number of 300 vehicles that have wheels which need reprofiling. We assume that 20 hot spots would benefit from this. The estimated cost consists of the installation and operation of a wheel flat monitoring station, the reprofiling of one wheel per vehicle per year and the early scrapping of 10% of all wheels with excessive wear due to reprofiling. For the system, a life cycle of 40 years is assumed. Collateral benefits in terms of a longer life cycle for the track are ignored.
4. For optimised track, we assume an existing track of 500 m that is not particularly well kept. As a measure, we would introduce tamping including track alignment and grinding on a 5-year basis, as well as rail pad renewal every 20 years. For under-sleeper pads, if applied, we assume an equal period of renewal of 20 years. We assume that this is the same life cycle as for the sleeper itself.
5. For measures in tunnels (not for retrofit), we assume a track length of 500 m and a life cycle of 30 years.
6. For columns under the track, we assume a life cycle of 100 years.
7. For measures in the propagation path, we have assumed life cycles of 40 years for the elastic mat barrier and the concrete mass barrier, 20 years for a trench and 10 years for a ditch.
8. For the measures at the residential building, we have assumed 40 premises per hot spot, and a life cycle of 20 years for the polyethylene coverage around the foundation, and 40 years for steel coils in the foundation and stiffening beams in the floors.

The assessment is based on a spread-sheet approach. Most parameters have a linear effect to the cost. This means that the calculation could easily be adapted to other assumptions.

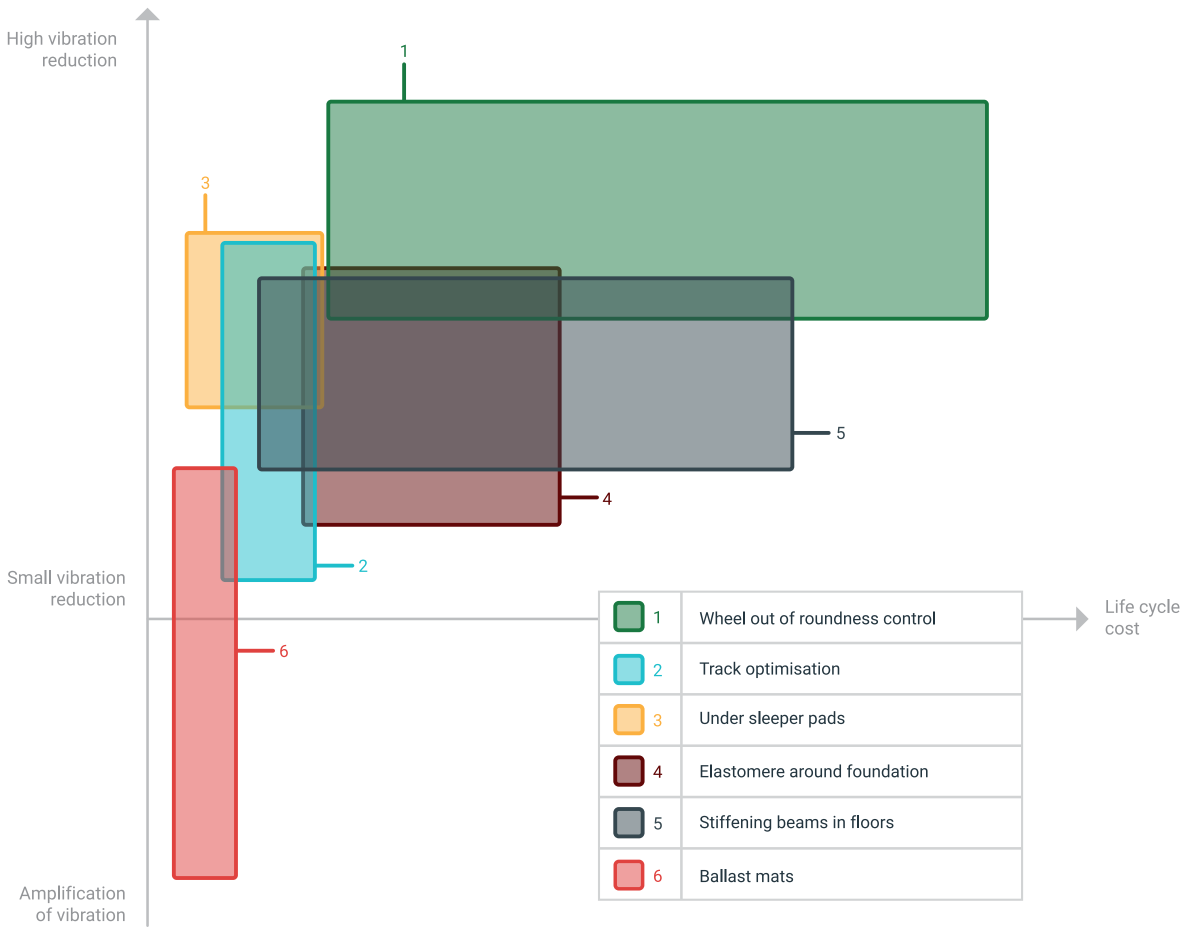


Graph 36. Comparison of mitigation measures suitable for application in new tunnel situations. Annual simplified life-cycle cost for mitigation at a hot spot of 500 m length with 40 premises, and their effectiveness in terms of percentage reduced of the rms vibration velocity.

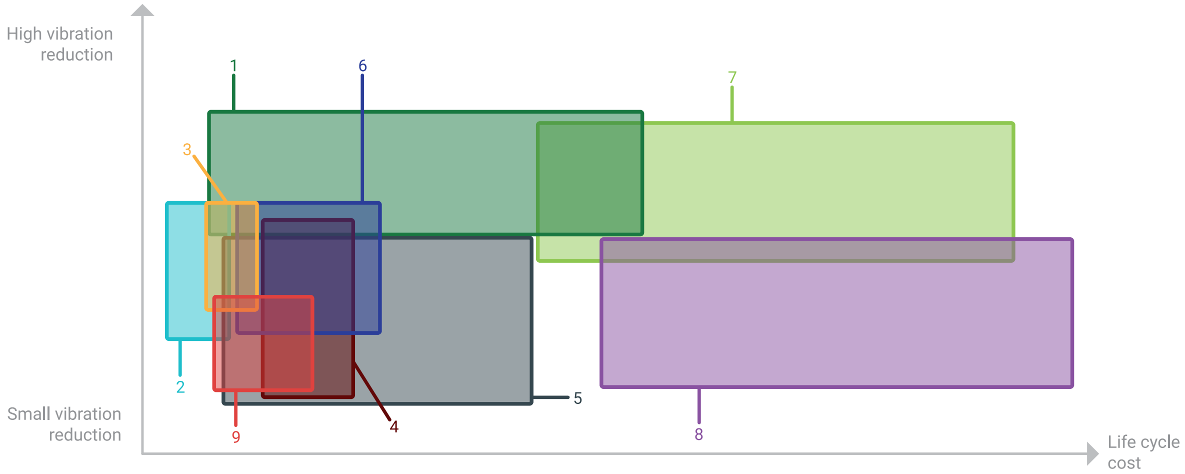


1	Wheel out of roundness	6	Elastic mat barrier (filled trench)
2	Under sleeper pads	7	Trench barrier (open trench)
3	Elastomere around foundation	8	Concrete mass barrier
4	Secondary suspension (replace vehicles)	9	Various types of slab track in surface lines
5	Stiffening wooden floors	10	Column track stabilisation

Graph 37. Comparison of mitigation measures suitable for application in new surface line situations. Annual simplified life-cycle cost for mitigation at a hot spot of 500 m length with 40 premises, and their effectiveness in terms of percentage reduced of the rms vibration velocity.



Graph 38. Comparison of mitigation measures suitable for application in existing tunnel situations. Annual simplified life-cycle cost for mitigation at a hot spot of 500 m length with 40 premises, and their effectiveness in terms of percentage reduced of the rms vibration velocity. A negative reduction means that there is a risk that the velocity will increase due to the measure being implemented.



1	Wheel out of roundness control
2	Track optimisation
3	Under sleeper pads
4	Elastomere around foundation
5	Stiffening beams in floors

6	Elastic mat barrier (filled trench)
7	Trench barrier (open trench)
8	Concrete mass barrier
9	Ditch

Graph 39. Comparison of mitigation measures suitable for application in existing surface line situations. Annual simplified life-cycle cost for mitigation at a hot spot of 500 m length with 40 premises, and their effectiveness in terms of percentage reduced of the rms vibration velocity.

In the four above graphs, the effectiveness for vibration and ground-borne noise has been averaged. In extreme cases, a good effectiveness for one phenomenon may represent a bad result for the other. This could not be reflected completely in the graphs.

For existing situations, the construction of a barrier in the ground between the track and the premises seems to be a very expensive measure. This may have been caused by a rather conservative estimate of the life cycle of these measures (40 years for a concrete barrier and 20 years for a trench). Wheel out of roundness monitoring and control comes out as a promising step (high effectiveness and moderate costs), together with track optimisation and under-sleeper pads, provided they are properly designed.

For new situations, floating slab track appears to be an expensive solution, possibly due to a conservative estimate of the life cycle (30 years). For under-ballast mats, the effectiveness gives rise to some doubts. Vehicle-related measures may be efficient at moderate costs, if a (political) solution can be found on the implementation (comparable to the cast iron brake block retrofitting, but with much higher costs). Measures at the dwellings (foundation and floors) may be cost-efficient but politically disputed.

7. Outlook

Railway vibration is not a new phenomenon, but the attention attributed to rail vibration lately has increased. Being an emerging field of work, rail vibration management and control lacks many of the elements necessary for a complete policy and strategy. Guidelines exist in several countries but there is a wide spread of methods to assess and mitigate vibration, a large variety of indicators and approaches. For new situations, a reliable prediction of the vibration levels to be expected is difficult and/or requires extensive field work to assess the behaviour of the local ground. Reliable predictions are feasible for individual dwellings, but reliability is not feasible for a complete urban area with a few hundred dwellings. For existing situations, the options to reliably and economically mitigate or reduce the vibration levels at reasonable cost are still limited.

In view of this situation, a gradual further (international) standardisation and harmonisation is to be expected. The initiatives taken in the ISO 14837 network are promising, even though it will take time to come up with reliable and validated methods. This process should lead to standardisation of units and quantities and to a further improvement of the reliability of prediction and assessment methods. This improvement may cause higher cost for assessment and predictions, since more effort than today will be required to collect reliable input data.

In this final chapter, some concrete recommendations are presented that are derived from the insights gained in the previous chapters.

7.1 Assessment methods

1. Measurements have shown that vibration on the higher floors of a building can be the same as at the foundation, but they can also be amplified by a factor of up to 15. This is a relevant finding when mitigation measures for railway lines are discussed. In the case of a large urban area with many different buildings, it is hardly possible to assess and guarantee compliance with limit values in all buildings, when the amplifications are so different (and unknown). A reasonable solution could be to agree on a target value set for the foundation vibration and leave the performance of the building to the responsibility of the builder or the owner of the property. This would be similar to the approach in noise control, where the exposure level outside the building in front of the façade is the quantity to be assessed, whereas the performance of the façade insulation and the resulting interior noise level are left to the responsibility of the building owner.
2. From the railway's point of view, the preferred approach when setting target values for vibration in buildings (even in guidelines and standards) would be:
   a. to define a measurement position, either next to the track (for existing lines) or next to a building (for new lines).
   b. Alternatively, a measurement position could be defined at the foundation of the building, using a harmonised default amplification which may depend on the type and age of the building. This would allow an

assessment for a wide range of buildings without unreasonable effort for assessment in all buildings and it would render more certainty for the party carrying out mitigation measures.

7.2 Risk assessment methods

It is in the interest of the party responsible for the spatial planning and environmental impact assessment for a new line or a significantly altered line to assess the risk of ground-borne vibration and ground-borne noise exceeding target values. In the following section, a proposed procedure for this risk assessment is presented for both significantly altered lines and new lines.

7.2.1 Significantly altered line

In this case there is an existing line with existing traffic and existing dwellings close to the track. A risk assessment basically consists of an assessment of levels of vibration and ground-borne noise in the existing and an estimate of the difference to each of these due to the alteration.

This includes:

1. Identification of one or more typical buildings close to the track (depending on the variety of buildings present, in terms of number of floors, age of the building, wooden or concrete floor, type of foundation, etc.).
2. Assessment of the existing levels of vibration and ground-borne noise for a sufficient length of time, in order to ascertain that all types of train are included in the measurement. Measurements to be carried out both on the foundation and on the centre of each floor.
3. Assessment of the existing levels of vibration in the ground on one or more lines perpendicular to the track, in order to assess the attenuation factor (Barkan Curve) and its variability in the area under concern.
4. Identification of the type of alterations. In principle, these can be geometrical (track position is changed or an additional track is added) or traffic-related (speed increase, change of train type). To estimate the effect of a geometrical change, the results of assessment 3 can be used. To estimate the effect of train speed and train type, the difference between different train passages assessed under 2 can be used.
5. The estimate under 4 can be used to estimate the resulting levels of vibration and ground-borne noise after the alteration in the buildings selected under 1. For additional buildings, either the amplification factor from foundation to higher floor as assessed under 2 can be used or a conservative estimate can be made of this amplification (up to 15x).
6. The resulting levels are compared to target values both for the absolute level and the increase due to the alteration.

7.2.2 New line

In order to estimate expected levels of vibration and ground-borne noise in new situations (existing residential buildings), the following steps are required:

1. The future location and type of the track and the future traffic in terms of numbers of trains, type of trains and speeds have to be assessed.
2. Identification of one or more typical buildings close to the track (depending on the variety of buildings present, in terms of number of floors, age of the building, wooden or concrete floor, type of foundation, etc.).
3. An indication of the type of soil and its variability has to be determined. In case there are no data, measurements have to be made to assess the basic soil properties.
4. The data has to be fed into a numerical or empirical prediction model.
5. A prediction has to be made of the levels of vibration at the foundation of the buildings identified under 2.
6. The amplification of the vibration in the building up to the higher floors has to be predicted.
7. The predicted levels have to be expanded to other buildings so as to cover the entire urban area.
8. Resulting levels of vibration and ground-borne noise have to be compared to target levels.
9. In case of an excess, mitigation measures have to be proposed and their cost and effectiveness assessed.

7.3 Future developments concerning prediction

A range of prediction methods are currently being used, from very scientific and analytical to very empirical and experimental. In future, a call for harmonisation may arise with a need for benchmarking. Then it will be important to take these differences into account.

The methods of prediction currently available are either very laborious or have a high degree of uncertainty. This can be managed by including a safety margin when designing mitigation, e.g. the Crossrail project in London included a safety margin of 10 dB within the vibration predictions. This was due to the criteria which required all reasonably foreseeable circumstances to be covered. To improve the prediction accuracy, further validation of the calculation method and input variables is necessary.

Currently, the methods to predict vibration in buildings caused by rail traffic on a future track are still of an academic nature. Assembling the necessary input parameters, such as the soil damping and soil layering, as well as the interaction between track and vehicle would have to be carried out for every single sensitive site along a new railway line. This is generally an uneconomically high effort.

In research, calculations are carried out to assess for example the effectiveness of certain mitigation measures. For that purpose, scientific methods are used, such as modelling the soil as a finite element system.

Although this approach produces interesting results in terms of a rating of mitigation measures or an estimate of what is required to comply with certain limit values, rough assumptions have to be made even in these sophisticated models with respect to the soil parameters, the excitation by the source, etc. Therefore, the model results cannot simply be transferred to real life without a very substantial amount of effort to find out the crucial parameters in the field.

This being the case, a slightly different approach to setting and complying with target values for future cases may be desirable. For instance, taking account of a large range of uncertainty, in combination with accepting a certain percentage of excess of the targets.

7.4 Recommended response to complaints about vibration

Whatever the measurable effects of vibration, some people may feel annoyed by vibration from running trains and express their concern. After all, as stated before, the individual response to railway vibration can differ considerably. Some networks have worked out strategies to respond to complaints. Essential elements in the preparation and communication of a response towards residents and other stakeholders are listed below.

Note that after each step, a decision has to be made whether or not it is necessary to make a further step. For example, in step 1, if the distance to the track exceeds a given number, further steps are not necessary and the response to the complaint would be: "on the basis of the location of your house with respect to the track, there is no need for further investigation".

1. An assessment of the distance to the track, in order to judge whether or not the complaint could be justified (Google Streetview can be a useful tool to assess the location of buildings, the number of floors, etc.).
2. An assessment of any other sources of vibration in the vicinity of the property, particularly in cases where there is doubt that railway operations are indeed the reason for complaint.
3. A review of earlier vibration measurements in the area that could support the assumption that high vibration strengths may occur.
4. A review of geophysical information, first to assess the basic characteristics of the ground, i.e. stiff, soft or very soft. In case of expected serious risk, an assessment of available results of geophysical measurements, as well as geological and geotechnical information regarding the area under concern, to determine if the area is susceptible to high vibration.
5. Based on past measurements and assumed data, a first, very rough estimate of vibration strengths at the foundation of the building due to rail traffic.
6. Whenever appropriate: a statement of reassurance to the resident that there is no risk of damage to the property due to rail traffic.
7. An assessment of the periods when vibration has been observed and possible relation to changes in the track geometry (maintenance and renewal) or train movements. Encourage residents to keep a logbook indicating times of observed "high" vibration.

8. An assessment on any track singularities and discontinuities (switches, joints, etc.) close to the resident under concern.
9. An indicative assessment of the static and dynamic quality of the property (concrete or timber construction, etc.).

Only if the outcome of the above assessment indicates a high risk that vibration levels are indeed high (preferably a threshold value should be defined), a further investigation could be arranged in the form of an indicative measurement at site, assessing the exact value of the vibration strength both on the foundation and in the building.

To conclude, both railway operators and infrastructure managers fully recognise the impact of their operations and are committed to pro-actively work with stakeholders to mitigate vibration. They recognise the importance of properly managing the interests of residents to build trust. Considering this report's conclusions, however, any proposal for further obligations to mitigate vibration must first establish a clear view of the full costs and benefits on a national scale. Furthermore, a level playing field with, for example, the road sector must be guaranteed.

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