Review of countermeasures and regulations for railway induced ground vibrations in tunnels

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1 Condition of use ... 3
2 Introduction ... 3
2.1 Research scope ... 4
2.2 Limitations ... 4
2.3 Method ... 4
3 Track based countermeasures ... 5
3.1.1 Rail, fastener and rail pad ... 5
3.1.2 Under sleeper pad ... 8
3.1.3 Sub-ballast mat ... 10
3.1.4 Floating slab track (mass spring system) ... 11
3.2 Summary of the effect of different track based countermeasures ... 13
3.3 Companies/firms working with ground vibration problem ... 13
4 Vibration discomfort - regulations and standards ... 14
4.1 Vibration and human exposure measures ... 14
4.1.1 Frequency weighting and time constant ... 15
4.1.2 Absolute threshold of perception ... 15
4.2 Standards and guidlines ... 17
Austria (ÖNORM S 9012:2010) ... 17
4.2.1 Germany DIN 4150-2:1999 ... 18
4.2.2 Italy UNI 9614:1990 ... 18
4.2.3 Japan Vibration regulation law ... 18
4.2.4 The Netherlands SBR Richtlijn – Deel B (2002) ... 19
4.2.5 Norway NS 8176:2005 ... 19
4.2.6 Spain (Real Decreto 1307/2007) ... 19
4.2.7 Sweden SS 460 48 61:1992 ... 20
4.2.8 Switzerland BEEKS 1999 ... 20
4.2.9 Unitet Kingdom BS 6472-1:2008 ... 20
4.2.10 United States of America FRA(2005), FTA(2006) ... 21
4.3 Combination effect of noise and vibrations ... 21
5 References ... 22

1 Condition of use

This report contains a literature review based on research publication, research reports and public documents. Parts of this report contain material directly cited from the references. This document shall not be used as a base for any financial decisions. For decision purpose the original information sources must be consulted. A more extensive review is also recommended for more specific research questions.

2 Introduction

Ground-borne vibrations due to railway traffic have become an important environmental issue, which are particularly critical when new rail infrastructure is introduced in an existing urban environment [1]. These vibrations propagate through the tunnel construction and the surrounding soil into nearby buildings, causing annoyance to people. Control of vibration from trains running in railway tunnels is an important issue and is now receiving increasing attention in research.

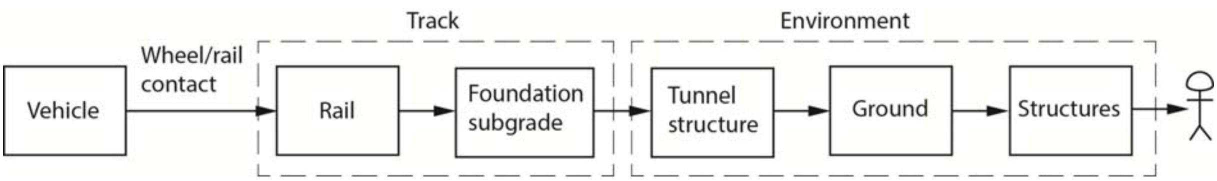

Figure 1 Ground vibration or stress wave propagation path. The figure describes the stress wave propagation path from the vehicle side to the human receiver side. The track section will be excited by the rolling stock and stress waves will propagate to the surrounding structures (eg. tunnel), ground and buildings/areas populated by humans.

In the vicinity of railway traffic airborne noise and structural vibrations can affect the wellbeing of humans. Structural vibrations can cause discomfort due to the perceived vibrations or due to noise generated by radiating surfaces affected by the structural vibrations, normally called structural borne sound. When dealing with railway traffic in tunnels the direct airborne sound, traveling from the train to the receiver (human) is neglected, however the effect of structural borne noise must be considered when analysing the effect of ground vibrations from railway traffic. Especially though a combination effect between annoyance due to vibrations and annoyance due to noise is reported in the literature. The scope of this report is however limited to focus on countermeasures and acceptable levels of ground born vibrations for the case illustrated in Figure 1.

Operational rail vibration arises at the wheel/rail interface and propagates via the track support system to the tunnel structure, the ground and surrounding buildings. Occupants of nearby buildings may detect “rumble” noise during the passage of trains, called ground-borne noise. In some cases, occupants may directly perceive vibration, called ground-borne vibration.

The ground bourn vibrations due to railway traffic are mainly generated in the contact zone between the wheel and the rail. It is therefore important that this excitation mechanism is reduced to a minimum. In principle airborne sound from a train in a tunnel could be transformed into structural borne sound when affecting the tunnel construction.

By nature the wheel rail interface will generate the largest contribution to ground vibration (Path C in Figure 2) compared to air borne sound, which is transformed into vibrations (Path B in Figure 2), but in principle this statement is dependent on the strengths of each individual source.

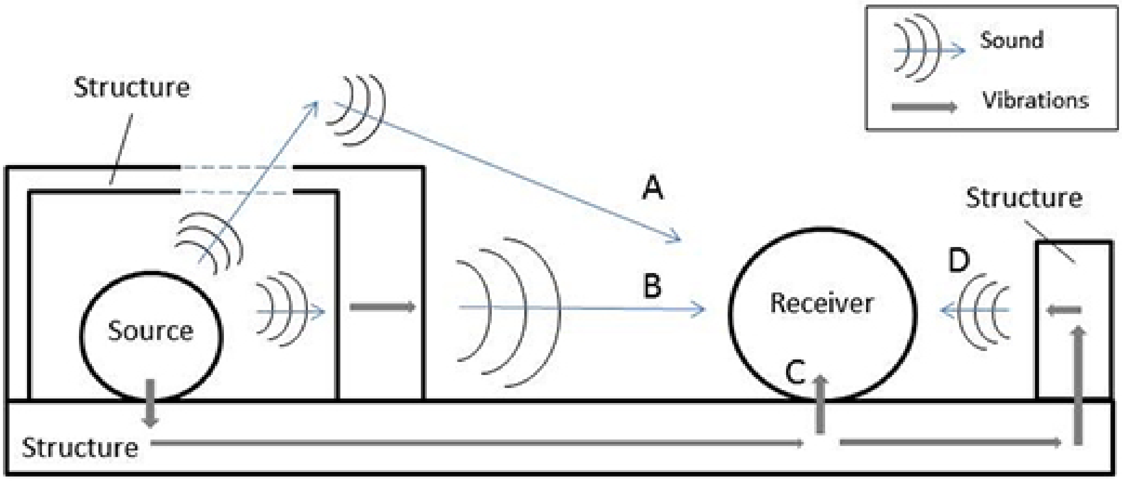

Figure 2 Vibration and sound propagation paths. A: Direct airborne sound. B: Airborne sound transformed into vibrations which excites a surface radiating airborne sound. C: Structural borne vibration. D: Structural borne sound which excites a surface radiating airborne sound.

To minimise the mechanical excitation mechanism of the wheel and the rail the connecting surfaces must be as smooth as possible. Vibrations generated by the wagon and bogie construction must also be kept to a minimum in order to reduce the amount of structural vibrations transmitted down to the rail. In order to achieve a system with desirable acoustic and structural dynamic properties with low impact on humans regarding structural borne vibrations the design of the track, wheels, bogies, wagons must be considered. Another important aspect is to ensure that these parts are maintained in an appropriate way. By performing adequate maintenance actions of the track and vehicle at the right time the system could be kept in a state close to the deigned requirements.

2.1 Research scope

The scope of this report is to perform a literature review of regulations and standards associated with railway induced ground vibrations (Path C in Figure 2) from tunnel based railway traffic and track based countermeasures and their performance.

2.2 Limitations

Each part in Figure 1 will affect the vibration levels at the human receiver side. However, the work presented in this document is focused on the problems and solutions associated with the track section part. Following the principle the; a problem should be addressed as close to the source as possible, measures at the track side will therefore normally grant the most cost efficient solutions for new railway tunnel constructions.

2.3 Method

Literature study in official and scientific databases

3 Track based countermeasures

This section describes different countermeasures related to the track section and their performance for reducing the effect of ground vibrations. Means of controlling vibrations from trains in tunnels are known. In most cases the most practical means are at the source—that is in the railway structure itself—rather than in the transmission path or at the receiver (for example by base isolation of buildings) [2].

This section is divided into different parts describing different types of countermeasures applied at different positions of the track and their performance. Figure 3 shows an example of different layers where countermeasures could be implemented.

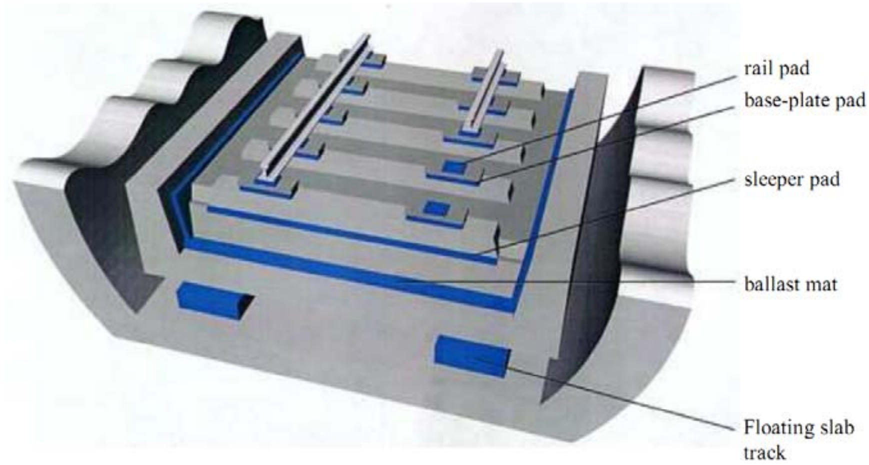

Figure 3 The various rubber products used to reduce noise and vibration transmission from railways (Getzner Werkstoffe GmbH, Bludenz, Austria [3])

3.1.1 Rail, fastener and rail pad

Rail fasteners are used to keep the rail at its designated position on the sleeper as shown in Figure 4. There are various variants that are optimal for different conditions. Using highly elastic (flexible) rail fastenings will permit larger deflections of the rail beneath the wheel which reduces the mechanical impedance of the superstructure and hence the vibrations. Using flexible fastenings reduces the vibrations between 30 to 50 Hz, where a higher reduction is observed at 50 Hz (about 6 to 10 dB) [4].

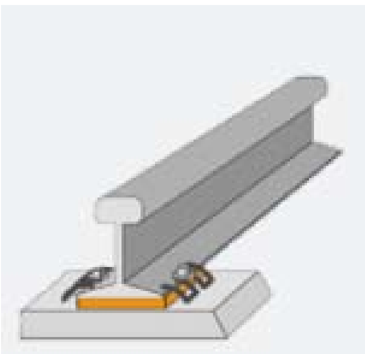

Figure 4 Rail, fastener and rail pad

Rail pads, sometimes also known as “sole” plates or pads, are placed between the rail and the (concrete) sleeper, please see Figure 4. They are usually made of rubber and their main function is to reduce fatigue cracking of the sleepers, but they are also believed to have a damping effect on vibrations. The measure here is either to install the pads or to use pads with a different stiffness [4].

The Pandrol Vanguard fastening system as shown in Figure 5 was developed to reduce significantly noise and vibration from underground railways within the constraints of an intensively used small tunnel.

Figure 5 Pandrol Vanguard system

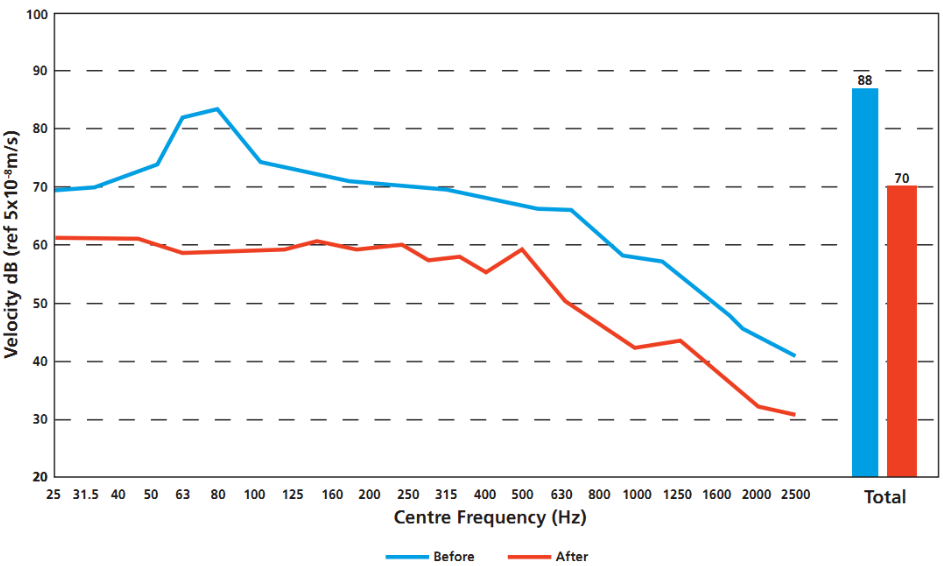

Figure 6 Performance of Pandrol Vanguard system for reducing tunnel vibrations. <u>Note that the effect of the system is not displayed for frequencies under 25 Hz.</u>

Noise and vibration measurements were recorded after the existing track at the trial site had been re-railed and re-aligned. This will represent the performance of London underground tube track in good condition. The measurements were repeated after the Pandrol Vanguard fastenings had been installed in order to obtain a direct measure of the benefits achieved. Instruments were installed in the tunnel half way along the trial site to measure lateral and vertical rail deflection, rail acceleration, tunnel invert acceleration and lateral and vertical tunnel wall acceleration. An accelerometer was also placed in Mill Street above the tunnels. The rail deflections and tunnel vibrations were measured during the morning peak period when the trains are the heaviest. The measurements showed that the average rail deflection was 3.5mm vertically and 0.4mm laterally, which compares favourably with the design values.

After Pandrol Vanguard had been fitted the vibration in the tunnel invert decreased by 18dB averaged over the frequency range below 2.5kHz as shown in Figure 6. The response is relatively flat up to 500Hz indicating that there is no significant track resonance. The small peak at 500Hz is probably due to corrugations forming on the rail head. This is a phenomenon observed at a number of sites on the Victoria Line.

The street level vibrations were recorded in the early morning to minimise the effect of ambient noise in the street. Before Pandrol Vanguard was fitted the vibration from both north and southbound tracks was similar at 76dB. After Pandrol Vanguard had been fitted to the southbound track the vibration from the northbound track was the same, but from the southbound track it had decreased by 7dB and was only 1dB above the background vertical vibration. This will be reflected in decreased vibration and hence noise in buildings. These results show that Pandrol Vanguard fastenings are a very effective means of reducing the vibration from railway tracks in tunnels.

The noise emission from railways can be reduced by increasing the damping of the rail. Reduction of 5-6 dB in the rail radiated noise can be achieved using rail vibration absorber/damper [5, 6], please see Figure 7. A system of rail dampers has been optimized and tested within the EU-funded project SILENCE.

Figure 7 Rail dampers

Balfour Beatty Rail has developed the Embedded Rail System (BBERS) [7] as shown in Figure 8 to improve rail performance and reduce life cycle costs. The system has been operational and proven under mixed freight and passenger traffic at Crewe, UK, since 2003. It has also undergone extensive testing for load and speed on the Spanish high speed test track at Medina del Campo. Measurements taken on the system in Spain found that it was less noisy than an equivalent section of adjacent ballasted track. With less noise generated at the rail the extent of any barriers for residual noise is reduced. The system also provides options for additional tuned noise absorption where required.

Figure 8 Embedded Rail System (BBERS)

The continuous support to the rail provided by the Balfour Beatty embedded rail system and the integrity and accuracy with which it can be installed provides the optimum conditions for a smooth track profile at all wavelengths. In particular it minimizes the risk of rail head corrugation and rail head roughness which cause vibration.

3.1.2 Under sleeper pad

In the so-called Arena tunnel, right in the heart of the City of Birmingham (UK), the padded wooden sleepers of the ballasted track were replaced by concrete sleepers fitted with under sleeper pads as shown in Figure 9. Vibration measurement at the lining of the tunnel following track renewal showed that the under sleeper pads delivered by the Getzner company were able to prevent any increase of train-born vibration [8].

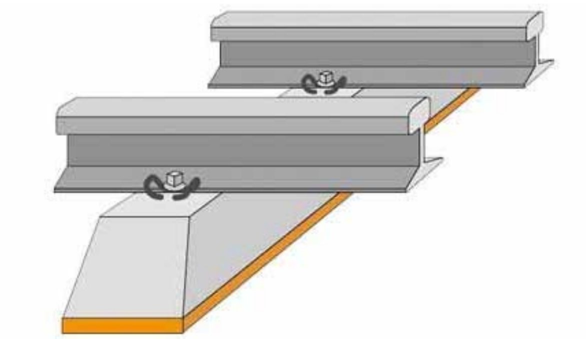

Figure 9 Under sleeper pad

Renewal of the tracks in the Birmingham Arena Tunnel was carried out at the beginning of 2010. This included replacing the rails, sleepers and ballast. In the course of the project, the old wooden sleepers featuring 20 millimetre rubber cork sleeper pads were replaced with new padded concrete sleepers.

To determine the effect of the track work on vibration emissions, measurements were performed before and after the track renewal. The automatic measuring equipment was installed next to the rebuilt track on the tunnel wall, adjacent to a safety niche. In doing so, the accelerometer was aligned vertically, laterally and longitudinally to the track.

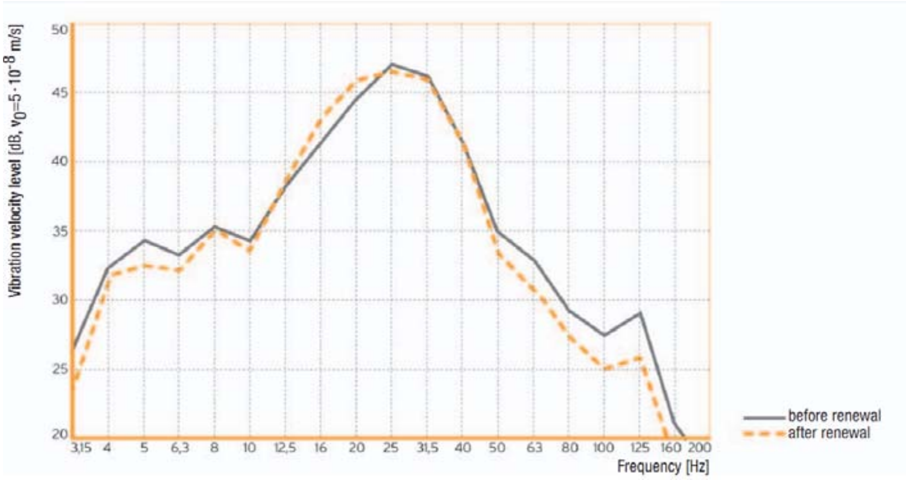

Figure 10 Vibration spectrum measured before and after track renewal

Figure 10 shows the vibration velocity levels recorded at the wall of the tunnel when an EMU class 323 passes by, measured before and after the track renewal. Prior to renewal, the peaks ranged from 25Hz to 31.5Hz, but after completion of the work, they stood at 20Hz to 31.5Hz. This indicates a slight downward shift in frequency. Very remarkable reductions in vibration were measured for frequencies below 6.3Hz and above 40Hz. Furthermore there was virtually no change recorded in the insertion of frequencies between 6.3Hz and 40Hz.

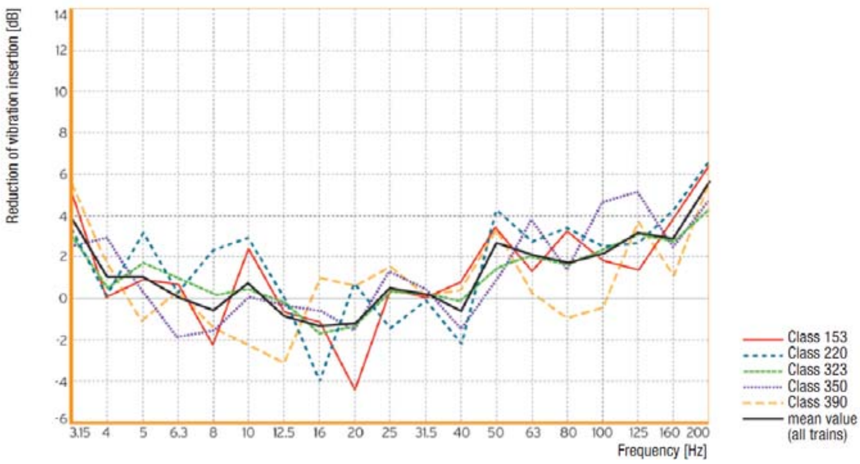

Figure 11 Reduction of vibration energy insertion due to track renewal

Figure 11 shows the reduction of vibration insertion before and after the renewal for five train classes. Positive values report that reduced vibration levels at the tunnel lining were detected after completion of the track renewal work. The mean reduction is a calculated value, derived from the arithmetic mean of the vibration level of the five train classes.

Under sleeper pads with vibration-isolating characteristics are also a very effective measure for reducing secondary air-borne noise. Depending on the maximum permissible rail deflection, under sleeper pads achieve insertion losses on the order of 10 15dB(v) at 63 Hz as shown in Figure 12.

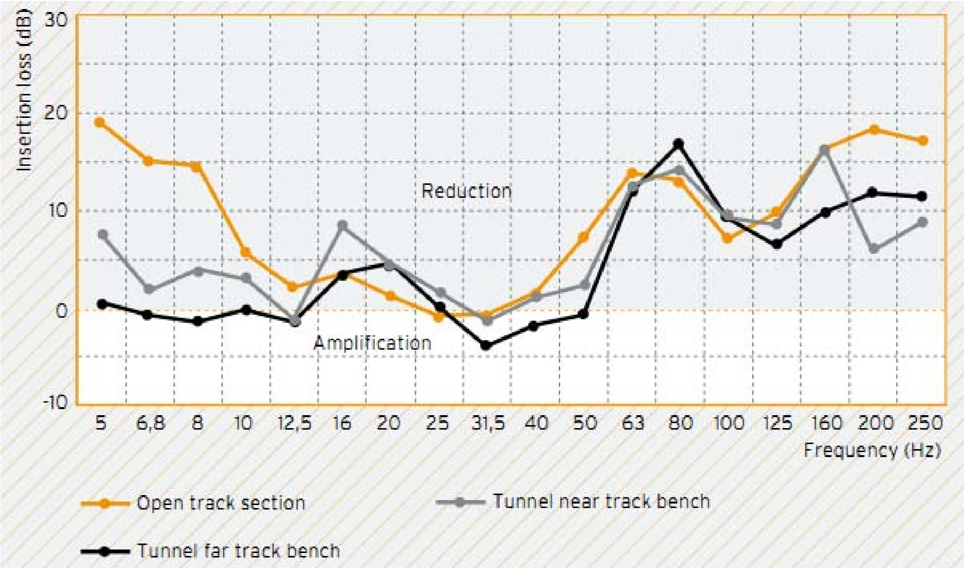

Figure 12 Effect of under sleeper pad [9]

3.1.3 Sub-ballast mat

Sub-ballast mats are elastic layers that are placed beneath or inside the ballast bed as shown in Figure 13. Ballast mats (thickness up to 80mm) are considered to have high efficiency to attenuate vibrations within the range 16 to 50Hz where a reduction as high as 20dB can be reached at 50Hz [10]. Kazamaki and Watanabe reported a reduction of 5 to 8dB due to the use of ballast mats. One type of ballast mat applied on concrete base generated reduction of about 10dB for frequencies above 40Hz. Placing the ballast mat higher up within the ballast results in higher attenuation. If the thickness of the ballast is increased from 0.3 to 0.6m in combination with sub-ballast mat, a reduction of 4dB can be added [4].

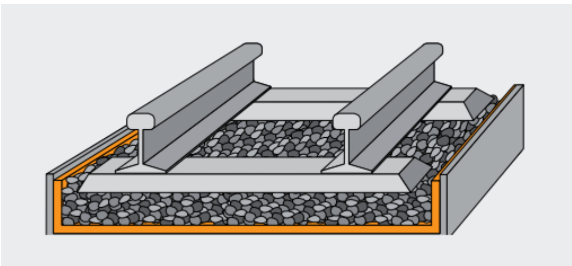

Figure 13 Sub-ballast mat

Sub-ballast mats are one of the most effective methods of reducing vibration transmission from ballasted track. Sub-ballast mats isolate the track structure from the supporting foundation or substrate, and can attenuate the transmission by 20dB in many cases, one example is shown in Figure 14 [11].

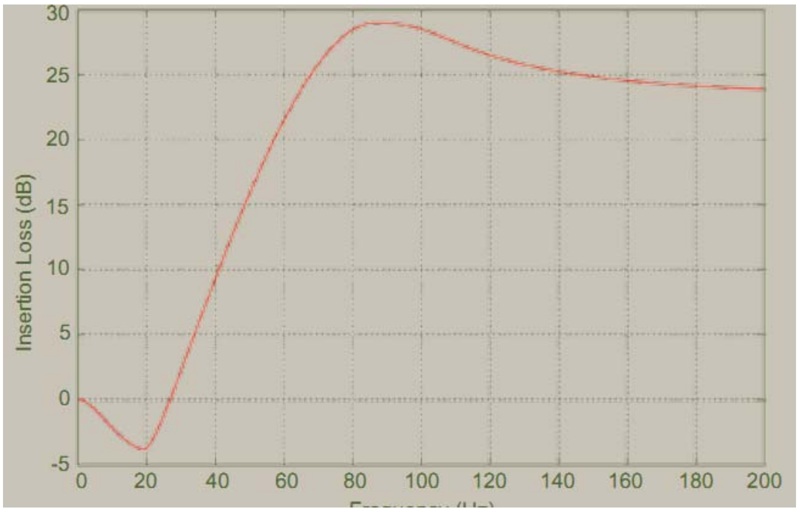

Figure 14 Predicted attenuation of vibrations over a range of disturbing frequencies, after laying the ballast mat. Note that this system will attenuate vibrations below 25 Hz.

3.1.4 Floating slab track (mass spring system)

Mass spring system, or floating track system, is the most effective measure for train-induced vibrations in tunnels [12]. Floating slab track, which basically consists of concrete slabs supported on resilient elements such as rubber bearings, has been used on modern rail transit system for years [13]. The design is aimed to reduce vibrations transmitting to the supporting foundations and surrounding areas [14]. The principle idea is to have a linear harmonic oscillator that has a very low natural frequency. Usually the oscillator is a heavy concrete slab that is isolated from the tunnel invert by rubber bearings or steel springs. A floating slab should have as low natural frequency as possible in order to attenuate the vibrations to as large extent as possible. It is not practically possible to have a natural frequency lower then 5Hz; neither should it exceed 14Hz [10]. Normally the natural frequency is between 8 to 12Hz. Hemsworth reported 10dB attenuation at 16Hz and 25dB at 125Hz, while Kazamaki and Watanabe reported attenuation levels between 15 to 21dB. However, Hunt showed, with the aid of numerical analysis, that if the natural frequency of the floating slab track system is not low enough, the attenuation effect would be diminishing.

Floating slab tracks are widely used to control vibration from underground trains [15,16] as shown in Figure 15. The track is mounted on a concrete slab that rests on rubber bearings, glass fiber, or steel springs. The slab may be cast in situ, resulting in a continuous length of concrete, or may be constructed in discrete precast sections laid end to end. In the USA, floating slab track was pioneered at Washington, DC rapid transit system (WMATA) at 1970s. The WMATA floating slabs are continuous concrete slabs broken only by required construction joints spacing at 18.3m. Later in 1980s, metro rapid system of Toronto and Hong Kong adopted floating track with short slabs of 1.45m. Even shorter slabs were used in Hong Kong airport express and west railway in late 1990s.

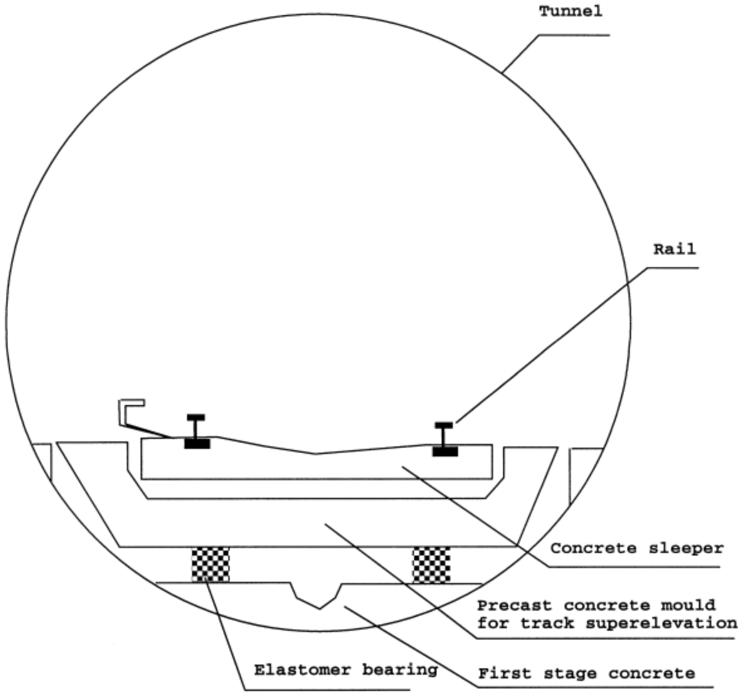

Figure 15 Floating slab track

Although many document report its effectiveness, it remains controversial for underground railways due to interactions with the tunnel and surrounding soil [17]. Jones suggested that soft mats under the sleepers may be a useful countermeasure above 20Hz and Nelson models 9-12 dB reductions above 30Hz [18,19]. Nelson reports a resonance frequency of 16Hz for the resonance frequency of the coupled vehicle-track system in the case of the continuous floating slab in use at the Washington Metropolitan Area Transit System and resonance frequencies between 8 and 16Hz for discontinuous slabs in several other rail transportation systems in the USA and Canada. Cui and Chew discuss the design of the floating slab track of the Singapore Mass Rapid Transit system with a resonance frequency of 10Hz [20]. Schillemans presents a study of the noise and vibration impact of the North-South high speed train connection through the city of Antwerp where a floating slab at 11Hz is proposed for a tunnel in close proximity of building foundations [1].

In practice, Saurenman pointed out that secondary effects of the wave motion in slab support and bending resonances of floating slabs prevent reduction higher than 20dB [21]. Moritoh conducted an in-situ noise measurement under a concrete bridge structure for a train passing at 240km/h and the measured peak at around 50Hz [22]. Zach conducted site rail vibration measurement on different traditional and new rail track types in Switzerland [23]. Saurenman and Phillips measured rail vibration with various floating slabs in the San Francisco Bay Area Rapid Transit, and they point out that there is noticeable degradation on floating slab vibration isolation when the natural frequency is close to the wheel rotation resonance [24]. Both of them analyze the floating slab used at grade or in a tunnel, but not on a viaduct structure. The maximum vibration reductions of these results were about 20dB.

3.2 Summary of the effect of different track based countermeasures

Although it is possible to apply vibration isolation at the receiver and this has been successfully applied in the design of new buildings or by the introduction of resilient elements into the foundations of existing buildings, it was considered that the most effective and economic measures are those performed on the track and the mitigation is outlined below [12].

- **Resilient rail fastenings and pads**: These can be effective for frequencies greater than 30Hz giving a 6-10dB reduction at about 50Hz. Limitations on their use are set by fatigue strength, geometric gauge widening and misalignment in case of rail fracture. To date, measurement data are only available for axle loads between 10 and 20 ton.
- **Under sleeper pads**: These pads have been successfully used on ballasted track where an insertion loss of 15dB has been achieved at 125Hz.
- **Sub-ballast mats**: Sub-ballast mats are considered to have high efficiency to attenuate vibration where an insertion loss between 8 and 18dB for frequencies greater than 63Hz can be reached.
- **Mass spring systems**: This is the most efficient but most expensive solution for inserting resilience under a slab. Mass spring systems with resonance frequency of 5-6 Hz have been installed in metro systems. 10dB insertion loss is available for frequencies above 16Hz, rising to 25dB at 125Hz.

3.3 Companies/firms working with ground vibration problem

In Table 1 different companies which has been identified during this work is listed.

Table 1 Commercial companies that are working with countermeasures for railway induced vibrations

Company	Contact	Country	Description
Pandrol	www.pandrol.com	UK	Rail fasteners
Getzner	www.getzner.com	Austria	Under sleeper pads
Christian Berner	www.christianberner.se	Sweden	Vibration isolation
Trelleborg	www.trelleborg.com.au	Australia	Ballast mats
Calenberg Ingenieure	www.calenberg-ingenieure.de	Germany	Track mats
Tiflex	www.tiflex.co.uk	UK	Track mats
Sonneville	www.sonneville.com	USA	Low vibration track
Balfour Beatty Rail	www.bbrail.co.uk	UK	Embedded rail
Bygg fakta DOCU	www.byggfaktadocu.se	Sweden	Vibration isolation

4 Vibration discomfort - regulations and standards

The assessment of low-frequency vibration has been the subject of national and international standards, including;

- ISO 2631-2 (1989)
- BS 6472 (1992)
- DIN 4150 (1992)
- ANSI S3.29 (1983)
- VDI 2057 (1987) and
- ONORM S 9012 (1996).

These standards normally take into consideration time of day, building usage and vibration duration. It is also generally recommended that the vibration level is specified at the point in the building where the person would feel the vibration (standing, lying or sitting). The vibrations should be measured at the point where it is as greatest. Assessment often depends on whether the vibration is classified as ''continuous'', ''intermittent'' or ''transient''. Railway vibration is identified differently in various standards; therefore an assessment of a particular railway vibration ''dose'' will vary in severity depending on the standard used [**Error! Bookmark not defined.**]. For further reading regarding ground vibrations from railway traffic a report from Transit Cooperative Research Program TCRP [25] and a report from the EU founded project RIVAS [26] is recommended.

4.1 Vibration and human exposure measures

The following sections of chapter 4 summarise the review presented in [26] with respect to ground vibrations. Vibrations are normally expressed in terms of acceleration, velocity or displacement and can be expressed by its respective units [m/s^2], [m/s] [m] or in decibel. When calculating the decibel level different reference values are used in different countries. According to [26] ISO 168:2008 definition is the most widely used definition. It uses 10^{-6} m/s^2 as a reference giving 100dB = 0.1 [m/s^2]. In Japan the reference is set to 10^{-5} m/s^2 giving 100dB = 1 m/s^2 and in the USA 100 dB is equal to 2.54 mm/s since the reference is set to 10^{-6} in/s. The difference in reference values will make some results more difficult to compare without performing a recalculation procedure. And different units are used in different countries Acceleration is used in: Austria, Italy, Spain and in UK. Velocity is used in: Germany, France, Switzerland and the USA. Acceleration and Velocity: in Sweden and Norway.

The assessment of exposure to vibrations is based on two types of descriptors in the standard Maximum running RMS and/or Fourth-power vibration dose. The maximum level is defined as the highest vibration value during a measurement sequence but in NS 8176:1999 (Norway) and in SBR-Part B:2002 (The Netherlands) the maximum value is represented by the 95 percentile of the total vibration amplitudes in a measurement sequence.

4.1.1 Frequency weighting and time constant

The purpose with frequency weighting is to weight the measured frequency content according to the human ability to perceive vibrations at different frequencies. In ISO 2631-1:2003 a definition of the frequency weighting W_m can be found. W_m is applicable in the frequency range 1 Hz to 80 Hz where the posture of an occupant does not need to be defined. Figure 16 shows different weighting functions used in different countries. Which frequency weighting function that is used in different countries differ. The time constant for the calculation of the running RMS is also varying between different countries.

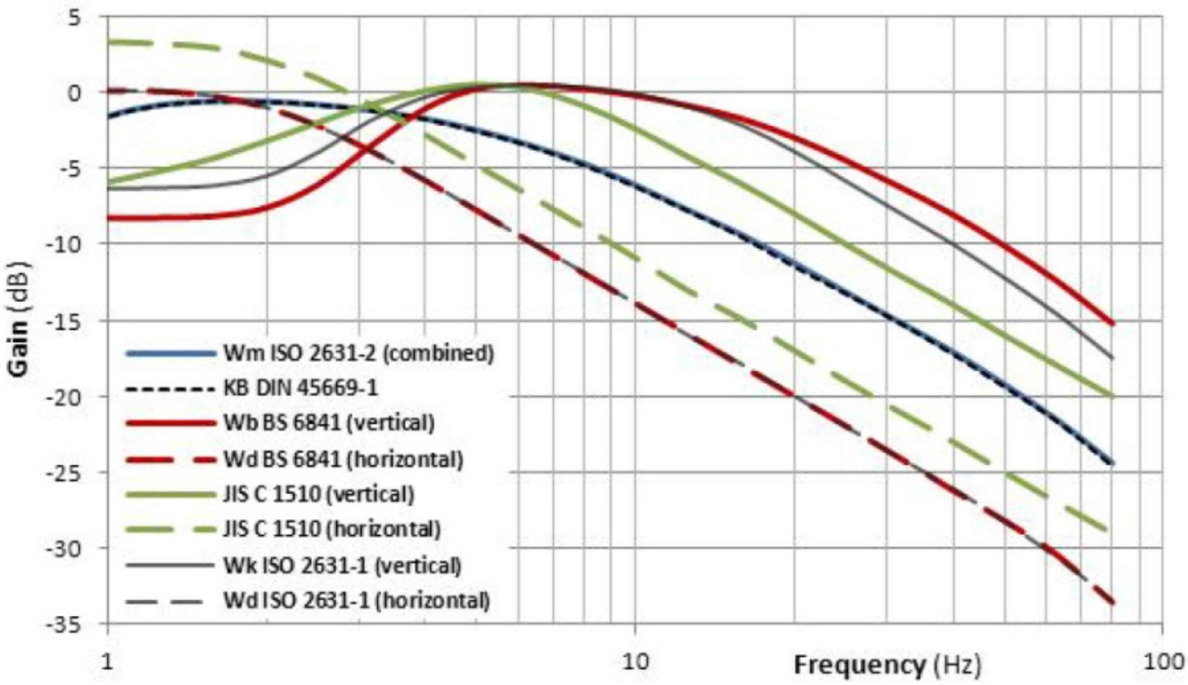

Figure 16 Different frequency weighting of measured vibrations for human exposure [26].

4.1.2 Absolute threshold of perception

According to [26] and VDI 2057 Blatt1 the threshold of perception for vibrations in terms of acceleration is 0.015 m/s^2 for sinusoidal vibration. The same threshold (0.015 m/s^2 = 85dB with a reference of $10^{-6}$of m/s^2) of perception is defined in ISO 2631-1:1997 using W_k-weighted vertical vibrations this however wariest with different human beings and frequency, see Figure 17.

The characteristic of the noise, time of the day and location, like;

- Critical working areas
- Residential
- Office
- workshop

are also properties that will affect the discomfort. Multiplying factors for location and time of day is combined with the combined direction base curves in the standard ISO 2631:2. The discomfort reaction presented by ISO2631-1:1997 can be seen in Table 2.

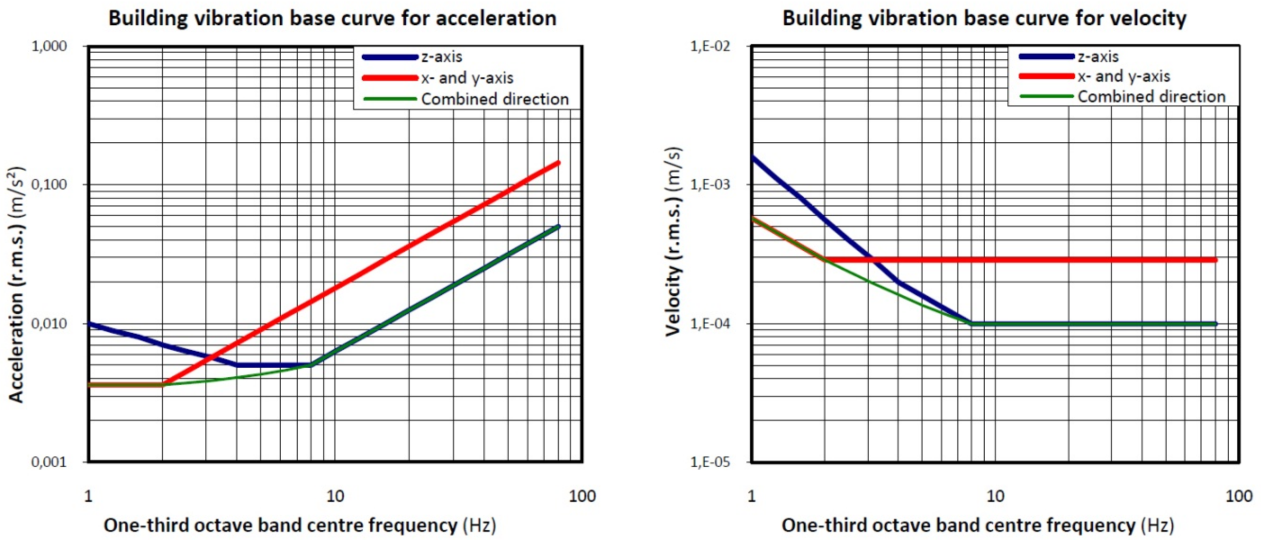

Figure 17 Building vibration base curve for acceleration and velocity. ISO 2631-2:1989 (According to [26], this graph has been removed in the 2003 version) but is still used in Sweden, USA and France)

Table 2 Discomfort reaction to vibrations (RIVAS and ISO 2631-1:1997)

RMS Acceleration (mm/s^2)	Reaction
Less than 0.315	Not uncomfortable
0.315-0.63	A little uncomfortable
0.5-1.0	Fairly uncomfortable
0.8-1.6	Uncomfortable
1.25-2.5	Very uncomfortable
>2.5	Extremely uncomfortable

4.2 Standards and guidlines

Except for the international standard ISO ISO2631 different standards and guidelines have been developed on a national level. This section lists the domestic standards/guidelines presented in [26] which have a bearing on the scoop of this review. Most of the standards and guidelines are defined in the frequency range 0.5 or 1 Hz to 80 Hz except for the Norwegian standard that goes up to 160 Hz.

- ÖNORM S 9012:2010 (Austria)
- DIN 4150-2:1999 (Germany)
- Guideline human exposure to mechanical vibrations VDI 2057:2002 (Germany)
- UNI 9614:1990 (Italy)
- Vibration regulation law (Japan)
- SBR Richtlijn – Deel B (2002) (The Netherlands)
- NS 8176:2005 (Norway)
- Real Decreto 1307/2007 (Spain)
- SS 460 48 61:1992 (Sweden)
- BEKS (1999) Switzerland
- BS 6472-1:2008 (Unitet Kingdom)
- FRA(2005), FTA(2006) (USA)
- CSA S16.1-1989 Canada (Not described here)

4.2.1 Austria (ÖNORM S 9012:2010)

In this standard two requirements are defined: satisfactory and good protection (For railway and road vibrations) in terms of E_{max} (Maximum value derived from a running RMS quantity, time constant slow) and E_r (Mean energy-equivalent acceleration during the assessment period). Values are defined for day and night and for different areas/locations;

- Rest areas, cure areas, hospitals
- Dwellings in suburban and country areas, schools
- Dwellings in urban areas, areas for forestry and agriculture building with dwelling
- Central areas, areas for not-inducing vibration and noise business activities
- Areas for low vibration and noise-inducing business activities
- Goods manufacturers and service companies

4.2.2 Germany DIN 4150-2:1999

In DIN the vibration levels is described in velocity and defined by KB_{Fmax} (maximum value derived from a running RMS quantity, time constant fast) and KB_{FTr} (time-weighted mean quantity depending on traffic). The German guideline Human exposure to mechanical vibrations VDI 2057:2002 aim at harmonising the German velocity based quantity with other acceleration based. In DIN 4150-2:1999 the limit values are defined for day and night and for different areas/locations;

- Industrial area
- Predominantly commercial areas
- Neither commercial nor residential predominantly areas
- Mainly residential areas
- Special areas like hospitals or health buildings

4.2.3 Italy UNI 9614:1990

In UNI 9614:1990 the limit value, running RMS weighted acceleration is defined for the vertical and horizontal direction for the following different areas/locations;

- Critical area
- Residential, Day (7h-22h) and Night (22-7h)
- Office
- Industrial

4.2.4 Japan Vibration regulation law

The Japanese descriptor for ground vibration is based on running RMS weighted acceleration and is defined by law for factory and road traffic for day and night time. There are also special regulations for areas where the High–speed trains are exciding specific values. The vibrations are measured at the boundary between investigated area and source and not inside residential buildings. The standard AIJES:2004 is dealing with limits for building vibrations. In the Japanese regulation two areas is defined;

- Quiet living environment areas
- Industrial/commercial areas and areas serving for residential purposes

4.2.5 The Netherlands SBR Richtlijn – Deel B (2002)

The Deutch descriptors are based on a running RMS quantity of the vibration velocity, similar to the German descriptors. The limit values are defined for two situations (new or existing road & rail situation) with different target values for day/evening and night and for different building categories;

- Health care, residential
- Education, office and public assembly
- Critical work areas

4.2.6 Norway NS 8176:2005

The Norwegian standard is focusing on vibrations from land-based transports and is based on the statistical 95-percentils derived from running RMS quantities velocity and acceleration. Four different classes are defined;

- A: Very good conditions. Disturbance due to vibrations is an exception.
- B: Good conditions. Some disturbance due to vibrations may occur.
- C: Limit for new residential buildings (15 % annoyed people)
- D: For existing buildings (25 % annoyed people)

4.2.7 Spain (Real Decreto 1307/2007)

Real Decreto 1307/2007 regulates by law the limits for preventing annoyance of people in buildings due to vibrations. The limits are described in terms of maximum running RMS of acceleration signals. In Real Decreto 1307/2007 the vibrations are assessed during night (23-7h) and day (7-23h) and the limits are described for three different usage of buildings;

- Dwelling or residential use
- Hospitals
- Education and culture

4.2.8 Sweden SS 460 48 61:1992

The descriptors in the Swedish standard SS 460 48 61:1992 are derived from the running RMS weighted quantities velocity and acceleration. In the standard three ranges of vibrations are defined for perception of annoyance;

- Below the ranged defined for Moderate disturbance: Few people will be disturbed
- Range of moderate disturbance: Some people may complain in some cases
- Probable disturbance is defined above the range of moderate disturbance: Most people will be disturbed

The Swedish transport administration (Trafikverket) has together with the Swedish environmental protection agency (Naturvårdsverket) has issued 2006 a guideline for vibration values (velocity and acceleration values) near rail tracks. In this guideline the limits are described for day (6-22h) and night-time (22-6h);

- New constructions for dwelling, leisure housing and care premises.
- Important refurbishment like new bedrooms at night-time (22-6h)
- Existing environments like bedrooms in permanent dwellings during night-time (22-6h)

4.2.9 Switzerland BEEKS 1999

Is referring to the German standard for evaluation of railway induced vibrations and define limits for the following areas;

- Leisure zones with high requirements of a noise free are
- Residential zones and public buildings
- Mixed zones (residential and industrial)
- Industrial zones

4.2.10 Unitet Kingdom BS 6472-1:2008

The limits in BS 6472-1:2008 is described as a vibration dose value derived from a frequency weighted acceleration value. The limits are given for residential areas for day (7-23h) and night-time 87-23h) and represents three different ranges of annoyance;

- Low probability of annoyance
- Adverse comments possible
- Adverse comments probable

4.2.11 United States of America FRA(2005), FTA(2006)

The two guidance manuals FRA and FTA deals with noise and vibration impact assessment for high speed ground transportation. The limits for groundborne vibrations are expressed by the number for vibration events exciding a certain limit defined by a maximum running RMS for a velocity vibration signal. The defined areas are;

- Buildings where vibrations would interfere with interior operations
- Residential buildings where people normally sleeps (Hotels, hospitals)
- Institutional buildings like schools churches and offices.

Special buildings

- Concert halls, Tv-studios
- Auditorium
- Theatres

4.3 Combination effect of noise and vibrations

When analysing the annoyance due to vibrations the presence of noise must also be considered due to a combination effect between the two, reported by numerous researchers. There have been studies reporting that vibrations have little influence on the judgement on noise but the assessment of vibration could be affected positively or negatively by noise, depending on the magnitudes of the two [27-30]. In a laboratory study Meloni and Krueger showed that the absolute perception threshold of vibrations was higher when noise was higher (over 64dB) due to a masking effect [31]. This effect was also reported by (Knall (1995)). In a Swedish vibration and noise combination effect study in Lund and Partille (Öhström and Skånberg, 1996; Öhström, 1997) reported that: In areas with non or weak vibrations (<1mm/s) 5% of the population where rather annoyed or very annoyed when exposed to railway noise below L_{Amax}= 80dB and L_{Aeq}=45dB [32,33]. In areas with "strong" vibrations (> 2 mm/s) the same annoyance was achieved with a 10 dB lower noise level. A following study (Öhrström et al., 2011) in the Swedish TVANE project the annoyance from noise was reported to increase in the presence of vibrations [34]. This contradicts the earlier findings by Howarth and Griffin and griffin and has to be examined further. According to [34] the proportion of people annoyed by railway noise is higher when exposed to higher vibration levels. They concluded that the proportion of annoyed people in an area without vibrations and with strong vibrations is the same if the noise is 5-7 dB lower in the area with the strong vibration. The main conclusion regarding the combination effect is that both the vibration and the sound (noise) must be considered when predicting the annoyance.

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