Innovation Agenda Source-Based Approach to Railway Vibrations (IBS)

Results and acquired knowledge
Final document

Summary

ProRail, commissioned by the Ministry of Infrastructure and Water Management, has carried out the Innovation Agenda: Source-Based Approach to Railway Vibrations (Innovatieagenda Bronaanpak Spoortrillingen, IBS). The IBS programme investigated how existing and new measures can help to reduce railway vibrations. Railway vibrations can cause nuisance for people living close to the tracks.

The first objective of the programme is to build up more knowledge about railway vibrations in order to better predict vibration levels. The second objective is to expand the toolbox with cost-effective measures to reduce vibrations. The IBS programme for reducing railway vibrations consists of the following components

1. developing knowledge for the Railway Vibrations Emission Model (Spoor Trillingen Emissie Model, STEM);
2. carrying out field trials;
3. communication and knowledge sharing.

TU Delft, Deltares and TNO are working together with ProRail to develop the STEM calculation model, an open-source model designed to predict under which conditions certain railway vibrations occur and in which situations specific measures are effective. Part of the development of the STEM model involves four PhD research projects at TU Delft, which are expected to be completed by the end of 2027.

A large number of field trials have been carried out within the IBS programme. In these trials, the vibration-reducing effect of measures was investigated through vibration measurements along the railway. Existing measures and their effect when applied to the Dutch rail network, as well as new innovative concepts, were studied. It was also examined whether measures primarily applied for other purposes have any effect on railway vibrations. The field trials are divided into four categories:

- **2A**: Infrastructure maintenance
- **2B**: Rolling stock maintenance
- **2C**: Infrastructure innovations
- **2D**: Rolling stock innovations

The scale of the field trials varies. Two major studies concerned the effect of wheel out-of-roundness and an investigation into environmentally focused management and maintenance. In these studies, in addition to extensive vibration measurements, substantial other data was collected and several statistical data analyses were performed. In smaller field trials, the focus was usually on determining the effect of a specific measure using vibration measurements alone. In a Small Business Innovation Research (SBIR) programme, market parties were challenged to come up with new innovative measure concepts, five of which were tested.

To ensure that the effect of measures in the field trials was determined as consistently and uniformly as possible, a Uniform Measurement Protocol was established at the start of the programme. The Uniform Measurement Protocol describes a standardised approach for performing vibration measurements. Because many vibration measurements were carried out in accordance with this protocol, ProRail has built a valuable database of measurement data.

In addition to the field trials, several research projects were carried out to increase understanding of the occurrence of railway vibrations and vibration nuisance. An indicator called Spoorligger has been developed to quantify the track geometry in terms of ‘vibration quality’. Potential hotspots in the track geometry where higher vibrations may be expected can easily be identified for the entire Dutch rail network using an accompanying Spoorligger visualisation tool.

The field trials show that many measures are effective in reducing railway vibrations, provided they are applied within specific boundary conditions such as particular soil types or train types. It was also found that measures are often only effective within a limited frequency range; in other frequency ranges, they may even have a negative effect. Some measures require further development before they can be applied on a larger scale. An example of this is a modification to the Y25 bogie, intended to reduce railway vibrations. In the IBS programme, this measure was referred to as the Y25+ bogie.

Ultimately, all investigated measures were assessed for their potential. The evaluation considered their likely effectiveness. Two measures achieved the highest score: 1) the removal of railway switches (points) and 2) the use of a rubber level crossing surface. Both measures show a vibration reduction effect of more than 6 dB, although their scope of application is limited. The measures with the second highest score are divided into four subcategories:

1. track improvement: a PSS layer and Geogrid;
2. mechanical maintenance measure: tamping;
3. vehicle measures: poor wheel quality and the Y25+ bogie;
4. innovative SBIR measures showing potential for improvement or positive side effects: Adjustable IRJ, BISI-TROC and MetaBarrier.

Three applications are expected to make a structural contribution to the ultimate goal of reducing the impact of railway vibrations on the environment: Spoorligger, the Uniform Measurement Protocol and the development of the STEM model.

The results of the IBS programme provide knowledge, new insights and practical tools that can be used in real-world applications. The results also call for follow-up actions. At the request of the Ministry of Infrastructure and Water Management, ProRail is preparing separate implementation plans for this purpose. Some measures are also being further developed by market parties.

Preface

The railways connect the Netherlands. Every day, hundreds of thousands of people travel by train and goods find their way through the country via the rail network. In addition to a well-functioning railway system, a good living environment is also important to ProRail. We want to be a good neighbour to everyone living alongside the railway.

That is why we have made such valuable investments over the past four years – together with the Ministry of Infrastructure and Water Management – in the Innovation Agenda: Source-Based Approach to Railway Vibrations. In this programme, we have not only studied how railway vibrations arise, but above all what can be done at the source to reduce nuisance.

We have not found an all-encompassing solution, but we have gained a wealth of knowledge and practical tools. Every situation is different, which is precisely why it is so important that we now have a far richer toolbox at our disposal. With the simulation software STEM (Railway Vibrations Emission Model) developed in the programme, and with an extensive database full of up-to-date measurement data, we will in future be able to advise on measures in a smarter and more targeted way. This is good news for local residents, for municipalities and for everyone involved in shaping our living environment.

The fact that we have completed this programme within the planned timeframe and available budget is a considerable achievement. My heartfelt thanks go to all the researchers, engineers, contractors and colleagues who have contributed to it. At ProRail, we are proud of this outcome – and we hope that in the coming years we will have the opportunity to apply this knowledge to help the Netherlands experience fewer vibrations and, as a result, a more pleasant living environment.

John Voppen
CEO ProRail

Readers guide

This final document presents the results and findings from the IBS programme over a period of about four years. Results up to early September 2025 have been included. Most of the results and insights have a technical character. Therefore, Part 1 begins with a number of theoretical concepts and basic principles concerning vibrations. This is followed by an explanation of the evaluation of vibrations and how consistent measurement and assessment were ensured within the IBS programme through the Uniform Measurement Protocol. Part 1 concludes with studies not focused on a specific measure, such as identifying the causes of complaints, the role of train types and the assessment of track geometry in relation to vibrations. The results of each study are summarised in a separate box.

Part 2 presents the results of field trials for more than twenty different measures, divided into four categories. The first category, 2A: Infrastructure maintenance, covers studies on possibilities for environmentally focused management and maintenance to reduce railway vibrations. This is followed by category 2B: Rolling stock maintenance, which covers research on wheel out-of-roundness. Most field trials fall under category 2C: Infrastructure innovations. These range from testing existing measures for their effect on railway vibrations to applying vibration-reducing measures in a different context and developing and testing entirely new concepts. The fourth category, 2D: Rolling stock innovation, covers one measure – a modification of the commonly used Y25 bogie on freight trains. For each measure studied in Part 2, a summary table is presented. The table summarises the observed effect and discusses the intended vibration-reducing mechanism, the uncertainty of the effect determination, the explanation of the results and the potential for further improvement. The vibration-reducing mechanism is always chosen from one of the five mechanisms discussed in the theory of railway vibrations (see Railway Vibrations).

Part 3 describes the long-term studies within the IBS programme, including the development of the STEM model and the scientific research by Deltares, TNO and TU Delft. A key part of this consists of four PhD projects at TU Delft. These studies have not yet been completed and will continue until the end of 2027 or early 2028. Therefore, this part explains the approach and objectives, but not yet the results.

The document concludes with Part 4, which reflects on the results. This part provides an overview of the observed effects and classifies the tested measures according to their potential for application and/or further development. This gives an indication of which measures, in the authors' opinion, are most suitable for reducing vibration nuisance. Readers are encouraged to form their own assessment, since effectiveness may vary depending on the specific situation. Part 4 ends with an overview of next steps following completion of the IBS programme.

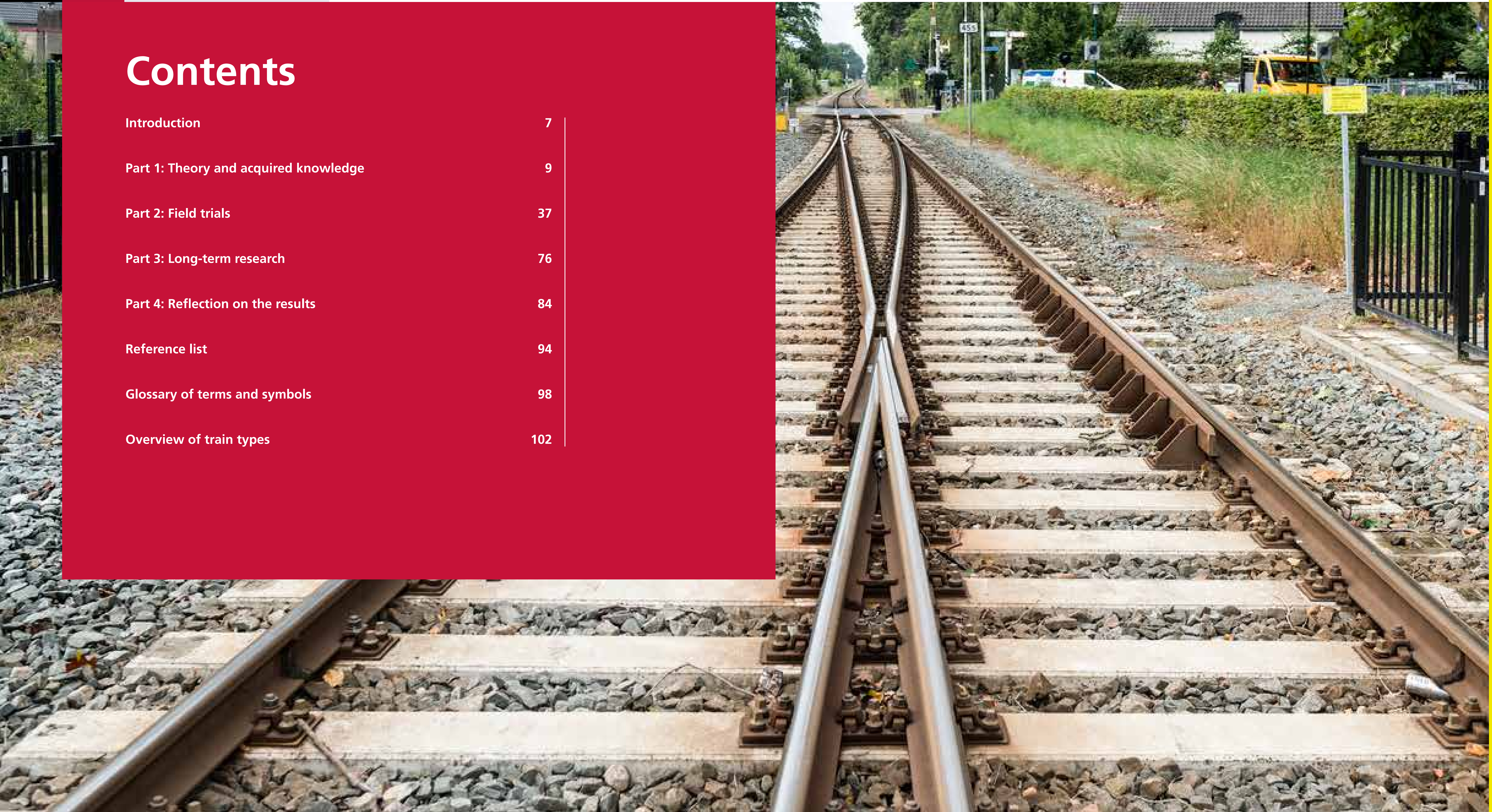
Throughout this document, cross-references are made to other sections.

Background documents

Much of the content of this report has been drawn from various research reports. Readers seeking more background information, or wishing to better understand the methodology used to obtain the results, are encouraged to consult those reports. All reports can be requested via:

https://www.prorail.nl/bronaanpak-spoortrillingen-resultaten

References to the reports are included at the end of this document.



Contents

Introduction

Background

In 2018, the State Secretary for Infrastructure and Water Management informed the House of Representatives that policy intensification on the topic of railway vibrations was necessary (Parliamentary Papers II 2017–2018, 29984, no. 765). The reason for this was the increasing attention to nuisance caused by railway vibrations and the growing number of complaints received by ProRail. A research programme was therefore envisaged to develop knowledge and strengthen policy. ProRail subsequently drafted an innovation agenda[1]: *the Innovation Agenda: Source-Based Approach to Railway Vibrations (IBS)*.

The Innovation Agenda: Source-Based Approach to Railway Vibrations consists of two components:

1. developing knowledge for the Railway Vibrations Emission Model (STEM); and
2. conducting field trials.

The Ministry of Infrastructure and Water Management invested €20 million in the IBS programme, which concluded in mid-2025. This does not mean, however, that all its components have been fully completed. For example, a scientific research programme consisting of four PhD projects has been launched and will continue for another two years. Most field trials and other studies, however, have been completed. This document summarises the knowledge acquired from the IBS programme.

Objective

ProRail describes the aim of the IBS programme as follows (ProRail, 2023):

> ‘To build up more knowledge about vibrations caused by railway traffic in order to better predict vibration levels, and to expand the toolbox with cost-effective measures.’

As the name of the programme suggests, the emphasis has been on tackling the source. The source can be defined as the entire system of train, track, and subsoil – generally the area within ProRail’s domain[2]. This is not a strict definition: several studies have also been carried out into innovative measures focused on ground-borne transmission applied within a zone up to 25 metres from the track.

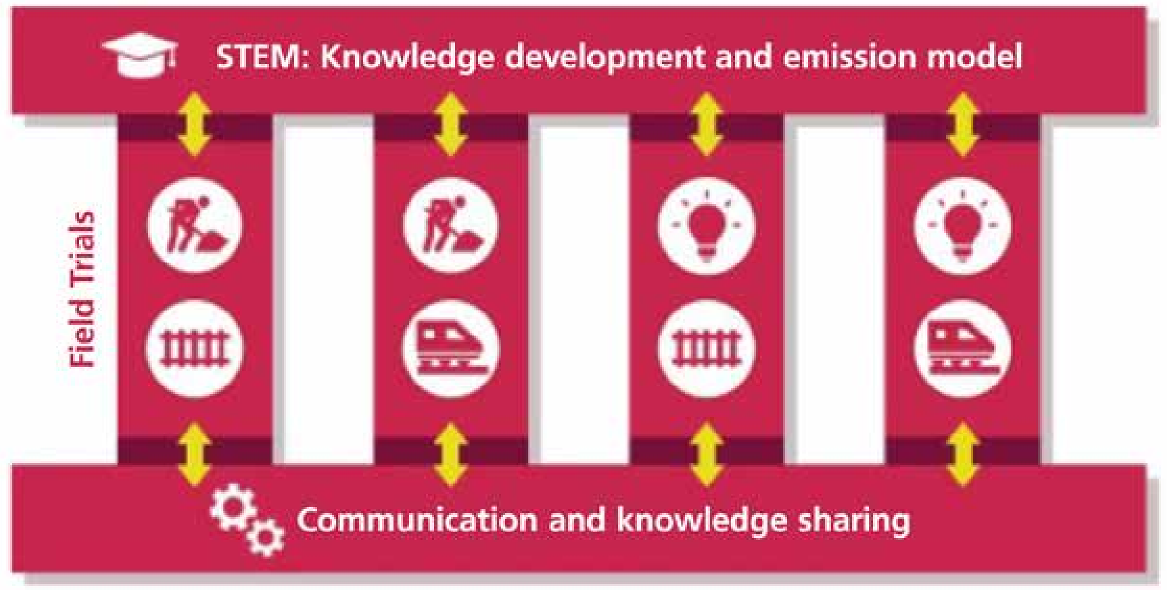
The structure of the programme is illustrated in Figure 1. The knowledge gained is consolidated within the STEM calculation model.

Development is supported by various field trials, which are divided into four pillars:

1. field trials on infrastructure maintenance;
2. field trials on rolling stock maintenance;
3. field trials on infrastructure innovations;
4. field trials on rolling stock innovations.

Some pillars evolved more extensively than others as new promising measures emerged that warranted further research.

Figure 1 Structure of the IBS programme



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[1] To prepare the agenda, ProRail requested input from nine market parties on their vision.

[2] ProRail does not manage rolling stock; therefore, the implementation of measures relating to trains always involves coordination with external stakeholders.

The results of the research programme assist in making choices for policy intensification. The insights gained indicate which measures can be deployed effectively and cost-efficiently in particular situations.

Structure of the report

This final report is divided into four parts. Each part discusses studies and findings. Some studies are part of broader themes that recur across several parts; in such cases, references are made to related research.

The four parts are:

Part 1: Theory and acquired knowledge
Part 2: Field trials
  2A: Infrastructure maintenance
  2B: Rolling stock maintenance
  2C: Infrastructure innovations
  2D: Rolling stock innovations
Part 3: Long-term research
Part 4: Reflection on the results

In describing research projects and field trials, this final document consistently addresses:

1. the motivation for the research;
2. the hypothesis formulated;
3. the method applied;
4. the results.

Part 1

Theory and acquired knowledge

Theory

Introduction

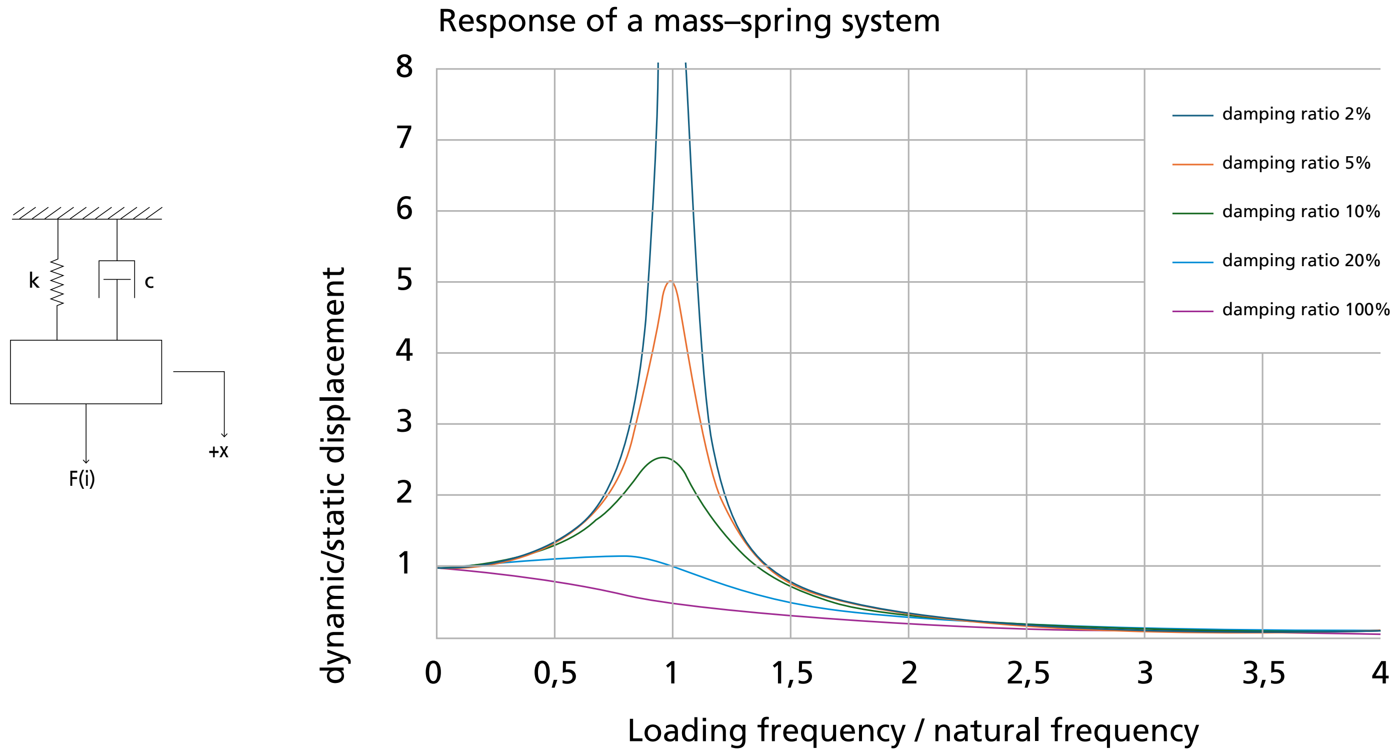
This document presents research results that are largely technical in nature. To help readers better understand and contextualise the results, this chapter outlines key theoretical concepts and definitions. These concepts reappear in the discussion of research findings. For additional background information, references are provided at relevant points.

Vibrations

A vibration is a repetitive motion of a mechanical system (Inman, 2001). Such a mechanical system may be part of a machine, a structure or a continuous medium. In the case of railway vibrations, the ground can be seen as a continuous medium, the track as a structure and the train as a machine. There is interaction between these three systems. If the receiver is also considered, for instance a building, then an additional structural element is added. Each of these systems can in turn be divided into subsystems with their own characteristics. For any arbitrary mechanical (sub)system, two types of vibration occur: **free vibration** and **forced vibration.**

The simplest mechanical system is a mass–spring system. This system also exhibits both forms of vibration and demonstrates several fundamental principles that frequently reappear when investigating more complex systems.

Figure 2 Response of a single-degree-of-freedom mass–spring system



The mass–spring system in Figure 2 has one **degree of freedom** because the mass can move in one direction. If the displacement of the spring is proportional to the applied force, this is referred to as **linear stiffness.** In many practical cases, linear stiffness is a reasonable simplification of reality when the displacements are small. The following then applies:

$$F = k \bullet u + m \bullet \ddot{u}$$

F = applied force on the spring, k = linear stiffness, m = mass, u = displacement, $\ddot{u}$ = acceleration. Many materials exhibit non-linear behaviour under large deformations, in which case the above equation no longer holds. No damping is included in the equation.

When the mass of a spring–mass system is displaced from its equilibrium position – for example, by an imposed displacement – the mass then oscillates around the equilibrium with a specific **natural frequency,** known as a free vibration. The natural frequency at which the system vibrates depends on its mass and stiffness. If there were no damping, the system would theoretically continue oscillating indefinitely. This is a theoretical situation. In reality, damping always occurs due to friction. The natural frequency therefore indicates the frequency at which the system naturally tends to vibrate. For a single-degree-of-freedom mass–spring system without damping, the natural frequency is given by:

$$\omega_n = \sqrt{\frac{k}{m}}$$

In this equation, ω_n is the natural frequency in radians per second, k is the stiffness and m is the mass. If a forced vibration occurs – for example, due to a passing train – the mass–spring system responds to the applied force. The system's response may include a component with the same form as the applied force, but the system may also begin to oscillate in its own natural mode. If the time-dependent force is harmonic, the response of the mass–spring system is a combination of two harmonic forms, provided the system was not in equilibrium when loading began. An important aspect is that the natural vibration decays over time; when the force continues long enough, only the steady response to the applied force remains. This is called the **steady-state response.**

A steady-state response occurs, for example, when a freight train passage lasts long enough and the force has a repetitive form. A vibration at ground level or within a building can then exhibit a steady-state response.

The effect of **resonance** arises when the applied force is harmonic in nature and the excitation frequency corresponds to the natural frequency of the excited system. The displacement of the system at the resonance frequency then becomes greater than it would under the same constant force. This phenomenon is known as amplification. The magnitude of the displacement in this case is largely determined by the damping within the system. Without damping, the displacement would theoretically approach infinity, as the force adds energy to the system with every oscillation, thereby increasing its amplitude, while damping removes energy from the system.

When a dynamic load acts on a continuous medium such as the ground, vibrations are generated that propagate through that medium. This results in **vibration waves** in the soil. The effect is comparable to waves in water: when a point source (for example, a stone thrown into the water) is introduced, waves spread through the water. The same occurs in the soil, although the wave pattern is usually much more complex. However, the comparison is not entirely accurate, because in the ground, shear waves occur that do not exist in water.

Vibration waves in the soil can be divided into compression and shear waves (body waves) and surface waves (Rayleigh and Love waves). The speed at which a wave travels through the medium is the **wave velocity**. In a perfectly homogeneous, non-layered soil, a vibration wave has a velocity that is independent of its excitation frequency; the medium is then non-dispersive. This does not apply when there are multiple soil layers with different wave velocities. In that case, wave patterns occur in which vibration waves transform from one type to another at certain frequencies. Such a medium is called dispersive. In reality, there are always multiple soil layers, so the medium is always dispersive.

The amplitude of a vibration wave decreases with distance from the source due to **material damping** of the soil and **geometrical spreading**. The amount of damping depends on the soil type and the type of wave: sandy soil, for example, has less damping than clay.

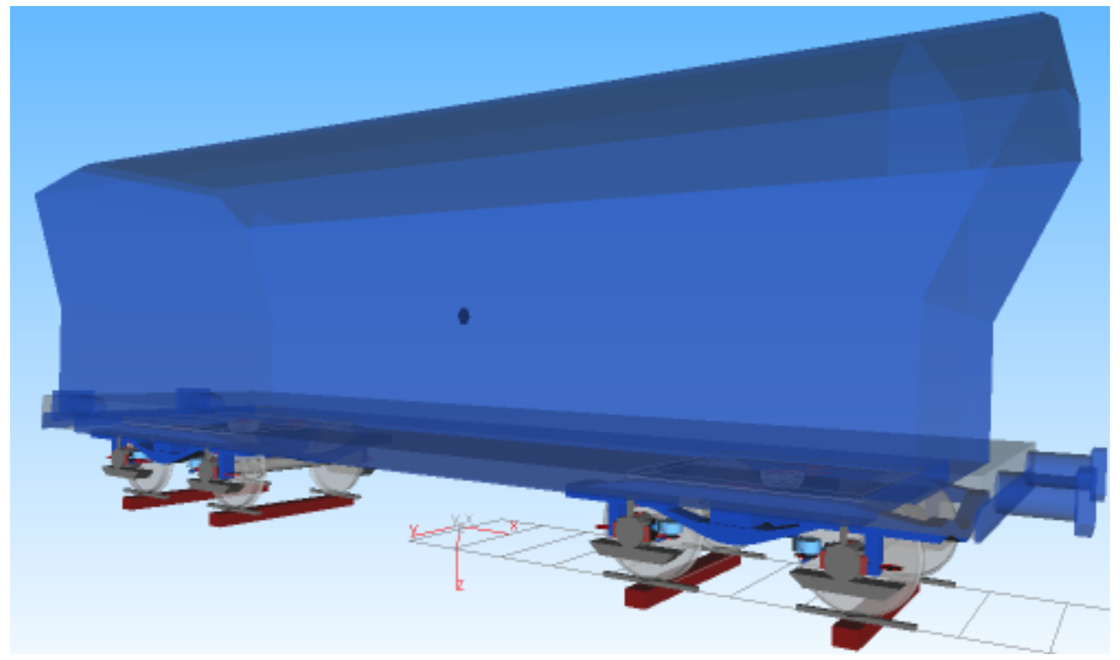
When a vibration of a certain frequency propagates through the soil with a given wave velocity, the vibration wave has a specific **wavelength**, defined in metres. The wave number[3] is defined as 2·π / wavelength (see Glossary of terms).

When a mechanical system (such as a trainset or the track) is represented by a calculation model, that model has many degrees of freedom – both translational and rotational.

When modelling vehicles, this typically results in a multi-body simulation model. Such a numerical model can be used to calculate the response of the vehicle. Figure 3 shows an example of a **multi-body simulation model** of a wagon of the Falns type.

Numerical models of vehicles or mechanical systems are often constructed from mass–spring systems. When a continuous medium such as the track or the ground is modelled, the **Finite Element Method (FEM)** is often used. This method divides the system under study into many small elements, within which the solution is approximated using predefined functions. Wave proagation through the ground is often modelled in this way.For accurate calculation and to prevent numerical errors, important conditions apply to the choice of element size, time step and other modelling parameters (Hughes, 1987).

Figure 3 Example of a multi-body simulation model of a Falns wagon using SIMULIA Simpack software



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[3] The wave number is a property of a wave that indicates how many repetitions occur per unit length.

Railway vibrations

During a train passage, vibrations occur in the track, the surrounding ground and nearby buildings. These vibrations are caused by the forces exerted by the trainset on the track. The magnitude and time variation of these forces depend on many parameters. The force is usually divided into a dynamic and a quasi-static component, both of which cause railway vibrations at a receiving point beside the track.

The mass of the trainset produces a vertical contact force at the points where the wheels touch the rails, i.e. at the wheel axles. A horizontal contact force also occurs, for example, in curves and at switches[4]. If the contact force is constant and does not vary over time, a deformation field is generated that moves together with the contact point. This load is referred to as a **quasi-static load**, because it is a constant (static) force that moves (quasi). At a fixed point beside the track, this moving deformation field passes by, causing movement at that point. Vibrations arise from the successive passage of multiple wheel axles. This means that even with a perfectly straight track, perfectly round wheels and no variations in stiffness or other parameters, vibrations in the ground beside the track can still be felt. These vibrations occur only near the track; they do not propagate further and are not attenuated by the ground. The distance over which the quasi-static load causes vibrations depends, among other things, on soil properties. The quasi-static component of the source is mainly determined by the mass and mass distribution of the train (the axle loads) and by the stiffness of the track and subsoil. The train speed, in combination with the distances between the wheel–rail contact points, determines the frequency content.

In reality, there are always variations that make the wheel–rail contact force time-dependent, creating a **dynamic** component. This dynamic component depends on many factors, including variations in track geometry, stiffness variations in the track structure and the characteristics of the trainset. A trainset has several bogies, each with its own **resonance frequency**. A bogie itself is composed of multiple mass–spring systems. A small portion of the total mass is in direct contact with the rails without an intervening spring – this is called the **unsprung mass.** This mass follows the track geometry and, if the track height profile is uneven, causes a dynamic load.

The magnitude of this dynamic load mainly depends on the stiffness of the track and subsoil. A single wheel can be considered as an unsprung mass, while the rest of the train is sprung but still exerts forces on the track. The wheel may also exhibit **out-of-roundness**, causing its centre of mass to move and resulting in a dynamic load.

The dynamic component of the load generates vibration waves[5] that propagate from the track into the surrounding area and also along the track, ahead of the train. In the case of surface waves with a low wave velocity – as sometimes occurs in soft clay or peat soils – the wave velocity may be so low that it is comparable to the train speed. This leads to an unfavourable condition in which large deformations can occur in the track structure. This can be compared to the occurrence of a *sonic boom* at the speed of sound. The train speed above which this effect occurs (or becomes excessive) is referred to as the critical train speed (Thompson, 2009). Problems with critical train speed are therefore expected only in soft soils and/or at high train speeds. ProRail has drawn up a design guideline for assessing critical train speed[6].

Railway vibrations can cause nuisance in buildings adjacent to the track if the vibration level or vibration characteristics within the building are perceived as disturbing. The vibration level at a given distance from the track depends on the strength of the **source,** the **transmission** of vibrations and how the **receiver** responds to them.

The response of a building structure can vary greatly – some buildings are more sensitive to railway vibrations than others. The vibration level on the floor within a building can, for example, be higher than in the soil due to **amplification**. Amplification occurs when the natural frequency of the floor or the entire building is excited – that is, when resonance occurs within the structure. The vibration level at mid-floor is important for assessing nuisance; the next chapter discusses this in detail.

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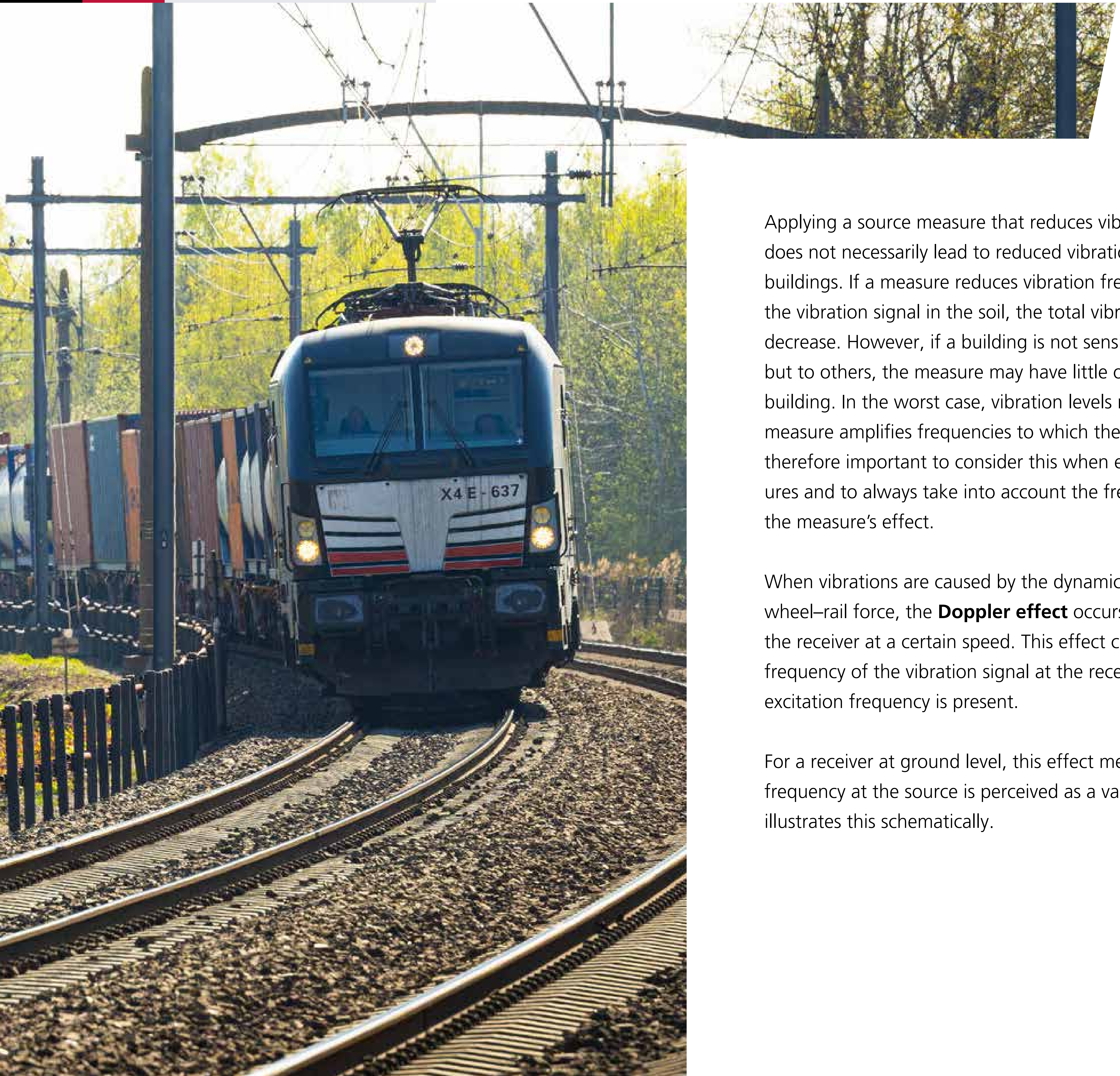
[4] The conical shape of the wheels, in combination with the shape of the rails, also generates a horizontal force at the wheel–rail contact point that centres the train towards the middle of the track.

[5] The vibration waves can be compression, shear or surface waves (see Vibrations).

[6] Design Guideline: Trackbed and Geotechnics, OVS00056-7.1.

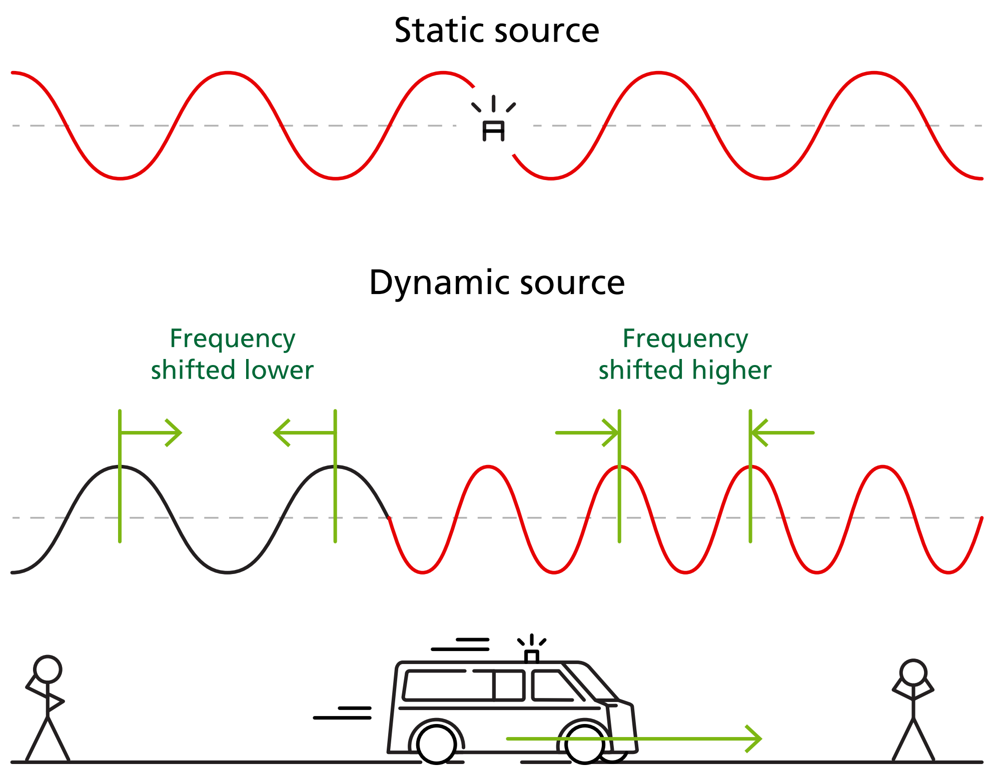


Applying a source measure that reduces vibration levels in the soil does not necessarily lead to reduced vibration levels in all nearby buildings. If a measure reduces vibration frequencies that dominate the vibration signal in the soil, the total vibration level in the soil will decrease. However, if a building is not sensitive to these frequencies but to others, the measure may have little or no effect inside the building. In the worst case, vibration levels may even increase if a measure amplifies frequencies to which the building is sensitive. It is therefore important to consider this when evaluating source measures and to always take into account the frequency dependency of the measure's effect.

When vibrations are caused by the dynamic component of the wheel–rail force, the **Doppler effect** occurs as the source passes the receiver at a certain speed. This effect causes a spread in the frequency of the vibration signal at the receiver, even if only one excitation frequency is present.

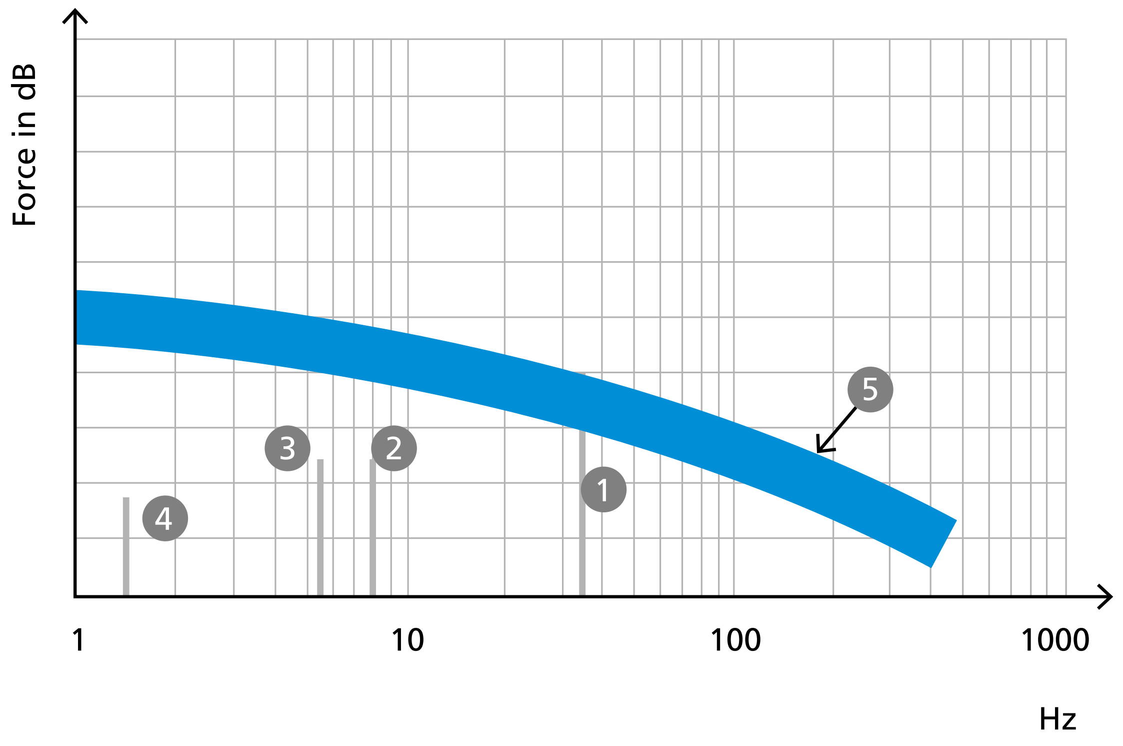
For a receiver at ground level, this effect means that the excitation frequency at the source is perceived as a varying frequency. Figure 4 illustrates this schematically.

Figure 4 Schematic representation of the Doppler effect



During a train passage, several mechanisms occur that lead to a dynamic load. These mechanisms often correspond to specific frequency ranges, which also depend on the train speed. The ISO standard 14837-1 (2005) explains various mechanisms and the expected frequency ranges for two different travel speeds.80 km/h. When the train speed changes, the excitation frequencies shift accordingly. irregularities in track geometry, for example vertical alignment.

Figure 5 Representation of loading frequencies of specific source mechanisms according to ISO 14837



The different excitation mechanisms corresponding to the numbering in Figure 5 are:

1. passing over sleepers;
2. passing of successive axle loads from the same bogie;
3. passing of different axle loads from different bogies;
4. passing of different axle loads from the same vehicle;
5. wheel and rail roughness.

Various other aspects influence the extent to which railway vibrations are generated, such as:

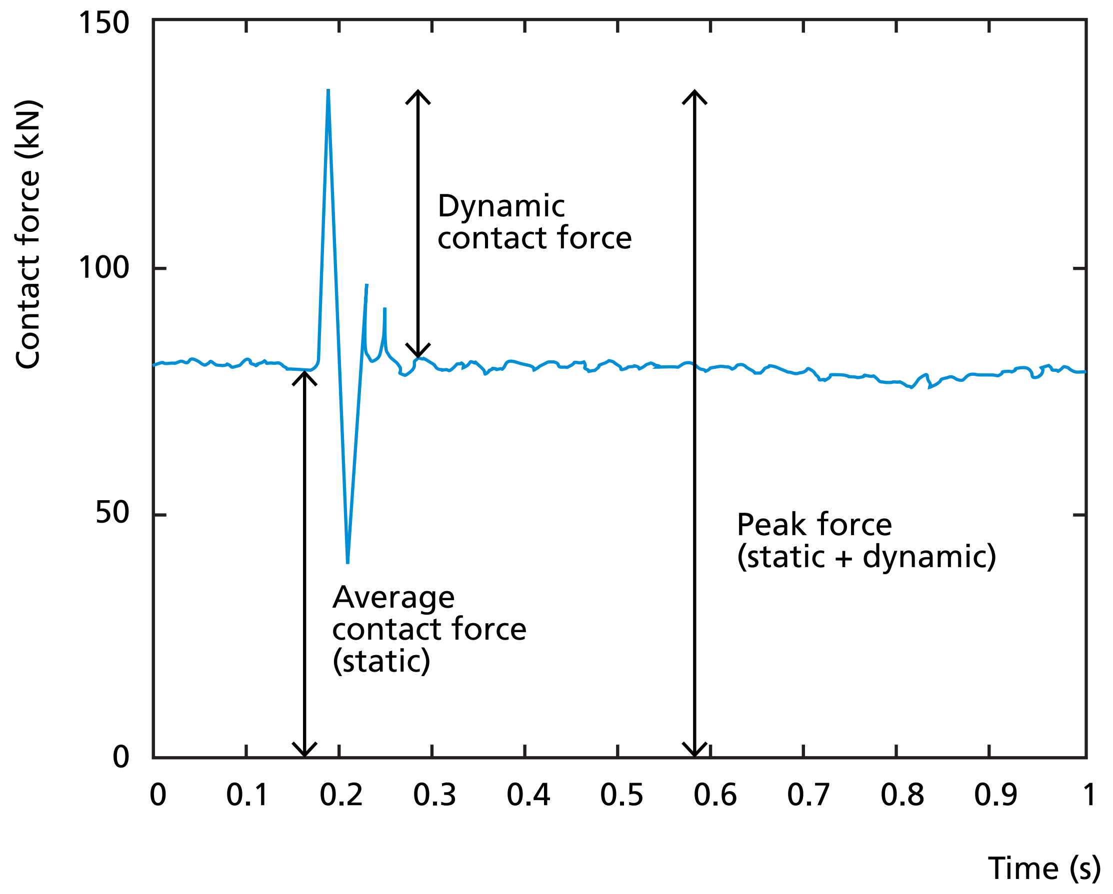
- discontinuities in the track;
- the characteristics of primary and secondary suspension of the bogie;
- irregularities in track geometry, for example vertical alignment;
- weather conditions;
- variation in soil stiffness beneath the track.

All of these mechanisms were studied in the IBS programme, using measurements, model calculations or a combination of both. Datasets of vibration measurements were often combined with data from passing trains obtained from the Quo Vadis monitoring system and/or track geometry measurements (BBMS data[7]).

Quo Vadis

Quo Vadis is the name given by ProRail to a monitoring system and underlying database used to record train passages at more than 40 locations along the Dutch railway network (ProRail, 2016). The Quo Vadis systems use optical fibres to measure rail deflection. Data is recorded for each passing axle.

Figure 6 Quo Vadis measurement system.



Several parameters are derived from the Quo Vadis measurement data. The directly measured parameters are:

- static axle loads;
- dynamic axle loads;
- axle spacings.

From the static axle loads, the system determines the weight at axle, vehicle and train level. It also derives information about wheel load and imbalance within the bogie. Based on the axle spacings, the system determines the train length and the type of rolling stock. Figure 6 provides a schematic representation of a Quo Vadis measurement signal, showing the mean static axle load and the dynamic load fluctuating around the mean.

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[7] BBMS stands for Branche Breed Monitoring Systeem (Sector-Wide Monitoring System).

Dynamic axle load

The Quo Vadis system assesses the condition of a wheel based on the measured dynamic axle load. It can detect deviations classified as out-of-roundness, flat spots and polygonisation[8]. From the dynamic axle load, the system calculates a Root Mean Square (RMS) value, which indicates wheel quality. When a wheel is out-of-round, it generally produces larger dynamic loads, resulting in a higher RMS value.

The Quo Vadis dataset contains two RMS values: **RMS_low and RMS_high.**

- RMS_low is based on signal content in the frequency range 7–200 Hz;
- RMS_high is based on signal content in the frequency range 200 – 1000 Hz.

For railway vibrations, the frequency range of 1–100 Hz is particularly relevant. Therefore, several studies have sought a correlation between the RMS_low value and the measured vibration levels.

Monitoring of track geometry

Since the late 1990s, track irregularities have been monitored by a measurement train. Twice a year, the geometric deviations of the Dutch railway network are measured. The measurements are normalised according to the European Standard EN 13848 and are used to plan track maintenance. In EN 13848, track geometry is defined by four parameters:

- vertical alignment;
- lateral alignment;
- cant;
- gauge.

Vertical alignment refers to the position of the track in the vertical plane. Lateral alignment is the lateral deviation of the track. Cant is the height difference between the two rails, while gauge is the lateral spacing between them.

For railway vibrations, deviations in vertical and lateral alignment are particularly important (Koopman, 2024). Deviations in cant and gauge are considered secondary effects. The European Standard EN 13848 defines various track quality levels based on the standard deviation of geometric deviations. It distinguishes between wavelength intervals, designated D0, D1 and D2 (see Glossary of terms). The standard is aimed at track quality from the perspective of safety and comfort, and thus not primarily at railway vibrations.

Figure 7 Euroscout Measurement Train

Relevance to railway vibrations

Railway vibrations are not always an immediate reason for taking mitigation measures. Measures are only required when the degree of nuisance in nearby buildings justifies them, or, in exceptional cases, when there is a risk of damage. Railway vibrations can also cause damage to the track structure itself, for example through settlement. At locations where these adverse effects do not occur, there is no need to take action. The next chapter discusses the assessment of railway vibrations in more detail.

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[8] Polygonisation is a form of wheel out-of-roundness caused by non-uniform wheel wear.

Vibration-reducing measures

When selecting vibration-reducing measures, a choice is generally made between solutions at the source, during transmission or at the receiver. The cost–benefit balance often plays a key role and varies from case to case. In new construction projects, a vibration-minimised design is often more cost-effective than implementing measures in the track or during transmission. This is explained in the guide New Construction and Railway Vibrations (Klumper et al., 2019). For existing buildings, the situation is different: source or transmission measures are usually more feasible (Vlijm et al., 2024).

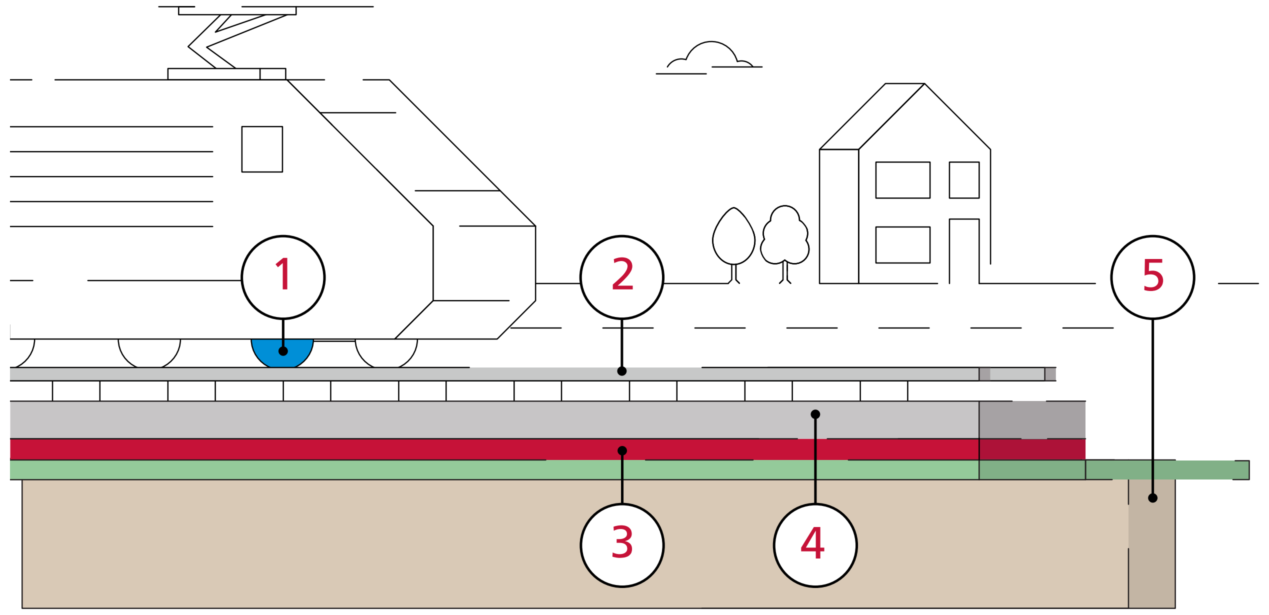
Within the IBS programme, the focus is on source measures. The programme's scope covers the physical area within ProRail's domain – that is, the train, the track and the subsoil surrounding the railway. The boundary between source and transmission measures is not always clear-cut. Therefore, several transmission measures were also studied in more detail (see Infrastructure innovations).

To assess the effectiveness of measures, it is important to understand which source mechanism each measure affects. Accurate determination requires both measurements and model calculations. The development of the STEM calculation model plays an important role in better understanding the results from the field trials. However, many trials were conducted before a usable version of the model was available. As a result, within the IBS programme, the STEM model was used in only a limited number of studies to explain practical results.

Nevertheless, to obtain as much insight as possible from the field trial results, this report refers to several fundamental mechanisms that are assumed to play a role when applying measures. Five mechanisms are distinguished, listed in the box below and shown schematically in Figure 8.

1. modification of the vehicle to reduce the dynamic wheel–rail force;
2. modification of the track to reduce the dynamic wheel–rail force;
3. application of a vibration-isolating material within the track structure;
4. stiffening or improving the trackbed to reduce deflection;
5. modification of the transmission to limit the propagation of railway vibrations into the surroundings.

Figure 8 Vibration-reducing measures



These descriptions are a strong simplification of reality, since measures often have multiple effects. For example, improving the trackbed can have both short- and long-term benefits. In some situations, track degradation occurs more slowly when a stiffer track structure is used. However, this is not always the case and is highly situation-dependent: ballast may fragment more quickly on a stiff foundation, for example on a concrete slab. Therefore, it is always important that design conditions are properly considered.

Vibration-reducing measures also have constraints. A measure is often effective in one frequency range but counterproductive in another. Thus, a measure may reduce vibration levels in one situation but not in another, or even increase them. Results from a field trial at a single site cannot therefore be applied directly elsewhere.

Although field trials always have limitations, the results nonetheless indicate whether the expected effect also occurs in practice. It is equally important to know when a measure works and when it does not, so that it can be applied effectively. In this way, a comprehensive set of effective measures can be established. The field trial results have also provided important information for the development of the STEM model, since practical measurements are needed to validate the theoretical model against real-world conditions.

European research literature

In several studies within the IBS programme, results from existing literature were used. Two European research projects are mentioned in particular: RIVAS and CargoVibes. RIVAS was a three-year research programme carried out between 2011 and 2013. RIVAS stands for Railway Induced Vibration Abatement Solutions[9]. In this programme, an international consortium conducted research into the reduction of railway vibrations. The study established a protocol for determining the effect of vibration-reducing measures. In addition, research was carried out into various types of vibration-reducing measures, divided into:

1. track–vehicle interaction; 2. ballast track and slab track; and 3. measures in the soil beneath and beside the railway. The influence of vehicle characteristics on railway vibrations was also investigated. CargoVibes[10] was a comparable research programme that focused specifically on vibrations along freight railway lines. In this project, another international consortium investigated effective vibration-reducing measures. This research took place during almost the same period as RIVAS, from 2011 until mid-2014. The main results of the research included: a guideline for evaluating the impact of vibrations from freight trains on people, a protocol for assessing mitigating measures, an overview of the performance of different mitigation measures and several new concepts for mitigation measures.

ProRail catalogue of measures

In 2016, Grontmij B.V.[11] prepared a catalogue of railway vibration measures for ProRail (Grontmij, 2016). The catalogue contains an inventory of vibration-reducing measures available at that time. Several of the measures later examined in the IBS programme were already mentioned in the catalogue. It stated that the inventory of vibration-reducing measures revealed a number of promising options that warranted further research. This mainly concerned the further development of measures in relation to their applicability within the Dutch railway system, to enable future implementation. The IBS programme has largely given substance to this recommendation.

Vibration measurements and signal processing

This section describes some basic operations and concepts for signal processing of vibration measurement data. Vibration measurement data can take many forms. Within the IBS programme, a Uniform Measurement Protocol was therefore developed to improve measurement consistency and ensure uniform signal processing across the programme. The next chapter discusses this protocol in more detail (see Uniform Measurement Protocol).

In vibration measurements, a continuous motion is converted into a **discrete signal** with a specific time-step size (Brandt, 2011). The inverse of the time-step size is known as the sampling frequency or sampling density. A typical sampling density for measuring train passages is 1000 Hz, although other values are possible depending on the frequency range of interest.

The Uniform Measurement Protocol specifies that the sampling density must be at least ten times greater than the measurement frequency.

The frequency content of a discrete signal can be determined using a Fourier transform (see Glossary of terms). For this purpose, a Fast Fourier Transform (**FFT**) is used. The discrete nature of the signal imposes certain conditions that must be met for the transformation to be valid: the frequency range in which the transformation is applicable depends on both the time-step size and the signal length.

By applying an FFT, the vibration level per frequency band is obtained – this is called a narrowband filter. By applying an octave-band filter, the vibration content per octave band (or per one-third octave band, also known as a terz band) is obtained (Brandt, 2011). The Uniform Measurement Protocol describes in greater detail how signal processing must be carried out.

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[9] For more information on RIVAS, see: https://cordis.europa.eu/project/id/265754

[10] For more information on CargoVibes, see: https://cordis.europa.eu/project/id/266248

[11] Now Sweco Nederland.

The decibel scale is widely used to compare vibration levels. The vibration level in decibels is defined as follows:

$$L_v(f) = 20 \, log_{10} \frac{v(f)}{v_0}$$

where v(f) is the vibration level per frequency band (narrowband, one-third octave band or octave band) and v0 is the reference vibration level, typically taken as $1 \bullet 10^{-9}$ m/s. This process is further explained in the Uniform Measurement Protocol. Table 1 shows how a reduction in vibration level in decibels (dB) corresponds to a percentage reduction in vibration level (mm/s).

Table 1 Conversion of dB to percentage reduction in mm/s[12]

Reduction in vibration level (dB)	Percentage reduction in vibration level (mm/s)
1 dB	11%
2–3 dB	21%–29%
4–5 dB	37%–44%
6 dB	50%

Assessment of vibrations

Vibration nuisance

In the Netherlands, nuisance caused by railway vibrations is generally assessed using SBR Guideline Part B (Waarts et al., 2002), except in the case of a railway project requiring a formal project decision. In that case, the Policy Rule for Railway.

Vibration Nuisance (Bts, 2014) applies, which in turn refers to certain aspects of the SBR Guideline Part B. For general assessment of vibration nuisance – not limited to railway vibrations but also including those from traffic or construction works – SBR Part B is almost always used in practice.

The amount of nuisance experienced from vibrations depends not only on the maximum vibration level, but also on how often vibrations of a certain level occur and at what times of day. SBR Part B and the Bts therefore use two key assessment parameters: V_{max} and V_{per}. V_{max} represents the maximum expected vibration level, a representative maximum of all $V_{eff,max}$ values over an assessment period[13]. $V_{eff,max}$ is the maximum vibration level during a signal. V_{per} is a periodic vibration level, meaning an energetic average over the assessment period. The characteristic train passages determine the V_{max} value. How often trains pass and at what times, together with the vibration level that occurs, are accounted for in V_{per}.

In addition to $V_{eff,max}$ and V_{per}, the V_{RMS} (root-mean-square) value is often calculated (see Glossary of terms), representing a weighted average. The V_{RMS} value can be calculated over any chosen time interval. In many IBS studies, V_{RMS} was evaluated over the entire passage duration or over a 5-second interval. For a 5-second interval, the value for each measurement direction is denoted V_{RMS},5,j (see Uniform Measurement Protocol).

In the SBR framework, the exposure metric is based on the German DIN 4150 standard, though this is not the only exposure metric for vibration nuisance. The European RIVAS study compared various exposure measures applied in different countries (Elias and Villot, 2011).

In most IBS studies, attention focused on how specific parameters affect $V_{eff,max}$ or V_{RMS}, usually subdivided by frequency band. Although the IBS programme focused mainly on the vibration source, its ultimate goal is to reduce the impact on the environment, and thus to prevent or mitigate nuisance. This explains why most IBS studies examined the effect of measures on $V_{eff,max}$; the periodic vibration level V_{per} received little attention, as a reduction in $V_{eff,max}$ generally implies a reduction in V_{per} though not always vice versa.

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[12] The Bts introduces a perceptibility threshold of 30%, which is regarded as a conservative average threshold. As a guideline, a reduction of 30% or more (i.e. > 3 dB) is considered a perceptible decrease.

[13] In the Bts, V_{max} is determined differently from in SBR Part B.

Vibration damage

Damage to buildings from railway vibrations rarely occurs in practice. Nuisance, however, is much more common, since it arises at lower vibration levels than those that cause damage. The limit values of SBR Guideline Part A: Damage to Buildings (Ostendorf, 2017) are higher than the target values for nuisance used in railway vibration assessment. SBR Part A is almost always applied as the framework for assessing structural damage. Whenever there is a potential risk of damage, the target values for nuisance will almost certainly have been exceeded. For this reason, the IBS programme concentrated on vibration levels expressed as $V_{eff,max}$, used for nuisance assessment, and did not further address damage evaluation.

Perception of nuisance

In 2019, the RIVM (National Institute for Public Health and the Environment) conducted a large-scale survey on the experience of railway vibrations in the Netherlands. A follow-up study was carried out in 2022–2023, with results published in September 2023 in the report 'Living near the railway' (van Kempen et al., 2023). This follow-up involved a survey of more than 5,600 people to assess the extent of vibration nuisance from rail traffic. It showed that in 2021, about 11% of Dutch residents aged 16 and older living within 300 metres of the railway experienced serious nuisance from vibrations, particularly those from freight trains, which also caused sleep disturbance. The RIVM report notes that, in addition to vibrations, social and personal factors influence the extent to which people feel disturbed or have their sleep disrupted. Residents are mainly concerned that vibrations might reduce their property value or cause structural damage. Their perception is also affected when they hear, feel or see windows, doors or crockery vibrating – a phenomenon commonly referred to as 'rattle'.

The RIVM study examined three different exposure metrics: 1) V_{max}, with frequency weighting depending on direction; 2) V_{RMS} (RMS value); and 3) V_{per}. The study found no clear preference for any single exposure metric – none correlated more strongly with perceived nuisance than the others.

The RIVM report presents exposure–response relationships (ER relationships), describing the relationship between the percentage of people experiencing severe nuisance and the degree of vibration exposure. In addition, the RIVM investigated several exposure measures, distinguishing between passenger trains, freight trains and total rail traffic.

Research on nuisance within the IBS programme

Within the IBS programme, the emphasis was on understanding the vibration source and finding effective source-based measures to reduce vibrations. When vibrations at the source are reduced, nuisance in the surrounding area is expected to decrease correspondingly – consistent with the RIVM's ER relationships. Two studies were carried out on the relationship between nuisance and vibrations. The first was a complaint survey, aimed at identifying trends between reported complaints and characteristics of the railway and its surroundings; this helped shape the direction of the programme. In addition, at several measurement sites, residents were invited to take part in a nuisance registration study, in which the most disturbing train passages were identified (see Disturbing train passages).

Uniform Measurement Protocol

In the early phase of the IBS programme, a Uniform Measurement Protocol was developed with the aim of defining a standardised approach and minimum requirements for the preparation, execution, analysis and reporting of vibration measurements, to support knowledge development and/or model validation (Boon, 2024). The Uniform Measurement Protocol was established with the following main and sub-objectives:

1. To define a standardised approach for vibration measurements, including:
    a. a sound research method, based on a hypothesis and research question, tailored to the desired level of accuracy;
    b. a fixed standard approach for measurements to ensure reproducibility;
    c. the use of high-quality equipment;
    d. results that are unambiguous and interpretable and can be used in future research;
    e. a pragmatic, workable execution of measurements.
2. To define a consistent method for determining the effect of mitigation measures.

The Uniform Measurement Protocol was created for a range of stakeholders – including research institutions, engineering firms, measurement companies and ProRail, usually as the commissioning party. By applying the Uniform Measurement Protocol as consistently as possible throughout the various IBS studies, an effort was made to ensure maximum uniformity and consistency in research results.

Preparation and execution of vibration measurements

The Uniform Measurement Protocol describes how to properly prepare a vibration measurement by establishing a hypothesis. The hypothesis influences decisions on what, where, when and how much to measure. The protocol provides guidance on how to determine an appropriate measurement location. It also includes guidelines for the placement of sensors and the required accuracy of measurement equipment.

Processing of measurement data

The Uniform Measurement Protocol prescribes a method for processing raw measurement data. It addresses topics such as signal processing, determining the effect of a measure and comparing the effects of measures between sites. Procedures are also set out for determining the effect of a measure applied to the track, based on measurements at a specific site or between sites. Different types of vibration sources are discussed, such as train passages and artificial vibration sources (for example, a drop weight). The protocol specifies that results must be analysed and presented in one-third octave bands.

Handling uncertainties

The Uniform Measurement Protocol pays particular attention to managing uncertainties in the processing of measurement data. It prescribes the determination of a coefficient of variation, which depends on several factors:

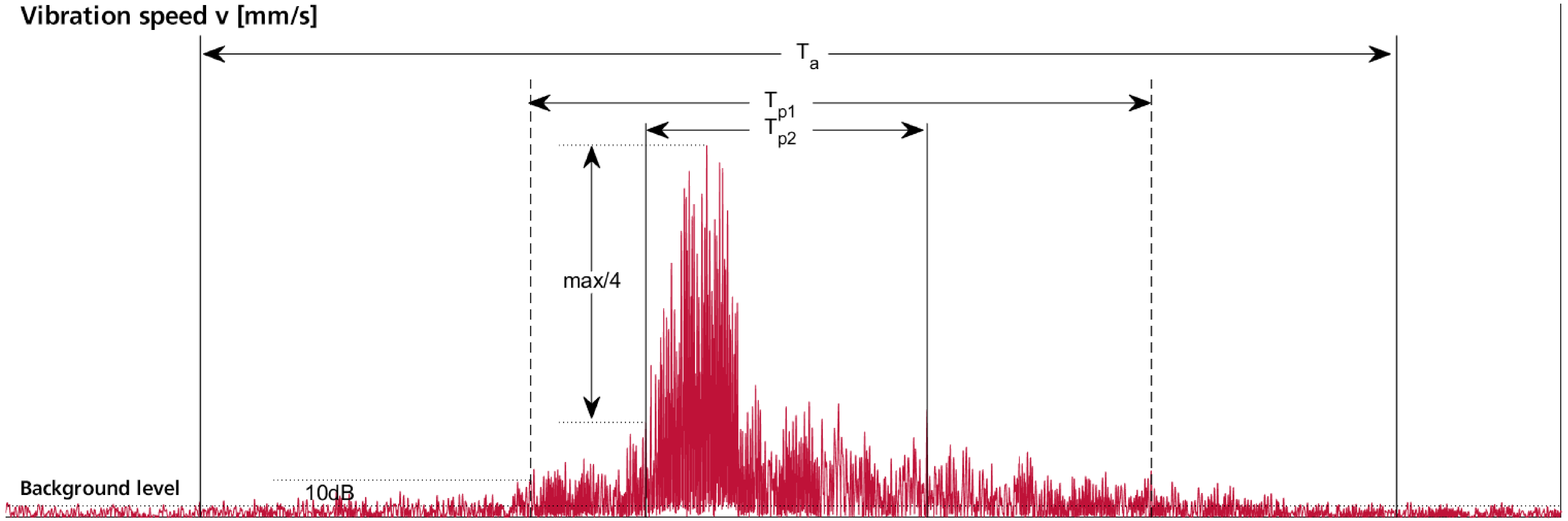
1. the measurement chain;
2. the number of measurement points;
3. the number of train passages;
4. the placement of measurement points;
5. time.

From the coefficients of variation for these factors, a total uncertainty is calculated, which can then be taken into account in the interpretation of measurement data.

The protocol contains rules for the measurement setup, measurement period and signal processing. A ‘standard setup’ is defined, which was used as much as possible across the various measurement campaigns (see Figure 10). It also prescribes how the beginning and end of a vibration signal caused by a train passage should be clearly determined. This is shown in Figure 9.

In Figure 9, T_a is the measurement duration of the full recorded vibration signal. Tp_1 is the time between the first and last moment when the signal rises 10 dB above the background level. T_{p2} is the time between the first and last moment when the signal exceeds one-quarter of its maximum value. The passage time T_p is defined as the longer of T_{p1} or T_{p2}. In Figure 9, T_p equals T_{p1} (Boon, 2024).

Figure 9 Definitions of passage duration of a vibration signal from the Uniform Measurement Protocol



Requirements for effect determination

The Uniform Measurement Protocol describes how to determine the effect of a particular measure using vibration measurements. Two procedures are defined, as well as a combined one. In procedure 1, a reference section is compared with a test section, where the measure has been implemented. This procedure may only be used when the reference and test sections are comparable. In procedure 2, a pre-measurement and post-measurement[14] of the test section are compared. By combining both procedures, the effect of a measure can be determined with greater accuracy. Ultimately, an insertion loss is obtained per one-third octave band, thereby determining a frequency-dependent mitigation effect.

Application within IBS measurement campaigns

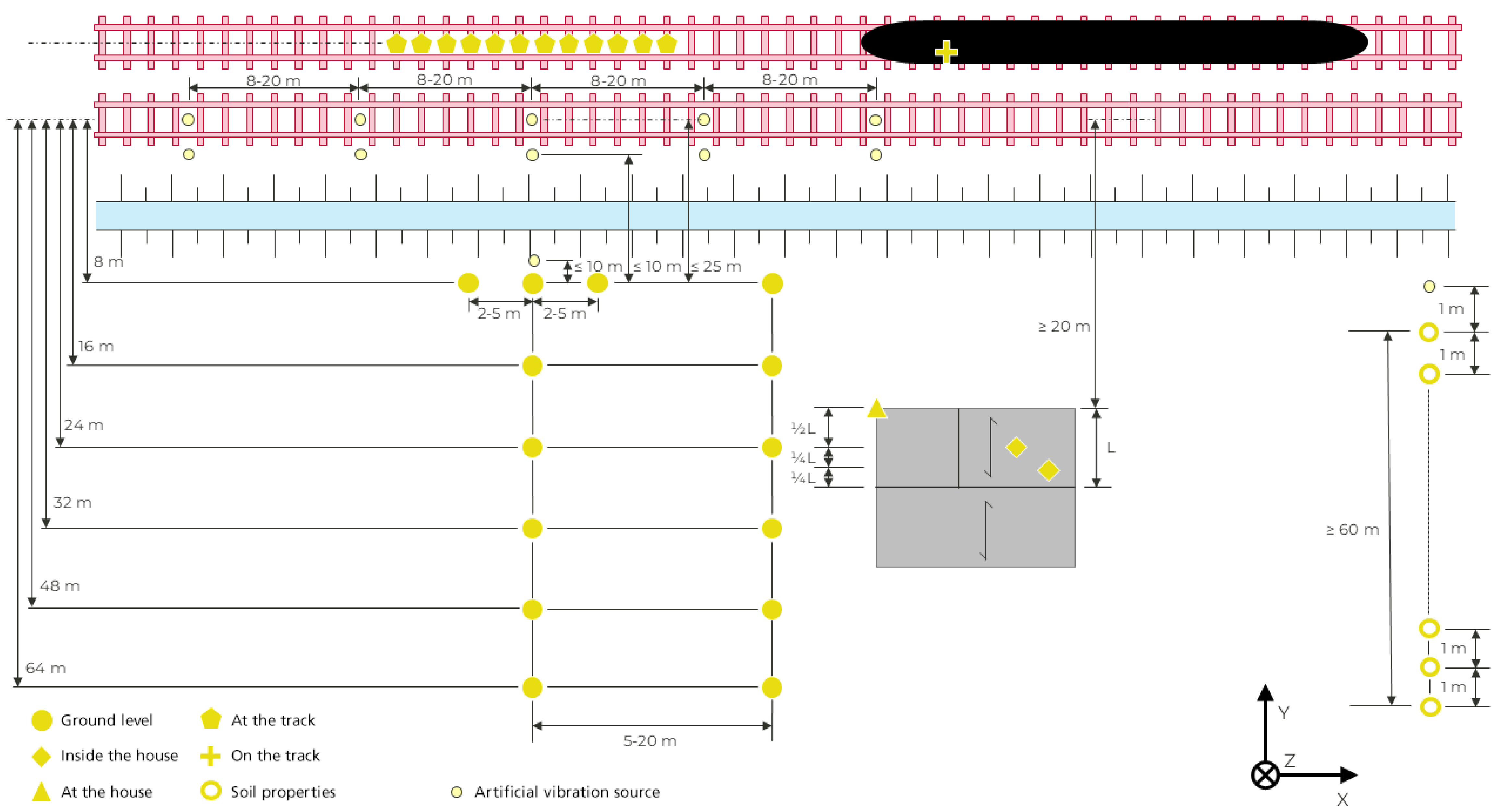
Within the IBS programme, the Uniform Measurement Protocol was applied as consistently as possible in carrying out vibration measurements. In the initial phase of the programme, some studies analysed measurement data that had been collected before the protocol was established. As a result, data was not always consistent in terms of minimum measurement duration or setup. Even for projects that followed the protocol, conditions often required deviations from the standard configuration.

Statistical analysis of measurement data

To identify relationships between various recorded parameters within large datasets, statistical analysis methods are often used. These methods can reveal correlations even when the underlying mechanisms are not yet fully understood – the relationships emerge from the data analysis itself. Several IBS studies used random forest models, a machine learning technique that explores numerous combinations of parameters to determine which combinations best correlate with, for example, the measured vibration level. Parameter combinations are classified (which combination correlates best?) and regression properties are determined (for instance, how much does the vibration level increase or decrease as a parameter combination changes?) (Hastie et al., 2017). Such models are 'trained' by adding more data and the quality of the measurement data is critical for the reliability of the identified relationships.

By combining the results of statistical analyses with those from the STEM computational model, it becomes possible to explain the data-derived relationships physically. Part 3 discusses the STEM model in more detail (see Railway Vibrations Emission Model).

Figure 10 Measurement setup according to the Uniform Measurement Protocol



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14 (In this document, 'pre-measurement' is also referred to as 'baseline measurement', and 'post-measurement' as 'repeat measurement'.)

Research projects

Complaint analysis

Background

To establish priorities within the IBS programme, We-Boost conducted a study in 2022 to identify the main causes of vibration complaints (Boon et al., 2022). The study examined whether specific situations or conditions could be identified where railway vibrations cause more nuisance.

Hypothesis

Experience from earlier studies indicates that relatively strong vibrations occur in specific parts of the track, for instance where discontinuities are present, such as switches, level crossings or insulated rail joints (IRJs) (Ostendorf, 2021). This can be explained by the fact that such discontinuities generate dynamic loads during train passages, which in turn cause vibrations (see Railway Vibrations).
By analysing vibration complaints from across the Netherlands, it might be possible to identify locations where complaints are significantly more frequent.

Method

A comprehensive data analysis using a random forest model was performed to determine which parameters do and do not influence the number of complaints. The analysis linked complaints about railway vibration nuisance received by ProRail in 2021 to characteristics such as soil type, building characteristics, demographic data, track geometry and the location of IRJs and switches.

Results

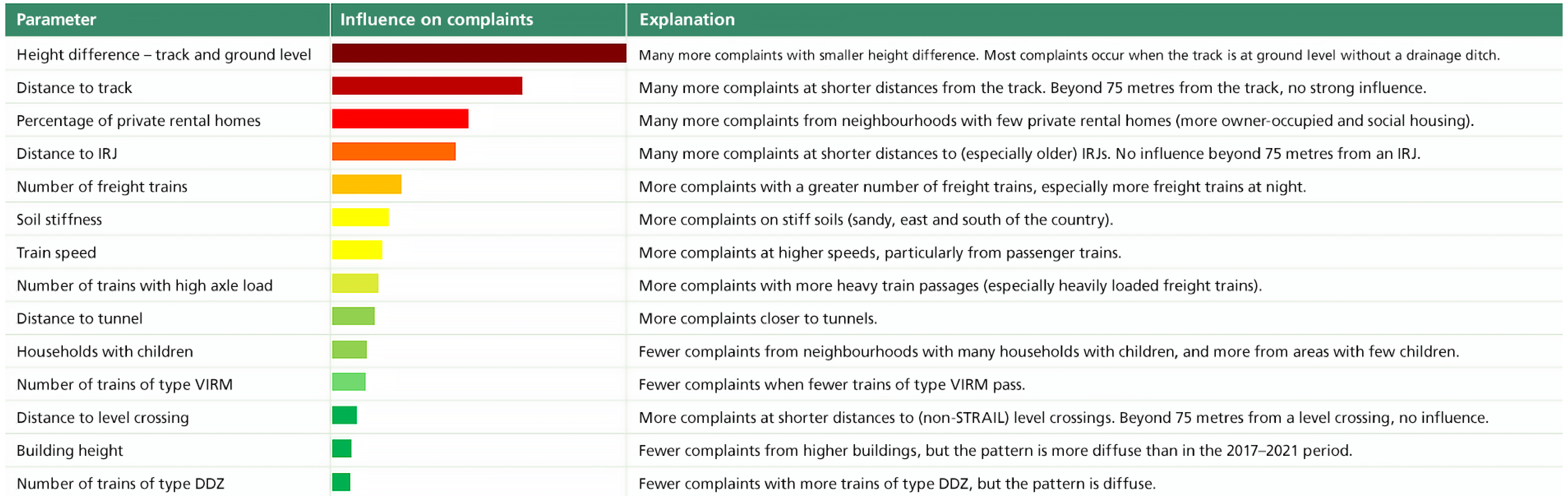
According to We-Boost's report, certain situations can be identified that result in complaints more frequently than expected (Boon et al., 2022). Changes, in particular, often lead to complaints – for example, track renewal, new level crossings, different trains or higher train speeds. This may be due to higher vibration levels, but also to shifts in the frequency content of vibrations, which alters how they are perceived. The role of media and action groups was also found to be important, as these contribute significantly to the number of reported complaints.

The report also notes that sociological factors may play a role in complaint reporting: more complaints originate from neighbourhoods with many single-person households, few families with children and a high proportion of residents aged 65 and older. More complaints are also reported from densely populated areas.

Based on the 2022 complaint analysis, We-Boost formulated the following recommendations for prioritising actions to reduce complaints (Boon et al., 2022):

- Focus measures on areas with:
    - Buildings located close to the railway, particularly on stiffer soil types (sand);
    - Heavily trafficked, mixed lines with frequent freight trains running at full speed.
- Conduct further research into complaints reported around (especially older) IRJs.

Figure 11 Overview of parameters influencing complaints (Boon et al., 2025)



Parameter	Influence on complaints	Explanation
Height difference – track and ground level		Many more complaints with smaller height difference. Most complaints occur when the track is at ground level without a drainage ditch.
Distance to track		Many more complaints at shorter distances from the track. Beyond 75 metres from the track, no strong influence.
Percentage of private rental homes		Many more complaints from neighbourhoods with few private rental homes (more owner-occupied and social housing).
Distance to IRJ		Many more complaints at shorter distances to (especially older) IRJs. No influence beyond 75 metres from an IRJ.
Number of freight trains		More complaints with a greater number of freight trains, especially more freight trains at night.
Soil stiffness		More complaints on stiff soils (sandy, east and south of the country).
Train speed		More complaints at higher speeds, particularly from passenger trains.
Number of trains with high axle load		More complaints with more heavy train passages (especially heavily loaded freight trains).
Distance to tunnel		More complaints closer to tunnels.
Households with children		Fewer complaints from neighbourhoods with many households with children, and more from areas with few children.
Number of trains of type VIRM		Fewer complaints when fewer trains of type VIRM pass.
Distance to level crossing		More complaints at shorter distances to (non-STRAIL) level crossings. Beyond 75 metres from a level crossing, no influence.
Building height		Fewer complaints from higher buildings, but the pattern is more diffuse than in the 2017–2021 period.
Number of trains of type DDZ		Fewer complaints with more trains of type DDZ, but the pattern is diffuse.

- Investigate options to reduce dynamic peak loads and RMS_low values according to the Quo Vadis measurement system.
- Preserve trackside drainage ditches as a relatively inexpensive anti-vibration measure – significantly fewer complaints occur where such a ditch separates the track from nearby buildings.

The study emphasises that railway vibrations must always be considered frequency-dependent: many complaints appear to be related to shifts in the vibration frequency spectrum, for example due to higher train speeds, different train types or changes in track structure.

An updated analysis based on complaints received between mid-2021 and mid-2024 (Boon et al., 2025) introduced some nuances compared to the 2022 results. Notably, the increasing trend in complaint numbers observed in 2022 was not confirmed in the update – in recent years (2021 – 2024), the number of complaints appears to have declined slightly. Figure 11 provides an overview of parameters influencing complaints according to the 2025 study.

Passenger rolling stock

In addition to the general complaint analysis for total rail traffic, a follow-up study focused on passenger rolling stock (Boon et al, 2025). This research found that some train types appear to be more strongly associated with complaints than others. Freight trains and TRAXX + ICRmh trains[15] were identified as the main contributors, along with VIRM, Flirt, DDZ and SNG types. Conversely, trains of the GTW type appear to cause fewer complaints – possibly because, on many routes where GTW units were introduced, they replaced older train types (such as the DM’90) that were known to cause more nuisance. The key findings are summarised in Box 1.

Box 1: Results of the complaint analysis

- Focus on heavily used routes with a high proportion of freight traffic and stiff sandy soils.
- Further investigation is needed into complaints related to IRJs in combination with switches and/or level crossings.
- Increases in complaints occur when changes are made, for example in train speed, train type or track construction.

Disturbing train passages

Background

Research by the RIVM on perceived nuisance (van Kempen et al., 2023) shows that people exposed to higher vibration levels and/or living closer to the railway report more nuisance from freight trains.

The complaint analysis indicates that many complaints arise following modifications to the track, suggesting a possible relationship between nuisance and the vibration frequency spectrum (see Complaint analysis). To gain greater insight into indicators of vibration nuisance, M+P carried out a study in 2024 – 2025 into the relationships between train characteristics, vibration levels and perceived nuisance (Kuijpers & Meeuwes, 2025).

Hypothesis

The main objective of the study was to analyse the relationship between train characteristics, vibration levels and residents’ perception of nuisance. The initial expectation was that certain train characteristics would contribute more strongly to perceived nuisance than others.

Method

At four locations in the Netherlands, residents were invited to take part in the study by anonymously reporting their perceived nuisance from railway vibrations (Kuijpers et al., 2025). The locations were Schalkwijk, America, Holten–Rijssen and Wierden. At the same time, vibration levels were measured according to the Uniform Measurement Protocol at various distances from the railway, along with the speeds of passing trains. Information on the passing trains was also collected from a nearby Quo Vadis monitoring station.
To map the relationship between train characteristics, the vibration measurement results at various ground-level distances from the track and the reported nuisance passages, all data recorded and collected was analysed using the CRISP-DM[16] methodology. The analysis explored correlations between vehicle characteristics on the one hand and vibration measurement data and nuisance registrations on the other. The study examined various quantities, including V_{RMS}, $V_{eff,max}$ and one-third octave spectra.

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[15] An overview of different train types is given in Annex II.
[16] CRISP-DM stands for Cross-Industry Standard Process for Data Mining.

Results

In its report, M+P concluded the following regarding the relationship between rolling stock type and perceived nuisance (Kuijpers & Meeuwes, 2025):

- Freight trains are relatively often recorded as causing nuisance.
- The proportion of passenger trains perceived as disturbing is relatively small but not negligible in absolute terms, because many passenger trains pass each site.
- Freight trains consisting mainly of container wagons, tank wagons or (open) bulk wagons are often reported as disturbing.
- Passenger trains of types VIRM-IV, SNG III and DDZ are recorded as disturbing more frequently than other intercity or sprinter types.
- The number of axles correlates with nuisance, but also with the rolling stock type: trains with many axles most often cause nuisance – and these are always long freight trains. For smaller numbers of axles, the axle count correlates strongly with train type and thus with nuisance.

The study also examined wheel damage classifications as recorded by the Quo Vadis system (polygonisation, flat spots or out-of-roundness) and their relationship to the registered nuisance passages. The findings were:

- If several wheel defects are present in a train, the probability of recorded nuisance increases (especially for flat spots).
- Multiple flat spots and/or polygonisation are stronger indicators of nuisance than out-of-roundness.
- Among the various wheel defects, flat spots occur most frequently in the Quo Vadis data. For the nuisance registrations, of the passages marked as disturbing due to wheel defects, most exhibited flat spots. However, the relative proportion is not larger: no specific defect type is significantly more associated with nuisance than others.
- The (average) diagonal imbalance[17] in a train cannot be related to measured vibration levels.
- For passenger trains, there appears to be a relationship between nuisance and the variation of diagonal imbalance: disturbing trains show less variation, though no explanation was found.

When considering properties of the measured vibration signals and their correlation with nuisance registrations, the following was observed:

- Variation in vibration level during a passage shows a slight correlation with nuisance – the greater the variation, the higher the probability of nuisance.
- For all implementation types, measurement directions and distances from the track, the mean spectrum of disturbing passages does not differ significantly from that of non-disturbing passages.

The study concludes that no clear relationship was found between perceived nuisance and the frequency characteristics of railway vibrations. This does not confirm the hypothesis that a shift in the frequency spectrum is an indicator of nuisance. However, there is a strong relationship with train type, axle load and number of axles. The results are summarised in Box 2.

Box 2: Results of the disturbing train passage study

- Freight trains are most often disturbing, due to high axle loads and large numbers of axles.
- If a passage involves multiple wheel defects according to Quo Vadis, the likelihood of nuisance increases.
- No relationship was found between nuisance and the vibration frequency spectrum.

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[17] A diagonal imbalance is an imbalance in a bogie that results in unequal forces on the two rails.

Research on rolling stock

Background

Between 2020 and 2022, Ricardo Rail and Cohere Consultants examined whether correlations could be found between rolling stock type, poor wheel quality and high measured vibration levels based on earlier measurements (Vlijm, 2020). Measurement points were located 25 m from the track at four sites along the A2 corridor. Since the Uniform Measurement Protocol had not yet been established, the measurements were not conducted in accordance with it. The results served as a starting point for subsequent wheel out-of-roundness research (see Wheel out-of-roundness study).

Hypothesis

The study assumed that the passage of wheels in poor condition should be detectable in vibration signals measured 25 m from the track. A specific harmonic order of wheel out-of-roundness produces a dynamic loading frequency at a given train speed. By analysing separate frequency bands, an increase should be visible in specific bands for passages involving one or more defective wheels.

Method

Wheel quality was determined using data from nearby Quo Vadis monitoring stations. The study also examined whether certain freight train types generated more vibration than others. Vibration signals were analysed for entire passages and divided into 1- and 2-second intervals to determine whether axles identified by Quo Vadis as having defective wheels caused increased vibration in specific frequency bands during the passage signal.

Results

The results show substantial variation among the four measurement sites. Train passages exhibiting the highest $V_{eff,max}$ at one site did not necessarily do so at others. Different excitation mechanisms appear to dominate at different sites, likely due to differences in soil composition. The hypothesis that poorly maintained wheels lead to elevated vibration levels within a specific frequency band (16 or 31.5 Hz) and to higher dynamic peak loads was not confirmed. For both 1- and 2-second time windows and for entire passages, no (linear) relationship was found between V_{RMS} and dynamic peak load in the 4, 8, 16 and 31.5 Hz frequency bands. When subdivided by wagon type, a relationship appeared at one location only. Cohere Consultants concluded that a statistically significant correlation between V_{RMS} frequency bands and dynamic peak load is best identified in datasets containing a single specific wagon type (Vlijm, 2020).

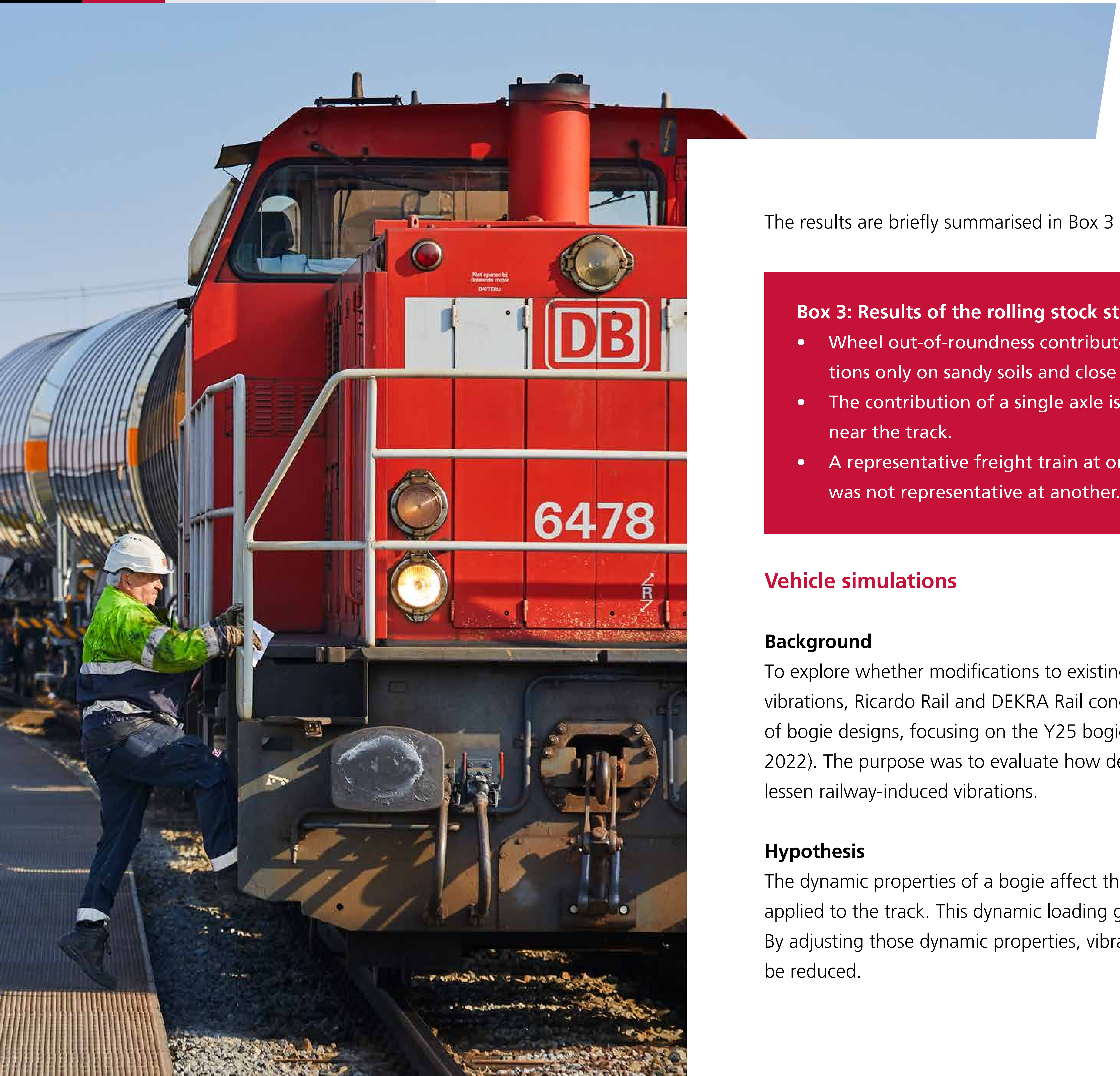
Follow-up study: axle box acceleration data for VIRM

As a follow-up, axle box acceleration data from a specific trainset was examined. The available measurement data included passages of the InfraMon train (a VIRM unit equipped with axle box accelerometers). Combined axle box and ground vibration data analyses were conducted (Roeleveld & Vlijm, 2021), with linkage to available Quo Vadis data. The research question was whether combined axle box and ground measurement data at 25 m from the track could provide insight into wheel out-of-roundness.

By comparing frequency analyses of ground and axle box signals within specific frequency bands (depending on train speed), the study investigated whether statistically significant correlations could be found for first-, second- and third-order wheel out-of-roundness. The relevant frequency bands were derived from train speed and out-of-roundness order (corresponding to specific wavelengths). The analyses clearly showed that low-frequency components dominate vibration signals on soft soils, whereas on stiffer sandy soils, high-frequency transmission is better, so higher frequencies remain visible in the signal even at greater distances.

Cohere Consultants concluded that at 25 m distance, the contribution of an individual axle is difficult to identify, as multiple axles contribute to the measured vibration signal. The study produced several valuable recommendations for the more extensive wheel-out-of-roundness research that followed. The main recommendations are:

- To capture the effect of wheel out-of-roundness on specific axles using vibration measurements, measurements must be taken close to the track; at a distance of 25 m, it is difficult to distinguish between the passages of different axles in the vibration signal.
- Stiff (sandy) soils exhibit strong transmission in the frequency ranges where wheel out-of-roundness plays a role (higher frequencies 25–40 Hz). When assessing the influence of wheel out-of-roundness on near-track railway vibrations, emphasis should be placed on stiff (sandy) soils.



The results are briefly summarised in Box 3

Box 3: Results of the rolling stock study

- Wheel out-of-roundness contributes to railway vibrations only on sandy soils and close to the track.
- The contribution of a single axle is detectable only near the track.
- A representative freight train at one measurement site was not representative at another.

Vehicle simulations

Background

To explore whether modifications to existing bogies could reduce vibrations, Ricardo Rail and DEKRA Rail conducted a simulation study of bogie designs, focusing on the Y25 bogie (Dirks & Roeleveld, 2022). The purpose was to evaluate how design adjustments might lessen railway-induced vibrations.

Hypothesis

The dynamic properties of a bogie affect the dynamic loading applied to the track. This dynamic loading generates vibrations. By adjusting those dynamic properties, vibration excitation might be reduced.

Approach

The study analysed and compared the dynamic loading of various rolling stock types on the track using multi-body dynamics simulations. In these simulations, trains were run virtually over track profiles containing irregularities. The resulting vehicle responses and wheel-rail contact forces formed the basis for determining the dynamic load the vehicle exerts on the track. Because each vehicle type has its own structural characteristics, comparing different types provides insight into how vehicle design influences vibration loading. Three different track models were used for the simulations:

1. A theoretical track with geometry based on the ERRI B176 report, adjusted to match Dutch track quality – this track excites the vehicle broadband, determining dynamic loads across all vibration-relevant wavelengths.
2. A real track section near Schalkwijk, approximately 1 km long, carrying both freight and passenger trains, where vibration measurements were also performed.
3. A theoretical track with a short-wavelength defect, where the defect excites the vehicle, which in turn exerts a dynamic vertical force on the track.

DEKRA Rail ran simulations for Falns wagons using five design variants of the Y25 bogie, combined with an existing Falns freight wagon model (Dirks & Hiensch, 2023). The first four variants were modifications that could be implemented relatively easily within the existing Y25 bogie:

- reduced unsprung (wheelset) mass;
- reduced vertical stiffness by inserting a rubber ring under the centre bowl;
- modified primary suspension using the Gigabox;
- modified spring-slide components;
- and a version with swing arms, representing a distinct bogie type.

Ricardo Rail performed additional simulations for Falns wagons with both the standard Y25 bogie and a 'three-piece bogie'[18] (Roeleveld & de Jong, 2023). Various locomotive and passenger train types were also simulated.

The Ricardo report notes that when interpreting results, it is important to remember that a vehicle's dynamic loading on the track is only one of the many factors determining the ultimate vibration levels in the ground and in nearby buildings. The final vibration level at the receiver depends on numerous interacting influences.

Results

Simulation results from both DEKRA and Ricardo Rail show that, for all track models, the wheel–rail forces of the loaded freight wagon are significantly higher than those of the empty wagon at frequencies below 20 Hz (Dirks & Roeleveld, 2022). At higher frequencies, the difference between loaded and empty wagons is minimal.

Consequently, the results for the loaded wagons are considered representative compared with empty wagons. In Ricardo Rail's report, results are described per frequency interval:

- Up to about 5 Hz, the loaded freight wagons produce the highest dynamic axle load, even compared with locomotives and passenger trains. This is related to the movement of the wagon body, including the heavy load, in the primary suspension[19].
- Between about 5 Hz and 10 Hz, the TRAXX[20] locomotive and the loaded freight wagon with the standard Y25 bogie generate the highest load. Vibrations in this frequency range are caused by the vertical movement of the bogie in the
- primary suspension. The load of the TRAXX locomotive is higher than that of the Loc 1700 and the Class 66.
- Between about 10 Hz and 30 Hz, the three locomotives in the simulation generate the highest dynamic axle loads. This is associated with the movement of the heavy wheelsets in the primary suspension. The axle loads of passenger trains and freight wagons are comparable and considerably lower.
- Above 30 Hz, the dynamic load decreases rapidly and is similar for the various vehicle types. However, within this range, the sleeper spacing produces a distinct load peak. At 80 km/h and 100 km/h, these frequencies are approximately 37 Hz and 46 Hz, respectively.

Simulations of the different freight bogie types show that the loaded wagon with the three-piece bogie generates a two- to fourfold lower dynamic load between 5 Hz and 10 Hz than the reference version with the Y25 bogie. The variant in which the wheelsets are attached to the bogie frame by swing arms with hydraulic suspension also shows a clear reduction in dynamic load within the 3–10 Hz frequency range. For the Schalkwijk track geometry, this effect applies in the range 1–10 Hz. In the 20–30 Hz range, there is a slight increase in dynamic load.

---

[18] A three-piece bogie is a running gear that, as the name implies, consists of three moving parts connected together.

[19] This refers to the dynamic component of the load, not the passing quasi-static deformation field. When an irregularity occurs in the track, the passage of axle loads also results in a dynamic component (see Theory).

[20] The various locomotive types are shown in Annex II.

Figure 12 Photo of the Y25 bogie

When comparing mixed traffic (freight wagons at 80 km/h and passenger rolling stock at 140 km/h), freight wagons produce the highest dynamic axle loads up to about 5 Hz. Above roughly 8–9 Hz, passenger rolling stock produces the highest dynamic axle loads.

Based on the track geometry at Schalkwijk, the contribution of these higher frequencies to the total load is, however, limited. The real-world Schalkwijk track shows that contributions at wavelengths below 3 m are lower than on the theoretical ERRI track, resulting in lower dynamic loads at higher frequencies. This means that the dominant locomotive vibrations between 10 Hz and 30 Hz play virtually no role there. The report notes that these conclusions represent general trends in dynamic loading; the frequency content of specific vehicles or speeds can deviate considerably.

Influence of train speed

Simulations show that increasing train speed on the theoretical ERRI track results in higher vertical excitation at all wavelengths/ frequencies. For locomotives and passenger rolling stock, this produces a load spectrum that remains nearly the same in shape but increases in amplitude. On average, the amplitude rises by a factor of ten when the train speed increases from 40 km/h to 140 km/h.[21] For freight wagons, the load also increases, but its characteristics change simultaneously. This is due to the non-linear behaviour of certain structural elements (such as friction plates), which causes the dynamic response to vary with excitation amplitude. Passenger rolling stock and locomotives, by contrast, behave largely linearly.

Influence of a rail dip

When a rail dip[22] was simulated, two influencing factors emerged: 1) the unsprung mass and 2) the axle load. The increase in force caused by the rail dip is dominated by the unsprung mass, which is highest for locomotives. Well below that are the force increases for passenger trains and freight wagons; because of their low unsprung mass, freight wagons show the smallest increase. For the maximum total force at the rail dip, axle load also plays a role: loaded freight wagons exhibit a relatively high force, lying between that of locomotives and that of passenger stock.

Possibilities for reducing vibrations

Based on the simulation results, DEKRA Rail's report describes several possibilities for reducing vibrations, derived from the various design modifications to the Y25 bogie (Dirks & Hiensch, 2023):

- Simulations with a rail dip show that three variants produce a reduction in maximum wheel–rail force compared with the reference model – namely variants 1, 3 and 5.
- Altering bogie parameters (stiffness, damping, mass, etc.) causes a frequency shift in the vehicle response, moving the peak response to another frequency range.
- Increasing train speed raises the wheel–rail force across the wavelength range corresponding to the 1–50 Hz frequency band. Especially in the higher-frequency region (20–50 Hz), a strong increase occurs as train speed rises.
- The bogie variant that performs equally well or better across all track models and the entire frequency range is variant 1, the version with reduced unsprung mass. The improvement is visible at frequencies above 10 Hz.

The report by Ricardo Rail (Roeleveld & de Jong, 2023) concludes that, based on the study results, the most effective optimisation of the Y25 bogie design combines variant 1 and variant 2.
This conclusion assumes that the Schalkwijk track geometry is representative of average track geometry.

---

[21] Such results are consistent with the literature, which frequently assumes a dependence of vibration level on train speed.
[22] A rail dip is a local irregularity in the railhead.

The study highlights the importance of further research into representative track geometry and its influence on simulation results. It is also important to view wheel–rail-force results in the context of the critical frequency range. For the most effective optimisation of the Y25 bogie design, further simulations are recommended to investigate the combined effects of variants 1, 2 and 3. The results of these follow-up steps are discussed in 2D: Rolling stock innovations (see Rolling stock innovations).

Effect of passing axle loads

In the simulations, wheel–rail forces were analysed for a single axle. However, the relationship between this force and the resulting track-borne ground vibrations alongside the railway was not investigated. In practice, the soil experiences the combined effect of multiple axles passing over the track. Where track irregularities such as rail dips exist, a dynamic load is generated by the successive passage of multiple axles. Because the simulations considered only a single axle, this effect was excluded[23]. The results are briefly summarised in Box 4.

Box 4: Results of vehicle simulations

- Up to 5 Hz, freight trains show the highest wheel–rail forces due to heavy loading in the primary suspension.
- Between 5 Hz and 10 Hz, the TRAXX locomotive and loaded freight wagon with the standard Y25 bogie produce the highest loads.
- Between 10 Hz and 30 Hz, three locomotives with heavy wheelsets produce the highest loads.
- Above 30 Hz, the loads rapidly decrease; sleeper spacing becomes visible in the signal.
- Increasing train speed leads to higher vibration levels
- Modifying the Y25 bogie to reduce unsprung mass and add a rubber ring appears to be an effective measure.

Environment-oriented management and maintenance

Within the IBS programme, research was carried out into how ProRail's maintenance and management strategy could incorporate measures to reduce railway-induced vibrations. This approach integrates environmental vibration exposure into maintenance planning. The study on environment-oriented management and maintenance is divided into several investigations that collectively contribute to the overall objective:

- developing and testing a track geometry quality indicator for vibrations to assess track geometry quality;
- conducting vibration measurements during different maintenance activities (see field trials OBO1 and OBO2);
- performing model calculations for specific locations or situations where track maintenance might also have a positive effect on environmental vibration exposure.

Each activity is described in a separate study; the following sections discuss these investigations.

---

[23] In a subsequent study, no correlation was found between wheel forces and measured ground vibrations next to the track in the low-frequency range. The absence of the effect of successive axles – which in practice often turns out to be the dominant excitation mechanism – explains this result.

Spoorligger: track geometry quality for vibrations

Background

Variations in track geometry generate vibrations when a train passes. This is discussed in the part on theory (see Theory).Within the IBS programme, there was therefore a need for a clear and practical indicator to quantify track geometry in terms of its 'vibration quality'. Level Acoustics & Vibration developed this indicator (Koopman, 2022), which was named Spoorligger.

Hypothesis

In developing Spoorligger, the premise was that track geometry quality in relation to vibrations should be measurable using a few unambiguous parameters. The development took into account which vibration frequencies arise from different track irregularities, as well as their dependence on train speed. The search for a suitable quality indicator drew on available data from routine Dutch track geometry monitoring (BBMS data, see Railway Vibrations). Irregularities in track geometry – such as weld seams, insulated rail joints, switches and crossings and variations in stiffness in transition zones near bridges or culverts – produce dynamic forces at the wheel–rail interface. Over time, these forces cause unevenness in track geometry, potentially creating longitudinal waves along the track that lead to vibration generation.

Method

Level Acoustics & Vibration sought characteristics related to the 'vibration quality' of the track within a database containing track geometry measurements (BBMS data) and system descriptions. These characteristics were translated into a set of parameters describing the track geometry quality. Taken together, these parameters provide an indication of track geometry quality and constitute the Spoorligger quality indicator. Spoorligger can be used to map 'hotspots' for vibration nuisance (Koopman, 2023).

Figure 13 Photo of track geometry

Results

To break down the track elevation along a section as a function of track length into its wavelength content, a Power Spectral Density (PSD) plot can be generated (Brandt, 2010), using a Fast Fourier Transform (FFT). A PSD provides insight into whether certain wavelengths are strongly present in vertical alignment deviations and which wavelengths these are.

Figure 14 illustrates an example of track deviations over a 200 m section. Spoorligger calculates the wavelength content of track geometry between 2 m and 12.5 m using the PSD derived from the measured data of that section.

Figure 14 Representation of geometric track deviation over a 200 m track segment

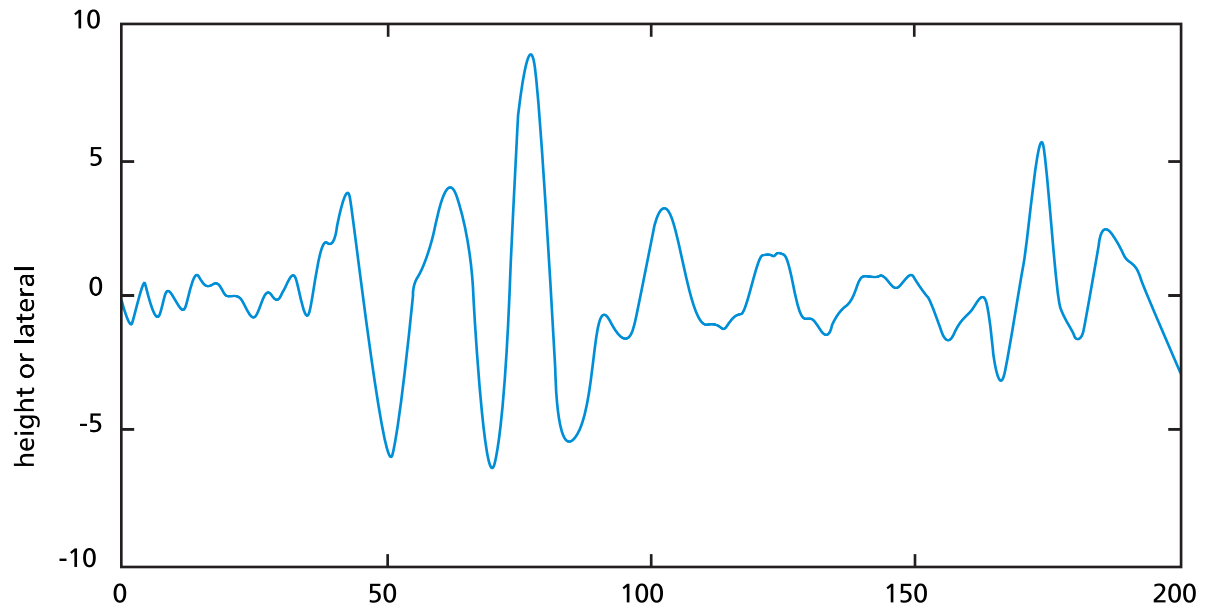


Figure 15 shows the result of a PSD diagram from Figure 14. The figure presents the energy content as a function of wavelength. The x-axis shows the inverse wavelength (1/λ), that is, the wavenumber. The figure schematically depicts the narrowband content of the FFT (blue line) and the content of the third-octave bands (red dotted line) and octave bands (red lines).

Ultimately, Spoorligger divides the wavelength spectrum into nine third-octave bands and the energy content is normalised. For shorter wavelengths (2 to 5 m), the data is differentiated twice. The results are then expressed in decibels. The outcome is a limited set of numbers that provide, per third-octave band, an indication of the quality of the track geometry.

For each third-octave band over a 200 m track segment, a root-mean-square value and a maximum value are determined, called H_{RMS} and H_{max}. The maximum value H_{max} is used to assess point sources such as IRJs, bridges or level crossings. The RMS value describes the average quality of the 200 m track segment. In total, Spoorligger consists of twenty parameters for vertical alignment and twenty for lateral alignment. For both height and lateral alignment there are twice nine third-octave bands plus the combined value for all wavelengths.

Using the developed Spoorligger, Level Acoustics & Vibration performed various analyses on geometry data for the entire rail network, including IRJs, level crossings and bridges (Koopman, 2022). The analyses show that the parameter H_{max} resulting from Spoorligger is log-normally distributed (see Figures 16 and 17). For IRJs, the data did not show a clear difference in quality level between design types, but for level crossings it did. Figures 16 and 17 reveal a clear difference in the distribution of geometry quality between crossings with rubber surfacing and those with concrete slabs. The median (P50) for crossings with concrete slabs is roughly twice as large as that for rubber-surfaced crossings.

The geometry quality for concrete slabs also shows larger outliers. A field trial with a concrete slab confirmed that relatively high vibration levels were measured (see Concrete slab).

Long-term trends in track geometry have also been studied by Level Acoustics & Vibration (Koopman, 2025). Figure 18 shows a histogram of the H_{RMS} values of 200 m track segments for the 7 m wavelength. The dataset combines fifteen measurement campaigns across the Netherlands from 2013 to 2020. The figure shows that the number of segments with an H_{RMS} value around 0.25 decreases over time, while the number of segments with values around 0.5 and 0.75 increases. Thus, the H_{RMS} value of geometric deviations in the 7 m wavelength for all track segments shows a rising trend. It can also be seen that the cumulative data from the measurement train varies between campaigns. The conclusion drawn is that deviations in track geometry have increased as a long-term trend, although differences between measurement campaigns distort the overall picture.

Figure 15 Example of a PSD of vertical alignment: blue line = narrowband (FFT), red dotted line = third-octave band, thick red line = octave band

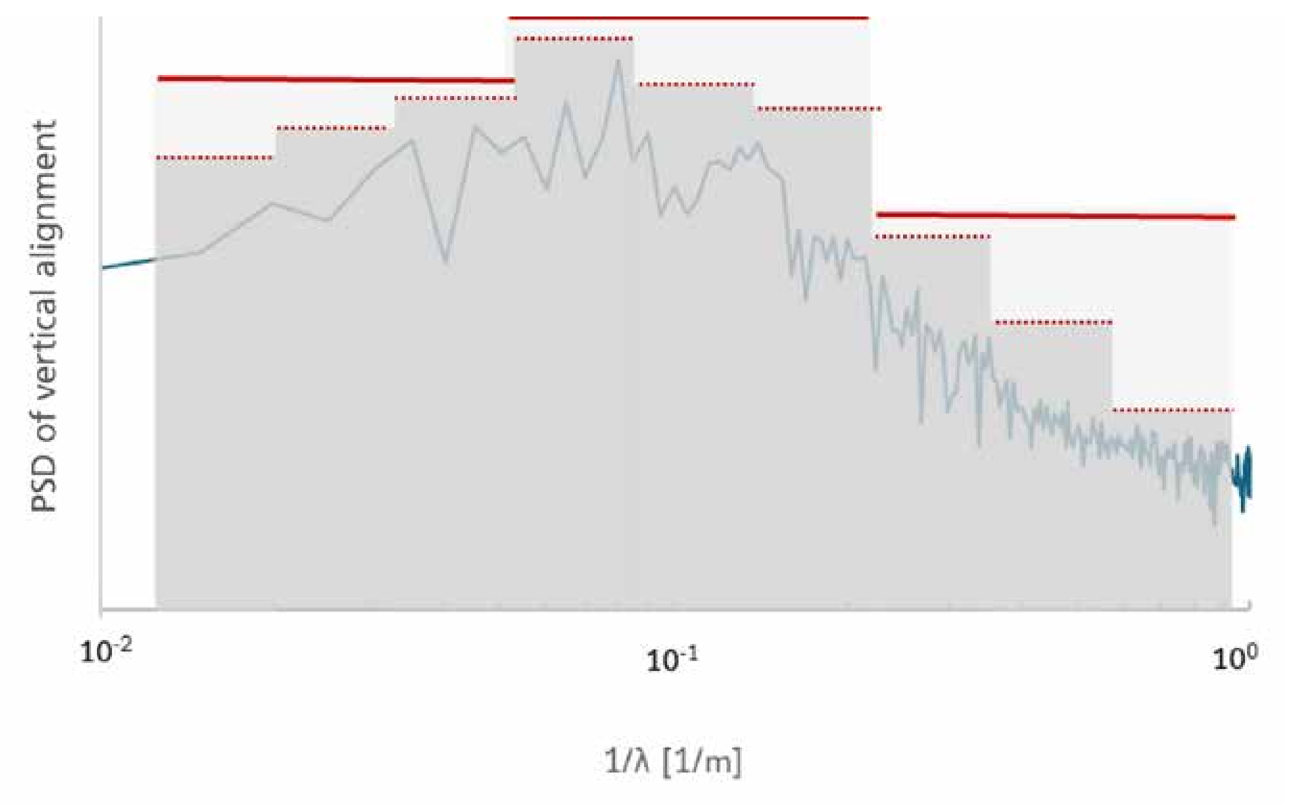


Figure 16 Distribution of H_{max} value at 4.5 m wavelength for conventional level crossings in the Netherlands (concrete slabs)

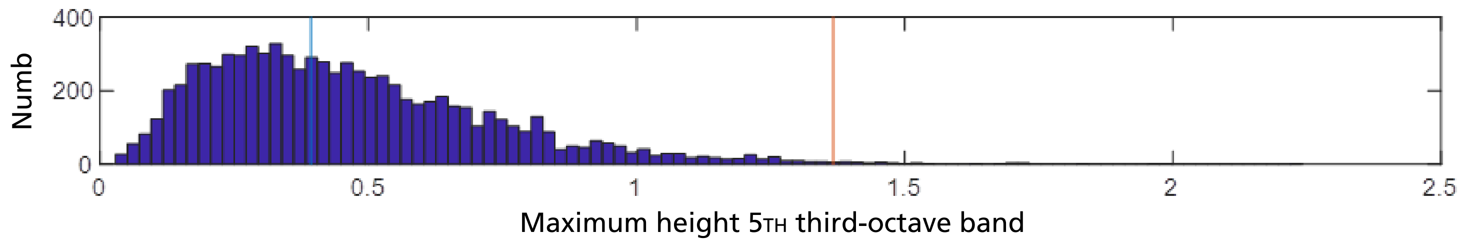


Figure 17 Distribution of H_{max} value at 4.5 m wavelength for level crossings with rubber surfacing in the Netherlands

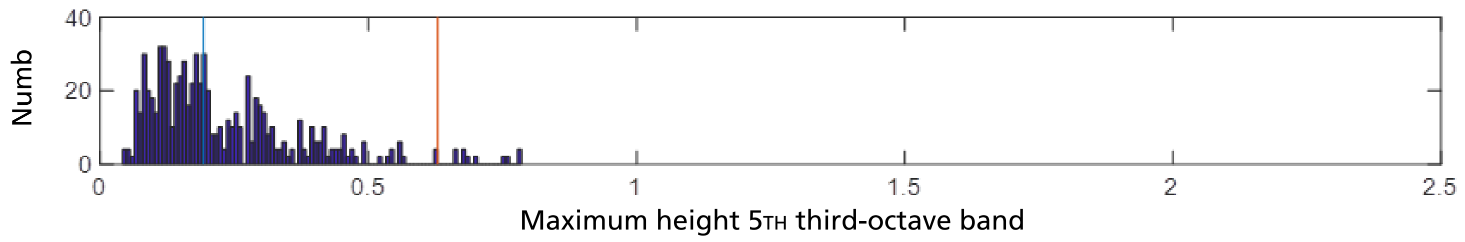
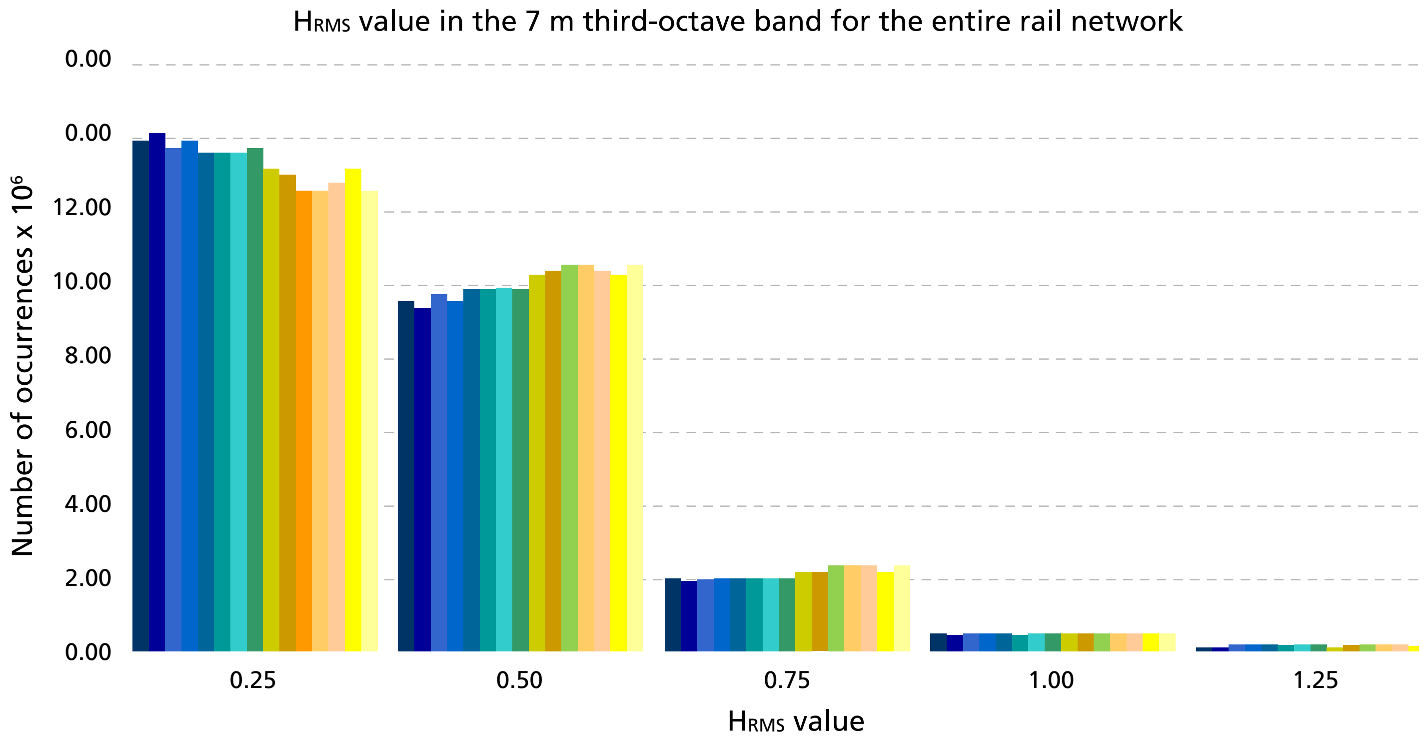


Figure 18 Histogram of H_{RMS} values of 200 m track segments in the 7 m third-octave band from 2013 (blue) to 2020 (yellow)



Summary of the quality indicator

By analysing track geometry in the wavelength domain and applying weighting across the different wavelengths, a new interpretation of track geometry data has been introduced. With the newly developed Spoorligger, it is possible to summarise track geometry in a limited set of parameters. This makes it possible to perform large-scale data analyses on historical ProRail track geometry data in combination with metadata on track components or segments. Long-term trends in track geometry development, long-term behaviour of components or differences in deterioration between construction types can thus be assessed more easily in terms of their effect on vibrations. Spoorligger also makes it possible to assess track geometry when residents report vibration nuisance.

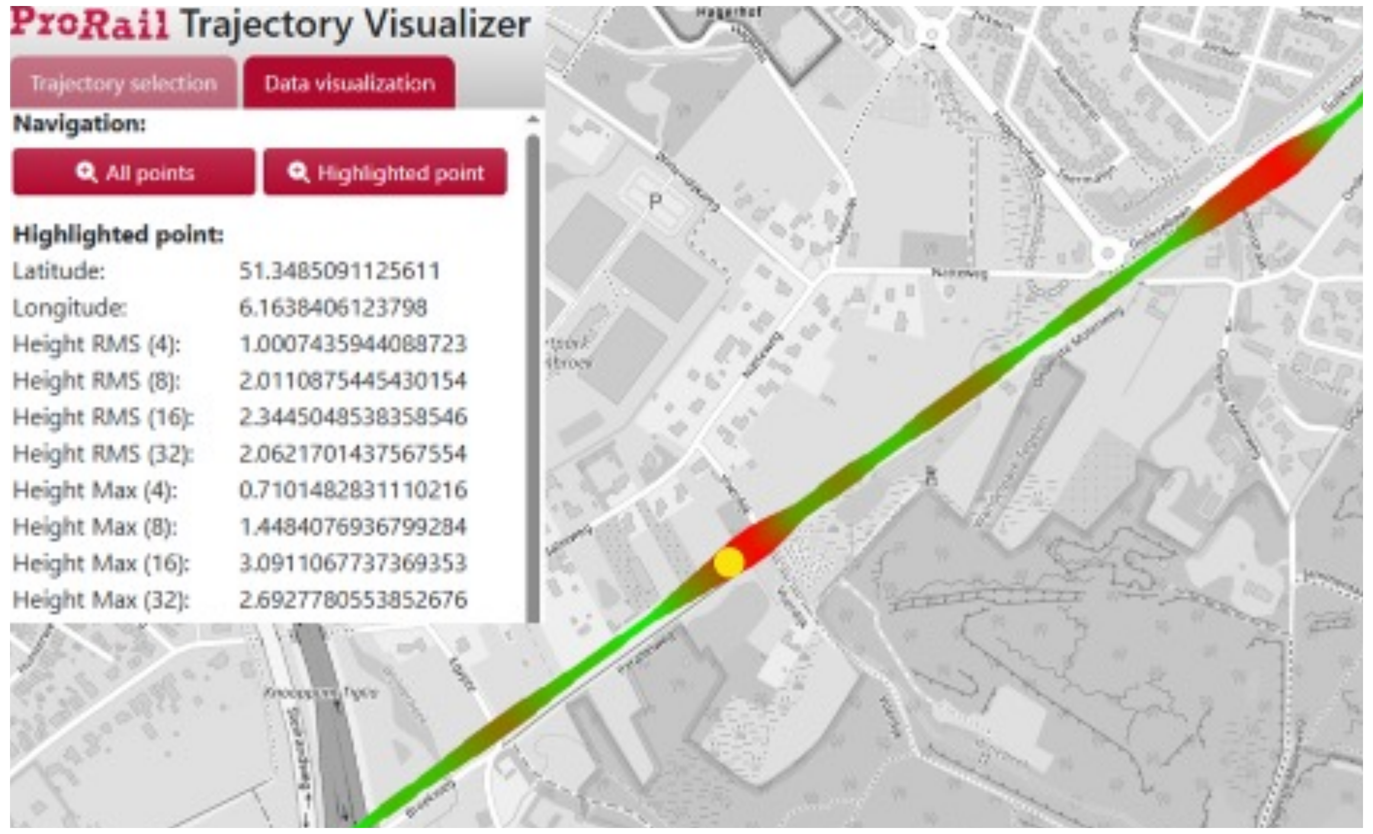
Spoorligger visualisation tool

To present the results of Spoorligger, a visualisation tool was developed. In this tool, the calculated parameters (H_{RMS} and H_{max}) are linked to geographic data in ProRail's track section model[24]. This allows the track geometry quality to be displayed visually per location. With the Spoorligger visualisation tool, track sections are selected and the tool then uses colour indicators to show deviation from the national average. The user can export the numerical values for each 200 m track segment for further analysis. An example is shown in Figure 19. Potential hotspots in the track geometry where higher vibrations are expected can easily be identified using the developed visualisation tool. The results are summarised in Box 5.

Box 5 Results of Spoorligger and the visualisation tool

- The vibration-related track geometry quality indicator Spoorligger considers vertical and lateral alignment over 200 m track segments.
- For each third-octave band and for the total of all bands, both an RMS value and a maximum value (H_{RMS} and H_{max}) are calculated.
- The visualisation tool enables simple and clear assessment of specific track sections.

Figure 19 Spoorligger visualisation tool showing H_{RMS} and H_{max} values relative to the Dutch average



Navigation:

Highlighted point:

Latitude:	51.3485091125611
Longitude:	6.1638406123798
Height RMS (4):	1.0007435944088723
Height RMS (8):	2.0110875445430154
Height RMS (16):	2.3445048538358546
Height RMS (32):	2.0621701437567554
Height Max (4):	0.7101482831110216
Height Max (8):	1.4484076936799284
Height Max (16):	3.0911067737369353
Height Max (32):	2.6927780553852676

Modelling of trackbed settlement

Background

Results from the Spoorligger study indicate that low track geometry quality is typically found around track objects such as transition structures, level crossings and IRJs. The deformation behaviour of transition structures differs according to their design and/or maintenance interventions. A train–track interaction model was used to determine whether the developed quality indicators for track geometry accurately represent deformation behaviour.

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[24] The track section model is a topological model of the Dutch railway network.

Hypothesis

Spoorligger quantifies track geometry differently from the regular maintenance parameters. The indicator may also provide a good representation of geometry degradation when settlements occur over time. This can be studied by calculating settlements for different maintenance scenarios and comparing the results after converting the outputs into the parameters H_{max} and H_{RMS}.

Method

To examine the influence of alignment maintenance on Spoorligger outcomes, Deltares performed simulations using the dynamic train–track interaction model ROSE (Zuada Coelho, 2023). The cumulative deformation of the superstructure and subgrade was calculated as a function of passing train traffic. Different configurations of track, rolling stock, subsoil and wheel/rail irregularities were studied.

Settlements calculated with the model were converted into the parameters H_{max} and H_{RMS} as defined by Spoorligger. Ultimately, three scenarios for track geometry were simulated: a perfect track with no stiffness variations or geometric irregularities, a track with geometric irregularities and a track with random stiffness variations in the subsoil. All scenarios included a transition zone from stiff to soft subsoil.

Results

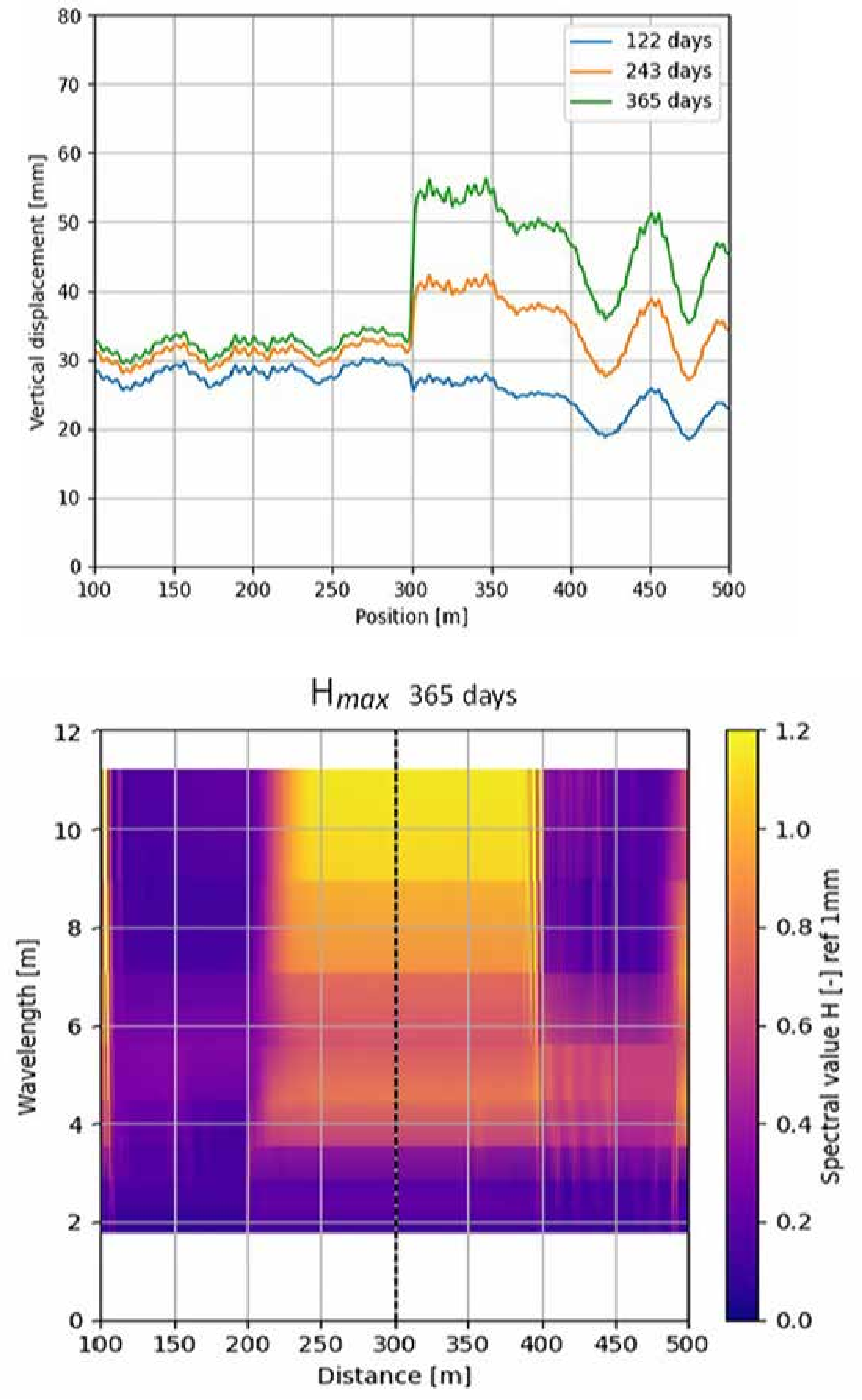
Figure 20 shows the results for degradation of track geometry at a transition from soft to stiff subsoil after 4, 8 and 12 months. The upper graph presents the degradation of settlement in millimetres. A noticeable feature is the growth of geometric irregularities over time on soft subsoil. The lower graph presents the results after twelve months expressed as H_{max} per wavelength for a 200 m track segment as defined in Spoorligger.

The Deltares report concludes that Spoorligger describes and reflects the simulated degradation of track geometry over time well (Zuada Coelho, 2023). The quality indicator can therefore also be effectively used as an additional indicator to determine when track maintenance is needed. The results are briefly summarised in Box 6.

Box 6 Results of trackbed settlement modelling

- Spoorligger accurately represents the degradation of track geometry over time.

Figure 20 Results of simulated track geometry degradation after 4, 8 and 12 months



Spoorligger assessment

Background

To further validate Spoorligger, Arcadis conducted a study comparing results obtained with Spoorligger to vibration measurements (Hosseinzadeh & Özdemir, 2024).

Hypothesis

Based on the results of the Spoorligger study, it is expected that Spoorligger provides a reliable prediction of track geometry quality in relation to railway vibrations.

Method

For this assessment, Arcadis used data from previously conducted vibration measurements in Dorst. These measurements were carried out in June 2021 at an existing level crossing with concrete slabs and embedded rails, which was replaced with a crossing featuring rubber surfacing (see Rubber level crossing surfacing). The renewal of this crossing was one of the activities within the IBS programme during which extensive vibration measurements were performed. The measurements followed the RIVAS protocol (WP2, 3, 4 and 5 Deliverable D1.2), which uses the same methodology later incorporated into the Uniform Measurement Protocol.

When the level crossing was renewed, the ballast bed was also replenished and reshaped by tamping. To assess the effect of the altered crossing on vibrations, measurements were taken before and after the works at ground level. These were performed at distances of 8, 16, 32 and 64 metres from the track (in accordance with the Uniform Measurement Protocol) and repeated after 6 and 12 months. The impact of the modified crossing on track geometry was determined from the biennial BBMS measurements. Arcadis correlated the measured geometry to vibration data by converting wavelengths to frequencies based on locally recorded train speeds.

Results

The study found a clear correspondence between the RMS values of historical track geometry data and vibration measurements at various distances from the track. Arcadis[25] also reported that the change in track geometry due to maintenance activities was reflected in the Spoorligger parameters (H_{RMS} and H_{max}).

The Arcadis report concludes that validation of Spoorligger through field vibration measurements shows a clear correlation between the difference in measured vibration levels and the difference in track geometry as represented by the quality indicator parameters. A particularly significant correlation was found between RMS values in the 32 Hz octave band, and to a lesser extent in the 16 Hz octave band.

A limitation of this validation is that it is based on measurement data from works where, besides geometry, part of the track structure itself was also modified.

The results are briefly summarised in Box 7.

Box 7 Results of the Spoorligger assessment

- The vibration-related track geometry quality indicator is an effective indicator showing correlation with vibration measurements.

Static deformation field

Background

In most measurements taken on the track and in the ground beside it, passing trains are used as the vibration source – a highly variable source. As described in the theory chapter, the quasi-static deformation field also contributes to ground vibration near the track (see Theory). To better understand this contribution, Swietelsky Rail Benelux conducted deformation measurements on the track and subsoil under load from a locomotive with a maximum axle load of 22.5 tonnes (Gilian, 2024).

Hypothesis

Static deformation due to the axle load of a train creates a deformation field. This field contributes to vibrations near the track as it passes. The extent of this contribution to overall vibration can be determined by measuring the deformation field.

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[25] In different reports the tool Spoorligger appears under various names, but all identify it as a quality indicator.

Method

Swietelsky Rail Benelux performed measurements for alternating unloaded and loaded conditions. A stationary locomotive was placed at the test site in Tegelen and measurements were repeated three times. The measurement setup consisted of a grid of monitoring points (deformation sensors with a tachymeter) extending from the track out to 14 metres beyond it.

Results

The measurements show that deformation occurred at the rail up to a maximum of 5 mm (Gilian, 2024). The greatest (vertical) deformation occurred directly beneath the loaded axle of the locomotive (axle load 22.5 tonnes). Deformation at points outside the rail (2.5 metres from track centreline and beyond) was minimal and did not exceed 1 mm. Taking measurement accuracy into account, no measurable deformation was observed beyond the track. Therefore, the contribution of the quasi-static component of the locomotive's load to environmental vibration is expected to be small.

The test site consisted primarily of stiff sandy soil, which explains the limited deformation observed. In such soil types, the static deformation field is small. This is not the case for soft soils, where greater settlement occurs and the contribution of the quasi-static deformation field to vibrations near the track can be significant. The results are briefly summarised in Box 8.

Box 8 Results of the static deformation field

- On stiff sandy soils, the quasi-static deformation field with a maximum axle load of 22.5 tonnes results in a maximum deformation of less than 1 mm outside the track (2.5 m from the track centre).
- The contribution of the quasi-static deformation field to environmental vibration is limited on stiff sandy soils, but not on soft soils.

Artificial vibration source

Background

To determine the effect of a vibration mitigation measure, sometimes an artificial vibration source is used instead of measuring train passages (see also Uniform Measurement Protocol). This approach has the advantage that the source can be well controlled, ensuring minimal variation between pre- and post-measurement conditions. In contrast, measurements from train passages require statistical processing due to variability in the source.

Hypothesis

Measurements using an artificial vibration source require specific conditions. To ensure uniformity of such measurements, it was expected that additional requirements or points of attention would be needed for evaluating the effect of mitigation measures.

Method

DEKRA Rail conducted a desk study and market study (Hiensch & Vermeulen, 2024). The study had two objectives:

- to define a standardised approach and minimum requirements for preparing, executing, analysing and reporting vibration measurements using an artificial vibration source to assess the effect of mitigation measures;
- to specify the artificial vibration source itself so that a uniform description is available for parties required to demonstrate the effectiveness of their measures.

Results

The study found that a DIN standard already exists for artificial vibration sources – DIN 45673-3 (2014). Where necessary, modifications and additions were made specifically for Dutch conditions. The DEKRA Rail report states that DIN 45673-3 (2014) must be applied when determining the insertion loss of a vibration-reducing measure in the track using an artificial vibration source. The DIN standard describes both measurement and evaluation methods for using such a source and provides examples of different types of artificial vibration sources. A key addition for the Dutch context concerns sites with relatively soft track or subsoil. In such conditions, dynamic loading from trains on the track often contains substantial low-frequency content. The frequency range of the artificial vibration source must therefore be adapted accordingly. Where the DIN specification sets a lower limit of 5 Hz for harmonic excitation, a lower limit of 2 Hz is preferred for the Dutch situation.

The Uniform Measurement Protocol applies to the procedure for conducting vibration measurements using an artificial vibration source.

According to the DIN standard, an artificial source is primarily suitable for relative comparison – comparing conditions with and without a mitigation measure. It is not, or only partly, suitable when quasi-static loading from passing trains is a dominant factor in vibrations. In cases where quasi-static loading governs environmental vibrations, the use of an artificial vibration source must therefore be considered critically – particularly for soft soils and flexible track structures.

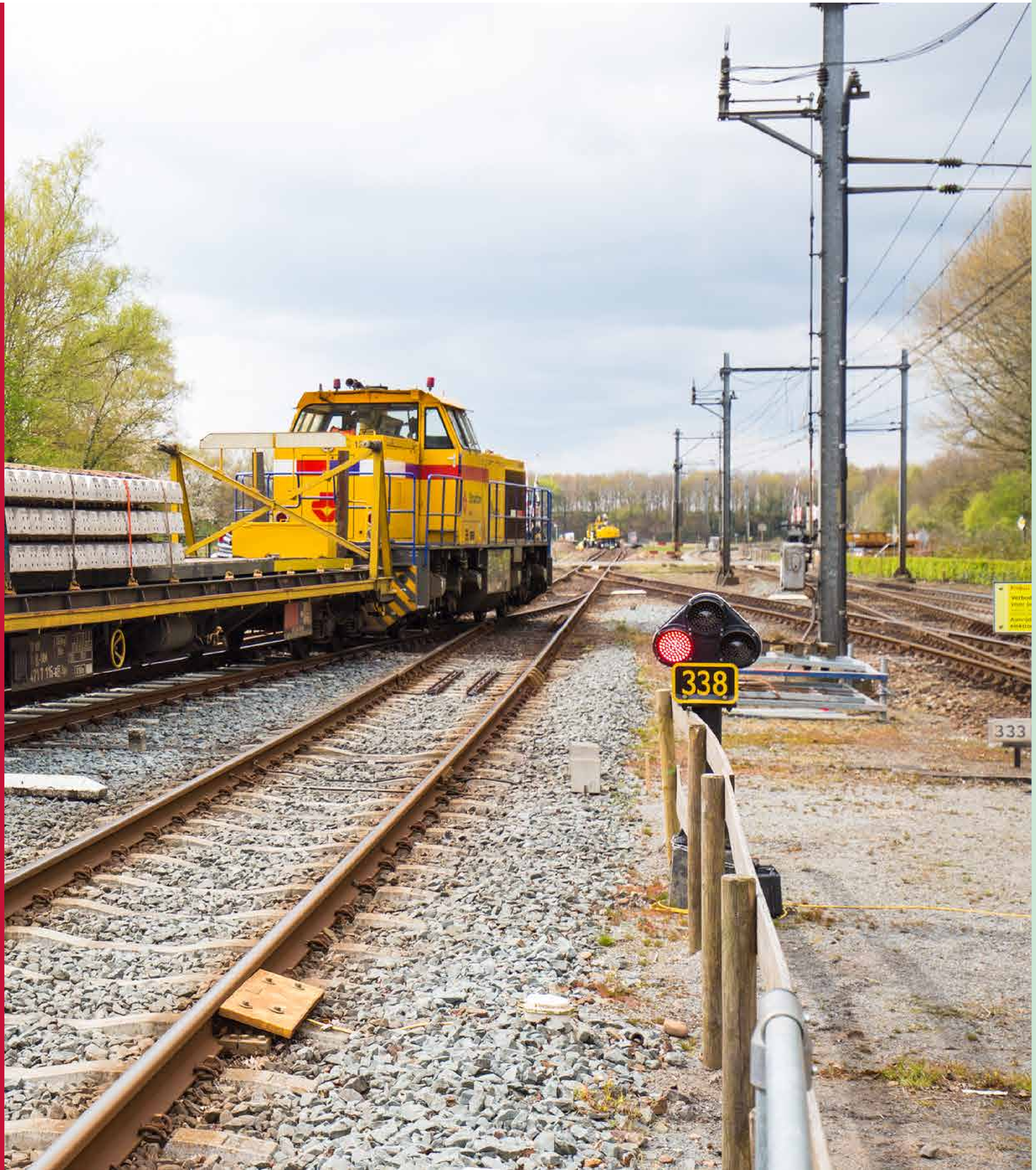
The results are briefly summarised in Box 9.

Box 9 Results of artificial vibration source

- The DIN 45673-3 standard must be applied when using an artificial vibration source.
- Several additions for Dutch conditions have been included in the Uniform Measurement Protocol.
- Special attention is required when quasi-static loading is the dominant factor.

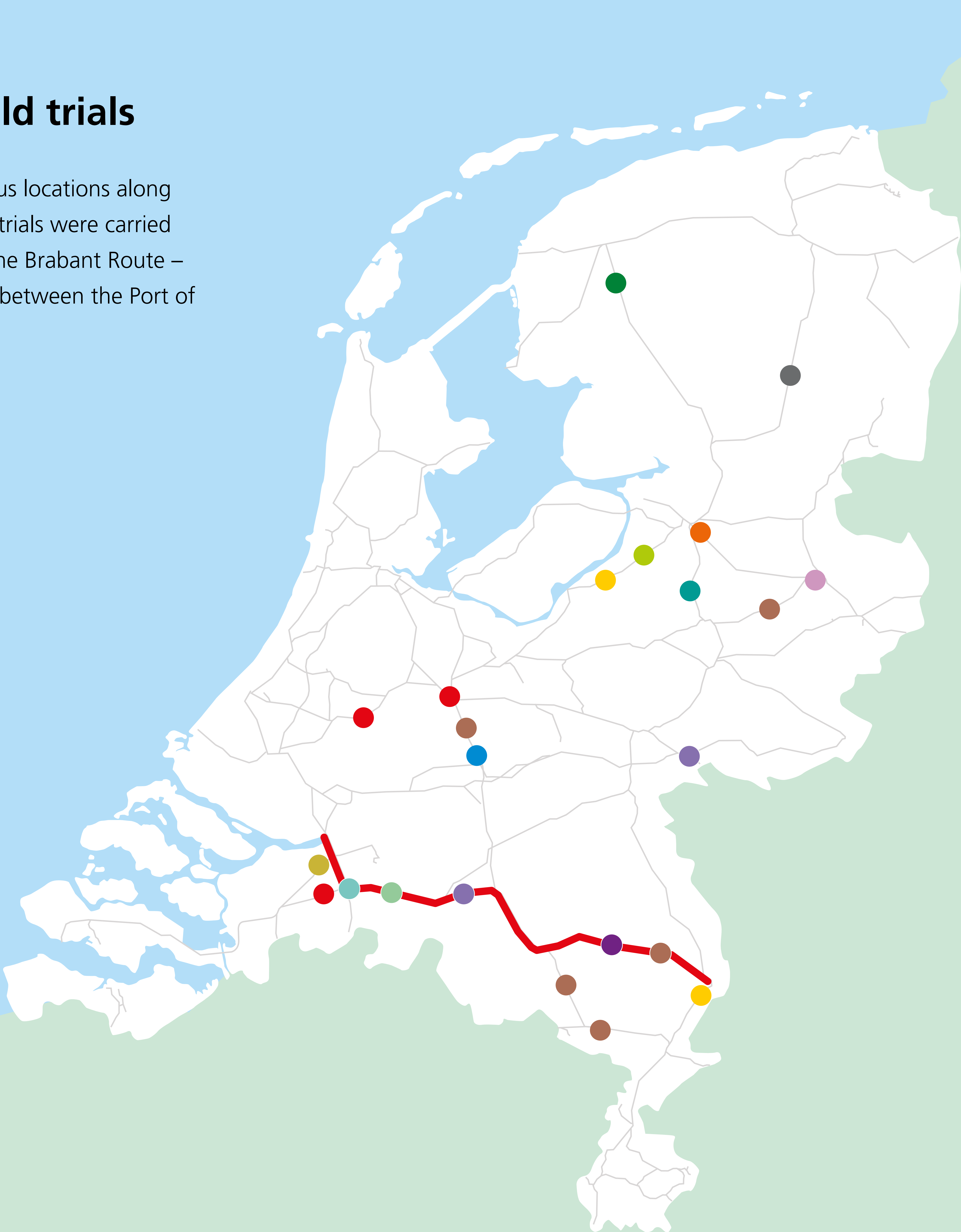
Part 2

Field trials



Overview of IBS field trials

This overview map shows the various locations along the Dutch rail network where field trials were carried out. The red line indicates part of the Brabant Route – a heavily trafficked freight corridor between the Port of Rotterdam and Venlo.



Grou

Date: 2023-2024
Geogrid: fabric under the ballast

Westerbork

Date: 2024-2025
Railtube: tubes installed in the ground

Wierden

Date: 2024-2025
Ballast mats: rubber mats under the ballast

Dorst

Date: 2021-2022
Rubber level crossing surfacing

Nunspeet and Tegelen

Date: 2022-2024
Wooden versus concrete sleepers

Wezep

Date: 2024-2025
Low-vibration sleeper (TAL)

Diepenveen

Date: 2024-2025
Bio Inspired Soil Improvement

Holten, Schalkwijk, Heeze, Weert, America

Date: 2023-2024
Measuring the effect of wheel out-of-roundness

Culemborg

Date: 2022
PSS: stiff layer under the ballast

Breda-Prinsenbeek

Date: 2024-2025
Adjustable IRJ and MetaBarrier

Zevenbergen

Date: 2023-2024
Switch removal

Oisterwijk and Zevenaar

Date: 2021-2022
Under sleeper pads: rubber cushions under sleepers

Zwolle

Date: 2022
Sleeper

Brabantroute, Gouda, Utrecht, Etten-Leur

Date: 2023-2025
Environment-oriented management and maintenance

Deurne

Date: 2022-2023
Adjustable-height fastening (ShimLifts)
Date: 2024
Concrete slab in the track

2A. Infrastructure maintenance

Field trials of track maintenance (OBO1)

Background

Within the IBS programme, numerous field trials were carried out on maintenance measures. The aim was to better understand their effect on railway vibrations. This insight allows planning and execution of maintenance work to be optimised to reduce vibrations. The various field trials fall under the overarching research project titled Environment-Oriented Management and Maintenance (abbreviated as OBO). The research is divided into two parts: OBO1 and OBO2, with OBO2 being a continuation of OBO1. The OBO1 study was conducted by We-Boost (Boon et al., 2024).

Hypothesis

The OBO1 study sought to find a correlation between changes observed in measured vibrations and the maintenance carried out. The hypothesis was that such a correlation exists. OBO1's main research question was: What is the effect of track maintenance on vibrations in the surrounding environment? In addition to this main question, the study also examined the duration of the effect, differences between maintenance types and whether train type or speed also influence the effect of maintenance.

Method

To answer the main research question, investigations were carried out on various components of the rail system at ten locations in total. Measurements were taken at IRJs, switches, level crossings, engineering structures and on plain lines. The procedure at each location was identical and followed the Uniform Measurement Protocol.

At each site, measurements were taken before maintenance, recording vibrations caused by passing trains at various distances from the track. A continuous measurement was also carried out, registering vibrations at a fixed point from several weeks before until several weeks or months after maintenance. Additionally, a measurement was taken after the maintenance. All measurements were performed at the exact same positions as the pre-measurements.

The maintenance work carried out was documented through inspections and maintenance logs. Using data analysis with a random forest algorithm, it was investigated whether (1) maintenance affects railway vibrations, and (2) which parameters influence this maintenance effect.

The study distinguished between two maintenance types: light manual maintenance at IRJs and switch points, and more extensive routine maintenance in the form of mechanical tamping.

Results

In the We-Boost report, conclusions were drawn about light and heavy maintenance activities (Boon et al., 2024):

1. The effect of light manual maintenance on railway vibrations is negligible. Sometimes a slight effect is observed for a few days, but in most cases there is no effect. After a few days, no effect remains visible.
2. The effect of mechanical tamping is variable:

    - at level crossings, no effect was found, because the last metres before and after the crossing are not tamped;
    - on plain lines, a noticeable positive effect was found, particularly for low-frequency vibrations and horizontal vibrations. This effect can persist for an extended period: especially for low frequencies (below 8 Hz), a clear effect is still visible after one month. At high frequencies (above 40 Hz), tamping can increase vibrations. A possible explanation given is the changed ballast contact pressure caused by tamping.
    - At IRJs and switch points, no conclusions could be drawn within OBO1 because insufficient data was available.

The study found that maintenance is often not performed optimally. We-Boost observed in various cases that this may affect vibrations. For example, at IRJs, the waiting time for head filling is often too short, ballast is not replenished and the proper tamping equipment is not used to reduce voided sleepers – especially at double sleepers. The report notes that vibrations may increase unless special attention is paid to the final sleepers near the level crossing.

In the We-Boost report, a number of additional observations are made that are evident from the results:

- the effect of tamping at locations with voided sleepers is greater for trains with higher unsprung mass, such as the TRAXX locomotive;
- tamping can increase the influence of train speed on railway vibrations;
- maintenance at IRJs and switch points appears (based on limited data) to have more effect for trains passing at low speed;
- train speed has a much greater influence on vibrations near hard points than on plain lines (especially at level crossings and transitions between structures and earthworks, and to a lesser extent at IRJs);
- periods of heavy rainfall can result in lower vibrations, especially at high frequencies (relevant for houses near the track);
- periods of high temperature can lead to higher vibrations, particularly at frequencies above 10 Hz;
- replacing defective rail components (in this case an IRJ) can lead to a substantial reduction in vibrations;
- at low vibration frequencies, variation in lateral track alignment plays a role in generating railway vibrations.

The study also provides recommendations for performing maintenance to minimise railway vibrations as much as possible, including points of attention for tamping procedures, the use of suitable equipment and specific aspects to focus on during tamping.

Table 2 Light manual maintenance

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
None	Variable, but mainly 2: Adjustment of the track to reduce dynamic wheel–rail forces.	Low – effects were studied through extensive measurement campaigns.	Results appear consistent with the hypothesis.	No, no substantial improvement seems possible.

Table 3 Effect of mechanical tamping

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
Variable 0-4 dB	4. Stiffening or improving the track to reduce settlement.	Moderate – effects examined through extensive measurement campaigns but varied in outcome.	Further study required to better understand in which situations a positive effect can be expected.	Yes, – additional insight needed to identify where improvement is possible.

Field trials of track maintenance – follow-up (OBO2)

Background

The OBO1 study showed that standard minor maintenance, such as grinding switch points and applying head filling, has minimal effect on reducing railway vibrations. Manual tamping was found to have a short-lived effect of only a few days. Tamping with a tamping train showed variable results: at some locations a reduction in vibrations was observed, while at others there was little or no effect. Within the OBO2 study, the focus was on the influence of mechanical maintenance on railway vibrations to gain insight into (1) ways of improving the effect of alignment maintenance on railway vibrations (both in magnitude and duration), and (2) the relationship between track geometry parameters and vibrations. The OBO2 study was also carried out by We-Boost (Boon, 2025).

Hypothesis / main research question

The ultimate goal of the OBO2 field trial was to define maintenance standards that keep railway vibrations within established limits.
The central research question of OBO2 was: How can ProRail reduce railway vibrations based on maintenance standards? These standards can then be incorporated into the maintenance specifications.

Approach

To answer the research question, the study examined:

1. how the effect of maintenance on railway vibrations can be increased and prolonged;
2. which track geometry parameters are most strongly correlated with railway vibrations.

The OBO2 study was conducted at 14 locations, supplemented by data from the earlier OBO1 study. The measurement strategy followed the Uniform Measurement Protocol and was nearly identical to that of OBO1.

The measurements were linked to data on track geometry, train types, weather conditions and groundwater levels. For the analysis, a random forest model was again used to isolate the effect of maintenance from other influences. The locations studied ranged from plain line to structures, level crossings and IRJs. Maintenance activities included standard tamping and additional measures such as:

- double squeezing;
- stabilisation;
- topping up ballast;
- rail replacement.

Locations were selected based on suitability for measurements, absence of disruptive sources and variation in soil type. Relationships were sought between measured vibrations and track geometry parameters from the BBMS such as lateral and vertical alignment, including height D1, height over 10 m and short-wave D0.
The parameters H_{max} and H_{RMS} from the Spoorligger tool were also examined (see Spoorligger).

Results

In the final OBO2 report by We-Boost (Boon, 2025), the following results are described:

1. Alignment maintenance mainly affects vibrations below 10 Hz, with an average reduction of 3 to 5 dB (30 to 50% reduction in vibrations). Above 10 Hz there is no significant effect and vibrations may either increase or decrease after alignment maintenance. Vibrations below 10 Hz occur mainly on softer soils (peat and clay) and with trains of higher axle load (freight trains).
2. Compared to OBO1, the OBO2 study found a stronger effect of alignment maintenance on measured vibrations, more variation in that effect, no significant negative effects at higher frequencies and that maintenance is effective at lower frequencies.
3. The effect of alignment maintenance decreases over time; after about two months it has diminished by roughly 1 dB on average.
4. The effect of alignment maintenance does not differ significantly between soil types (sand, peat, clay, etc.).
5. The effect is greater for train types with high unsprung mass (TRAXX + ICR), but for those trains the effect also fades more quickly over time.
6. The effect is greater at locations where the track geometry is poorer.
7. Additional maintenance actions such as double squeezing, stabilising and profiling have limited effect on measured vibrations (maximum of 1 dB improvement at frequencies below 8 Hz). However, stabilising and profiling in particular help slow down the rate at which the maintenance effect diminishes.

A point of attention with double squeezing and stabilising is that ballast depletion occurs more quickly, which may have a negative effect at frequencies between 10 and 30 Hz.

8. Removing the level crossing surface before tamping has a significant effect: about 3 to 5 dB lower vibrations at frequencies below 8 Hz compared to when the crossing surface is not removed.

Regarding track geometry standards, the final We-Boost report concludes:

1. The track geometry standards in EN 13231, ISV 00001 and EN 13848 show only limited correlation with measured vibrations up to 40 Hz and low correlation above 40 Hz.
2. Up to 10 Hz, the height D1 and height 10 m parameters are the best predictors of vibrations; between 10 and 50 Hz, the short-wave D0 parameter is the best predictor. The track geometry parameters height D1, short-wave D0, lateral alignment D1 and twist 3 m together predict about 80 to 90% of the measured variation in vibration levels. The remaining 10 to 20% can be attributed to differences in ballast quality and subgrade composition.
3. The correlation found between the wavelength parameters H_{max} and H_{RMS} (as defined by Spoorligger) and measured vibrations varies and is weaker overall. At certain wavelengths, however, the parameters H_{max} and H_{RMS} correlate more strongly with measured vibrations.

The conclusion that the wavelength parameters H_{max} and H_{RMS} correlate better at specific wavelengths than at others indicates that the Spoorligger tool may also have limitations. These findings complement the Arcadis study, which concluded that there is a significant correspondence in changes to H_{RMS} and H_{max} at various distances, particularly for the 31.5 Hz octave band[26] (see Spoorligger assessment).

The study did not establish clear threshold values of track geometry beyond which vibrations suddenly increase. However, it produced a general indication that when track geometry improves by 50%, vibrations decrease by about 25% – a ratio of roughly two to one. Tightening the maintenance thresholds for height, lateral alignment, twist and settlement therefore results in reduced vibrations. Which track geometry parameter has the greatest influence, and which standard should be adjusted, depends on vibration frequency:

a. Below 6 Hz: the height D1 parameter has the strongest relation with vertical vibrations. If height D1 is halved, vibrations decrease by 15 to 25%. These low-frequency vibrations are especially relevant for soft soils (peat, clay), heavy trains (freight) and greater distances from the track.
b. Between 6 and 50 Hz: the short-wave D0 parameter has the strongest relation with vibrations; for horizontal vibrations, lateral alignment D1 (up to 20 Hz) and twist 3 m (between 4 and 8 Hz) also show a fairly strong relation. When short-wave D0 is halved, vibration levels decrease by 15 to 30%. These mid-frequency vibrations are most relevant on stiffer soils (sand), at point sources (level crossings, IRJs, switches) and at shorter distances from the track.
c. Above 50 Hz: the picture is diffuse for horizontal vibrations; for vertical vibrations, height D1 and height 10 m remain the most important parameters, but their influence is relatively small.

Summary of results

The OBO2 study concludes that introducing a standard for height D1 and locally tightening the standard for short-wave D0 are the most effective means of reducing railway vibrations. Height D1 mainly affects vibrations from freight trains on softer soils (peat, clay; frequencies below 6 Hz), whereas short-wave D0 mainly affects vibrations on sandy soils and around point sources (frequencies between 6 and 50 Hz).

Overall, the OBO2 study confirms that:

1. alignment maintenance influences vibrations and is frequency-dependent (mainly positive for low frequencies < 10 Hz);
2. the effect generally decreases with time after maintenance;
3. the effect depends on train type;
4. mechanical tamping shows considerable variation but in many cases has a favourable effect on vibrations, ranging between 0 and 8 dB;
5. for tamping, the effect depends on where it is carried out (plain line, near structures or transitions, or at IRJs – see Figure 21);
6. the track geometry parameters height D1, short-wave D0, lateral alignment D1 and twist 3 m together predict about 80–90% of measured vibration differences;

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[26] It is not yet clear why the correlation between H_{max}/H_{RMS} and measured vibrations is sometimes weaker. Further analysis of the relationship between the Spoorligger parameters and measured vibration levels is needed.

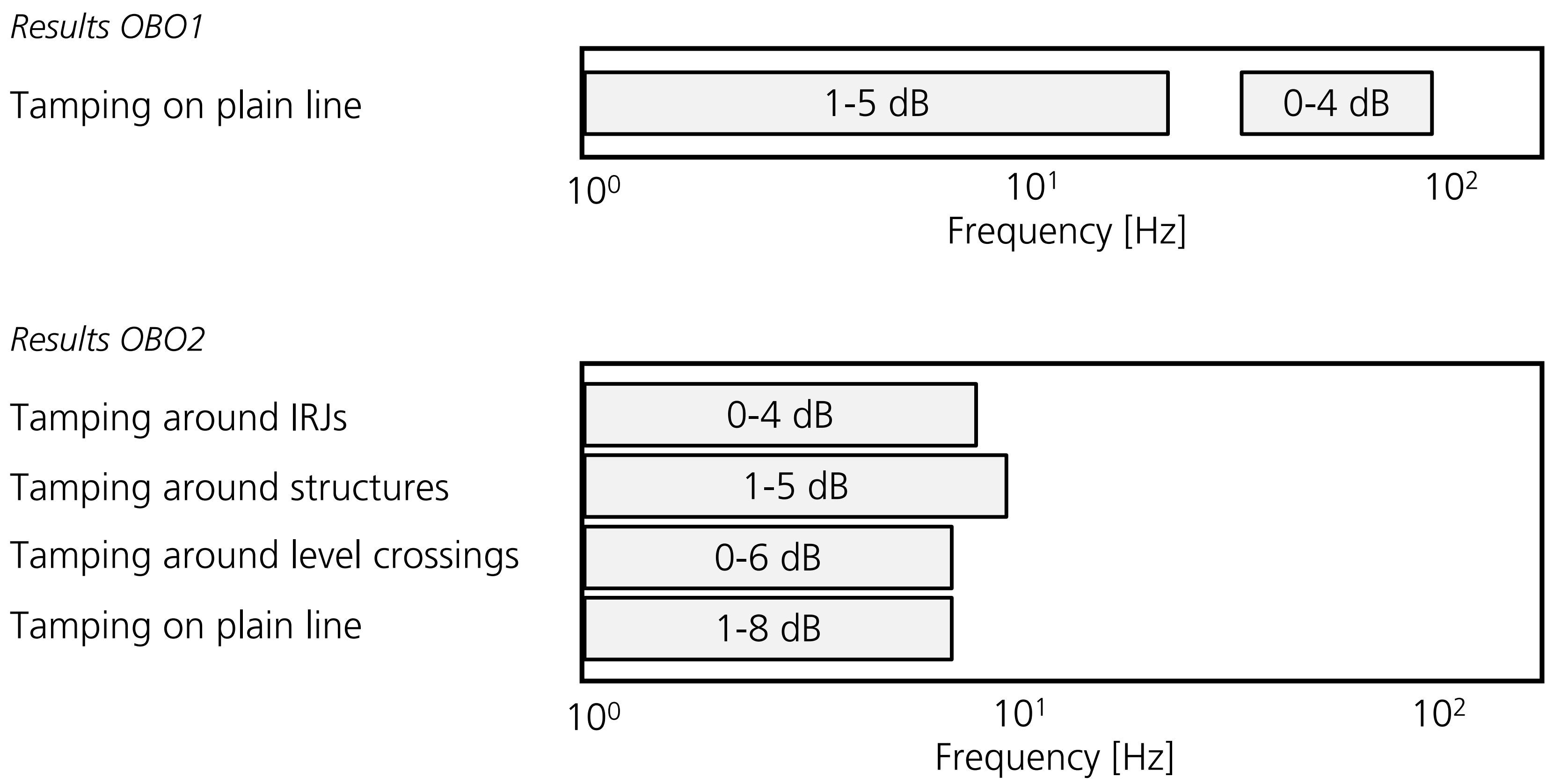
7. when track geometry improves by 50%, vibrations decrease by roughly 25%.

A number of recommendations on optimal track alignment maintenance follow from the OBO2 study. These recommendations are described in the We-Boost report (Boon et al., 2025).

Table 4 Effect of mechanical tamping (OBO2 study)

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
Variable: · Around IRJs: 0–4 dB · Around structures: 1–5 dB · Around level crossings 0–6 dB · On plain line: 1–8 dB	Stiffening or improving the track to reduce settlement (and thereby vibration amplitude).	Low – effects examined through extensive measurement campaigns but results varied.	Partial explanation available. Ballast properties under varying conditions remain under study.	Yes – better understanding needed of where a positive effect can be expected.

Figure 21 Effect of mechanical tamping according to OBO1 and OBO2



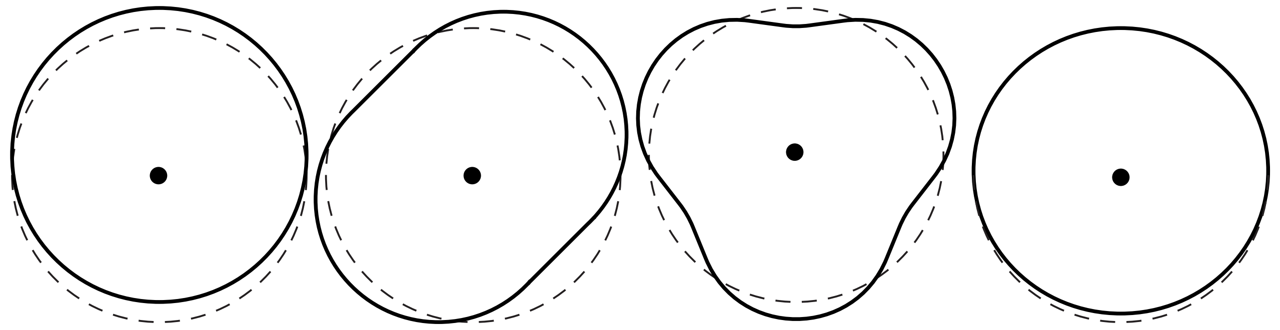
2B. Rolling stock maintenance

Wheel out-of-roundness

Background

Train wheels can become out-of-round through uneven wear or abrupt braking. This can take many different forms. Figure 22 schematically shows several types of wheel out-of-roundness. Wheel out-of-roundness results in a dynamic wheel–rail force that generates vibrations (see Railway Vibrations). For this reason, within the IBS programme a large-scale trial was conducted to map out the effect of wheel out-of-roundness. The study examined how much impact removing poor-quality wheels has on the resulting vibration load in the surrounding environment. The field trial was carried out under the technical supervision of Ricardo Rail.

Figure 22 Various forms of wheel out-of-roundness (shown enlarged)



Hypothesis

Based on preliminary studies, it was expected that in some situations, poor-quality wheels would lead to high vibration levels in the vicinity of the track (see Rolling stock study). For those cases, addressing poor-quality wheels was expected to be an effective measure to reduce vibrations.

The objective of the field trial was defined as follows:

- to gain more insight into the extent to which railway vibrations can be reduced by internationally applying new wheel maintenance rules based on new monitoring techniques;
- to map the impact of other types of wheel maintenance on cost, availability and safety of rail transport.

This chapter discusses the study results that relate primarily to the first objective. In Part 4, the results relating to cost, availability and safety are discussed (see Lessons learned).

Method

Various parties contributed to the field trial: RailGood and Evofenedex, passenger operator NS, wagon owners Ermewa and VTG, shippers Sabic, Fibrant, Tata Steel and Nedmag, and freight operator RTB Cargo.

A key part of the trial was to carry out different types of measurements to map various aspects, namely:

- wheel roundness;
- railway vibrations;
- wheel–rail forces.

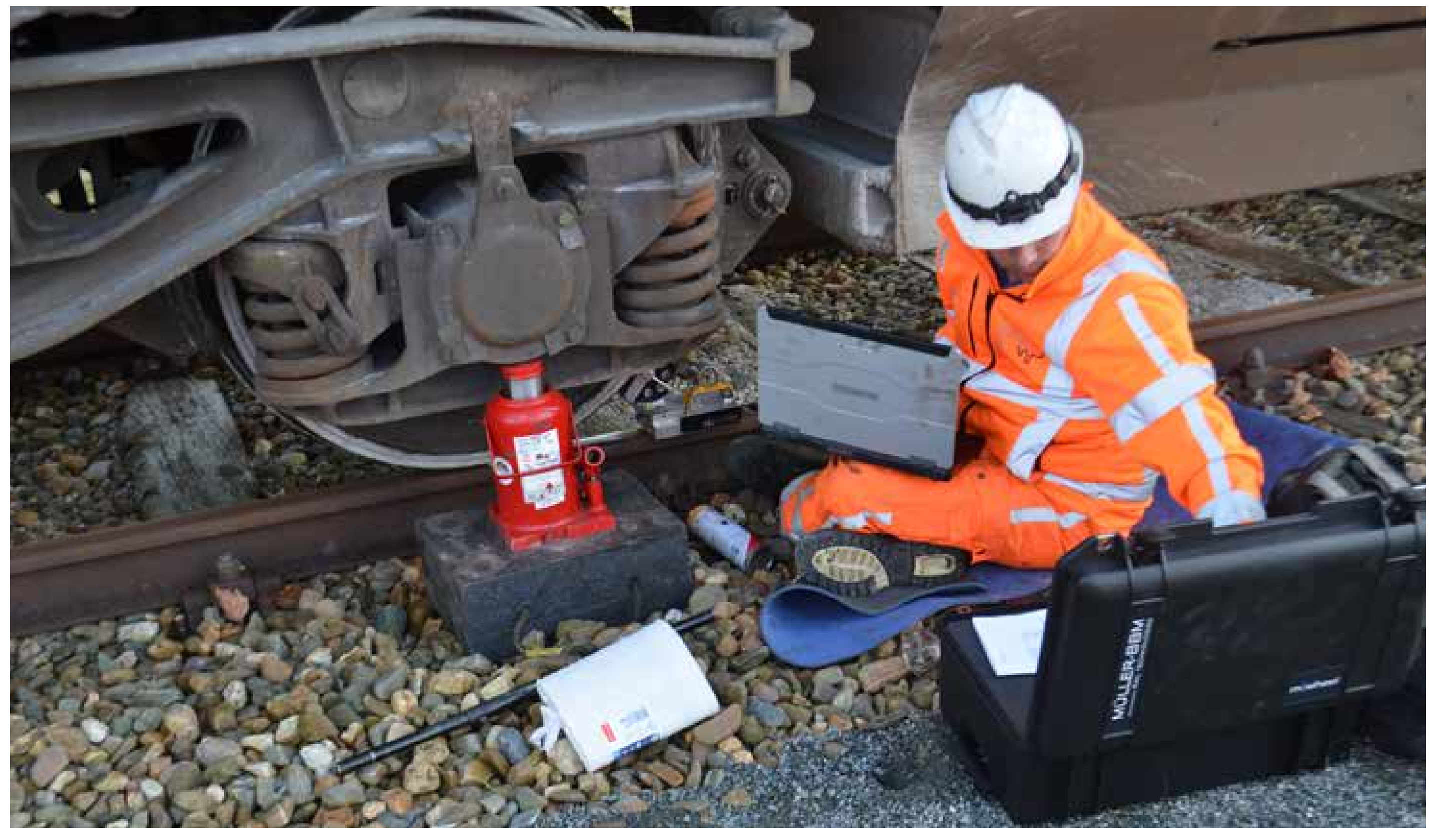
The trial focused mainly on freight wagons, since they were expected to have the most effect on railway vibrations. Locomotives and passenger trains were also examined, but the results confirmed that, for various reasons, there is virtually no improvement potential there (Baltus, 2025).

Freight wagons proved, under certain conditions of ground type, track structure and construction, to be decisive for the vibration levels observed at particular locations. For part of the train passages, this was caused by measurably reduced wheel quality. It was expected that in such cases, carrying out additional wheel maintenance would effectively reduce railway vibrations.

Measuring wheel out-of-roundness

Measurements of wheel out-of-roundness were carried out on regular freight trains from different operators. The rolling stock belonged to various owners serving different shippers. The wheel roundness of freight wagons was measured after selecting the wagons based on recorded railway vibrations. The selected wagons had to be withdrawn from service and set aside for the wheel measurements (see Figure 23).

Figure 23 Measuring a freight wagon wheel



For passenger trainsets, data was taken from the wheel lathe. This machine regularly restores wheel roundness and records roundness data in the process. The difference between the wheel roundness measurements for freight and passenger trains is thus that passenger train wheels received maintenance after measurement, while those of freight wagons did not. Some freight wagons did undergo wheel maintenance during the trial and the wagon owners shared the maintenance data so it could be included in the data analysis.

For maintenance activities on freight wagons, work is carried out in accordance with manufacturer specifications and applicable European standards. The TSI WAG[27] sets requirements for the maintenance and certification of freight wagons to ensure a high level of safety and reliability. This includes regular inspections and surements of wheel profiles and wear checks.

Vibration meas

Witteveen+Bos measured vibrations using an experimental setup in accordance with the Uniform Measurement Protocol (de Bruijn et al., 2025). Measurements were taken at five locations along the railway, over periods varying from one to twelve months. At each location, sensors were installed in the ground at 4 m, 8 m and 25 m from the track. In addition, measurements were taken at the foundation of a building located about 25 m from the track. Groundwater levels were also recorded. The locations differed in soil type and in the types of trains passing. Measurements were taken at:

- Heeze;
- Weert;
- Schalkwijk;
- America;
- Holten.

The wheel–rail forces were measured using ProRail's Quo Vadis monitoring system. The vibration measurement setups, ProRail's Quo Vadis monitoring stations, the freight trains measured and the soil types were combined into a single comprehensive dataset.

Using the collected data, analyses were performed to determine how frequently wheels of reduced quality occur and what correlation exists between these and the vibrations measured in the environment. The study also investigated how well Quo Vadis monitoring stations can detect wheels of reduced quality and whether different maintenance approaches help reduce vibrations caused by such wheels.

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[27] TSI refers to a Technical Specification for Interoperability adopted by the European Commission. The addition WAG indicates that it concerns rolling stock.

Results

Witteveen+Bos performed statistical analyses on the collected data to reveal correlations between measured vibration levels and wheel parameters (de Bruijn et al., 2025). By examining spectrograms of specific train passages and combining these with Quo Vadis data from the same passages, the study identified individual wheels of reduced quality. Figure 24 gives an example of train passages in which poor-quality wheels can be recognised. Many passages did not show such a clear pattern as the one in Figure 24.

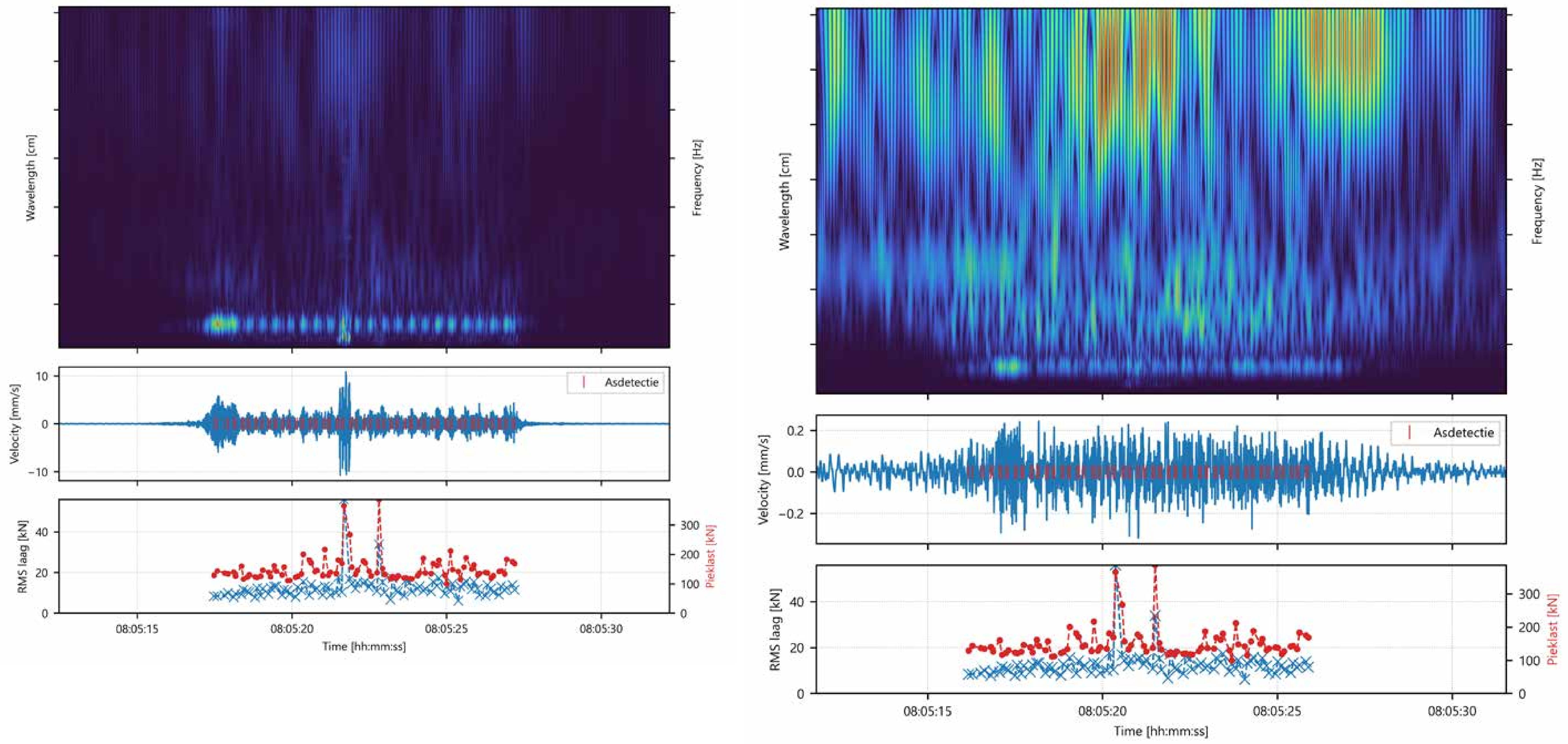
The analyses show that the influence of wheel quality differs between measurement sites. The Weert site shows the greatest influence of wheel quality on measured vibration levels. The soil at Weert is relatively stiff (sandy). To a lesser extent, wheel quality also affects the site at America, and even less so at Holten. These two sites have similar, less stiff soil types. At the Schalkwijk site, the influence of wheel quality is barely visible in the measured vibration signals in the ground. The soil at Schalkwijk is soft and the factor with the this means that vibrations cannot be reduced through improved wheel maintenance.influence there is passing axle load. The higher the axle load, the higher the vibration levels. In addition to axle load. greatestthe type of rolling stock and the train speed influence the vibration levels observed. For Schalkwijk, with its soft ground,

The calculated potential reduction for rolling stock with high vibration levels and poor wheel quality varies significantly between the measurement sites. The effect also differs between ground level and buildings. Wheel roundness measurements on passenger trainsets were carried out immediately before wheel maintenance, making it possible to compare passages by the same trainsets before and after maintenance.

The analysis shows that improving wheel quality in those passenger trains has a positive impact on the measured vibration levels.

Vibration levels decrease after wheel maintenance. The Weert site is an example where a substantial reduction can be achieved by improving the wheel quality of a relatively small group of wagons. The America and Holten sites show a different picture, where improving wheel quality results in little or no reduction of vibration levels at greater distances from the track or in nearby buildings. The achievable reduction in railway vibrations for the group of passages producing the highest vibration levels ranges on average from a few per cent to several tens of per cent.

Figure 24 Spectrogram and time signal of vertical vibration signal



The achievable reduction depends on the site and on the population of passing trains.

The analysis also shows that vibration levels from trains hauled by a locomotive are generally higher than from other passages. This applies to both passenger and freight trains. The passages where the locomotive determines the vibration level were examined further. It was found that vibration levels are not affected by the wheel quality of the locomotive, since locomotives with reduced wheel quality are extremely rare.[28] The higher vibration levels are explained by the locomotive's high axle load. It was also found that the spread of vibration levels among freight trains is much larger than among passenger trains.

Statistical model calculations
Statistical models were used to further quantify the influence of removing poor-quality wheels on the resulting vibration levels in the environment. Witteveen+Bos trained random forest models using all collected data to let the model determine relationships between wheel roundness, wheel–rail force and railway vibrations. The models were then used to predict the influence of wheel quality on the resulting dominant vibration level in the environment for different train compositions, focusing specifically on freight trains.

The model results show that, for the group of passages with the highest vibration levels where the wagons are decisive, a substantial reduction in vibration levels is possible. This does, however, depend on the location and wagon types.

For extreme cases where wheel quality is very poor, a reduction by a factor of 2 to 3 was found.[29] To ultimately reduce nuisance, it therefore appears effective to carry out extra wheel maintenance for this limited group of wagons. For the Heeze measurement site, the results were not quantified because that site was used as a pilot location to test the measurement methodology. However, it was established that at this site, wheel maintenance also has a positive effect on vibration levels in the environment.

Location	**Average reduction in vibration levels***
Weert	14%–24% Largest calculated reduction up to a factor of 2.5
America	5%–19% Largest calculated reduction up to a factor of 3.5
Holten	< 5% Largest calculated reduction up to a factor of 2.4
Schalkwijk	< 5% Largest calculated reduction up to a factor of 1.25

** Calculated reduction achieved by carrying out wheel maintenance on the 10% of train passages with the highest vibration levels at 25 m from the track and a measured dynamic wheel–rail force, according to Quo Vadis, above 7.5 kN.*

Witteveen+Bos note in their report that some caution is needed when using Quo Vadis measurement data to determine a relationship between poor wheel quality and vibrations (de Bruijn et al., 2025). To establish a reliable correlation, corrections per Quo Vadis measuring point are required based on the loading level and/or axle load. Witteveen+Bos recommend improving the algorithm that determines poor-quality wheels based on Quo Vadis data.

Detection of wheel out-of-roundness using Quo Vadis
Voestalpine Signaling Siershahn, together with Witteveen+Bos, investigated the possibilities of developing a new Quo Vadis algorithm (van Balveren, 2025). Voestalpine Signaling Siershahn is the supplier and specialist responsible for the Quo Vadis measurement systems. The purpose of the new algorithm was to describe the geometry of passing wheels more accurately based on the raw Quo Vadis measurement data. The wheel out-of-roundness study showed that current parameters such as RMS_low do not always detect wheel defects effectively – especially in the case of low-order out-of-round wheels. For low-order out-of-round wheels, a low correlation was found between ground vibrations and RMS_low values, whereas higher-order (higher-frequency) components showed stronger correlations.

Witteveen+Bos examined whether an initial concept of a new algorithm demonstrated a reliable correlation between ground vibrations and wheel out-of-roundness. To this end, the algorithm was applied to a large dataset of Quo Vadis measurement data, combined with

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[28] This is also why little improvement potential is expected for locomotives.
[29] A reduction by a factor of 2 corresponds to a 50% reduction (6 dB), while a reduction by a factor of 3 corresponds to a 67% reduction (9.5 dB).

vibration measurements from various sites. Using machine learning techniques, it was investigated whether the algorithm yielded significant correlations (de Bruijn et al., 2025). The results showed weaker relationships than expected, indicating that further improvement of the algorithm is required. Ultimately, it proved unfeasible to refine the algorithm further within the scope of the wheel out-of-roundness study.

Table 5 Effect of addressing poor-quality freight wagon wheels

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
0–25%, but in specific cases possibly 50–67% (0–2.5 dB increasing to 9.6 dB).	1. Modification of the vehicle to reduce the dynamic wheel–rail force.	The uncertainty of the effect determination appears reasonably limited. Extensive study with statistical analyses.	The effect seems strongly location-dependent and applies only to stiff sandy soils. The stiffer the ground, the greater the dynamic load for an irregularity.	Yes – in specific situations where freight wagons with poor wheel quality cause the highest vibration levels, this can be a potentially effective measure. Freight train passages with multiple poor-quality wheels also appear to correlate with nuisance (see Disturbing train passages).

2C. Infrastructure innovations

Within the IBS programme, research was conducted into whether various design modifications to the track structure – already applied in practice for other primary purposes (such as improving track stability) – could also contribute to reducing railway vibrations. By examining whether these existing measures have a vibration-reducing effect, the project sought innovative applications of already-implemented infrastructure measures. In addition, several existing vibration-reducing measures were assessed for their effectiveness when applied on the Dutch railway network. ProRail also used an SBIR (Small Business Innovation Research) process to challenge market parties to develop and test innovative ideas. Five of these were ultimately selected and investigated through field trials.

Ballast mats

Background

Ballast mats are standardly used in structures such as tunnels and viaducts. They are applied to prevent ballast pulverisation. In some cases, ballast mats are also used as a vibration-reducing measure, for example in rail tunnels. Both theory and practice show that using a ballast mat results in insertion loss (i.e. vibration reduction) in frequency bands above the achieved resonance frequency (Thompson, 2009). Around the resonance frequency, however, vibration levels increase, as the ballast mat acts as an additional spring. In general, ballast mats mainly affect the reduction of frequency bands in which low-frequency noise may cause disturbance. The effect of a ballast mat depends on various parameters, including axle load, the stiffness of the supporting structure (ground or construction beneath the mat) and the dynamic stiffness of the mat itself. The dynamic stiffness is specified in ProRail's specification SPC00062.

As part of the IBS programme, a study was launched to determine the vibration-reducing effect of applying a ballast mat in an earthwork situation. A further aim was to establish whether this effect degrades over time.

Figure 25 Installation of ballast mats at the test site

Hypothesis

Ballast mats also have a favourable vibration-reducing effect when placed between the earthwork and the ballast.

Method

Witteveen+Bos conducted vibration measurements in accordance with the Uniform Measurement Protocol on a partial superstructure renewal[30] where ballast mats were installed (de Bruijn & Hoekstra, 2025). The ballast mats used were of types USM 2020 and USM Ciprotec 6018. The dynamic stiffness of the mats depends on the load magnitude. The supplier's specified stiffness at 40 Hz is given in Table 6. At the test site, the subsoil consists of sand and the section is double-track. The ballast mats were installed under one of the two tracks. The test site is located on the Wierden-Deventer line.

Table 6 Dynamic stiffness modulus of ballast mat USM 2020 at 40 Hz

Pre-load (N/mm²)	Stiffness (N/mm³)
0.030	0.020
0.060	0.037
0.100	0.042

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[30] Only the ballast was renewed.

Results

The study distinguishes between the effect in the first few weeks after installation and after a settlement period of 4–5 weeks. Both $V_{eff,max}$ and V_{RMS} were analysed. In the first weeks after installation, a reduction in vibration levels was observed at 16 m from the track where the ballast mat was installed. A comparable reduction was found for the other track.

According to the Witteveen+Bos report, after a settlement period of 4–5 weeks, the measurement point at 8 m from the track showed a reduction for the track with ballast mat of up to about 8 dB in the vertical direction for intercity and freight trains. At the same time, vibration levels increased for the adjacent track.

At greater distances from the track (16, 32 and 48 m), vibration levels for the track with a ballast mat were on average higher than in the baseline measurement. The largest increase was found at the most distant measurement point – about 8 dB for intercity trains and 6 dB for freight trains. Third-octave spectra show that this increase is related to frequencies below 35 Hz, while vibration levels at higher frequencies generally decrease. This reveals the negative insertion loss effect of a ballast mat below the resonance frequency. Close to the track, vibration signals contain more high-frequency content than farther away, since high-frequency vibrations decay more quickly with distance. The positive insertion loss above the resonance frequency therefore has the greatest effect near the track, whereas farther away the negative insertion loss at low frequencies dominates.

Witteveen+Bos recommend studying the effect of a ballast mat at another site with a different soil type. The frequency-dependent effect of the ballast mat should be determined at various distances from the track. For the test site, it appears that farther from the track, the beneficial effect of a ballast mat is no longer visible and that only the negative effect at low frequencies remains. Further research in different track situations could present a different picture, where the beneficial effect (at higher frequencies) is more pronounced – for example, in cases involving both vibration nuisance and low-frequency noise.

Table 7 Effect of ballast mats

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
Positive > 30 Hz (up to 8 dB); negative < 30 Hz (down to –8 dB); distance from track important.	3. Use of a vibration-isolating material within the track structure.	High – follow-up measurements appear unreliable due to multiple observed effects.	Ballast mats produce a resonance frequency above which a positive effect and below which a negative effect are expected.	No substantial potential for improvement; the mechanism is already well understood.

Foamed ballast

Background

By fixating/bonding the ballast, the material properties of the ballast bed change. One possible bonding method is the use of Durflex. With a view to potentially reducing maintenance costs, ProRail prepared a business case for this application in 2010. The use of Durflex as a possible vibration-reducing measure was then considered in 2019, but ultimately not pursued. Within the IBS programme it was therefore investigated whether fixating the ballast could nevertheless have a beneficial effect on railway vibrations. Various techniques were inventoried: (1) bonding the top layer or the side of the ballast bed, (2) applying Durflex, and (3) using concrete in combination with a softer rail support (an idea from the engineering firm Movares). In the end Durflex was selected for detailed study. Durflex is produced by Hyperion and is comparable to polyurethane foam. The supplier estimates its service life at 50 years.

Table 8 Effect of foamed ballast

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
Not immediately clear.	4. Stiffening or improving the trackbed to reduce deflection.	Medium – a laboratory setup determines the effect in a controlled way. The effects found are difficult to explain at present.	Results do not yet align with the hypothesis.	Unclear – better explanation of the results is needed.

Hypothesis

Applying Durflex fills the voids between the stones in the ballast bed with foam, preventing or reducing ballast movement. The expected mechanism is improved load distribution on the one hand and long-term fixation of the (correct) track geometry on the other.

Whether Durflex would have a damping effect on vibrations was not clear in advance. The measure was assessed beforehand for expected impact, which indicated that Durflex could lead to either an increase or a decrease in vibrations. At certain frequencies an amplification is expected, creating a risk of an overall increase in vibration level. Another risk is that conventional maintenance is no longer possible. In the event of subgrade settlement, once Durflex has been applied the ballast would have to be removed completely.

Method

A laboratory test was carried out to determine the effect of Durflex. A rail segment was subjected to dynamic loading. The rail segment was fastened to a sleeper placed in a tray filled with ballast. Around the sleeper the ballast was bonded with Durflex (see Figure 26). The deformation and acceleration at the top of the sleeper were monitored. Based on the measured deformation per cycle, the degree of damping was determined from the force–displacement diagram.

Figure 26 Test setup for foamed ballast

The stiffness was determined by comparing the displacement of the sleeper with that of the bottom of the tray.

The mechanical tests were performed by DEKRA Rail (Deckers & Horst, 2025). The tests were based on standards DIN 45673-5 / EN 17282, which also form part of ProRail specification SPC00061 for ballast mats.

Results

The laboratory results show that injecting with Durflex clearly affects the mechanical behaviour of the ballast. Comparing the situations with and without Durflex, the following differences were established (Deckers & Horst, 2025):

1. The stiffness of the ballast after applying Durflex is significantly lower at all measured frequencies with valid results (1–20 Hz), ranging from a factor of 2 to almost a factor of 4.
2. The relative damping after applying Durflex is significantly higher in the above frequency range, by roughly a factor of 1.5.
3. The absolute damping (dissipated energy) is higher after applying Durflex, by a factor of 3 to 6.
4. In successive measurements, with a durability test in between, the stiffness of Durflex-treated ballast keeps decreasing, with only a small difference between the last two tests.
5. Under initial loading after applying Durflex, much less compaction occurs than with untreated ballast.
6. During the durability tests after applying Durflex, some compaction seems to occur, but the ballast largely springs back afterwards.
7. At all frequencies, including higher ones, the difference in vibration level between the sleeper and the bottom of the ballast tray is greater when Durflex is used. The results are striking and contrary to expectations. Bonding the ballast was expected to increase stiffness, which is not borne out by the lab tests.
   As a next step it is envisaged to use the STEM computational model to explain the results and the behaviour of fixed ballast. This study could potentially be combined with results from one of the PhD projects (see PhD research).

Adjustable-height fastening

Background

High vibration levels are regularly measured around discrete discontinuities in the track. This is the result of dynamic excitation (see Railway Vibrations). At such discontinuities, vertical level differences in the track may occur. To counter deviations in vertical track geometry, the ShimLift has been developed, which allows the rail height to be adjusted[31].

Hypothesis

A ShimLift improves the vertical geometry of the rail, reducing dynamic excitation and thus leading to vibration reduction.

Method

A field trial was carried out to determine the effect of applying an adjustable-height fastening on railway vibrations.

Figure 27 Photo of a ShimLift

DGMR conducted vibration measurements at a double-track level crossing in Deurne where ShimLifts were installed (Fennema, 2023).

Vibration levels from train passages on both tracks were measured, with a split between passenger and freight trains. Both V_{RMS} and $V_{eff,max}$ were considered. Train speeds were recorded and measurements were taken at various distances from the track at ground level. Measurements were also taken on a transformer kiosk at 55 m from the track.

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[31] See https://kampa-international.nl/shimlift/

Results

DGMR found mixed effects, but overall the installation of ShimLifts did not show large reductions in total vibration levels V_{RMS} and V_{max} (Fennema, 2023). When the vibration level is broken down by frequency band, the effect varies: for freight trains, a 2–4 dB reduction was found between 3.2 and 5 Hz, but a 0–3 dB increase between 8 and 10 Hz. A reduction of 0–3 dB was found at 40 Hz. For passenger trains, a similar pattern was observed with slightly smaller decreases, but with a 0–2 dB increase at 8–10 Hz. The conclusion is a negative effect around 8–10 Hz and a positive effect between 32 and 63 Hz. The result is reported to depend on soil composition. The effect on total V_{RMS} also differs between the two tracks measured: on one track the effect is negligible and on the other a 1–2 dB reduction is seen.

DGMR's report concludes that, at a level crossing, ShimLifts influence the reduction of the impact occurring at the transition from track founded on concrete slabs to the regular track structure (Fennema, 2023). ShimLifts eliminate any height difference between the two structures. What remains is the stiffness contrast between the two track structures, which still generates an impact force at the transition. The report states that reducing this impact force in any case affects the low frequencies around 4 Hz, corresponding to the bogie pass-by frequency. Reducing the impact force by installing ShimLifts decreases excitation at this frequency. In terms of total vibration strength V_{RMS} or V_{max}, this shows up mainly for freight trains with high axle loads. The report notes that at greater distances from the track this can occur in relatively soft soils, where resonance at these low frequencies may be possible. This was not the case at the Deurne site.

The effect of a ShimLift has been investigated before. Those studies show that ShimLifts do affect vibrations, but the effect varies strongly by location and train type (Boon, 2022). The frequency dependence – particularly a favourable effect at higher frequencies – was also concluded in earlier work (Boon, 2022). The DGMR research findings are consistent with this.

In the DGMR report, vibration levels are also plotted against train speed, yielding different linear relations per train type. The increase of V_{RMS} with train speed thus becomes apparent. Additionally, track geometry data before and after installing the ShimLift was examined. No major effect on the track's vertical alignment was found, with the caveat that the measurement train may not reliably detect such small improvements in track geometry.[32]

Table 9 Effect of adjustable-height fastening

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
Varies from 0–2 dB in the surroundings; negative effects also observed.	4. Stiffening or improving the trackbed to reduce deflection.	High – multiple influences are present simultaneously in the measurement results.	Track geometry seems to improve only slightly.	To be determined – perhaps at locations where track geometry is very poor.

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32 One of the SBIR studies involves re-setting a ShimLift based on sensors in the track (for results, see Adjustable IRJ).

Geogrid

Background

Geogrids are used in certain situations as a maintenance-limiting measure during superstructure renewals. Within the IBS programme, the use of geogrids was considered a promising measure for reducing railway vibrations. For that reason, the vibration-reducing effect of geogrids was investigated.

Hypothesis

It is expected that the application of a geogrid may have a reducing effect on railway vibrations. A geogrid provides additional stability and stiffness of the track. In the short term, a limited effect is expected through better load distribution. In the long term, a favourable effect is expected through a more durable track geometry.

Table 10 Effect of geogrid

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
0 to 5 dB in the environment	4. Stiffening or improving the trackbed to reduce deflection.	High – multiple influences are present in the results, and only passenger stock was measured.	Results appear consistent with the hypothesis.	Effect should also be determined for freight train passages. The long-term effect on track geometry still needs to be determined.

Method

M+P carried out measurements on the track at Akkrum to determine the short-term effect (Burgmeijer, 2024).

Any follow-up measurements to establish the long-term effect still need to be performed, in combination with an analysis of the track geometry data.

The vibration measurements were carried out in accordance with the Uniform Measurement Protocol, with both a baseline (pre-) and follow-up (post-) survey. The test site used an RK4 Geocomposite geogrid. The location lies on the Leeuwarden–Akkrum line, 1.7 kilometres north of Grou station.

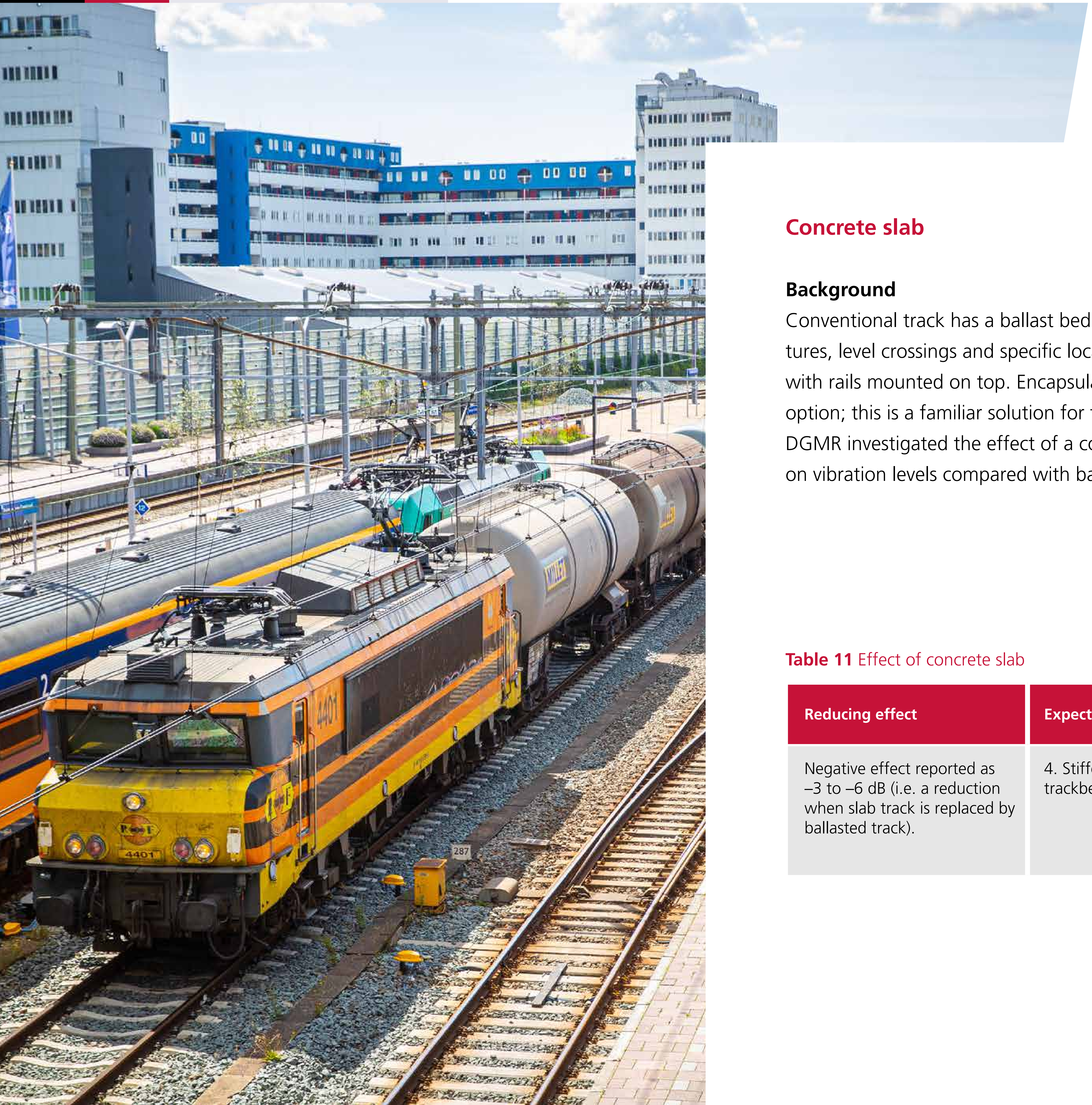
Results

M+P concludes that, in the short term (six months), the measured vibration levels either remained the same or decreased. Only passenger trains were studied, because only this rolling stock operated on the line at the test location.

Insertion losses per one-third octave band vary with distance from the track, but are predominantly positive.

M+P concludes that geogrids can be applied as a maintenance measure without adverse effects on vibrations. Considering the average vibration level V_{RMS} (1-100 Hz), the insertion loss for intercity stock ranges from 0 to about 5 dB.

The study notes that, in addition to the installation of geogrids, other works were carried out (including track renewal) that may have influenced the measured vibration levels. The long-term effect on track geometry still needs to be determined.



Concrete slab

Background

Conventional track has a ballast bed beneath the sleepers. At structures, level crossings and specific locations, a concrete slab is used with rails mounted on top. Encapsulated (embedded) rails are an option; this is a familiar solution for tram and metro in urban areas. DGMR investigated the effect of a concrete slab with embedded rails on vibration levels compared with ballasted track (Fennema, 2024).

Hypothesis

A concrete slab produces a stiff structure under the track that can spread loads more effectively, potentially giving a beneficial vibration effect. The transition from earthwork to slab, however, may have an adverse effect.

Method

To determine the influence of a concrete slab relative to ballasted track, DGMR performed vibration measurements in accordance with the Uniform Measurement Protocol. Measurements were taken at various distances from the track, with both a pre-measurement and a post-measurement. At the test site, a concrete construction with embedded rails was replaced by ballasted track.

Table 11 Effect of concrete slab

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
Negative effect reported as –3 to –6 dB (i.e. a reduction when slab track is replaced by ballasted track).	4. Stiffening or improving the trackbed to reduce deflection.	High – the slab track situation measured is not representative of typical cases.	Possible poor track construction/geometry with the slabs may explain the improvement after conversion.	Possible – should be investigated for more representative situations.

The test section was 240 metres long; the concrete slabs were each six metres long and connected together. A cork-rubber layer was present between the rails and the slabs. The site lies on the Eindhoven–Venlo line.

Results

DGMR reports the following results (Fennema, 2024):

- Lower vibration levels were measured up to 40 Hz with ballasted track. The reduction in V_{RMS} is about 4–10 dB.
- An increase in vibration levels from 50 Hz was measured with ballasted track due to the presence of sleepers (which were absent in the slab-track situation). For V_{RMS} this increase is 6–10 dB.
- A reduction in total vibration $V_{eff,max}$ was measured for ballasted track compared to the slab situation.
- The reduction is greater for passenger trains than for freight trains. With slab track, freight trains produced vibrations with substantial content around 16 Hz. After the track conversion, content around the sleeper-passing frequency (40–50 Hz) increased enough to become governing.

Thus, replacing slab track with standard ballasted track led to a reduction in vibration level.

DGMR's report notes that the test site is not representative for drawing a general conclusion. An important limitation was that the properties of the six-metre slabs were not fully known and their dimensions differ from standard slabs.

Concrete versus timber sleepers

Background

After superstructure renewals in which timber sleepers are replaced with concrete sleepers, ProRail sometimes receives complaints about vibration. The IBS programme therefore investigated how the two sleeper types differ in terms of the resulting railway vibrations.

Hypothesis

The expectation was that sleeper type influences ground-borne vibration beside the track. Concrete sleepers might be less favourable than timber sleepers, based on experience with complaints after superstructure renewals.

Method

Cauberg Huygen carried out vibration measurements at two locations before and after a superstructure renewal in which existing track with timber sleepers was replaced by track with concrete sleepers. The sites are at Nunspeet and Tegelen. At both locations, measurements followed the Uniform Measurement Protocol.

In designing the study, allowance was made for the expectation that not only sleeper type but also the geometric track position affects vibration. Because a superstructure renewal both replaces the ballast and re-tamps the track, the geometry changes as well. The data analysis therefore corrected for geometric irregularities of the track.

At Nunspeet, measurements were taken at 8, 12,24 and 32 m from the track (Van der Vecht & Williams, 2023). These were supplemented with continuous monitoring on a house foundation. The post-renewal measurements were carried out a considerable time after completion of the works, to avoid short-term effects immediately after the renewal influencing the results. The study focused on $V_{eff,max}$. In addition, 5-second one-third octave spectra (V_{RMS},5s) were examined[33]. The results are based on passenger trains only, as no freight passages were recorded.

North of Tegelen station, Cauberg Huygen performed vibration measurements in 2024 in a manner largely comparable to Nunspeet (Ostendorf & Teegelbeckers, 2025). Here too, timber sleepers were replaced with concrete sleepers. However, the rails were also replaced by another type and the ballast bed renewed. Cauberg Huygen therefore notes that comparison with Nunspeet is not like-for-like.

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[33] Cauberg Huygen also notes that a 5-second signal has limitations and leads to inaccuracies for low frequency bands 1–3.15 Hz, because the smallest achievable frequency resolution is 0.2 Hz.

Results

At Nunspeet, the measured vibration level $V_{\text{eff,max}}$ for intercity stock over the track with concrete sleepers is 0 to 2 dB higher than over the track with timber sleepers at distances up to 16 m from the track. From 24 m, the vibration level is 2 to 4 dB lower. At the foundation point, the level is 0.5 dB lower. Differences in the frequency spectra of the recorded vibration signals show wide scatter across the one-third octave bands. For the total vibration V_{RMS},5s, the spread is smaller: +2 dB to –5 dB at ground level and +1 dB to –0.5 dB at the fixed foundation point of the house. These are results of measured vibration levels before accounting for the influence of geometric track quality.

From an analysis of geometric track quality at Nunspeet it follows that, after the superstructure renewal, geometric irregularities are greater than before – i.e. a deterioration of track geometry. These larger irregularities strongly affect all one-third octave bands in the vibration spectrum.

The difference in measured vibration reduction with distance from the track is explained by frequency-dependent soil damping. Close to the track (up to roughly 16 m), higher frequencies (50–80 Hz) dominate in the measured vibrations, while at greater distances the lower bands dominate. This is because higher frequencies are damped more strongly as distance from the source increases. The same phenomenon was observed in other field trials, such as with the application of ballast mats (see Ballast mats).

Table 12 Effect of concrete versus wooden sleepers

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
4–8 dB lower with concrete sleepers than with timber sleepers in the surroundings at distances >16 m. This applies to Nunspeet; at Tegelen, by contrast, an increase was found.	4. Stiffening or improving the trackbed to reduce deflection..	High – multiple influences are present simultaneously in the measurement results.	Results do not appear consistent with the hypothesis.	Concrete sleepers are standard practice; consequently, there seems little scope for substantial improvement.

It is noteworthy how much the track geometry differed before and after the superstructure renewal. It is unclear why, at Nunspeet, the track geometry was not delivered at least at the prior level.

In Cauberg Huygen’s report for Tegelen, results for measured vibration levels are discussed alongside results for track geometry before and after the superstructure renewal (Ostendorf & Teegelbeckers, 2025). Here, the track geometry was markedly improved – unlike at Nunspeet.

The vibration measurements at Tegelen show lower vibration levels after the superstructure renewal than before: a reduction of 0 to 3 dB for freight trains and 0 to 5 dB for passenger trains. Only when a net effect is computed for replacing the sleeper type (i.e. after accounting for the effect of improved track geometry) is an increase calculated by a factor of 2.0–3.0. The calculated increases and decreases refer to averages of $V_{\text{eff,max}}$ for all relevant train passages.

Based on the Nunspeet vibration study, Cauberg Huygen concludes that the vibration emission of track with concrete sleepers is 4 to 8 dB lower than that of track with timber sleepers (Van der Vecht & Williams, 2023). The results are frequency-dependent and depend on distance from the track. This conclusion is strongly influenced by the treatment of track geometry; track geometry appears to be more important than sleeper type.

A track with concrete sleepers is the standard track design. This standard is not in question. For that reason, no further in-depth comparative analysis was conducted between track with timber sleepers and track with concrete sleepers.

Durable sleepers

Background

In recent years, various durable sleepers have come onto the market. To study the effect of such sleepers on vibration, Fugro conducted a test with four types of sleeper (Snethlage & Drieman, 2022). The test site was a single-track section between Zwolle and Heino. Three of the four sleeper types were made of plastic; the fourth type was made of sulphur concrete.

Hypothesis

The use of a new type of plastic sleeper affects railway vibrations. This effect is due to a difference in stiffness and/or mass between standard concrete sleepers and the durable sleeper. Any possible secondary long-term effect of the durable sleepers on track geometry was not investigated. The results were corrected for track geometry so that the direct effect could be isolated. The measurements were short-term, covering one or several parts of a day.

Method

Fugro took measurements at 8 m and 16 m from the track in different test sections. The measurements followed as closely as possible the protocol of the RIVAS project (WP2, 3, 4 and 5 Deliverable D1.2), as the Uniform Measurement Protocol was not yet available.

Table 14 Effect of durable sleepers

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
On average no effect: –1 to +2 dB	4. Stiffening or improving the trackbed to reduce deflection..	High – different corrections had to be applied between test sections; measurements lasted only part of a day.	Results appear plausible; the various sleeper types have a broadly similar mechanical behaviour.	There is little potential for improvement. The differences between sleeper types appear small.

Each test section contained a different sleeper type, compared with a reference section of standard concrete sleepers. MASW measurements[34] were carried out to characterise subsurface differences between the test sections.

Results

The study found no difference at 8 m distance between the various sleeper types and the standard concrete sleepers. At 16 m, small differences were found, ranging from –1 to +2 dB. Fugro concludes that virtually no effect of sleeper type was measured (Snethlage & Drieman, 2022). Only passenger trains run on the test section, so the results are representative for that type of rolling stock. Corrections had to be applied for differences in track elevation and soil type between test sections, introducing uncertainty into the results.

Halving sleeper spacing

Background

In addition to testing different sleeper types, the influence of sleeper spacing on railway vibrations was investigated. This study was conducted by DEKRA Rail (Berssenbrugge & Linders, 2025). The effect of halving the sleeper spacing was examined. Because the rail bends between sleepers, the greatest deflection occurs halfway

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[34] MASW stands for Multichannel Analysis of Surface Waves.

between them. As a result, a train wheel experiences variation in rail deflection as it passes over each sleeper, generating vibrations. The frequency of these vibrations equals the train speed divided by the sleeper spacing (see Railway Vibrations).

When the sleeper spacing is halved, this frequency doubles and the rail deflection decreases.

Hypothesis

A decrease in rail deflection and a doubling of the excitation frequency have a beneficial effect on vibrations, especially because higher-frequency vibrations attenuate more rapidly with distance from the track.

Method

Using computer simulations, DEKRA Rail examined the effect of halving sleeper spacing on the wheel–rail force. The simulations were performed with the multi-body software package VAMPIRE Pro.

Results

The simulations show that halving the sleeper spacing produces multiple, partly opposing effects on railway vibrations. The outcome depends on train type and speed. DEKRA Rail (Berssenbrugge & Linders, 2025) reports the following findings:

- Doubling the number of sleepers per metre makes the overall track structure stiffer.
- Because of this increased stiffness, irregularities in track geometry lead to greater dynamic forces between train wheels and rails. These forces occur at higher frequencies.
- The shift to higher frequencies can result in reduced amplitudes of dynamic forces at lower frequencies – for example, in simulations with passenger rolling stock at 18–52 Hz.
- With halved sleeper spacing, the rails deflect significantly less between sleepers, so the dynamic forces arising from sleeper spacing are smaller and occur at twice the frequency.
- The simulations show that the influence of reduced rail deflection on the wheel–rail dynamic forces is much smaller than the influence of the increased stiffness of the track structure[35].
- The larger dynamic forces in the wheel–rail contact cause higher vibration loading on the superstructure, at higher frequencies than for the current spacing.
- This increased track vibration loading is expected to raise ground vibration levels, depending on soil properties, because the excitation frequencies increase.

DEKRA Rail's report concludes that the research results do not establish that halving the sleeper spacing leads to reduced railway vibrations. The study assumed a theoretical halving of sleeper spacing based on an elevated version of the ERRI-high model for track geometry.

Table 13 Effect of halving sleeper spacing

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
Not clearly established	4. Stiffening or improving the trackbed to reduce deflection..	Low – for simulation results themselves, but the effect on ground vibrations was not determined.	Results appear consistent and interpretable.	Limited. Halving sleeper spacing presents numerous practical drawbacks.

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[35] The dynamic loading from track irregularities therefore increases, while loading from discrete support (deflection) decreases.

Switch removal

Background

A switch introduces a discrete discontinuity in the rail, creating a local dynamic force that is expected to cause higher vibration levels in the surrounding area. The extent to which a switch contributes to environmental vibration was studied by Movares (Gardien, 2025).

Hypothesis

A switch acts as a local point source. Removing the switch eliminates this source, thereby locally reducing railway vibrations.

Method

Movares performed vibration measurements in accordance with the Uniform Measurement Protocol at a site in Zevenbergen where a switch was removed (Gardien, 2025). Two switches were located there – one on the western track and one on the eastern track.

Results

The measurements showed that the switch on the eastern track generated substantially higher vibration levels than the western one. Movares' report (Gardien, 2025) concludes:

- The measurements of the switch removal on the western track show a reduction in vibrations mainly in the frequency range of 20 to 40 Hz; the reduction is of the order of magnitude of 5 to 7 dB for VIRM trains and of the order of magnitude of 5 to 10 dB for SNG trains.
- The measurements of the switch removal on the eastern track show a reduction in vibrations mainly in the frequency range of 20 to 50 Hz. The effect is a maximum of 20 dB.
- For SNG trains, the reduction is greater than for VIRM trains.
- At distances of 40 m and more from the track, the switch removal in Zevenbergen showed a smaller effect than close to the switch.

Table 15 Effect of switch removal

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
Varies from 5 to as much as 20 dB.	2. Modification to the track to reduce the dynamic wheel–rail force.	Medium – differences in train speed between pre- and post-measurements; only passenger trains measured	Results appear consistent with the hypothesis.	Although uncertainty remains, switch removal can in some cases be highly effective in reducing vibration.

During the first post-measurement, a train speed restriction applied on the section. The trains therefore ran at a lower speed during the post-measurement than during the baseline measurement. This creates uncertainty in the comparison between the measurement results before and after removal. A second post-measurement was therefore carried out a year later, when no train speed restriction was in force. Only passenger trains were included in the analysis. The number of freight train passages during the measurement periods was small and the passages showed great variation in measured vibration levels. This was not the case for passenger trains. For freight trains, no reliable effect could therefore be determined.

Movares concludes that, due to the large difference in the measured effect of switch removal between the two switches, a general conclusion about the effect of a switch removal cannot be drawn on the basis of this study. The removal of a switch can lead to a considerable reduction in vibrations, but this does not necessarily have to be the case. It probably depends on the condition and alignment of the switch that is being removed.

In the report, Movares gives the recommendation that, when a switch removal is considered as a vibration mitigation measure, an investigation should be carried out at the location of the switch to be removed into the extent to which the switch contributes to vibration levels in the surroundings. This contribution may be limited, but in some cases it is considerable.

PSS layer

Background

Due to problems with track stability on the section between Culemborg and Geldermalsen, a Planum Schütz Schicht (PSS) layer was installed around July 2022. The layer was applied beneath the ballast and on top of the subgrade. A PSS layer is a fine-grained, cement-like type of sand that is mainly used in Germany. The primary purpose of a PSS layer is to improve load-bearing capacity. In addition, when combined with a drainage system, a PSS layer ensures proper drainage of rainwater. The layer might also provide stiffness and strength to the track structure, which could potentially have a favourable effect on vibrations. An increase in track stiffness is expected to lead to lower amplitudes and a beneficial influence on vibration transmission. Witteveen+Bos investigated the effect of the PSS layer (Kortendijk, 2023).

Hypothesis

Applying a PSS layer is expected to reduce the transmission of vibrations in the range of 1–10 Hz to the surroundings.

It was also expected that:

1. the critical train speed would increase when a PSS layer is applied between the ballast and the subgrade;
2. by applying a stiff layer in the substructure of the track bed, the bending and shear stiffness of the embankment would increase. As a result, for a given axle load, a redistribution of stresses would occur. This effect is relevant in particular for longer wavelengths, that is, lower frequencies.

Table 16 Effect of PSS layer

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
Below 10 Hz, approx. 3 dB. Above that, little to no effect. Above 20 Hz, a slight average increase.	4. Stiffening or improving the trackbed to reduce deflection.	High – as a complete superstructure renewal was carried out at the same time.	Appears well-explained – improvement of the track structure affects deformation of the track particularly at low frequencies.	Effect determination needs improvement, but particularly for soft ground there seems to be potential.

Method

Before and after the installation of the PSS layer, Witteveen+Bos conducted vibration measurements in nearby houses. The effect was determined only for freight trains, as these operated at the same speed before and after installation of the PSS layer.

Results

The Witteveen+Bos report presents the results per frequency interval (Kortendijk, 2023):

- Between 2 and 7 Hz, the PSS layer has a reducing effect, with an average insertion loss of approximately 3 dB.
- Between 1 and 20 Hz, the PSS layer has on average a limited reducing effect.
- Above 20 Hz, the PSS layer on average results in an increase in vibration amplitude.
- For the total vibration level $V_{\text{eff,max}}$, the PSS layer provides an average reduction of 30%, or 3.1 dB.
- For the total vibration level V_{RMS}, the PSS layer provides an average reduction of 28%, or 2.8 dB.
- For most of the buildings where sensors were installed, the distance from the track was relatively large.

For houses further from the track, higher frequencies are less dominant in the measured vibration levels due to attenuation with distance. For houses close to the track, higher frequencies may be dominant and therefore show increases in vibration levels. However, results from a substation close to the track show a clear reduction in V_{RMS} and $V_{eff,max}$. The Witteveen+Bos report states:

- There appears to be no strong influence of train speed on the values of V_{RMS} and/or $V_{eff,max}$, but the sample on which this conclusion is based is too small to determine this with certainty.
- No significant time effect yet appears in the measurements taken after reconstruction, but the duration of the post-measurement period was too short to draw conclusions from it.

The report notes that the study involves an uncertainty factor because, during installation of the PSS layer, the entire superstructure and track geometry were also renewed (Kortendijk, 2023). Consequently, it is unclear whether the measured effect was caused by the PSS layer or by other changes. The two tracks do not show the same effect and the subsoil beneath the two tracks also differs. Different effects were found at different measurement points and the results therefore do not present a consistent picture.

The report concludes that stiffening the subsoil with a PSS layer at a location with soft ground appears to reduce low-frequency vibrations. To better understand the effect, much longer measurements should be conducted per location.

An additional analysis of the measurement data was carried out by examining subgroups (Kortendijk, 2024). The report notes that it quickly became clear that the subgroups resulted in such small datasets that no statistically relevant conclusions could be drawn.

The supplementary study therefore provided little additional insight into the performance of the PSS layer. However, it did lead to several recommendations that have been incorporated into a revised version of the Uniform Measurement Protocol.

The study demonstrates that carrying out vibration measurements in practice to determine a single effect is complex: often more factors change than the one under investigation.

Tamping

Background

Tamping is a maintenance measure in which the ballast bed is stabilised and compacted. The measure is applied to improve track geometry and the track structure. It is expected to have a favourable effect on railway vibrations. In the OBO studies, tamping was also examined extensively (see Infrastructure maintenance).

Hypothesis

Tamping results in a reduction of vibrations because it improves the track geometry. By comparing measured vibration levels at different distances from the track with BBMS data, an indication of the effect can be obtained.

Method

In 2023–2024 Witteveen+Bos investigated the influence of tamping on railway vibrations using measurement data available from threelocations where the track had been tamped (De Bruijn & Bezemer, 2024).

The measurement sites were located near the stations of Nunspeet, Oisterwijk and Heeze. Measurement data was available for both the situation before and after tamping. The measurements had been performed as part of other studies and in accordance with the Uniform Measurement Protocol. For each site, a statistical analysis was carried out to determine whether the effect of tamping was statistically significant.

The study considered $V_{eff,max}$ and V_{RMS} per train passage and the various octave bands.

The soil at all three sites was characterised as sandy, so the conclusions of the study provide no insight into the effects of tamping on softer soils.

At Nunspeet station, a superstructure renewal had been carried out in which new types of sleepers were installed (see Concrete versus wooden sleepers). Tamping was part of the same works. The measured effect therefore includes the combined influence of tamping and of replacing the sleeper type. The effect of the combined works was determined according to procedure 2 of the Uniform Measurement Protocol (see Uniform Measurement Protocol).

At Oisterwijk, various types of under sleeper pads (USPs) were installed under the track, and the track was also tamped (see Under sleeper pads). At this location, multiple measurement series were conducted, allowing a comparison of the effect according to the combined procedure of the Uniform Measurement Protocol.

At Heeze, two measurement campaigns were conducted, the second of which included tamping. The effect of tamping was determined through direct analysis of the data according to procedure 2 of the Uniform Measurement Protocol. This analysis was combined with a statistical test to determine the significance of the effect. A further data analysis was then carried out using a random forest model trained to describe vibration levels, including the effect of tamping. The results were compared with tamping data.

Results

At Nunspeet, the Witteveen+Bos report shows that vibration levels measured close to the track increased after the works.

At greater distances of 32 m or more from the track, vibration levels decreased (De Bruijn & Bezemer, 2024). The effect is frequency-dependent: for the 63 Hz octave band, a negative insertion loss (0–4 dB) was found at almost all measurement points. For the 16 and 31.5 Hz bands, a positive insertion loss was found, mostly ranging from 0–2 dB. The results apply to the ICM train type. Not all frequency bands showed a significant effect; this was true for all three sites.

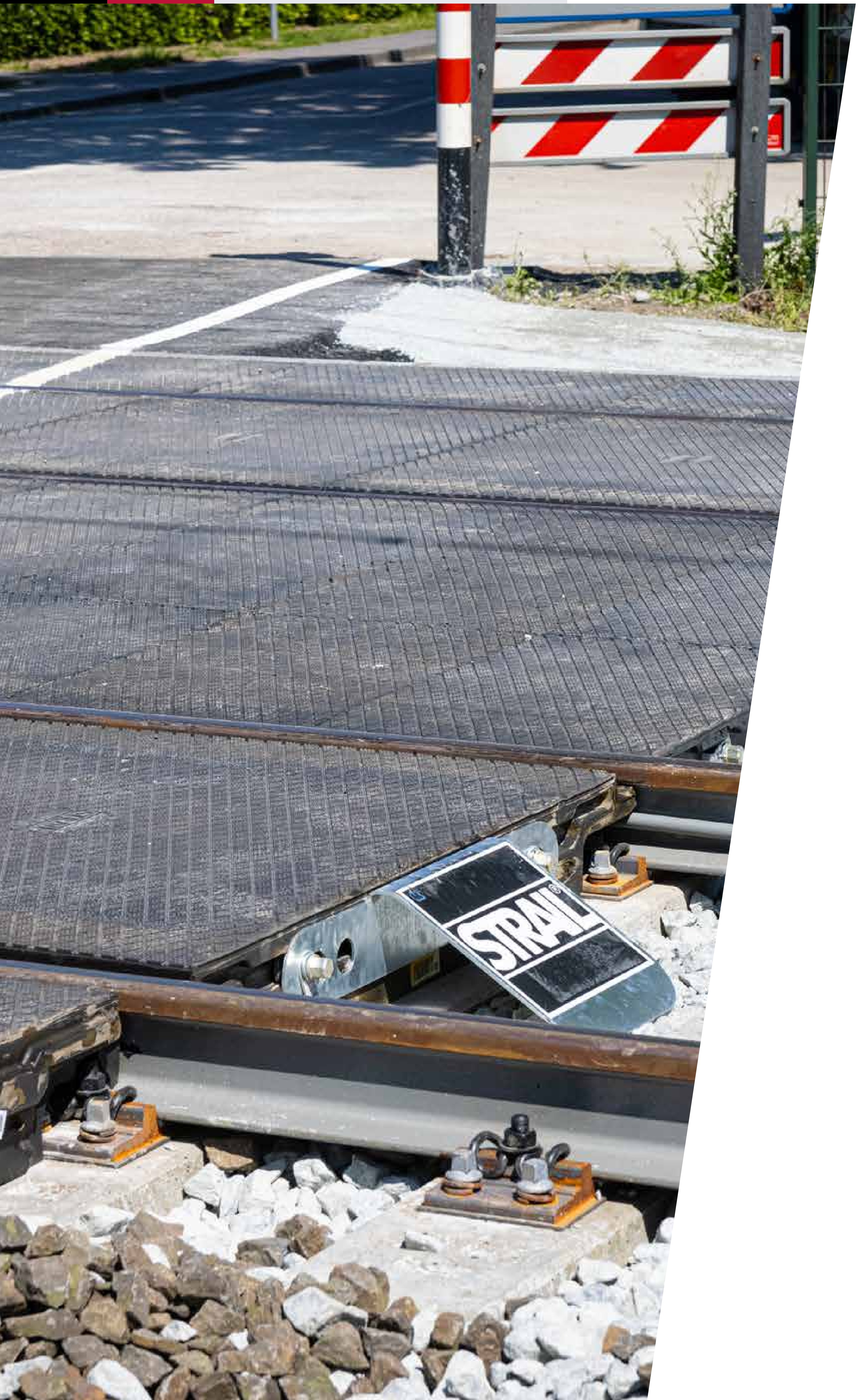
At Oisterwijk, the Witteveen+Bos report states that for the TRAXX+ICRmh trainset combination, tamping consistently led to a significant increase in vibrations at 20 m from the track, varying from about 3 to 8 dB. For freight trains, only a significant increase was seen in the horizontal x-direction. Examining individual frequency bands shows that at 4 and 8 Hz, mainly a positive insertion loss (increase) was found, ranging from 3 to 7.5 dB, while at 16–63 Hz, negative insertion losses (decreases) were found, ranging from about 3 to 8 dB.

At Heeze, both the direct data analysis and the random forest model analysis show that, for passenger trains close to the track, vibrations decreased after tamping. For freight trains close to the track, no significant effect was observed. Both analyses show that at greater distances and in buildings, there was a slight increase in vibrations after tamping, of about 1 dB. The increases were found for the 8 and 16 Hz frequency bands (ranging from about 0 to 4 dB). For the higher frequency bands (31.5 and 63 Hz), positive insertion losses (reductions) of about 0–3 dB were found, mainly near the track.

Overall, the three measurement sites do not show a consistent pattern. There is considerable variation. The effect depends on distance from the track and train type, and whether an increase or decrease was found varies by location. Witteveen+Bos therefore concludes that the relationship between tamping and vibrations is difficult to establish. Tamping was studied more extensively in the OBO investigations, which show a clearer effect (see Infrastructrure maintenance).

Table 17 Effect of tamping

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
Highly variable – both increases and decreases observed. Difficult to establish a consistent effect.	2. Modification to the track to reduce the dynamic wheel–rail force.	Moderate – results based on training a model with extensive data.	Effect depends strongly on distance; tamping may influence the frequency content of vibrations.	Too much variation to obtain a clear picture of potential See also Infrastructure maintenance.



Rubber level crossing surfacing

Background

Level crossings create a local stiffness discontinuity in the track. This produces a dynamic load that can lead to a local increase in vibrations. Replacing standard concrete crossing panels with a rubber level crossing surfacing creates a softer transition, which may be beneficial for vibrations.

Hypothesis

Replacing a standard Harmelen crossing surfacing involving concrete panels with a rubber surfacing reduces railway vibrations.

Method

In 2021, a Harmelen-type crossing surfacing at Dorst was replaced with a STRAIL rubber crossing. To determine the vibration effect of the rubber level crossing surfacing, Witteveen+Bos and D2S International carried out a study (Bezemer, 2022).

To determine the vibration effect of the rubber level crossing surfacing, Witteveen+Bos and D2S International carried out a study (Bezemer, 2022). To assess the effect, three short measurement campaigns were conducted: before replacement, immediately after replacement and six months after replacement. In addition, a continuous measurement lasting 15 months was performed at a corner of a nearby house. The study was conducted at the start of the IBS programme, before the Uniform Measurement Protocol was available. The before/after measurements were compared and insertion loss was determined using the RIVAS protocol (WP2, 3, 4 and 5 Deliverable D1.2), which is the same methodology later adopted in the Uniform Measurement Protocol.

Results

According to the Witteveen+Bos report, the measurements clearly show insertion loss when comparing before and after. Vibration levels vary by measurement direction, train type and frequency band.

Table 18 Effect of rubber level crossing surfacing

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
Large reductions up to 15 dB.	2. Modification to the track to reduce the dynamic wheel–rail force.	Medium – results come from a multi-timescale measurement campaign; note that the effect measured is that of the full package of measures.	Yes – a rubber level crossing provides a less stiff transition, reducing local impact loading and therefore vibration emission.	The measure is potentially applicable at many sites in the Netherlands (level crossings).

The insertion loss rises to as much as 15 dB (Bezemer, 2022)[36]. The results show a clear decrease in vibration level with increasing distance from the crossing, an effect that is larger at higher frequencies. This is because higher frequencies (from about 31.5 Hz) are more attenuated with distance from the track.

The Witteveen+Bos report concludes that replacing the crossing, in combination with other works, led to a substantial reduction in railway vibrations. The greatest reduction is seen for TRAXX+ICRmh consists, the train type responsible for the highest vibration levels both before and after the conversion. For this combination the reduction found is well over 50% in the horizontal directions and up to 75% in the vertical direction at measurement points close to the track. At larger distances the conversion resulted in a reduction of over 25% in the horizontal directions and nearly 50% in the vertical direction. An important caveat is that this reduction cannot be attributed solely to replacing the crossing type, but to the full package of measures[37].

Under sleeper pads

Background

Under sleeper pads (USPs) are elastic pads fitted beneath sleepers and used as a measure to reduce railway vibrations.

This technology has long been used successfully abroad and is available from multiple suppliers. In the Netherlands, USPs have not yet been widely applied. To assess effectiveness in the Dutch context, a field trial was carried out.

Hypothesis

Under sleeper pads are an effective vibration reduction measure for Dutch railways.

Method

Field trials with USPs were carried out at two sites, both in 2021. Different variants from the Austrian manufacturer Getzner were tested. The static stiffness Cstat of the pads ranged from 0.07 to 0.3 N/mm2. The two test sites were Oisterwijk and Zevenaar. Measurements were performed by Witteveen+Bos (Bezemer-Krijnen et al., 2021) and DGMR (Fennema, 2021). We-Boost subsequently produced a summary report (Boon, 2021).

Results

We-Boost reports that the various measurements show USPs to be effective mainly above 30 Hz for freight trains and above 40 Hz for passenger trains. Vibrations at these higher frequencies are only perceptible close to the track and content in these bands decreases rapidly with distance. High-frequency vibrations decrease by about a factor of 3 with USPs – that is, a 67% reduction, or 9.5 dB.

When USPs are installed, tamping is also carried out. For the combination of USPs and tamping, reductions at low frequencies (below 6 Hz) were also found (Boon, 2021). Figure 29 summarises the results in two plots; the reduction is about 50%. However, tamping can lead to increases in vibration levels at mid-frequencies between 10 and 40 Hz (see Tamping and Infrastructure maintenance).

The effects of tamping – both the beneficial effect at low frequencies and the adverse effect at mid-frequencies – did not significantly diminish over a year and are therefore presumably persistent.

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[36] The report by Witteveen+Bos designates a reduction as a negative insertion loss (i.e. –15 dB).

[37] In ProRail's design specification for level crossing surfaces, text has now been included concerning environmental nuisance caused by railway vibrations (see OVS00056-5.2 Surfacing for level crossings, pedestrian crossings and rail access points). It states that when there are buildings near the level crossing that may experience vibration nuisance from the surfacing, (complete) replacement or installation of a rubber or plastic surfacing is preferred.

The effect of USPs decreases with distance from the track; at distances greater than 40–50 m, little or no effect was found. USPs appear more effective for freight trains than for passenger trains, likely because the higher axle loads of freight trains lower the natural frequency of the USPs (Boon, 2021).

On stiff ground (sand), USPs appear more effective than on soft ground (clay or peat). At Oisterwijk (sand), USPs were already effective from 10 Hz, whereas at Zevenaar (clay with sand) they were only effective from 30 Hz. Particularly below 30 Hz, the effectiveness claimed by manufacturers appears to have been estimated too optimistically.

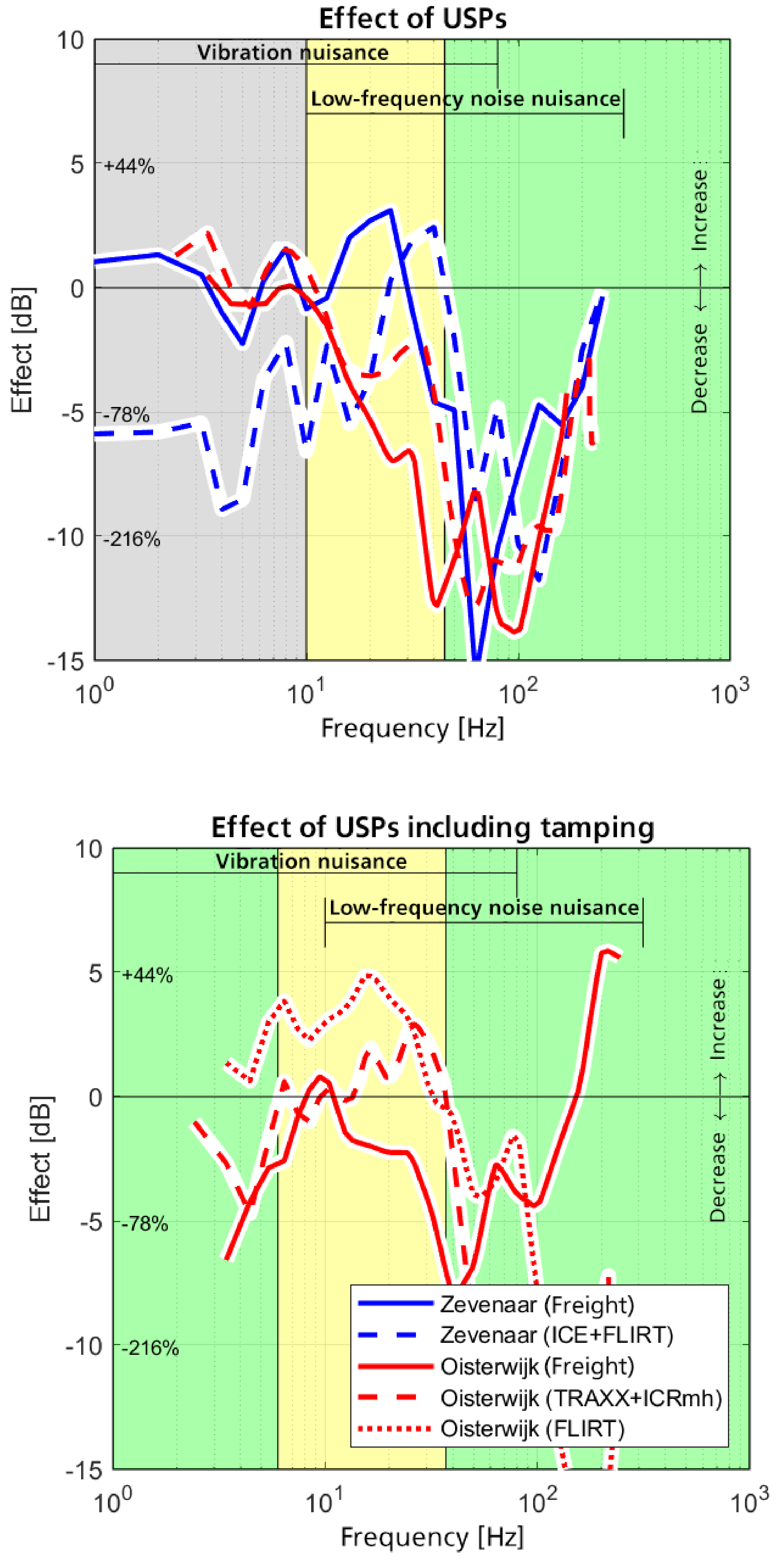
The report by We-Boost concludes that USPs are particularly effective against high-frequency vibrations, which are mainly perceptible close to the track on stiffer ground conditions (Boon, 2021). In combination with tamping, reductions in vibration levels are also visible at lower frequencies.

The report concludes that USPs can be an effective measure against railway vibrations and against low-frequency vibrations that are experienced as bothersome at many other locations. The qualification that We-Boost adds in the report is that, for dwellings sensitive to vibrations between 10 and 40 Hz, the installation of USPs may not result in a reduction of vibrations. New results from a test with USPs in the track at Best are expected to become available in the autumn of 2025.

Table 19 Effect of USPs

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
5–10 dB above 40 Hz; between 10–40 Hz an increase of 0–3 dB; below 6 Hz possibly a positive effect.	3. Use of a vibration-isolating material within the track structure.	Medium – two sites were measured, but combined effects (notably tamping) also play a role.	The theoretically expected under sleeper pad effect is reflected in the measurements.	Limited. The mechanism and its limitations are known.

Figure 29 Measured effect of USPs in Zevenaar and Oisterwijk (Boon, 2021).



SBIR innovation: Low-Vibration Sleeper

Background

Damaged IRJs are a potential source of vibrations. In the SBIR innovation 'TrillingsArme Ligger' (Low-Vibration Sleeper, TAL), the consortium Witteveen+Bos, Logitech and Alom proposed a measure aimed specifically at this potential source. The concept evolved during the project. The original idea was to develop a new type of insulated rail joint – the TrillingsArme Elektrische Scheidingslas (Low-Vibration Insulated Rail Joint, TAS joint). Compared with a standard IRJ, the TAS joint incorporates several design changes to the fishplate, the rail contact and the sleeper, making it (among other things) stiffer and less sensitive to disturbances than a normal IRJ. This was expected to have a favourable effect on railway vibrations. During preparation for the field trial, the design was changed to a Low-Vibration Sleeper (TAL), because the TAS joint did not yet meet the requirements for installation in track. The TAL concept consists of two lightweight sleepers coupled together and installed beneath an IRJ. The TAL provides additional load distribution and support to the rail on both sides of the IRJ, thereby preventing degradation of the track – especially voided sleepers.

The primary aim is therefore not an immediate short-term vibration improvement, but improved geometry and quality of the IRJ location in the longer term, ultimately yielding lower vibration levels near IRJs over time.

Hypothesis

Installing a TAL beneath an IRJ prevents degradation of track geometry around the IRJ. Over the longer term this offers an advantage over standard joints, preventing increases in vibrations due to geometry degradation.

Method

The effect of the TAL is being determined in a field trial. On the line between Wezep and 't Harde, a TAL was installed in one of the two tracks at the location of an existing IRJ. In total, vibrations were measured in three sections along the track in accordance with the Uniform Measurement Protocol. Measurements were performed by Cohere Consultants and IV-Infra. Multiple sections were used so the TAL's effect could be assessed in several ways: by comparing measurements in the same section before and after TAL installation to determine the TAL's direct effect; by comparing with the effect of a standard welded joint (installed in a different section at the same time) to determine the TAL's performance relative to a standard welded joint. The standard welded joint is built into another section at the same time as the TAL. The third section is a reference section in which nothing on the track was changed between the pre- and post-measurements. The measurements in this section are carried out to determine how great the influence of other factors is. By re-measuring at several times after installation, the (medium-term) effect will be determined.

Results

As of early July 2025, no results are yet available from the before/after comparison of vibration measurements for the TAL. Results are expected in autumn 2025.

Table 20 Effect of Low-Vibration Sleeper

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
Not yet available	Not yet available	Not yet available	Not yet available	Not yet available

SBIR innovation: Adjustable IRJ

Background

Within the SBIR programme, We-Boost and Kampa proposed the concept of the Adjustable IRJ. In this measure, a sensor is used to monitor the position of an IRJ. When the position is insufficiently good (due to voided sleepers), a ShimLift is installed. If the position deviates again after installation, the ShimLift is 'readjusted'. The aim is to optimise the effect of installing the ShimLift. An optimal position prevents voided sleepers from developing over time at IRJs.

The measure consists of three components:

1. the tested and approved product ShimLift (see Adjustable-height fastening);
2. a newly developed vibration sensor;
3. new algorithms to predict maintenance requirements.

Hypothesis

The innovative aspect of the measure lies primarily in the fact that the operation of the ShimLift is optimised through smartmonitoring of track geometry in combination with underlying data analysis. From the data analysis follows a prediction of when and by how much adjustment is required.This optimises the effect of installing the ShimLift over time. Ultimately, this prevents hammering of IRJs and thus eliminates an important source of railway vibrations.

Method

In December 2024, baseline measurements were carried out at three locations along the Brabant route in accordance with the Uniform Measurement Protocol. The locations were near Overbroek in Breda, near Galgestraat in Teteringen and near Zwartvenseweg in Tilburg. The measurements were performed by the partnership Cohere Consultants and IV-Infra.

IRJs are present in both tracks at all three locations. At all three locations, there was poor track geometry, determined by We-Boost based on BBMS data and observed by the performance-based maintenance contractor. Between January and March 2025, ShimLifts were installed at the sites. At two of the three locations, adjustable IRJs were installed in both tracks; at the third, only in one track. The ShimLifts were then readjusted after several weeks. Two of the five ShimLifts were ultimately not readjusted for technical reasons. Follow-up measurements were carried out in April 2025, at exactly the same points as the baseline measurements.

Results

According to the report by We-Boost and Kampa, the configuration comprising the three components functions well in practice (Kampa & We-Boost, 2025). When the ShimLift is installed on aged IRJs, the deflection and impact effects are reduced – particularly after readjustment. The report concludes that the measure provides insight and control over the condition of the IRJ. Installation and readjustment were found to be safe, practical and efficient.
The report concludes that, after installation, a performance-based maintenance contractor or asset manager no longer needs to enter the track to detect voided sleepers. There is now daily insight instead of the usual semi-annual inspection with the measurement train. The sensor issues a signal when a preset threshold value is exceeded, giving the performance-based maintenance contractor a basis to take timely action. With the adjustable IRJ, maintenance acquires the intended preventive character instead of the current corrective character.

Table 21 Effect of Adjustable IRJ

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
The sensor functions well. Readjustment based on sensor data appears to be effective in addressing voided sleepers and impact effects. Vibration measurements show variable results.	2. Modification to the track to reduce the dynamic wheel–rail force.	Moderate – measurements followed the Uniform Measurement Protocol and were specifically designed for effect determination. Long-term effects have not yet been determined; readjustment may be needed again. Possible influence from replacing	The effect of the ShimLift varies, which was also found in other field trials.	Yes – particularly potential to further develop the sensor.

Vibration measurements show a difference in vibration-reducing effect between the three test sites. A distinction is made between the effect of installation and that of readjustment of the ShimLift. At the Breda site, a positive insertion loss is found between 10 and 40 Hz, rising to just above 5 dB. At this location, the IRJ was replaced one day after installation of the ShimLift, which subsequently led to additional insertion loss. For higher frequencies of 63 Hz and above, a negative insertion loss was measured, rising to more than –5 dB.

For the Tilburg and Teteringen sites, less effect is found when looking at the installation of the ShimLift. Mainly positive insertion loss is found between 20 and 40 Hz, and negative insertion loss at higher frequencies, similar to site 1 but to a lesser degree. Readjustment does not appear to have much effect on the measured vibrations. Insertion loss fluctuates by frequency band between –2 and +2 dB.

Figure 30 Photo of installed sensor – Adjustable IRJ

SBIR innovation: Railtube

Background

Within the SBIR programme, the company MIS7 proposed the innovative measure Railtube. This measure is based on a bioplastic tube developed by MIS7. The tube is installed in the ground and is completely biodegradable. Installing several tubes in a specific pattern in the ground is expected to 'break up' and scatter vibration waves, thus having a vibration-reducing effect.

Hypothesis

By installing tubes in a specific pattern in the ground, a type of metamaterial is created locally. This material has different properties from the surrounding soil for specific frequencies. According to the MIS7 report, this is expected to result in a negative refractive index. MIS7 ultimately expects that vibration waves will be absorbed, damped and deflected, resulting in a reduction of vibrations in the soil behind the tubes (Voorma, 2025).

By placing the tubes in a regular pattern (a grid), an interference pattern is expected to arise that affects the transmission of certain wavelengths.

Method

Railway vibrations with these specific wavelengths are mitigated in this way, while other wavelengths are unaffected and pass through the grid undisturbed. Based on model calculations, an effect is expected between 25 and 40 Hz. A different computational model from the STEM model was used.

In a field trial, Movares carried out vibration measurements before and after installation of the Railtube in the ground. Unlike the other four SBIR field trials, this measure was tested using an artificial vibration source. The test site was not located along the railway. The artificial vibration source consisted of a drop weight generating vibration waves – i.e. a drop test. The drop test was conducted before and after installation of the grid and in accordance with the Uniform Measurement Protocol (see Artificial vibration source).

Three configurations were tested in the field trial:
- a grid of three rows, with tubes filled with air;
- a grid of four rows, with tubes filled with air;
- a grid of four rows, with tubes filled with water.

Table 22 Effect of Railtube

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
2 to 10 dB between 20 and 31.5 Hz.	5. Modification of the transmission to limit the propagation of railway vibrations into the surroundings.	High – the model is not yet able to make predictions. The measure has also only been tested with an artificial source..	In line with the expected working principle, but in a different frequency range.	Improvement may be possible through the use of steel tubes. The computational model requires further refinement

The tubes were driven five metres deep into the ground. The distance between the rows was four metres, so a four-row grid required an area of 12 × 12 metres. This imposes a limitation for application beside the track, as that amount of space is often unavailable.

In the measurement setup, the force exerted on the ground by the drop weight was determined by measuring its acceleration over time and multiplying by its mass. At distances of 1, 12, 17 and 25 metres from the drop weight setup, the ground's vibration response was measured. Subsequently, the so-called mobility was determined in the frequency domain for each measuring point (mobility is defined as vibration velocity divided by force). By comparing mobility before and after installing the Railtube at each receiver point, the influence of the measure was determined. A computational model was used to attempt to calculate the effect of the Railtube before and after installation.

Results

The initial measurement results with the drop weight show that the expected operating principle is confirmed. Specifically, a frequency range was identified in which a lower mobility was measured after installation of the Railtube. The frequency range in which reduction occurred (20–32 Hz) differed, however, from that calculated by the model (25–40 Hz). It was not possible to calibrate the model to the measurement results, so the computational model cannot yet be used to predict the vibration-reducing effect.

The measurements show no difference between tubes filled with air and those filled with water, which is advantageous in practice because it means tubes can in principle be installed both above and below the groundwater level. The biopolymer proved rather fragile when installing larger diameters, so steel tubes are recommended for further development.

Figure 31 Overview photo of Railtube test setup

SBIR innovation: Modular MetaBarrier

Introduction

Within the SBIR programme, the Modular MetaBarrier was proposed by Kampa, We-Boost and Arcadis. This is an underground concrete barrier composed of internally adjustable mass-spring systems (see Figure 32). The modular ground barrier is installed directly alongside the railway track. The product has already been successfully tested once in Germany[38]. As a result, it was expected that the solution could be easily and quickly implemented in the Dutch context. A major advantage of the MetaBarrier is that it requires only a shallow installation depth of 1 to 1.5 m.

Hypothesis

According to the report by Arcadis, Kampa and We-Boost, the modular MetaBarrier not only reflects vibration waves but also has a unique absorbing function (Arcadis, Kampa & We-Boost, 2025). Based on earlier test results, it was expected that the barrier would be particularly effective against vibrations in the frequency range between 20 and 40 Hz. The expectation was that the barrier would be especially effective for point sources and on sandy soils.

The elements act as mass-spring systems that absorb vibrations. The MetaBarrier therefore does not need to be as deep as other underground vibration barriers (TROCs – Trillings Reducerende Ondergrondse Constructies, vibration-reducing underground structures) that reflect and deflect vibrations.

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[38] The product was developed by the Italian company Phononic Vibes.

Method

The MetaBarrier was installed over a 60 m section beneath the inspection path alongside the railway track near Prinsenbeek. The effect of using the Modular MetaBarrier was determined by vibration measurements carried out by Movares. Measurements before and after installation were conducted in accordance with the Uniform Measurement Protocol. Subsequently, the insertion loss was determined at various distances from the track. The measurement results were validated by We-Boost through model calculations using the STEM calculation model.

According to the report by Arcadis, We-Boost and Kampa, finding a suitable location for carrying out the trial was a major challenge due to a number of conditions set for the site, including soil characteristics.

Figure 32 Cross-section of MetaBarrier showing internal mass-spring system

Table 23 Effect of MetaBarrier

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
Limited. For frequencies above 20 Hz up to a maximum of 3 dB.	5. Modification of the transmission to limit the propagation of railway vibrations into the surroundings.	Low – measurements according to the Uniform Measurement Protocol, specifically for determining the effect of the measure.	Softer soil than initially assumed.	Limited – the effect may be somewhat better on stiff sandy soils.

Results

The measurements show that the vibration-reducing effect of the MetaBarrier is smaller than initially expected. The MetaBarrier mainly affects high-frequency vibrations, from approximately 20 Hz upwards. The effect reaches a maximum of about 3 dB. The reduction effect decreases with distance from the track. The results ultimately deviate from expectations.

Using the STEM calculation model, the real-life test situation was simulated and the insertion loss of the MetaBarrier was calculated. The calculations show that the stiffness of the soil has a strong influence on the functioning of the MetaBarrier (Arcadis, Kampa & We-Boost, 2025). The calculations also show that the effect of a MetaBarrier installed very close to the track, as in the field trial, is less than anticipated. The explanation given in the report by Arcadis, We-Boost and Kampa is that the soil composition was weaker than initially assumed.

The report by Arcadis, We-Boost and Kampa ultimately concludes that, although the effect is smaller than expected, part of the research questions can be answered positively. No negative effect was found from placing the block (the MetaBarrier) deeper with only a thin soil layer above it, no negative effect was found from interruptions and no adverse influence on the track geometry was observed. Installation could be carried out efficiently. Experience gained from a preliminary trial led to faster installation than originally planned.

Figure 33 Installation of MetaBarrier

SBIR innovation: Bio Inspired Soil Improvement

Introduction

Within the SBIR programme, the consortium of Groundwater Technology, Cohere Consultants and CBBG[39] has proposed an innovative measure based on Bio Inspired Soil Improvement (BISI). This technique uses bacteria that trigger a cementation process in the soil. The result is a kind of calcareous sandstone formed within the ground. This creates a vibration-reducing underground structure (BISI-TROC) (van der Heijden et al., 2025). The BISI-TROC influences the propagation of vibrations through the soil.

Hypothesis

The functioning of various TROC variants has been studied multiple times in the past (Andersen & Nielsen, 2005; Coulier et al., 2013; van Gaal, 2024). It was expected that, by creating a sufficiently stiff BISI-TROC, vibrations would be reduced by at least 30% in a zone behind the BISI-TROC. The effect was expected to be frequency-dependent.

Method

The BISI-TROC was tested at a trial site 8 m from the track near Diepenveen. The BISI-TROC is 50 m long, 2 m wide and 4 m deep. Various measurements were carried out in the field trial, including local CPTs (cone penetration tests), shear-wave velocity measurements before and after construction and vibration measurements at various distances from the track to determine the effect of the measure, in accordance with the Uniform Measurement Protocol. The combined procedure of the Uniform Measurement Protocol was applied, in which vibrations were measured in both a reference section and a test section where the BISI-TROC was installed. The vibration measurements were conducted by Movares.

Results

The effect of the BISI-TROC was ultimately determined for passenger trains. For freight trains, it was not possible to perform a quantitative analysis due to the small number of measured passages. According to the report by Groundwater Technology and Cohere Consultants (van der Heijden et al., 2025), the following conclusions were drawn for passenger trains:

- At 8 and 12 metres from the track, vibration reduction was observed on and behind the BISI-TROC in the horizontal measurement directions.
- Between 8 and 32 metres from the track, a consistent pattern was recorded in which the BISI-TROC increased vibrations at higher frequencies and slightly reduced them at lower frequencies.
- At 48 and 64 metres from the track, this pattern was reversed: at lower frequencies, no effect was observed, while at higher frequencies a reduction in vibrations was observed.
- A difference was found between the comparison of the before-and-after measurements in the test section and the comparison with the reference section. The report notes that the observed vibration increase caused by the BISI-TROC at higher frequencies may have been the result of differing measurement results in the reference section (van der Heijden et al., 2025).

Using the STEM calculation model, two-dimensional models were developed to calculate insertion losses. The models took into account the local soil conditions and the measured increase in soil stiffness at the location of the BISI-TROC. CPTs and shear-wave velocity measurements show that the stiffness increased by a factor of 1.5 to 2 – lower than the factor of 8 initially expected based on literature (van der Heijden et al., 2025). The measurements do confirm that the cementation process affected the soil properties. The developed model was validated against the CPTs and shear-wave velocity data.

The calculation models showed less fluctuation in outcomes than the measurements. The insertion loss behind the BISI-TROC in the embankment was calculated at approximately 1 dB. In the shallow soil directly behind the treated zone, the measurements showed a vibration reduction of 2 to 5 dB.

Both measurement and calculation results indicate that the vibration-reducing effect of a BISI-TROC depends on distance from the track, on the spatial distribution of soil properties and on frequency. According to the report by Groundwater Technology and Cohere Consultants, the calculation model for the field trial leads to the following conclusions:

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[39] CBBG is a consortium of US universities.

- A BISI-TROC constructed solely in an embankment reduces vibrations only within that embankment, and the effect is limited – about 1 dB according to calculations (while measurements show 2 to 5 dB).
- To achieve vibration reduction at greater distances and lower frequencies, a deeper TROC is required.

The report notes the importance of improving construction methods so that the degree of cementation – and thus the resulting increase in stiffness – is greater.

Additional model calculations of the field trial indicate that a stiffness increase by a factor of 4 would lead to insertion losses behind the BISI-TROC of approximately 2 to 3 dB, corresponding to a 20–30% reduction.

Despite its limitations, the field trial shows that the BISI-TROC is a technically feasible and innovative solution, provided it is well designed and adapted to local soil conditions. The installation was successful and the cementation process occurred without disrupting train traffic. The track geometry was not adversely affected.

The measurement results correspond fairly well with the calculated results. The models produced smaller effects than the measurements showed. Groundwater Technology and Cohere Consultants conclude that the models are particularly valuable for estimating effects and comparing design variants.

Table 24 Effect of BISI-TROC

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
2–5 dB in a limited zone behind the BISI-TROC. Effective only for sandy soils with sufficient permeability.	5. Modification of the transmission to limit the propagation of railway vibrations into the surroundings.	Low – measurements according to the Uniform Measurement Protocol, specifically for determining the effect of the measure.	The effect of the BISI-TROC is smaller than originally expected; the process produced a smaller increase in soil stiffness than anticipated.	There is scope for improvement. Literature reports much greater improvements in soil parameters.

Figure 34 Photo of BISI-TROC installation during construction

2D. Rolling stock innovations

Y25+ bogie

Background

Following the vehicle simulations (see Vehicle simulations), Ricardo Rail carried out an exploratory desk study on the technical and commercial feasibility of large-scale implementation of two modifications to the Y25 bogie as vibration-reducing measures (Thijssen & Baltus, 2024). The simulations identified two potentially promising modifications to the Y25 bogie[40]:

1. a reduction of the unsprung mass by 20%;
2. the addition of a rubber element as a secondary suspension between the bogie and the wagon.

Within the IBS programme, the modified Y25 bogie has been given the name Y25+ bogie, incorporating both of these modifications.

Hypothesis

It was expected that developing and testing a prototype would be feasible.

Method

In this study, existing literature was reviewed and relevant available suppliers were consulted. The investigation identified a difference in the Technical Readiness Level (TRL).

Results

Other innovative bogies have been designed in the past, such as the LEILA bogie[41]. As far as is known, the influence of other innovative bogies on railway vibrations has never been studied. Due to high investment costs, there appears to be limited support for the application of these other innovative bogies. Therefore, within the IBS programme it was decided to investigate a modification of the existing Y25 bogie instead.

Reduction of unsprung mass

A reduction of unsprung mass appears possible based on currently available technologies. The maximum feasible reduction is estimated at around 20%. This can be achieved through the use of hollow axles made of high-grade steel and Compact Tapered Bearing Units (CTBU). The TRL of these technologies is rated at 9, indicating that the technology has already proven itself in an operational environment. In principle, the technology can therefore be applied on a large scale. The main drawback is the increased sensitivity of the hollow high-grade steel axles to corrosion and cracking, which affects safety. With appropriate measures to address this (which have an impact on maintenance and costs), hollow axles can be implemented.

Retrofitting existing Y25 bogies can be carried out relatively easily, as wheelsets have their own life cycle and maintenance schedule independent of the bogie. Replacing a standard wheelset with another (lightweight) wheelset is a normal maintenance activity.

Addition of rubber element

The addition of a rubber element as secondary suspension is a technological concept that has not yet been implemented. The TRL of this technology is assessed at 2. To raise the concept to a higher TRL, a test with a prototype rubber element has been proposed. Several challenges must be overcome before the technology can be implemented on a large scale.

The impact of adding the rubber element as secondary suspension on maintenance aspects (RAMSHE – Reliability, Availability, Maintainability, Safety, Health & Environment) is expected to be mainly negative, as the availability of the rolling stock is expected to decrease and maintenance costs to rise. When the technology has been further developed, a solution must therefore be found for this impact on RAMSHE aspects. In any case, an increase in costs must be anticipated for both investment and maintenance.

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[40] There is also potential for vibration reduction through the development of new innovative bogies. However, this did not form part of the IBS programme, as the focus was on optimising existing rolling stock.

[41] LEILA is a bogie designed as part of a Swiss research project conducted between 2005 and 2009. See: https://www.aramis.admin.ch/Grunddaten/?projectid=23098

A test with a prototype rubber element is expected to provide insight into the reduction of railway vibrations and how this performs in combination with reduced unsprung mass.

Several design concepts were considered during the feasibility study. One of these solutions appears feasible for a prototype, but further research is required for possible large-scale implementation. The design must meet a specific set of requirements. Consultations with several manufacturers indicated that these prototype requirements can be met.

Discussions with manufacturers and wagon owners also revealed that the requirements for a prototype differ substantially from those for a design intended for full-scale rollout.

Summary of results

Testing with a prototype appears feasible. However, several challenges must be overcome before wider implementation can take place. The next step foreseen is a field trial to test the functioning of the concept. At the time of writing this report, a concept design for the Y25+ bogie has been developed which could potentially be installed in a test train. A field trial could take place at the beginning of 2026.

Table 25 Effect of Y25+ bogie

Reducing effect	Expected mechanism	Uncertainty of effect determination	Explanation of results	Potential (improvement possible?)
To be determined.	1. Modifications to the vehicle to reduce the dynamic wheel–rail force.	High – at this stage, only model simulations have been carried out. Practical measurements are required.	Reduction of unsprung mass decreases dynamic excitation at the wheel–rail contact.	Yes – the design is currently at the concept stage.

Part 3

Long-term research

Railway Vibrations Emission Model (STEM)

Since 2022, TU Delft, Deltares and TNO have been working with ProRail on the development of a computational model for the generation of railway vibrations – the Railway Vibrations Emission Model (Spoor Trillingen Emissie Model, STEM). M+P developed the approach for the research programme in 2020 (Kuijpers, 2020). The aim of the STEM model is to predict under which circumstances certain railway vibrations occur and in which situations particular measures are effective. The model makes it possible to identify more precisely the causes of high vibration levels and the impact of railway vibrations on the surrounding environment.

Open-source finite element model

The development of the STEM model builds on the earlier OURS model developed by the RIVM, which can calculate the transmission of vibrations through the soil to buildings. In the STEM model[42], the interaction between train and track and the propagation of vibrations through the subsoil are simulated. The model can calculate vibration levels at the ground surface, taking into account irregularities in track geometry, train type and speed, and the spatial variability of the track and soil properties.

The STEM model is an open-source calculation model based on the finite element method and operated via Kratos Multiphysics. Because it is open-source, anyone can use the model without licence costs. However, using it requires background knowledge of the finite element method and the Python programming language.

The model has been developed specifically for engineering consultancies specialising in vibration analysis. With STEM, such consultancies can advise more accurately on the most effective mitigation measures at specific sites.

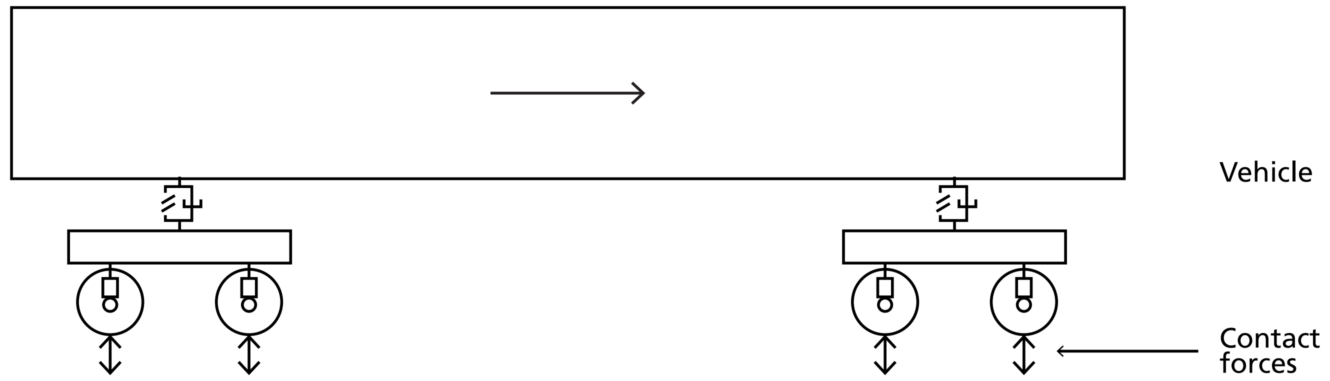
Comparison with other models

A variety of computational models exist for predicting railway vibrations. In 2016, the RIVM produced an overview of different models for the development of the OURS model (de Gruijter et al., 2016). The report identifies different types of models, including:

- finite element and boundary element method models (FEM and BEM);
- statistical energy analysis models (SEA);
- numerical train–track–soil models (often multi-body systems);
- analytical half-space models;
- empirical models.

The STEM model is a finite element model coupled with a multi-body vehicle model, designed as an emission model in which vehicle–track interaction is represented in detail. The basic methodology is not new – two- and three-dimensional finite element models for railway vibration modelling have been developed in the past, using both commercial software packages (such as LS-DYNA or ABAQUS) and in-house academic software. However, such models are not available off the shelf and require additional modelling and programming by the user.

Figure 35 Vehicle model in STEM



What makes the STEM model unique are a number of additional and combined features that, as far as is known, are not available in any other model:

- a vehicle model with ten degrees of freedom, strongly coupled with a three-dimensional finite element model in which wheel and track irregularities of varying wavelengths can be modelled. The vehicle model can easily be adapted to other configurations;
- the ability to model an IRJ within a fully three-dimensional subsurface model;
- time-dependent train passages can be modelled, with stochastic distributions in soil material parameters to investigate uncertainties in defined soil characteristics;
- modelling of spatial variability in the subsoil using conditional random fields, conditioned on ground investigations such as cone penetration tests (CPTs);
- future constitutive equations for ballast and modelling of the local impact of an IRJ based on new insights from PhD research.

These features make the STEM model unique and enable the investigation of source mechanisms through modelling.

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[42] OURS stands for Ontwikkeling Uniform Rekenmodel Spoortrillingen – Development of a Uniform Railway Vibration Model.

Figure 36 Visual representation of random field on material parameter soil stiffness (E-modulus)

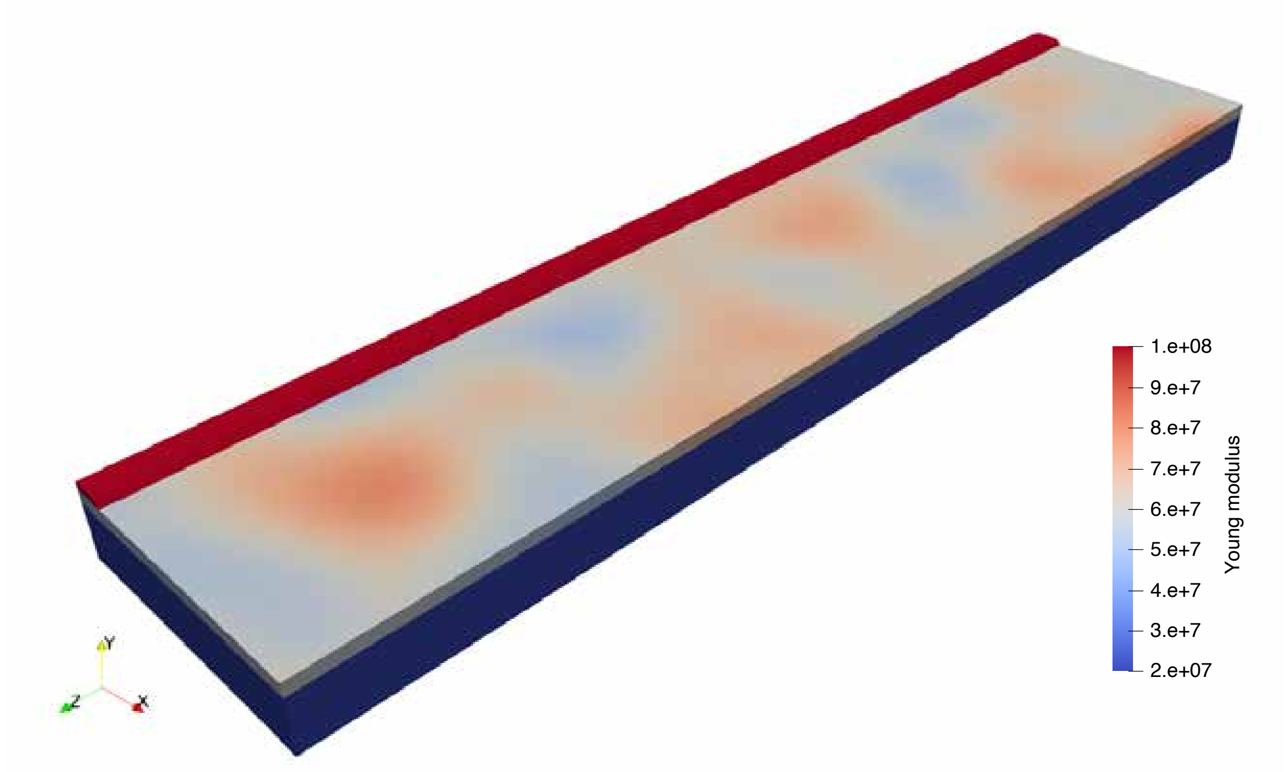
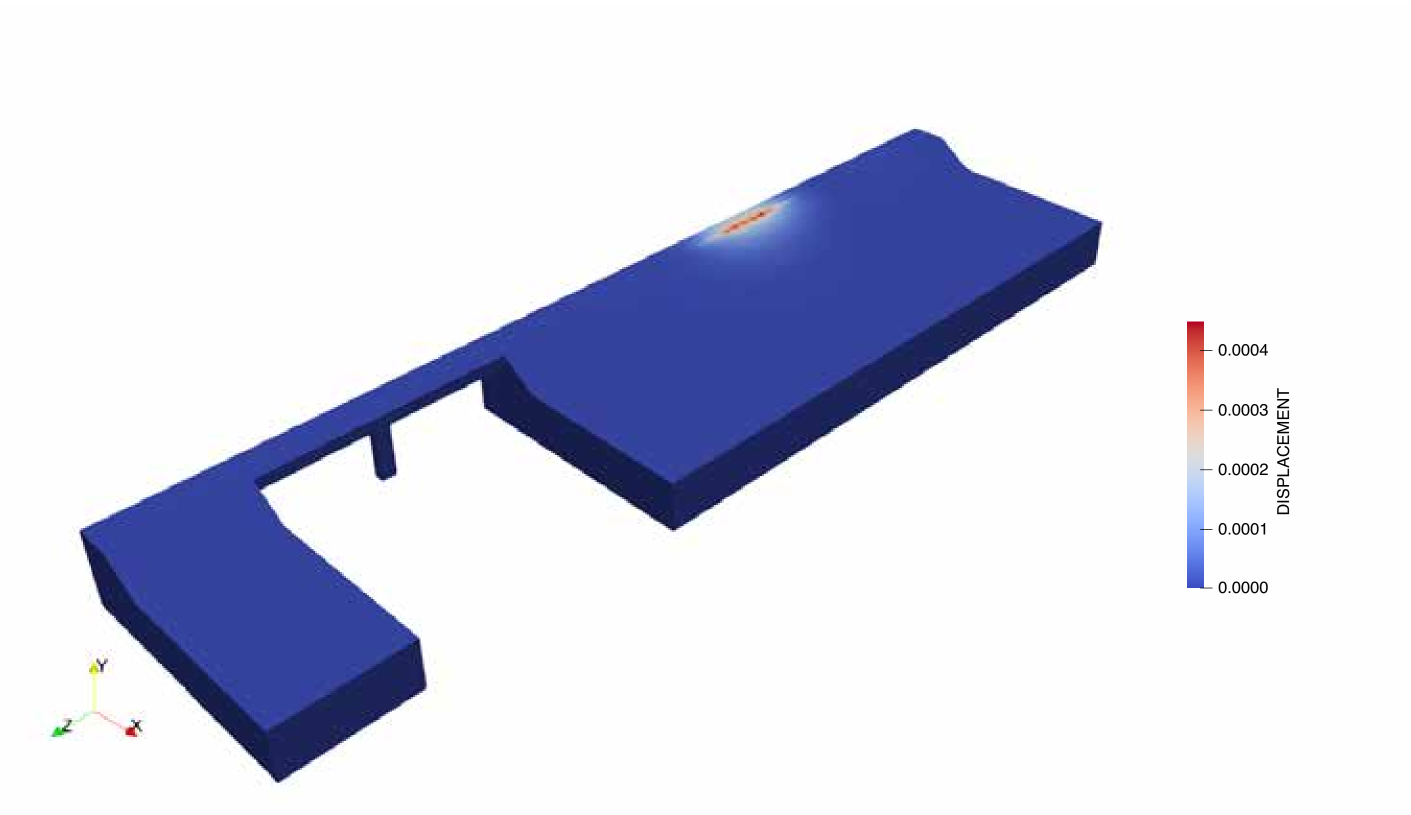


Figure 37 Representation of a discontinuity (viaduct) in the third direction of the STEM calculation model



Limitations

The only limitations of the STEM calculation model are as follows:

- The use of the model requires programming skills and background knowledge. There is no graphical interface as in commercial software; the user must run the calculations via scripts.
- Although the STEM calculation model is a comprehensive three-dimensional model that incorporates many effects, the assumptions underlying the model influence the results, including:

    - Hertzian contact force between rail and wheel;
    - the current material model for ballast is a linear model;
    - the contact force between wheel and rail currently includes only a vertical component. Horizontal contact forces between wheel and rail are therefore not yet present in the model (see Directionality of train-induced vibration).
    - for three-dimensional calculation models, a large amount of computing power is required to carry out a time-dependent analysis. For calculations in which spatial variability in the subsoil is investigated using stochastic analyses, considerable computing power is needed, for which an ordinary laptop is not suitable. This is why an option has been built in to perform calculations via cloud computing.

When using the model, as with commercial software packages, the user must make the right choices concerning element type and size, as well as solver settings, to prevent the model from producing incorrect results. As with any model, the user must be aware of what is and is not being simulated with the model.

Annual test session with practice board

To ensure that the STEM calculation model and its functionalities align with design practice, a practice board has been asked to test the model annually since development began in 2022. From this, recommendations and suggestions for improvement arise regarding user-friendliness and functionalities that, in the practice board's view, could be added. The results of the test sessions held on 6 and 7 December 2023 and 19 December 2024 show that the model in its current state meets expectations and that the practice board is positive about its development. At present, various consultants still use different software and types of models to calculate railway vibrations. The disadvantage of this is that it can lead to differences in results. The STEM calculation model provides a standard model that ensures uniformity. It is also expected that the STEM calculation model will help to interpret research results, for instance from measurement campaigns, more effectively. Further development is needed for this purpose.

Meanwhile, the second release of the Railway Vibrations Emission Model (STEM) was issued in early 2025. This updated version builds on earlier improvements.

Further development

Development of the STEM calculation model began in 2022. Other studies within the IBS programme were already well underway or even completed by that time. As a result, it was not possible to carry out simulations with the STEM calculation model during the preparation and design of the field trials. However, the measurement results are being used for the model's ongoing development and validation, which continues beyond the formal completion of the programme.

It is therefore expected that future versions will be released, offering even more functionality. For the year 2025, the following adjustments and improvements have been formulated:

- improving the track structure in the model (sleepers);
- adding multiple element types (i.e. computational element types, such as second-order elements);
- adding a constitutive model for ballast;
- adding other types of boundary conditions when necessary (possibly Perfectly Matched Layers, PML);
- adding functionality to model voided sleepers.

Important input from the various scientific studies contributes to this process. Those scientific studies will also continue for longer and they are discussed in the next chapter.

Information about the STEM calculation model can be found at: https://stemvibrations.readthedocs.io/v1.2/#

Doctoral research projects

As part of the Railway Vibrations Emission Model, scientific research is being carried out by TU Delft, Deltares and TNO (v.d. Poel et al., 2023). The research projects are divided into four work packages:

- work package 1: Spatial Variation;
- work package 2: Time Dependency;
- work package 3: Embankment;
- work package 4: Tooling.

Within these work packages, various activities are being carried out, including literature reviews, gathering data from previous studies and consulting specialists. The work package Tooling (the STEM calculation model) was described in the previous chapter. The main part of the other work packages consists of four PhD projects being carried out at Delft University of Technology (TU Delft). An important goal of the research is to develop a better understanding of specific source mechanisms of railway vibrations and to implement these subsequently in the STEM model. The working titles of the four PhD projects are as follows:

1. Characterisation of the Origin of Vibration Nuisance at Train-Track Discontinuities, PhD candidate: You Wu.
2. Railway Vibrations Emission Model – Time Dependencies, PhD candidate: Andrea Jara.
3. Numerical and geophysical modelling of wave propagation due to rail traffic, PhD candidate: Lexin Li.
4. Directionality of train-induced vibration, PhD candidate: Sijia Zhou.

Each of the four studies is briefly discussed below.

1. Characterisation of the Origin of Vibration Nuisance at TrainTrack Discontinuities

This research focuses on discontinuities in rails, with an emphasis on IRJs. The study aims to provide a description of vibrations occurring at IRJs. Based on this, a method will be developed to model the interaction between the train and the track at an IRJ. Ultimately, this can be added as a new functionality to the STEM calculation model. To this end, the research focuses on understanding the generation of vibrations at IRJs, the precise mechanism of dynamic excitation and the characteristics of an IRJ.

As part of the research, a measurement campaign was carried out at an IRJ near Oisterwijk, where an extensive measuring setup was installed. This setup was used as input for several PhD projects. For the IRJ study, in addition to surface measurements, accelerometers were mounted on the rail and sleepers and a hammer test was conducted to measure the track’s receptance. Naturally, train passages were also measured.

The results of the hammer test are compared with a finite element model in which the rail and sleepers are modelled with 3D volume elements. Springs and dampers are placed between the rails and sleepers to represent the rail fastening, and springs and dampers under the sleepers to represent the ballast bed. The measurement results are used to validate the calculation model.

The next step is to investigate how to model the IRJ accurately in such a way that:

1. a dynamic excitation is simulated and validated with the measurement results;
2. further research is carried out into variation among IRJs and its effect on vibration levels in the surroundings;
3. the model can be converted into a functionality in the STEM calculation model based on the results of steps 1 and 2.

These steps still need to be carried out. At present, no firm conclusions can be drawn from the work performed so far, as the research is only halfway complete.

2. Railway Vibrations Emission Model – Time Dependencies

The vibration levels occurring near the track depend on many parameters. Various studies show that time dependency plays an important role. The Uniform Measurement Protocol therefore explicitly addresses this aspect. However, how much change occurs over time in the track and underlying soil, and what effect this has on railway vibrations, is not yet known. This study aims to provide insight into this, with specific attention to the ballast bed.
The research questions are:

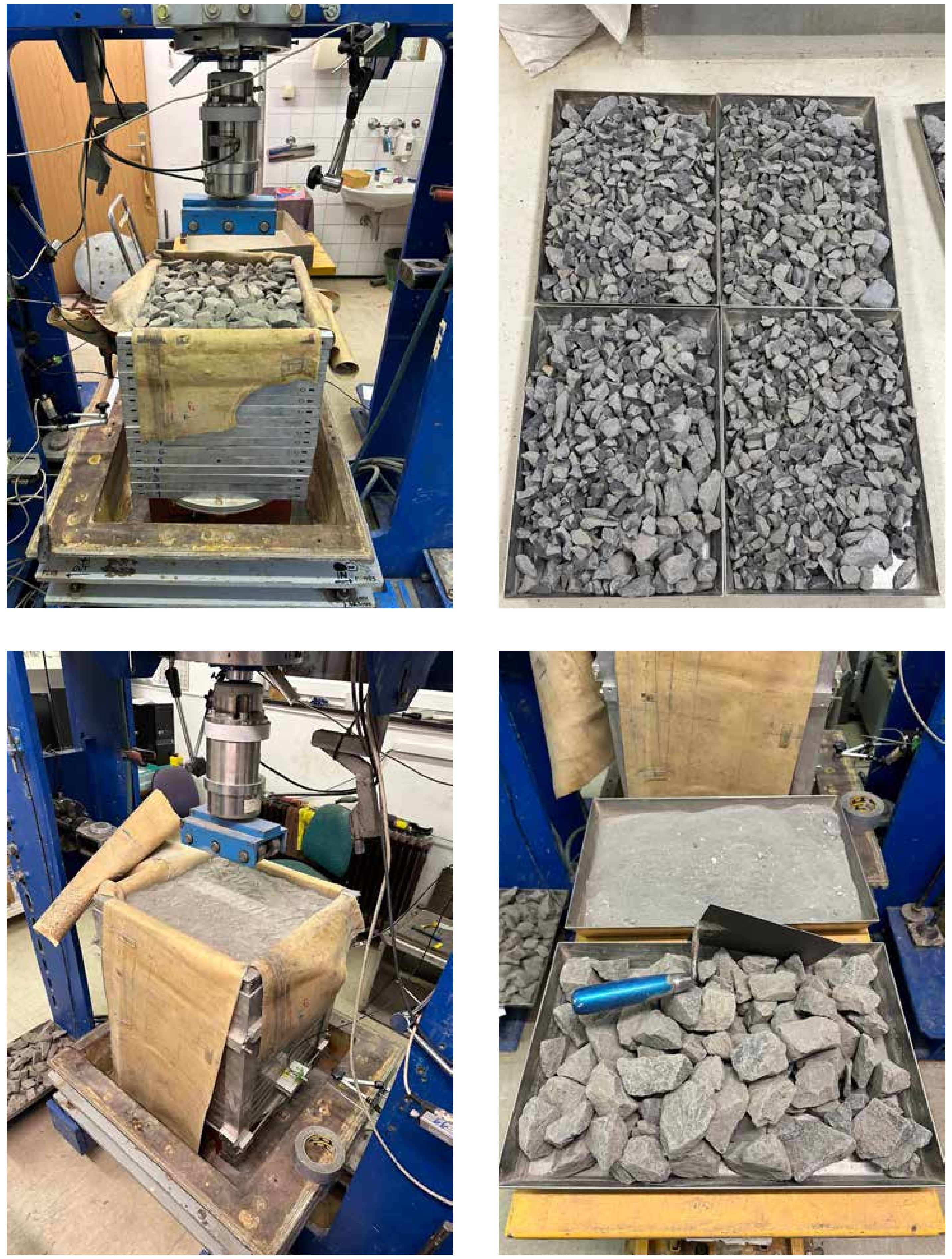
1. Which degradation mechanisms occur due to train passages, as well as due to maintenance work and wet or dry periods?
2. How is the mechanical behaviour of ballast specifically affected by degradation mechanisms?
3. How can this behaviour be captured in a constitutive model?
4. How does variation over time affect the change in vibration generation during train passages?

To answer these questions, both model calculations and measurements are used to study the behaviour of ballast. For measurement results, the same measurement campaign is used as in the other PhD projects. Laboratory tests have meanwhile been conducted on four different ballast conditions:

- Ballast Fresh[43];
- Ballast Abraded;
- Ballast Fresh + fouled;
- Ballast Abraded + fouled.

Various tests have been carried out to determine the mechanical behaviour of ballast in different stages of degradation. Based on the results, constitutive equations are derived, which are incorporated into the STEM calculation model.

Figure 38 Test setup for mechanical ballast testing



The material behaviour is being studied with a dedicated numerical model based on the Discrete Element Method (DEM[44]). The next steps that still need to be taken are:

- calibrating the DEM model with laboratory tests;
- establishing a constitutive relationship based on the results of the laboratory tests;
- performing simulations with the STEM calculation model in which the constitutive relationship is implemented;
- comparing the results of field measurements with simulation results.

3. Numerical and geophysical modelling of wave propagation due to rail traffic

How vibration waves propagate through the soil partly determines the vibration levels that occur in the surrounding area. As discussed in the chapter on railway vibrations, both surface waves and body waves occur (see Railway Vibrations). Dispersion of waves arises in layered (non-homogeneous) soil. The subsurface exhibits considerable spatial variability – it can change significantly within just a few metres. This affects how vibration waves propagate and can also influence the dynamic force between wheel and rail when such variation exists beneath the track.

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[43] Fresh ballast = a new ballast bed; abraded means worn/weathered; fouled is when the voids between the stones are filled with finer material.

[44] DEM is a numerical calculation method.

In this study, particular attention is paid to spatial variability and the following research questions have been formulated:

- How can the propagation of railway vibrations through the ground be modelled effectively while accounting for this variability?
- What is the influence of soil variability on vibration propagation?
- How can data be collected and characterised with respect to soil variability?

To answer these questions, finite element models are used to simulate the propagation of vibrations, paying particular attention to boundary conditions, discretisation methods and high-performance computing. In addition, cone penetration test data and geophysical data is used to characterise spatial variability. Random field theory is applied to develop a random finite element model based on field investigations. In the study, the influence of PML[45] boundaries has now been examined. The remaining steps still need to be taken.

4. Directionality of train-induced vibration

Nowadays, vibration measurements along the railway are usually taken in three directions using triaxial sensors. It does not always turn out that the vertical vibration level in the soil during train passages is the decisive component; quite often, the (lateral) y-direction shows the highest levels and therefore dominates compared with the other directions.

State-of-the-art calculation models generally compute both vertical and horizontal vibration levels but typically only on the basis of the vertical interaction between vehicle and track. These models are not yet able to explain the dominance of the horizontal y-direction. This research investigates the extent to which models that rely solely on vertical interaction can adequately predict vibration levels in all directions. The central question is how much the lateral vehicle–track interaction contributes to horizontal vibration levels, and what the magnitude of that contribution is.

This PhD project addresses rather fundamental questions.
The research consists of:

- Data analysis on a large dataset of vibration measurements in the soil at various distances from the track and at several locations, from which quantitative conclusions will be drawn.
- Developing an elementary model consisting of an elastic half-space loaded by a rectilinearly moving point load describing an arbitrary angle with the surface in the transverse plane of the track – the load thus varies from purely normal to purely tangential. Performing an analysis of the effect of the transverse load angle on the response of the half-space and in particular on the surface.
- Extending the model from a constant point load (static axle load) to a point load with a defined frequency content (dynamic axle load). Analysing the effect of the transverse angle of loading on the (asymmetrical) radiated wave field into the surroundings.

Alongside these fundamental issues, a concrete goal of the study is to gain insight into the validity of the STEM calculation model under different conditions. Does the model systematically predict vibration levels in the ground that are too low because it includes only the vertical wheel–rail interaction? Or does this apply only in certain conditions – and if so, which ones? And what portion of the overall response might we currently be overlooking?

The research started in 2024 and is therefore expected to continue until 2028. Concrete research results are not yet available.

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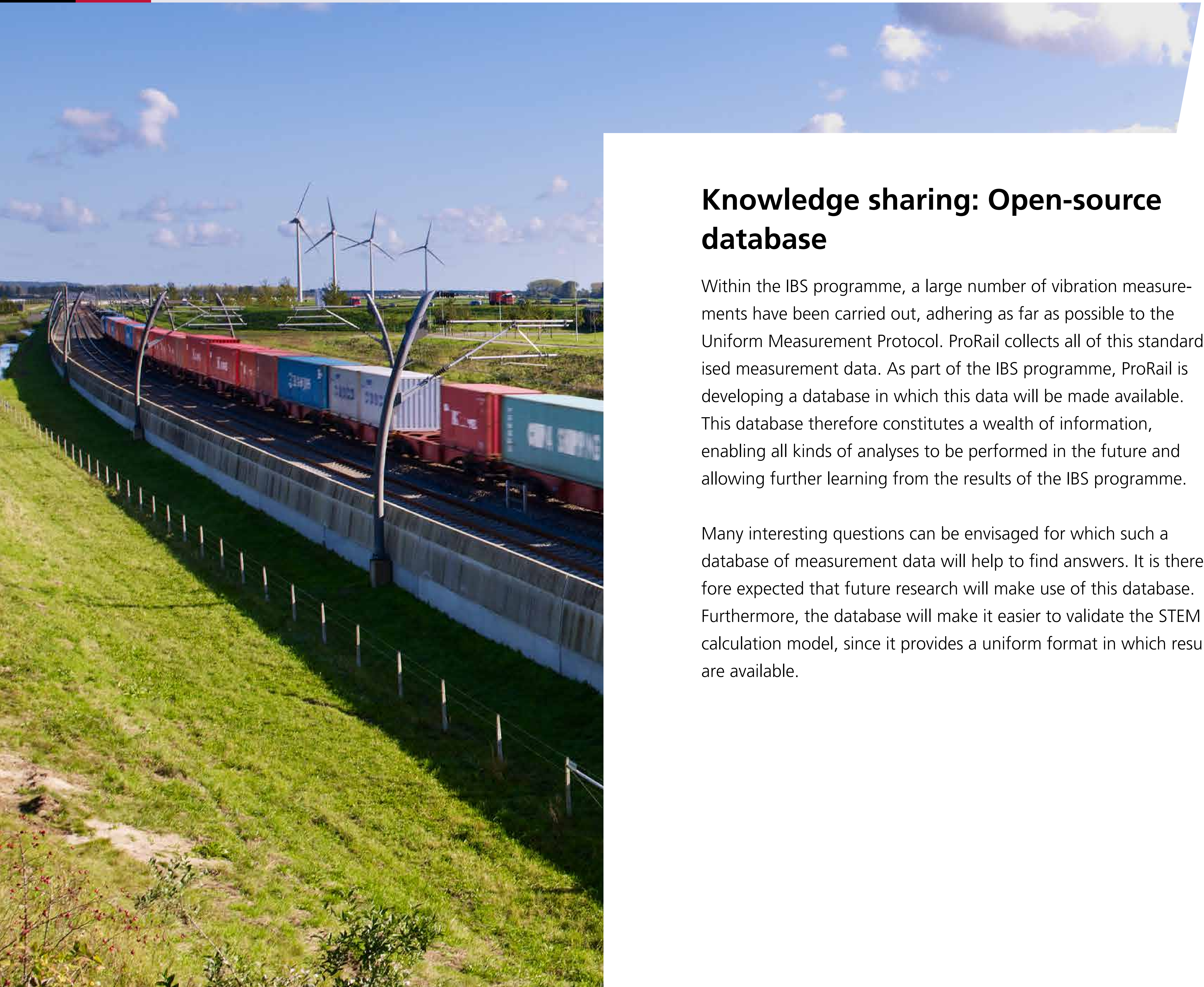
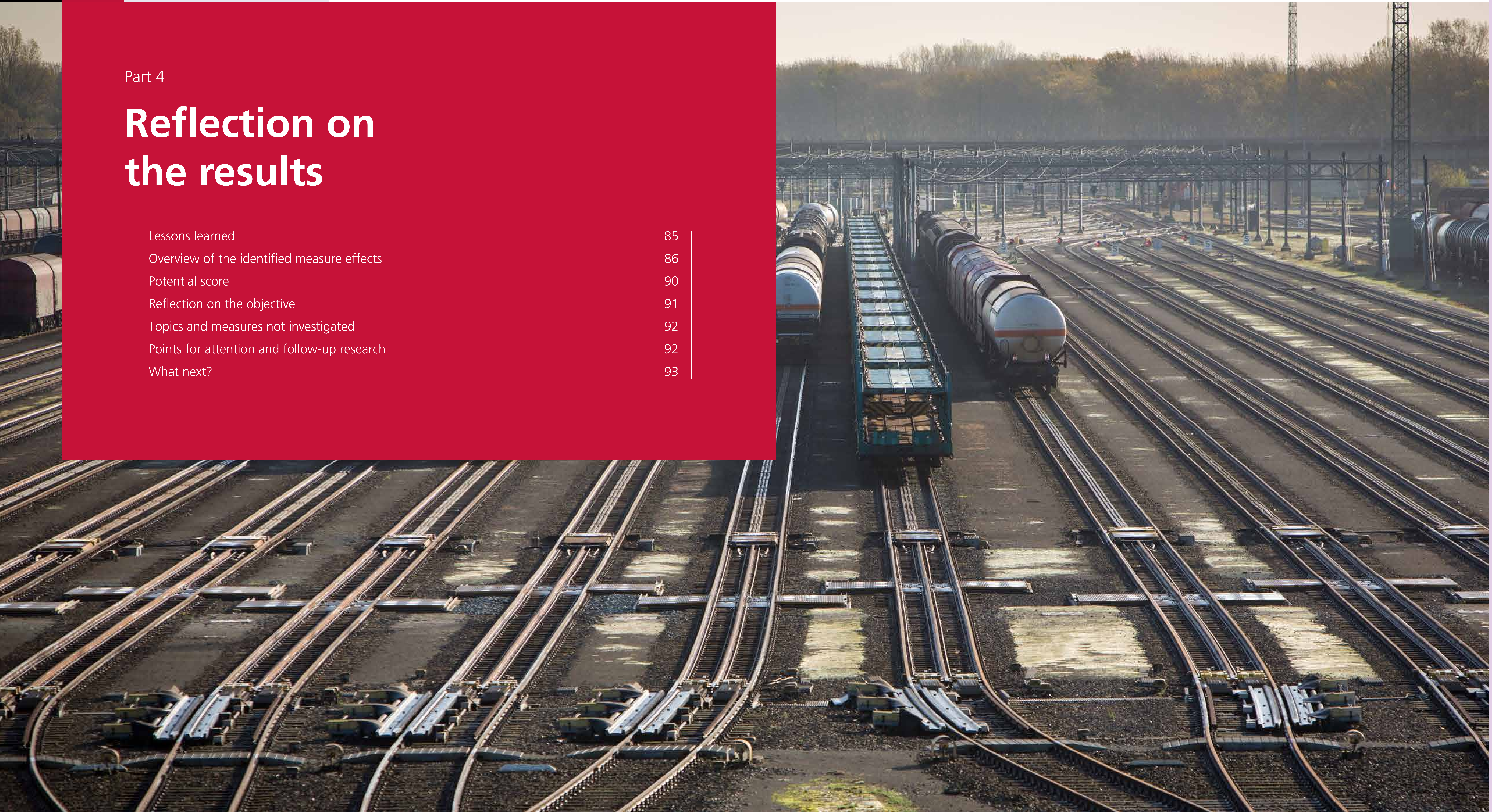
[45] PML staat voor Perfectly Matched Layers.



Knowledge sharing: Open-source database

Within the IBS programme, a large number of vibration measurements have been carried out, adhering as far as possible to the Uniform Measurement Protocol. ProRail collects all of this standardised measurement data. As part of the IBS programme, ProRail is developing a database in which this data will be made available. This database therefore constitutes a wealth of information, enabling all kinds of analyses to be performed in the future and allowing further learning from the results of the IBS programme.

Many interesting questions can be envisaged for which such a database of measurement data will help to find answers. It is therefore expected that future research will make use of this database. Furthermore, the database will make it easier to validate the STEM calculation model, since it provides a uniform format in which results are available.



Part 4

Reflection on the results

Lessons learned

Within the IBS programme, valuable lessons have been learned. The authors of this final report acknowledge that not all insights are included in this chapter, but they have attempted to highlight the most relevant ones. A distinction has been made between three categories: lessons from the field trials, lessons relating to track and rolling stock maintenance and lessons regarding procedural aspects. Readers are invited to draw their own conclusions and learning points based on the research results.

Field trials

The field trials have provided valuable insights into the vibration-reducing effect of different measures. The results vary widely, and on that basis, the outcomes have been divided into three categories:

1. measures showing little or no effect, where further research is expected to yield little additional insight;
2. measures showing limited effect but with potential for greater effectiveness;
3. measures showing relatively strong effects and promising for implementation.

This chapter provides an overview of all the measures tested. The discussion covers the three groups, focusing mainly on the measures in categories 2 and 3. The results of the field trials show that the effect of a measure always depends on both the vibration frequency and the location where it is applied.

An important lesson learned is that, before implementation, careful attention must be paid to all aspects that influence the vibrations to be measured. The chosen approach must account in advance for ways to limit the influence of side effects on determining the effect. In several field trials, it proved difficult to determine the effect of the measure unambiguously because other influences interfered with the measurements, thereby increasing uncertainty in assessing the effect.

Track and rolling stock maintenance

With regard to track maintenance, the following lessons have been formulated:

- Using Spoorligger makes it possible to identify locations with **poor track geometry** where high vibration levels are also expected. By taking targeted measures at these locations, vibration nuisance can be addressed effectively (see Spoorligger). The complaint survey indicates that nuisance reports occur more frequently at such locations (see Complaint survey).
- Many forms of standard track maintenance lead to little or no reduction in railway vibrations. However, some maintenance activities do sometimes have an effect, such as **mechanical ballast tamping**. The OBO2 study shows that mechanical tamping can, in some cases, improve track geometry and reduce vibrations, though not always. When track geometry improves by 50%, vibrations decrease by about 25% (see OBO2).

With regard to rolling stock maintenance, the following lessons have been formulated:

- Freight trains with **poor wheel quality** can generate substantial vibrations (see Wheel out-of-roundness). Improving these wheels can reduce vibration levels in certain situations, leading to reduced nuisance, especially when several poor-quality wheels occur within a single train passage. Freight train passages with multiple poor-quality wheels appear to correlate with recorded nuisance (see Disturbing train passages).
- Wheel maintenance is currently carried out under uniform European regulations primarily for safety purposes. Within the IBS programme, progress has been made towards determining more precisely in which specific situations addressing wheel defects through additional condition-based maintenance is effective. This approach has proven particularly effective in areas with stiff sandy soils.

The IBS programme has also examined the feasibility and costs of condition-based supplementary wheel maintenance. Specifically for freight wagons, several scenarios with different maintenance conditions were investigated. For each scenario, the boundary conditions for feasibility were analysed. Key prerequisites include commitment by a large number of international stakeholders, numerous mutual agreements that must be reached and the establishment of new operational processes. Additional shunting and maintenance facilities must also be built. Furthermore, monitoring system outputs must be streamlined and preferably standardised at the European level. The scenarios examined would result in increased costs for rail freight transport in the Netherlands, estimated at several to several tens of millions of euros per year. It must be weighed up whether carrying out the additional maintenance in order to reduce vibration nuisance is cost-effective. The costs cannot be borne by the sector itself without having a major impact on transport volumes, which would counteract the desired modal shift from road to rail transport. Therefore, sufficient financial resources will need to be made available to the sector for the implementation of the additional maintenance.

Procedural aspects
From the IBS programme, the following procedural lessons can be drawn:

- In tackling freight trains with wheels of poor quality, the **international** context plays an important role. A lot of freight traffic crosses national borders. This approach therefore requires coordination with various foreign parties. The Quo Vadis monitoring system is operational only in the Netherlands. Consequently, it is not possible at European level to base detection solely on the Quo Vadis system. For detection at European level, further harmonisation of monitoring systems is desirable.
- At the start of the IBS programme, a Uniform Measurement Protocol was established (see Uniform Measurement Protocol). As a result, most studies were conducted in a consistent manner. This has greatly improved the comparability of results and has led to the creation of a valuable database. The database can be used for future research and thus contributes to further knowledge development.
- The scheduling of the field trials did not coincide with the development of the STEM computational model and the implementation of scientific studies. This had several causes. In an ideal situation, this would have been the case, which would have allowed a better interpretation of the results. In particular, the comparison between measured data and model calculations could then have provided greater insight into the underlying mechanisms of action. This provides leads for follow-up research after completion of the IBS programme.

Overview of the identified measure effects

From the field trials, the measured vibration-reducing effect is available for each measure studied, see Part 2. These effects are summarised in Table 27.

In this table, each measure indicates on which type of soil the measure is likely to work well and how great the uncertainty is concerning the results obtained. In addition, each measure has been assigned a potential score. The score indicates the extent to which the measure is suitable for application and/or further development.

The score is largely determined by the vibration-reducing effect. In addition, consideration is given to the improvement potential and whether there are other aspects such as costs, feasibility of implementation and side effects in which the measure stands out compared with the other measures. The score ranges from 0 to 5. The evaluation is defined in Table 26.

Table 26 Classification of potential score

Potential score	Description
0	No applicability: negative to no effect of the measure combined with no potential for improvement and/or other negative aspects.
1	Hardly any applicability: negative to no effect of the measure combined with hardly any potential for improvement and/or other negative aspects.
2	Limited applicability: limited positive effect of the measure (up to 3 dB) combined with limited potential for improvement. No decisive negative or positive other aspects.
3	Moderate applicability: positive effect of the measure (3 dB or more) combined with potential for improvement or decisive positive other aspects.
4	High applicability: positive effect of the measure (3 dB or more) combined with potential for improvement and positive other aspects.
5	High applicability: large positive effect of the measure (6 dB or more) combined with favourable other aspects.

** The improvement potential takes into account (1) whether there are opportunities to improve the technology and (2) whether, due to uncertainties in determining the effect of the measure, an improved performance can reasonably be expected. Other aspects mainly concern costs, feasibility and side effects.*

Table 27 Overview of measures The results apply to the specific field trial situations. In other situations, the results may differ significantly.

Measure	Effect < 10 Hz	Effect 1040 Hz	Effect > 40 Hz	Effect on total vibration level	Effective on soil type	Uncertainty in effect determination	Potential score
OBO1: requirements for light manual maintenance	No effect	No effect	No effect	No effect	-	Medium	0
OBO2: requirements for mechanical maintenance	Variable: 0 to 8 dB	Variable	Variable	Variable	To be determined	Medium	3
Wheel out-of-roundness	No effect	Dependent on speed and order of out-of-roundness	Dependent on speed and order of out-of-roundness	Positive effect: 0 to 2.5 dB, but more in specific situations	Sandy soil	Low – effect determined based on extensive measurement campaign and statistical analyses.	3
Ballast mats	Negative effect: –2 to –5 dB	Negative effect: up to –8 dB	Positive effect up to 8 dB	Varies with distance from track; increase below 35 Hz	Sandy soil	Medium – first follow-up measurement appears unreliable.	2
Foamed ballast	Unknown	Unknown	Unknown	Unknown	Unknown. Expected for soft soils.	Medium – but effect determination opposite of what is expected.	2
Adjustable-height fastening	Positive effect: 2 to 4 dB	Negative effect: 0 to –3 dB	Positive effect: 0 to 3 dB	Positive effect: 0 to 2 dB	Sandy soil	Medium – measurement results contain multiple effects.	2
Geogrid	Positive effect: 3 to 5 dB	Positive effect: 3 to 5 dB	Positive effect: 3 to 5 dB	Positive effect: 3 to 5 dB	To be determined	High – measurement results show various effects and only passenger trains were examined.	3
Concrete slab	Negative effect: –4 to –10 dB	Negative effect: –4 to –10 dB	Positive effect compared with ballasted track: no sleeper passage	Negative effect: –3 to –6 dB. Therefore higher vibration levels than ballasted track	Unknown	High – representativeness of concrete slab in study is questionable; effect is compared with ballasted track.	1
Wooden sleepers	No effect	No effect	Negative effect: distance-dependent	Negative effect: –4 to –8 dB. Therefore higher vibration levels than ballasted track	Sandy soil	High – measurement results vary strongly and appear inconsistent.	0
Durable sleepers	No effect	No effect	No effect	On average, no effect; varies between –1 and 2 dB	Sandy soil	Medium – measurement results corrected for variation in subsoil.	0
Halving sleeper spacing	Not clear, appears rather negative	Not clear, appears rather negative	Not clear, appears rather negative	Not clear, appears rather negative	To be determined	Low – simulation calculations can be explained well, but translation to ground vibrations is required.	0

Measure	Effect < 10 Hz	Effect 1040 Hz	Effect > 40 Hz	Effect on total vibration level	Effective on soil type	Uncertainty in effect determination	Potential score
Switch removal	No effect	Positive effect: 5 to 10 dB	Positive effect: up to 20 dB	Varying positive effect: from 5 to 20 dB	Study on sandy soil, but effect also expected on soft soil	Medium – only passenger trains investigated.	4
PSS layer	Positive effect: up to 3 dB	No effect	Negative effect: up to –3 dB	Positive effect: up to 3 dB for low-frequency vibrations	Soft soil	High – measurement results include several effects due to superstructure renewal.	3
Tamping	0 to 3 dB	Variable. Varies by location	Variable. Varies by location	Variable but positive effect up to 3 dB. Varies by location	To be determined	Low – effect determined from measurements and statistical analyses.	3
Rubber level crossing surfacing	No effect	Positive effect: 5 to 10 dB	Positive effect: 5 to 20 dB	Positive effect: increasing up to 15 dB for specific train type (TRAXX-ICRmh)	Potentially various soil types	Medium – effect determination based on several measurement campaigns; measurement results include multiple effects.	4
Under sleeper pads	Positive effect below 6 Hz: up to 6 dB	Negative effect: 0 to –3 dB	Positive effect: 5 to 10 dB	Positive effect: only close to the track; effect limited	Sandy soil	Medium – two measurement campaigns; tamping included in effect.	2
SBIR innovation: Adjustable IRJ	Variable	Variable	Variable	Varying effect: –2 to 2 dB; sensor in particular is promising	Not yet available	Low – measurements specifically for determining measure effect.	3
SBIR innovation: Railtube	No effect	Positive effect: 6 to 10 dB	No effect	Positive effect for specific frequency; effect on total level therefore varies greatly	Unknown	Medium – measurements specifically for determining measure effect; better understanding of effect required.	2
SBIR innovation: Modular MetaBarrier	No effect	No effect	Positive effect: up to 3 dB	Limited positive effect and close to the track	Sandy soil	Low – measurements specifically for determining measure effect.	3
SBIR innovation: BISI-TROC	Positive effect: 2 to 5 dB in limited zone behind BISI-TROC	Positive effect: 2 to 5 dB in limited zone behind BISI-TROC	Negative effect	Limited positive effect: 1 to 5 dB n limited zone behind BISI-TROC	Sandy soil	Low – measurements specifically for determining measure effect.	3
SBIR innovation: TAL (formerly TAS joint)	Not yet available	Not yet available	Not yet available	Not yet available	Not yet available	Low – measurements carried out in accordance with Uniform Measurement Protocol and specifically for determining measure effect.	Not yet available
Y25+ bogie	To be determined	To be determined	To be determined	To be determined – dynamic wheel–rail contact up to 20% reduction	To be determined	Low – simulation results provide a clear picture; effect on ground vibrations still to be determined.	3

** The effects presented in Tables 27 and 28 are generally rounded and provide a global indication. In most studies, the effect varies per train type and with distance from the track.*

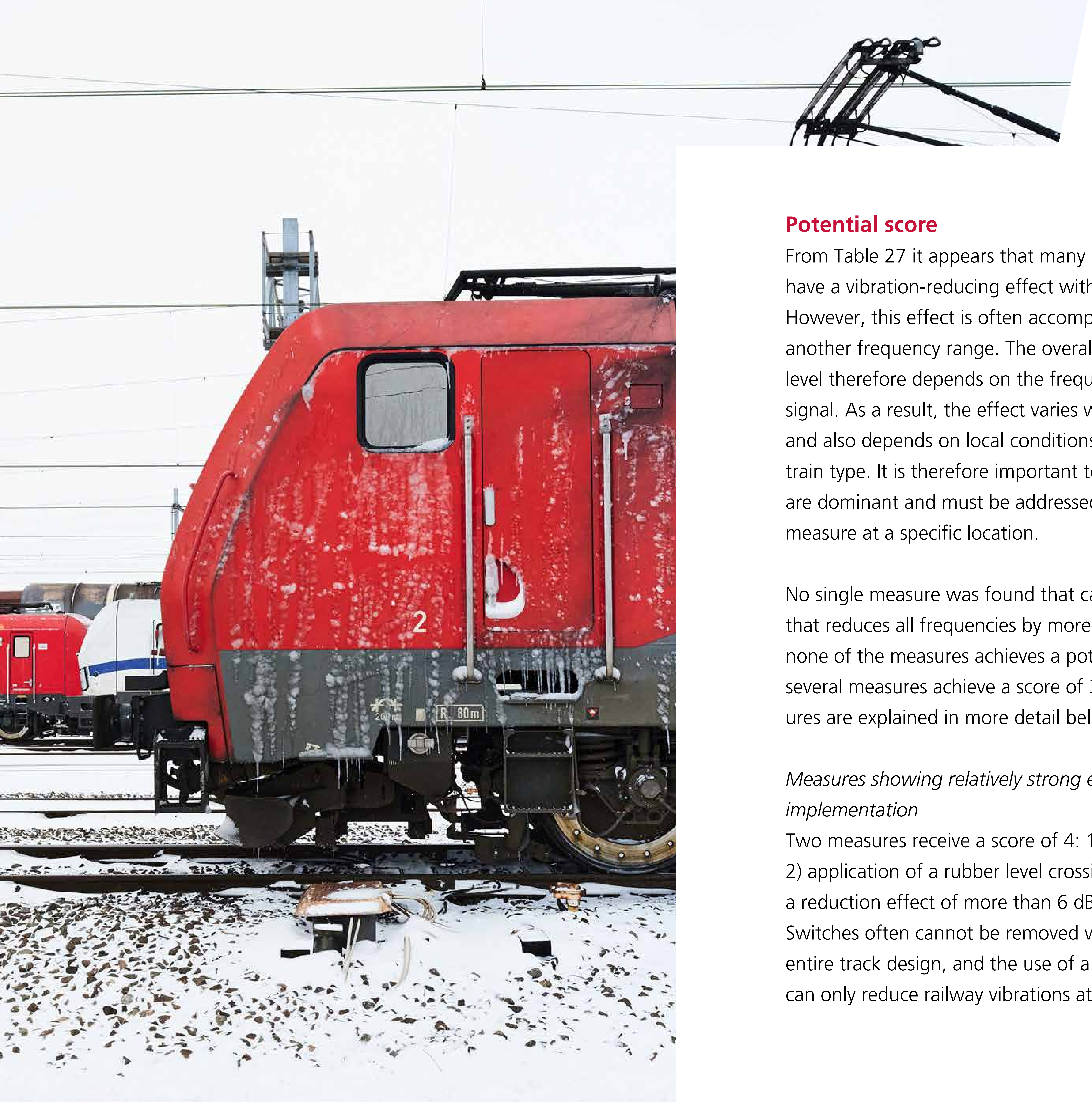
Table 28 General overview of the measure effects identified in the field trials of the IBS programme The results apply to the specific field trial situations. In other situations, the results may differ significantly.

Measures investigated	0-10 Hz	10-20 Hz	20-30 Hz	30-40 Hz	40-50 Hz	50-60 Hz	60 -70 Hz	70-80 Hz	Total level	Boundary conditions for the effect
OBO1: requirements for light manual maintenance			0						0 dB	Small effects found.
OBO1/OBO2: requirements for mechanical maintenance	0 to 8 dB	0			0				0 to 5 dB	Results apply to mechanical tamping; effect varies for different situations.
Wheel out-of-roundness	0						2,5 dB		0 to 2,5 dB	Works only for a small proportion of trains on sandy soils and mainly close to the track (up to 25 m).
Ballast mats	-2 to -5 dB		-2 to -5 dB	0 to 5 dB		5 to 8 dB			-5 dB to 8 dB	At greater distances from the track, low frequencies are more present. Favourable effect only
Foamed ballast			Further study required							
Adjustable-height fastening	2 to 4 dB	0 to -3 dB	0 to -3 dB			0 to 3 dB			0 tot 2 dB	The effect of the ShimLift varies by location and train type.
Geogrid			0 to 5 dB						0 to 5 dB	Effect determined for passenger trains and concerns a short-term effect.
Concrete slab		-4 to -10 dB							-3 to -6 dB	Results are not representative for standard concrete slab track. Effect applies relative to ballasted track.
Type of sleepers (concrete versus wood)			-2 to 2 dB						-2 to 2 dB	Results vary by measurement location. Overall effect appears limited.
Type of sleepers (durable plastic sleepers)			-1 to 2 dB						-1 to 2 dB	Limited effect found. Results apply to passenger trains.
Halving sleeper spacing									Negative?	Increase in dynamic wheel–rail forces at higher frequencies. Overall effect appears negative. Translation of wheel–rail forces into ground vibrations required.
Switch removal				5 to 20 dB					5 to 10 dB	Effect differs by location and is based on passenger train measurements.
PSS layer	3 dB								0 to 3 dB	Effect is short-term and differences were found between the two tracks.
Tamping	3 dB								0 to 3 dB	Tamping proves beneficial for low frequencies, not for high frequencies. Large variation present in results.
Rubber level crossing surfacing					5 to 20 dB				to 15 dB	Found effect is the result of complete replacement (influence also from improved track geometry, for example).
Under sleeper pads			0 to -3 dB			5 to 10 dB			-3 to 10 dB	Favourable effect only when high frequencies are decisive, close to the track in sandy soils.
SBIR innovation: Adjustable IRJ			-5 to 5 dB						-2 to 2 dB	Results vary by location. Comparable with effect of ShimLift.
SBIR innovation: Railtube			2 to 10 dB but for a specific frequency						Limited?	Effect depends on grid configuration. Specific frequencies are mitigated. Effect on total vibration level unknown but probably limited.
SBIR innovation: Modular MetaBarrier							3 dB		to 3 dB	Works only for sandy soils.
SBIR innovation: BISI-TROC									-3 to 3 dB	Effect only in zone behind BISI-TROC. Works only for sandy soils. Technical improvement required.
SBIR innovation: TAL (formerly TAS joint)			Results expected end 2025							
Y25+ bogie									Positive	Results apply to reduction of dynamic wheel–rail forces. Translation to ground vibrations required.

Impact of tools and guidelines	0-10 Hz	10-20 Hz	20-30 Hz	30-40 Hz	40-50 Hz	50-60 Hz	60 -70 Hz	70-80 Hz	Total level	Boundary conditions for the effect
Uniform Measurement Protocol			Procedural effect: helps promote reduction of railway vibrations.							Effect is procedural and cannot meaningfully be expressed in vibration reduction in dB.
Spoorligger			Procedural effect: helps promote reduction of railway vibrations.							Effect is procedural and cannot meaningfully be expressed in vibration reduction in dB.
STEM calculation model			Procedural effect: helps promote reduction of railway vibrations.							Effect is procedural and cannot meaningfully be expressed in vibration reduction in dB.

🟩	> 5 dB
🟩	3 to 5 dB
🟩	0 to 2 dB
⬜	0 dB
🟨	0 to -2 dB
🟧	-3 to -5 dB
🟥	< -5 dB

** The effects presented in Tables 27 and 28 are generally rounded and provide a global indication. In most studies, the effect varies per train type and with distance from the track.*



Potential score

From Table 27 it appears that many of the measures investigated have a vibration-reducing effect within a specific frequency range. However, this effect is often accompanied by a negative effect in another frequency range. The overall effect on the total vibration level therefore depends on the frequency content of the vibration signal. As a result, the effect varies with distance from the track and also depends on local conditions such as soil composition and train type. It is therefore important to understand which frequencies are dominant and must be addressed in order to apply an effective measure at a specific location.

No single measure was found that can be applied everywhere and that reduces all frequencies by more than 3 dB. This means that none of the measures achieves a potential score of 5. However, several measures achieve a score of 3 or 4. These promising measures are explained in more detail below.

Measures showing relatively strong effects and promising for implementation
Two measures receive a score of 4: 1) removal of switches and 2) application of a rubber level crossing surface. Both measures have a reduction effect of more than 6 dB but have limited applicability. Switches often cannot be removed without a major impact on the entire track design, and the use of a rubber level crossing surface can only reduce railway vibrations at locations where a concrete crossing surface currently exists. At locations where these measures are feasible, railway vibrations can therefore be effectively reduced.

Measures showing limited effect but expected to have potential for greater effectiveness
For measures with a potential score of 3, it is expected that the vibration-reducing effect in specific situations exceeds 3 dB. Thus, the measure has the potential for a relatively significant effect. This expectation follows from the vibration measurements and/or calculation results. The measures are divided into four sub-categories:

1. **track improvement and track geometry**: a PSS layer and Geogrid;
2. **mechanical maintenance measure**: tamping;
3. **vehicle-related measures**: poor-quality wheels and the Y25+ bogie;
4. **innovative SBIR measures** showing potential for improvement or positive side effects: Adjustable IRJ, BISI-TROC and MetaBarrier.

Both the application of a Geogrid and the addition of a PSS layer show a vibration-reducing effect, particularly at low frequencies. Since these measures are primarily applied to improve track stability, a win-win situation arises in which vibration nuisance is also reduced. This combination of objectives makes both measures promising for further application.

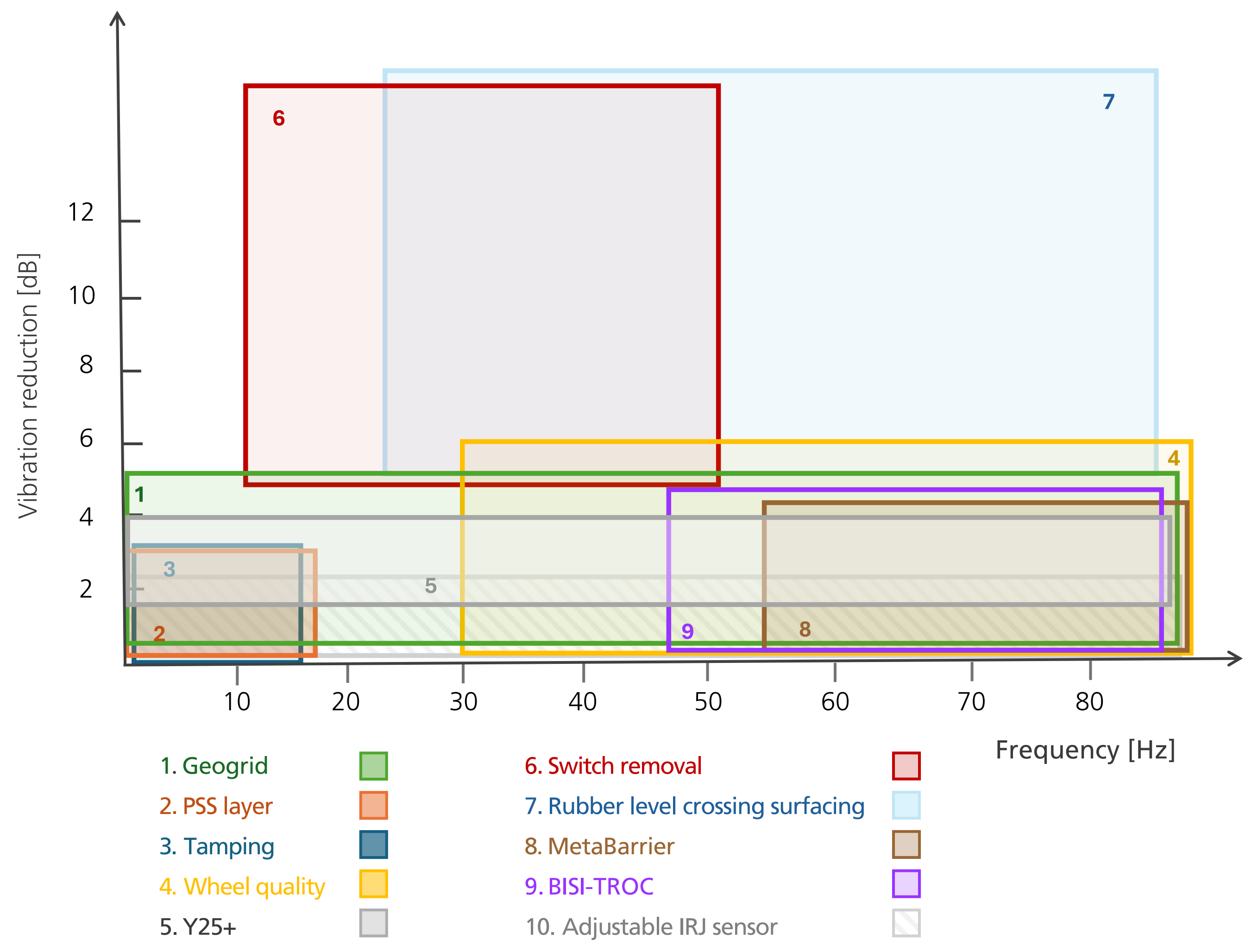
Mechanical tamping of the ballast is a common maintenance measure. By specifically optimising the method with a view to vibration reduction and track geometry, a noticeable effect can be achieved with relatively limited adjustments.

Addressing poor-quality wheels and the Y25+ bogie both require further elaboration and development. However, these measures are not location-specific and may therefore have a large potential impact.

Regarding the innovative SBIR measures, both BISI-TROC and MetaBarrier require further development. Both have the potential to achieve a vibration reduction of at least 3 to 6 dB. These measures form alternatives to existing TROC variants, for which a ProRail design specification exists[46]. For the Adjustable IRJ, the developed sensor – which provides real-time information on track geometry – is considered particularly promising. By actively monitoring the track geometry at locations with a higher probability of problems, such as voided sleepers, an increase in railway vibrations can be detected at an early stage. Figure 39 illustrates the vibration-reducing effect found for the promising measures in the frequency domain.

For almost all measures, further research and development are required to determine under which circumstances the measure is effective. In this context, further development of the STEM calculation model also plays an important role in deepening the understanding of how these measures work.

Figure 39 Overview of promising measures



Application of existing vibration-reducing measures on standard Dutch track
Within the IBS programme, ballast mats and USPs have been examined for their effectiveness on regular Dutch ballasted track.

These are both measures that are applied abroad but not on standard plain line in the Netherlands. The effect found corresponds with the theoretical expectation – namely, that for higher frequencies above the resonance frequency (40 Hz or higher), a reduction effect is observed, while at lower frequencies there is an increase. The measures are therefore sometimes effective close to the track in sandy soils, where high-frequency railway vibrations dominate. They are not effective for soft soils and at greater distances from the track, where low-frequency vibrations are dominant.

Developed tools and specifications
The IBS programme has produced three applications that can structurally contribute to the ultimate goal of reducing the impact of railway vibrations on the environment. These are:

1. application of Spoorligger, which helps identify and schedule maintenance at locations where relatively high vibration levels are expected[47];
2. standard prescription of the Uniform Measurement Protocol for conducting vibration measurements, ensuring that environmental vibration loads are consistently and accurately mapped;
3. further development and use of the STEM calculation model to predict railway vibrations and to support interpretation of measurement results. The STEM model can be used to study potential mitigation measures at locations identified through the Spoorligger tool.

Reflection on the objective

In this section we look back at the objective of the IBS programme: *'To build up more knowledge about vibrations caused by railway traffic in order to better predict vibration levels, and to expand the toolbox with cost-effective measures.'*

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[46] OVS00246: Design Specification for Vibration-Reducing Underground Structures.

[47] Results from the OBO2 study show a less clear relationship between the measured vibration levels and the Hrms and Hmax parameters of the Spoorligger tool, in contrast to earlier findings. This inconsistency still needs to be investigated.

To achieve this goal, the programme was divided into field trials and knowledge research. An important component of the knowledge research is the development of a source model (the STEM calculation model). This approach has led to many insights, because:

1. the effects in practical situations have been studied for a wide range of potential measures, providing insight into which measures are and are not worth applying;
2. an extensive source model has been developed, in which several source mechanisms have already been incorporated and additional aspects will be included in future versions.

The objective of building knowledge has thus been achieved (and the knowledge-building process is still ongoing). The goal of expanding the toolbox with cost-efficient measures has been partially achieved. The toolbox has been expanded, but the tools are applicable only in specific situations and may have adverse effects in others. A continuing point of attention is the often high cost of the measures.

There is potential for gaining deeper understanding by using the STEM model to further explain the results of the field trials. This important step – combining theory and practice – has been taken in part but deserves further expansion. At the start of the IBS programme, the intention was to use the theoretical STEM model to explain the results of the field trials. Because the model's development lagged behind the field trials, this could only be achieved to a limited extent. It is expected that a great deal of knowledge still lies 'hidden' within the available results.

Topics and measures not investigated

Within the IBS programme, a large number of existing and innovative measures have been studied. However, not all (potential) measures were tested. To determine which measures would or would not be selected for further trials, Firm Ground Engineering conducted a selection process (Damen, 2022).

As a first step, a desktop and literature study was carried out, based on which selection criteria were established. Using these criteria, scores were assigned to an extensive list of proposed measures. Measures with too low a score were excluded from field trials. The selection focused specifically on measures relating to the infrastructure.

Measures that were examined but not selected for a field trial:

1. grinding;
2. heavier rail profile;
3. resilient rail fastener;
4. low-stiffness rail pad;
5. smart rail pad;
6. ladder track;
7. frame sleeper;
8. wide sleeper;
9. varying sleeper spacing;
10. under sleeper pads;
11. composite sleepers;
12. stiffening the track body;
13. steep track embankment slope.

A number of the measures not initially selected were ultimately investigated in a field trial after all, such as under sleeper pads. The measures that were not tested were assessed as the least promising. A possible reconsideration could be made in a future research project.

Points for attention and follow-up research

Within the IBS programme the focus has been on tackling the source. The underlying aim is to minimise the negative impact of vibrations at the receiver. In cases of nuisance, not only the vibration level plays a role. It is therefore important, when drafting any specifications, to remain aligned with the ultimate goal: **reducing the impact on the surrounding environment**.

For a number of studies/pilot trials, follow-up steps are now being taken. The various studies are briefly discussed.

Ongoing SBIR innovation field trials

Research into the Low-Vibration Sleeper (TAL) was still in progress in mid-2025. The post-installation measurements will be carried out in autumn 2025. An additional follow-up measurement to determine the medium-term effect of the TAL is expected to be carried out at the end of 2025. Final results will therefore only become available at the end of 2025 / start of 2026.

Foamed ballast

The results of the laboratory tests with foamed ballast do not align with expectations. Follow-up research is under way to better understand the results.

Follow-up to the STEM computational model and scientific studies

Part 3 of this report discussed the various PhD studies and the STEM model. These studies will continue for at least another two years. The final results can therefore only be included in an updated version of this report at the end of 2027 / beginning of 2028.

Update to the Uniform Measurement Protocol

The Uniform Measurement Protocol has been supplemented over the course of the programme based on insights from various studies. Version 4.0, incorporating the most up-to-date insights, will be published at the end of 2025.

What next?

This final document is a compilation of research findings and knowledge gained within the IBS programme. The results provide new insights and tools that can be used in practice. The results also call for follow-up actions. The purpose of this document is not to advise on which measures should or should not be applied, nor exactly what a follow-up should look like. For this, ProRail, at the request of the Ministry of Infrastructure and Water Management, will draw up separate implementation plans. Some measures will also be further developed by market parties.

This document is the final document of the IBS programme. Although the programme formally ends in July 2025 and this document forms part of the conclusion, it cannot yet be considered a definitive final document. This is because there are still ongoing studies that contribute to the accumulation of knowledge.

European collaboration

ProRail is participating in the European research programme Europe's Rail Joint Undertaking (ERJU). In this programme, European railway undertakings and industry conduct research into breakthrough innovations and renewals for the rail sector. The relevant IBS projects have been incorporated into the Rail4Earth part of the ERJU programme. Rail4Earth includes laboratory tests on the vibration-reducing properties of alternative ballast stones (so-called NeoBallast). This also encompasses the long-running studies of the STEM model by TNO, Deltares and TU Delft. It is expected that, within this collaboration, further knowledge on the subject of railway vibrations will be built up over the coming years. At present, ProRail is testing and further developing a number of applications of fibre optic measurements. Part of this involves proof-of-concept trial measurements in which data communication cables alongside the track are used as vibration sensors to monitor environmental vibrations and/or track quality. The research is part of the European Rail4EARTH sub-programme. Results will be published later in the context of this programme.

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Glossary of terms and symbols

Resonance frequency	(Natural) frequency of a system due to the placement of a spring, above which the system is relatively insensitive to vibrations.
Earthwork	Part of the track bed or railway structure that transfers loads from the track and consists of an earth mass (i.e. not a concrete engineering structure).
Voided sleepers	Phenomenon where a gap exists between the sleepers and the ballast, causing the sleepers to ‘float’.
Bts	Policy Rule on Railway Vibration Nuisance (Beleidsregel trillinghinder spoor).
Decibel	Ratio on a logarithmic scale relative to a reference value.
Discrete Element Method	Numerical calculation method.
D0, D1, D2	Parameters defining the geometrical track quality in accordance with NEN-EN 13848. A distinction is made according to the wavelength range in which the rail height variations are measured: – D0 1 m < λ ≤ 5 m; – D1 3 m < λ ≤ 25 m; – D2 25 m < λ ≤ 70 m; – D3 70 m < λ ≤ 150 m
Elastic half-space	Calculation model of a medium through which vibration waves propagate in an elastic material.
IRJ	Insulated Rail Joint.
Fourier transformation	Mathematical operation used to determine the frequency content of a signal. Every signal consists of a series of harmonic vibrations. The composition of this structure is determined using a **Fourier transformation**. A Fourier transformation is defined as: $X(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} x(t)\, e^{-i\omega t} dt$ This integral describes how any continuous time-domain signal x(t) can be transformed into a frequency-domain signal X(ω). Applying this transformation reveals the frequency content of the signal.
Wave number	A property of a wave indicating how many repetitions occur per unit length, defined as 2•ϖ / wavelength.
Hammer test	A test in which vibrations are generated with a hammer and the structural response is measured.

Harmonic vibration	A harmonic vibration with a certain frequency can be expressed as a sine or cosine function: $x(t) = A \cdot sin(\omega t + \varphi)$ Here A is the amplitude, φ the phase of the vibration and ω the frequency in radians per second. The vibration intensity is characterised by the amplitude.
H_{max}	Maximum value of the track geometry (height or lateral alignment) according to the Spoorligger tool.
Vertical alignment	Vertical positioning of the track.
H_{RMS}	RMS value of the track geometry (height or lateral alignment) according to the Spoorligger tool.
Hz	Hertz. Unit of frequency for sound and vibration. The number of pressure variations per second represents the frequency.
Kratos Multi Physics	Open-source numerical computation kernel used for developing calculation models.
Wheel lathe pit	Workshop or machine used to re-profile train wheels to the correct dimensions.
MASW	Multichannel Analysis of Surface Waves. Seismological measurement method used to determine the wave velocity of different soil layers.

Mobility	A measure of how easily a material or the soil vibrates, defined as v(ω)/F(ω) (the inverse of impedance).
Amplification	Increase in amplitude relative to static loading due to resonance.
Oscillation	Another term for vibration – a repetitive motion of an object.
PML layer	Perfectly Matched Layer. A boundary method used to impose vibration absorption along the edges of a finite element model.
Power Spectral Density	Distribution of vibration energy (proportional to the square of the vibration velocity) plotted in the frequency domain.
PSS layer	Planum Schütz Schicht layer – a fine, cement-like layer below the ballast bed.
Receptance	A measure of how easily a material or soil deforms, defined as u(ω)/F(ω).
Rotational degree of freedom	Parameter describing a rotating (angular) motion of a physical system.
RMS	Root-mean-square value over the duration of a signal (see also V_{RMS}). An exposure measure (a quadratic mean) over a specified period of time.
SBR Guideline Part B	Stichting Bouwresearch Guideline B. This (non-statutory) guideline provides an initial approach for handling vibration nuisance, encouraging consultation between all parties involved to consider measures and to assess whether the nuisance is acceptable.

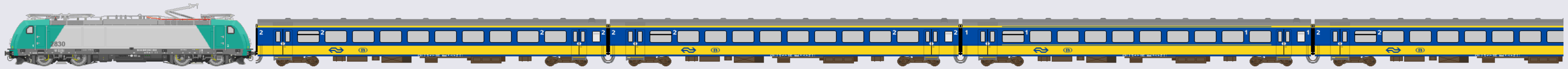
Twist	A deformation measure describing the vertical deviation of one point relative to three other coplanar points. When considering two rails of a track, this indicates bending deformation of one rail in the vertical direction.
Lateral alignment	Lateral alignment of the track.
SBIR	Small Business Innovation Research – a procurement programme specifically aimed at innovation.
Track gauge	Lateral distance between the two rails.
Standard deviation	Statistical concept expressing the degree of dispersion within a distribution.
TRL	Technical Readiness Level – measure of technological maturity.
$V_{eff,max}$	The maximum vibration level of a signal according to SBR Guideline Part B. It represents the maximum of Veff(t) during a signal. The definition of Veff(t) according to SBR Guideline Part B (SBR, 2006) is: $V_{eff}(t) = \sqrt{\frac{1}{\tau}\int_{0}^{t} g(\xi)v^{2}(t-\xi)d\xi}$ Here v(t) is the vibration signal in mm/s, g an exponential weighting function, τ a time constant and t the continuous time in seconds. For g and τ, the following applies respectively: $g(\xi) = e^{-\xi/\tau}$ $\tau = 0{,}125$ $V_{eff}(t)$ is time-dependent and therefore varies throughout the occurrence of a vibration signal. By taking the maximum level over the entire duration of the passage, $V_{eff,max}$ is obtained. Note: $V_{eff,max}$ must be determined according to the SBR Guideline over 30-second intervals per measurement direction, denoted as $V_{eff,max}$,30,i.
Cant	Height difference between the two rails.
Deformation field	Description of how the deformation caused by, for example, a train load appears at various distances/locations from the track (the source).

V_{max}	The highest effective vibration intensity during a given evaluation period (SBR B).
V_{per}	Periodic vibration level according to SBR Guideline Part B. The definition of V_{per} is as follows: $Vper,meet = \sqrt{\left[\frac{1}{n}\cdot\sum_{i=1}^{n}(Veff,max,30)^2\right]}$ Here n is the number of 30-second periods in the measurement period. If $V_{eff,max}$,30,i ≤ 0.1, then a value of 0 must be entered for $V_{eff,max}$,30,i. To determine V_{per}, the duration of the evaluation period must be taken into account: $Vper = Vper,meet \cdot \sqrt{\frac{Tb}{T0}}$ Here Tb is the total duration of the vibration source within the evaluation period and T0 the total evaluation period: – day period 07:00–19:00 = 43,200 s (12 hours) – evening period 19:00–23:00 = 14,400 s (4 hours) – night period 23:00–07:00 = 28,800 s (8 hours)
V_{RMS}	Root-mean-square value of a velocity signal. The definition of V_{RMS} for a total signal of duration T is as follows (Brandt, 2010): $Vrms = \sqrt{\frac{1}{T}\int_0^T v^2(\xi)d\xi}$ The so-called running RMS value, which resembles the Veff value from SBR Part B (the difference being that Veff includes exponential weighting, while the running RMS does not), is defined as follows: $Vrms(t) = \sqrt{\frac{1}{\tau}\int_{t-\tau}^{t} v^2(\xi)d\xi}$

Overview of train types

This annex provides an overview of the train types mentioned in this document.
It is a concise selection of all train types operating on the Dutch railway network. Source: www.arthurstreinenpagina.nl

Passenger trains



TRAXX-ICRmh

VIRMm-IV

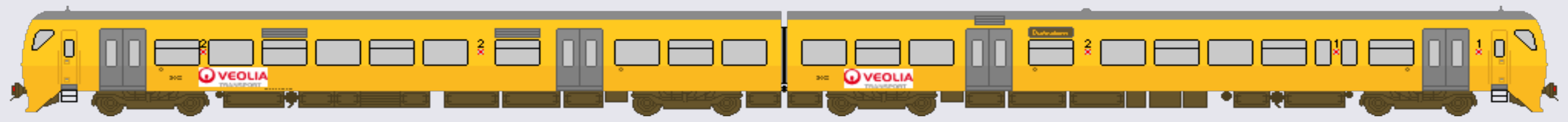
Flirt III

DDZ-4

SNG-III

SLT S100

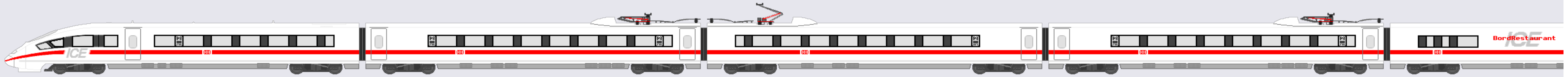
GTW 2/8



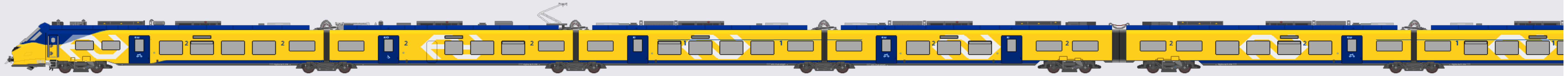
DM ‘90

Passenger trains (continued)

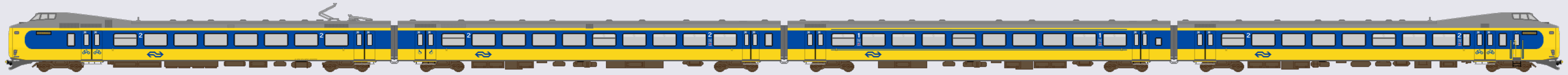
ICE -3M



ICNG

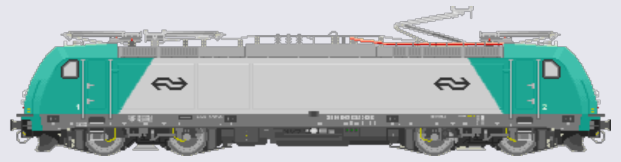


ICMm series 4200

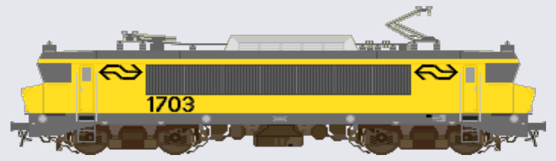


Locomotives

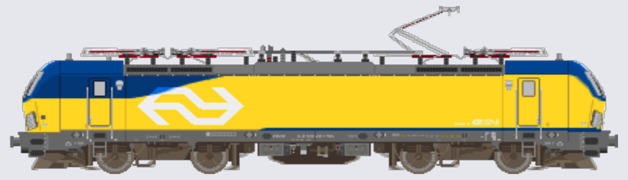
TRAXX



1800/1700/1600



Siemens



Class

V100

6400

Colophon

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