



UIC SUSTAINABILITY

**Optimised Rail Pad Performance for Noise  
Reduction: Outcomes and Recommendations**

**LOWNOISEPAD Final Report**

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# ABBREVIATIONS, UNITS AND SYMBOLS

## ABBREVIATIONS

|                      |                                                                                                                                                                      |
|----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>A/D Convertor</b> | Analog to digital converter                                                                                                                                          |
| <b>EN</b>            | European Standard                                                                                                                                                    |
| <b>EMU</b>           | Electric multiple unit                                                                                                                                               |
| <b>H Pad</b>         | Stiff rail pad                                                                                                                                                       |
| <b>IM</b>            | Railway Infrastructure Manager                                                                                                                                       |
| <b>IEC</b>           | International Electrotechnical Commission                                                                                                                            |
| <b>IRS</b>           | International Railway Solution ©, UIC                                                                                                                                |
| <b>ISO</b>           | International Organisation for Standardisation                                                                                                                       |
| <b>LCC</b>           | Life Cycle Cost                                                                                                                                                      |
| <b>LOWNOISEPAD</b>   | Low-cost noise control by optimised rail pad                                                                                                                         |
| <b>L Pad</b>         | Soft rail pad                                                                                                                                                        |
| <b>OPTI Pad</b>      | Optimised rail pad                                                                                                                                                   |
| <b>PP</b>            | Project partner                                                                                                                                                      |
| <b>SPOC</b>          | Single point of contact for LOWNOISEPAD financial members                                                                                                            |
| <b>TDR</b>           | The decay rate on a track is often also known as the “track decay rate”, abbreviated as TDR, in acoustics academia. This common abbreviation is used in this report. |
| <b>WP</b>            | Work Package                                                                                                                                                         |
| <b>UIC</b>           | International Union of Railways                                                                                                                                      |

## LIST OF UNITS AND SYMBOLS

|                         |                                                                                                       |
|-------------------------|-------------------------------------------------------------------------------------------------------|
| <b>dB</b>               | Decibel                                                                                               |
| <b>FRF</b>              | Frequency response functions                                                                          |
| <b>IL</b>               | Insertion Loss                                                                                        |
| <b>IL<sub>PBc</sub></b> | Based on the actual measured direct noise insertion loss, IL <sub>PB</sub> in 1/3 octave bands        |
| <b>kSA</b>              | The static stiffness of assembly, in MN/m                                                             |
| <b>kLFA</b>             | The low-frequency dynamic stiffness of assembly, in MN/m                                              |
| <b>kLFPf</b>            | The low-frequency dynamic stiffness of a pad at a specific frequency, in MN/m                         |
| <b>kLFPmean</b>         | The mean of pad low-frequency dynamic stiffness measurements, measured at 5Hz, 10Hz and 20Hz, in MN/m |
| <b>LpAeq,T</b>          | A-weighted equivalent continuous sound pressure level in dB                                           |
| <b>Lr</b>               | The acoustic roughness level in dB                                                                    |
| <b>Lw</b>               | Sound power level                                                                                     |
| <b>mV/g</b>             | millivolts per gravity, and is used to denote the sensitivity of accelerometer                        |
| <b>mV/Pa</b>            | millivolts per pascal, and is used to denote the sensitivity of microphone                            |
| <b>NIL</b>              | Noise insertion loss                                                                                  |
| <b>NR<sub>pot</sub></b> | Noise Reduction Potential                                                                             |
| <b>OPTI Pad</b>         | Optimised rail pad                                                                                    |
| <b>p<sub>0</sub></b>    | Reference sound pressure; p <sub>0</sub> = 20 µPa                                                     |
| <b>pA (t)</b>           | A-weighted instantaneous sound pressure at running time t in Pa                                       |
| <b>r<sub>0</sub></b>    | Reference roughness; r <sub>0</sub> = 1 µm                                                            |
| <b>RMS</b>              | Root mean square roughness in micrometres (µm)                                                        |
| <b>SIL</b>              | Spectral insertion loss                                                                               |
| <b>v<sub>ref</sub></b>  | Corresponding reference value for velocity                                                            |
| <b>TDR<sub>sv</sub></b> | Single value of the decay rate on the track                                                           |
| <b>T=Tp</b>             | Measurement time interval in s                                                                        |
| <b>W<sub>ref</sub></b>  | Reference value used for the definition of the sound power level                                      |

# GLOSSARY

The subject of the glossary below is vocabulary used in the domain of optimised rail pad performance for noise reduction on railways.

## 1. Track component

*A manufactured part of the track superstructure, including the rail, fastening system and sleepers, or any other type of rail support system.*

## 2. Rail pad

*A component of the fastening system installed between the rail foot and sleeper or baseplate to transfer the rail load (more information in IRS 80864-5).*

## 3. Tension clamp

*Tension clamps secure rails to sleepers, maintaining rail alignment and stability. The clamping force is set by tensioning a bolt that fits into a dowel embedded in the sleeper. It accommodates thermal expansion and contraction (e.g., W14 or SKL, more information in EN 13481-2). This definition has been developed to facilitate communication and to distinguish between the fastening systems in use by each participant in this project.*

## 4. Clip

*Tension clamps secure rails to sleepers, maintaining rail alignment and stability, without a bolt that needs to be tensioned individually for each fixation point and in this document this type of fastening system is called clip or rail clip. The clamping force is therefore independent to the mounting operation. It allows controlled movement and stability to accommodate any changes in temperature (e.g., E-clip and Fast Clip, more information in EN 13481-2). This definition has been developed to facilitate communication and to distinguish between the fastening systems in use by each participant in this project.*

## 5. Track decay rate

*A key indicator for characterising the behaviour of the attenuation of waves along the rails from excitation. It describes the decrease in rail vibration per metre rail [dB/m] in the third-octave bands with a dynamic load (passage of a train). The measurement framework is given by EN 15461:2008+A1;2010. The decay rate on a track is often also known as the “track decay rate”, abbreviated as TDR, in acoustics academia. This common abbreviation is used in this report and in IRS 75717.*

## 6. Optimised rail pad

*An optimised rail pad engineered to be as soft as possible (in accordance with specified requirements and specifications) while maintaining a high TDR value is a critical component in modern railway systems. It plays a pivotal role in extending the lifespan of tracks, minimising noise and vibration disturbances, and enhancing overall railway system performance for the benefit of both passengers and nearby communities. In this project, rail pad designs are modified to ensure that they are as soft as possible in a given scenario for each PP, while at the same time ensuring that they have as high a TDR as possible.*

## 7. Stiffness

*The force per unit of travel with which an elastic system opposes displacement. The project has observed that each PP uses a different range to define the soft and stiff value when selecting a rail pad. The definition in here is intended to simplify communication and assist in the selection of suitable rail pad options for this project. A standardised approach was adopted to categorise the stiffness of rail pads based on the guidelines set out in EN13481-2 standard, with soft rail pads being classified as "L" and stiff rail pads as "H".*

## 8. One-third (1/3) octave bands

*Fractional octave bands, such as +1/3 of an octave, are widely used in engineering acoustics and environmental and noise control. A one-third octave is a logarithmic unit of a frequency ratio equal to either one third of an octave or one tenth of a decade.*

## 9. Data

*Raw, unfiltered, and unweighted simultaneously sampled vertical rail acceleration and microphone sound pressure collected from two adjacent 100 metre test sites. Data is therefore inputs collected from a minimum of 4 channels.*

## 10. Averaged data

*The mean results of analysed data. Within this project there are different datasets involved (e.g. data before and after optimised pad installation) which should not be combined or averaged.*

## 11. Simultaneous- sample-and-hold

*For most digital converters, sampling is performed by a sample-and hold (S/H) circuit. The S/H performs the true sampling of the input and operates between the input anti-aliasing/low-pass filter and the analogue-to-digital (A/D) converter.*

## 12. In-situ

*Onsite with real tracks and real trains*



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# EXECUTIVE SUMMARY

Through its [Noise and Vibration Sector](#) (NV), the International Union of Railways (UIC) works with its members to better understand noise-generating sources in railways in order to make tangible progress towards being a better neighbour. The UIC NV Sector's vision is to provide a platform for global dialogue with a common goal to better manage noise emissions, and to integrate sustainability into railway operations and maintenance.

This report presents the findings and recommendations of the Low-Cost Noise Control by Optimised Rail Pad (LOWNOISEPAD) project, which focused on evaluating rail pad performance in reducing noise emissions during train pass-bys. The project involved extensive measurement taking and analysis of various rail pads across different test sites and rolling stock types. Additionally, a software tool was developed to visualise and assess the project results, allowing for changes in noise emission to be estimated when rail pads are changed. The report highlights the influence of rolling stock, operational procedure, temperature, and wheel/rail roughness on noise reduction. It also recommends the future testing and optimisation of rail pads to further enhance noise mitigation efforts.

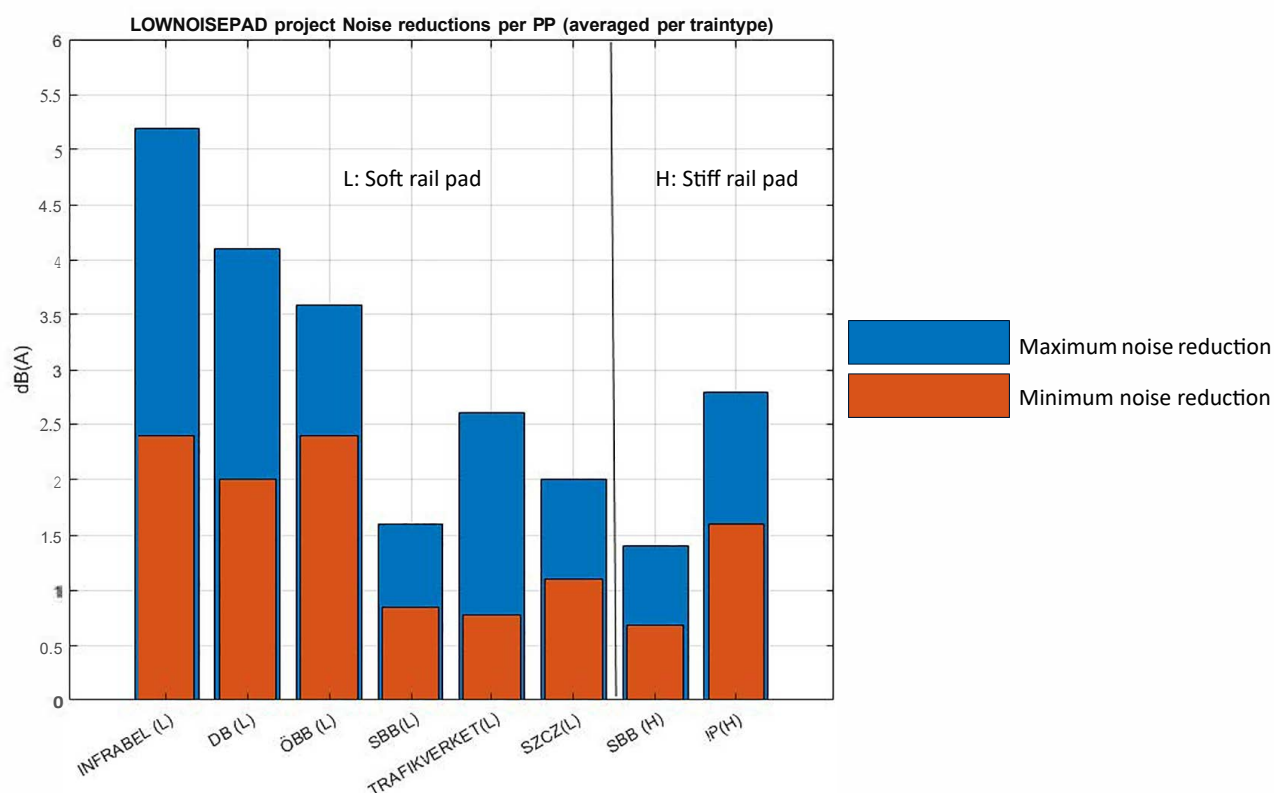


*Figure 1: Overview of the achieved minimum and maximum noise reduction by comparing the optimised rail pads with the standard rail pads (L): soft rail pad, (H) stiff rail pads*

The project demonstrated that optimised pads could lower overall noise levels by 1-2 dB when compared to stiff pads and 3-5 dB when compared to soft pads. Given these promising results, it is advisable to consider further investigation on the retention of “soft” qualities usually associated with better track protection. Further studies on rail pads could examine these issues in more detail.

# INTRODUCTION

This final report provides a comprehensive overview of the UIC LOWNOISEPAD, giving all project participants (PPs), interested parties and other stakeholders a clear overview of the project implementation and results. It aims to ensure that participants gain a complete outlook on the project's progress and outcomes, while also encouraging other stakeholders to align their noise mitigation research and development activities with the findings presented in this document.

The report begins by offering an overview of the project's origins, ensuring that readers, especially those unfamiliar with the project, have a solid understanding of the basic principles. It highlights the purpose and objectives of the project, providing context to facilitate engagement with the report's contents.

In addition to providing operational guidance, the report refines the collective knowledge and experiences gained during the project, presenting definitive conclusions and informed recommendations for the global railway sector. These insights and lessons learned will contribute to future endeavours and ongoing research and development in the railway domain. As a final report, it constitutes a reliable source of background information for noise measurement activities, facilitating the adoption and dissemination of a harmonised methodology aligned with [IRS 75717](#) developed within the LOWNOISEPAD project. Overall, it serves as a testament to the collective efforts of all participants and provides a valuable resource for ongoing research and the advancement of railway noise management practices.

## OBJECTIVE

The objective of this report is to investigate the influence of rail pad properties on railway noise and identify possible opportunities for noise mitigation on railway networks around the world. The results obtained in this project are not intended to compare the products of different rail pad, fastening system, and sleeper manufacturers, but to demonstrate how railway infrastructure managers (IM) may reduce noise levels by optimising their own assets. It aims to build upon existing knowledge, conducting in-situ measurement campaigns on several European railway networks, analysing their data, and proposing recommendations for optimising rail pad designs for the sector.

## TARGET

The target of this report is to provide a comprehensive analysis of the impact of rail pad stiffness, the geometric distribution of stiffness, and damping characteristics on train noise emissions. The report will focus on the track decay rate (TDR) in the frequency range of 800Hz-2kHz, with emphasis on the 1kHz energy band, representing the pin-pin mode of vertical rail vibration. The aim is to determine the expected reduction in noise, both in terms of overall pass-by noise levels and of specific frequency bands, by modifying and optimising rail pad properties.

Additionally, the report addresses the project's aims to:

- Provide an overview of the different types of rail pads available in the network and select a reference pad for testing based on the rail fastening type, potential test section, and available data on TDR and static/dynamic stiffness.
- Conduct measurement campaigns to assess TDR, pass-by noise, and rail roughness using standardised procedures across all participating members.
- Investigate the potential for optimising existing rail pads and evaluate the feasibility of an internal optimisation process within the project's timeframe and budget.
- Communicate findings and recommendations among track and acoustic engineers, explaining the impact of rail pad properties on noise reduction.

The ultimate target of this report is to provide insights and recommendations that can contribute to the development of rail pad designs with a low-noise approach, leading to quieter train operations and an improved quality of life for lineside residents.

# BACKGROUND

Rail pad stiffness is a crucial factor in train noise emissions, but its influence cannot be determined solely based on stiffness. Factors such as the static/dynamic stiffness ratio, geometric distribution of the stiffness over the rail pad surface and its influence on damping the rail rotation (with the pin-pin mode) also play a significant role. The polymeric insulator, which distributes clamping force, can also contribute to overall damping. Previous projects in Belgium, Switzerland, Austria, and Germany have shown the potential for significant noise reduction with acoustically optimised rail pads. For instance, INFRABEL demonstrated and then published information on the potential for a 2.5 to 4 dB noise reduction when using acoustically optimised rail pads compared to the existing Belgian standard soft rail pads [1]. This project aims to expand on existing knowledge by conducting in-situ measurements and analysis. Each PP decided upon and agreed to carry out the following steps within work packages:

- **Measure the track decay rate:** High-quality decay rate measurements on track (TDR) in accordance with EN 15461:2008+A1:2010 were a crucial first step and was decisive for determining the inclusion of a rail pad in further testing
- **Conduct pass-by measurements and rail roughness evaluations:** In the second step of the measurement campaign, clearly defined pass-by-measurements in accordance with ISO 3095:2013 were carried out. These measurements along with rail roughness measurements were conducted using a standardised procedure across all PPs. The data collected during this phase, enabled the project to draw final conclusions regarding the expected reduction in noise, both in terms of overall pass-by levels and specific frequency bands, by changing or optimising rail pad properties.
- **Noise mitigation tuning:** The TDR within the frequency range of 800Hz-2kHz, with particular emphasis on the 1kHz energy band representing pin-pin mode of the vertical rail vibration, served as the ideal parameter for fine-tuning and designing/selecting better noise-reducing rail pads. Simulating the rotational movement of the rail foot on a rail pad in a laboratory environment or a model poses problem as it is challenging to monitor damping behaviour in detail. This is the reason why measurement campaigns involving both TDR and pass-by noise were necessary for this study.

As part of the project, the PPs declared the different types of rail pads available on their networks, and decided which rail pad to consider as the reference pad and which one to test comparatively in order to quantify and compare the changes in noise levels based on:

- The type of rail fastening
- The potential test section
- The available TDR and static/dynamic stiffness data

Different types of rail pads were considered, and an optimisation process was initiated by 10 participants including BANENOR, SZCZ, DB, INFRABEL, IP, NetworkRail, ÖBB, SBB, SNCF, Trafikverket.

A further point to note is that there is a big difference between quasi-static 4Hz stiffness (relevant for the passage of axles) for distributing the forces in the ballast, and the stiffness and damping at 1000Hz, where the rail emits noise. The LOWNOISEPAD project aimed to measure rail displacement and accelerations to ensure that the results were not only based on noise measurements, but also that results of noise measurements could be validated by track engineers. For instance, extremely high rail pad stiffness around towards 500kN/mm, is not needed to reduce railway noise. The rail pad shall be designed to strike a balance between two key attributes: softness and Track Decay Rate (TDR). While there is a minor stiffness at 4Hz, the dynamic properties exhibited at 1000Hz are substantially different due to the pad's composition and geometry modifications. The primary goal is to develop a rail pad that is as soft as possible in a given scenario (in accordance with specified requirements and specifications) while maintaining a high TDR value.

# PROJECT PARTICIPANTS

The project brought together experts from twelve countries, with each country's infrastructure manager (IM) assigning a single point of contact (SPOC) to coordinate internal activities. The participating countries, IMs are alphabetically listed by country name in Table 1.

*Table 1: Track assets and track type for each IM*

| Country        | IM           | Rail Type | Track Assets (Fasteners and Sleepers) |
|----------------|--------------|-----------|---------------------------------------|
| Austria        | ÖBB          | 60E1      | Tension clamp, SKL14, Monoblock       |
| Belgium        | INFRABEL     | 60E1      | Rail E-clip, Monoblock                |
| Czech Republic | SZCZ         | 60E2      | Tension clamp, B 91S Monoblock        |
| France         | SNCF         | 60E1      | Rail Fast clip, Monoblock             |
| Germany        | DB           | 60E2      | Tension clamp, B70 Monoblock          |
| Italy          | RFI          | 60E1      | Tension clamp, Monoblock              |
| Netherlands    | ProRail      | 60E1      | Tension clamp, Monoblock              |
| Norway         | BaneNor      | 60E1      | Rail Fast clip, Monoblock             |
| Portugal       | IP           | 60E1      | Tension clamp, B70 Monoblock          |
| Sweden         | Trafikverket | 60E1      | Rail Fast-/E-clip, Monoblock          |
| Switzerland    | SBB          | 60E2      | Tension clamp, Monoblock,             |
| United Kingdom | Network Rail | 60E1      | Rail Fast clip, Monoblock             |

Preparatory meetings were held to address the key points and challenges, and individual meetings were held to discuss specific topics. The project aimed to solve these issues and enable successful participation.

# PROJECT EXECUTION

The project involved coordinating and harmonising the project steps among the participants, collecting data, and carrying out measurements based on IRS 75717 [2]. Each participant was responsible for collecting rail asset and TDR information, preparing test sections, and providing measurement data. The subcontractor appointed by UIC handled discussions, technical support, data collection from the test sites, data analysis, and reporting. The project was divided into six work packages, each with assigned PPs responsible for execution and support:



## WP1: Preparation of procedures



## WP2: Analysis of the current situation



## WP3: Selection of the rail pads to be tested



## WP4: Test site selection and rail pad installation



## WP5: Measurements



## WP6: Data processing and dissemination

# 1. WP1: PREPARATION OF PROCEDURES

WP1 served as the project execution plan for both the PPs and the project itself. It was based on literature, paper reviews, and similar successful projects (from INFRABEL, SBB, ÖBB and DB). The guide consists of detailed information for all work packages including product and site selection procedures, measurement protocols, data analysis protocols, and so on. The aim was to ensure a consistent approach among all of the PPs, ultimately leading to clear and comparable conclusions. High-quality measurement data using appropriate and calibrated sensors, e.g., TDR measurement quality, are essential for an exact and precise conclusion when selecting a rail pad.

## 1.1. THE RAILS CONTRIBUTION TO NOISE GENERATION

The methodologies prepared for the PPs also focused on how a rail component contributes to the emission of railway noise in the context of rolling noise. The analysis is based on a typical example derived from a TWINS model calculation in Figure 2, which provides valuable insight into the noise characteristics of a freight vehicle travelling at 100km/h on a track with a relatively soft rail pad [3]. The aim is to highlight the dominant role of a rail in noise emissions in comparison to other potential sources such as wheels or sleepers, particularly in the frequency range of 500Hz to 2kHz. Additionally, the yellow zone, showing the impact region of rail pad optimisation in the graph, formed the core of this project and helped to understand how these components influence the overall noise emissions of different types of tracks and rolling stock, and at different speeds. Another important factor that set this project apart was that large-scale in-situ pass-by noise measurements, carried out in 12 countries with a harmonised procedure, would prove and validate the prediction of the models.

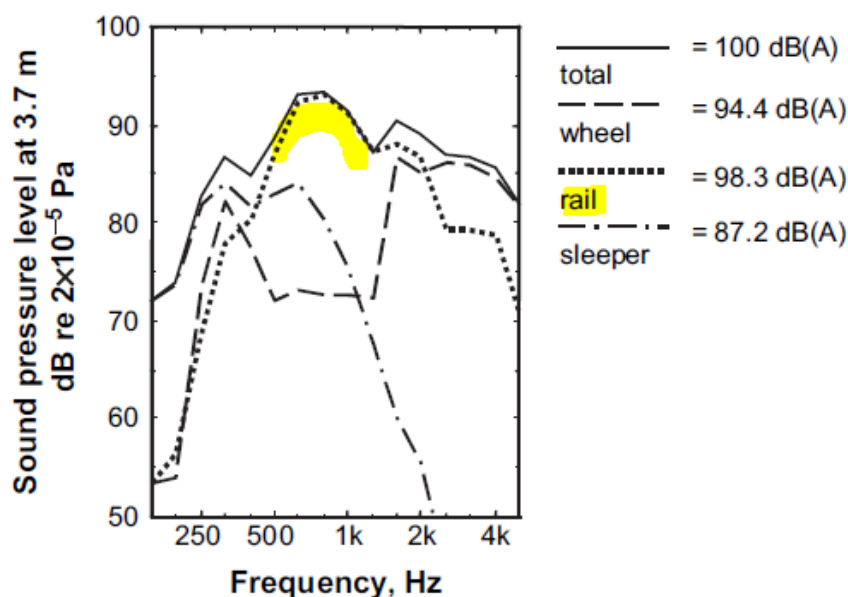


Figure 2: Results from a typical prediction using the TWINS model, showing the contribution of wheel, rail and sleeper components to overall noise for freight trains [3]

## 2. WP2: ANALYSIS OF THE CURRENT SITUATION

The aim of WP2 was to understand the link between the current track design and the associated acoustic quality. Acoustic quality is primarily characterised by two parameters:

- Acoustical rail roughness, with dominant wavelengths between 0.5cm and 50cm
- TDR with dominant frequencies between 500Hz and 2.5kHz. This project specifically focused on investigating TDR

The track's design and its components, such as the fastening systems are precisely defined by track engineers, but often the design focus is on force distribution and the flexibility required in the quasi-static domain, as well as the link with the frequency at which the rail emits sound during a train pass-by not always being established. In WP2, the plan was to fill this knowledge gap for the 12 PPs by using a database focusing on the track design parameters that can influence TDR measurements. Additionally, the focus was also on the rail pad properties that have a known influence on TDR, dynamic stiffness, and damping.

### 2.1. METHODOLOGY

Analysis of the current situation was conducted using two main frameworks, requiring information to be gathered from each SPOC for their company, for inclusion in the LOWNOISEPAD Track Database. Each PP was tasked with collecting and reviewing track and acoustic data for the database, as follows:

#### ■ Track

- Detailed information about the type of track design/rail fastening systems
- Detailed information about the material properties listed in the specifications of the rail pads, including norms used, stiffness, damping, dimensions, thickness

#### ■ Acoustics

- TDR measurements in accordance with EN 15461, with temperatures recorded alongside each measurement
- The available pass-by measurements according to ISO 3095

WP2 encouraged close collaboration between track and acoustic engineers and ensured that the project was carried out in consultation with both parties, thus allowing different perspectives on noise reduction to be heard.

Detailed information and guidelines were then provided to the PPs on how to input data into the LOWNOISEPAD Track Database, which contains data on the track and track components to be tested in WP5. The aim of having the database was to collect information from the 12 PPs to relate the **mechanical and acoustical properties of their tracks**. While for most PPs a standard track was in use (shown in Table 1), further information is detailed in the document in Figure 3.

| LOWNOISEPAD SPOC | COUNTRY       | LM              | total km of lines       | total km of tracks | mandatory to fit                        |          | optional to fit |               |      |                       |                     |           |            |            |              |           |                                     |                |                    |                                 |                |        |              |
|------------------|---------------|-----------------|-------------------------|--------------------|-----------------------------------------|----------|-----------------|---------------|------|-----------------------|---------------------|-----------|------------|------------|--------------|-----------|-------------------------------------|----------------|--------------------|---------------------------------|----------------|--------|--------------|
|                  |               |                 |                         |                    |                                         |          |                 |               |      |                       |                     |           |            |            |              |           |                                     |                |                    |                                 |                |        |              |
| Track            |               |                 |                         |                    | Track components (others than rail pad) |          |                 |               |      |                       |                     |           |            |            |              |           |                                     |                | Fastening system   |                                 |                |        |              |
| Naming           |               | dimension       | quantity                | Installation       |                                         | rail     |                 | rail location |      |                       |                     | Sleeper   |            |            | Ballast      |           | Isolator between rail toe and clamp |                | Stiffness EN 15461 |                                 |                |        |              |
| TYPE no.         | name          | track gauge (m) | presence on network (%) | Real install date  | Real install date                       | Type     | Size (mm)       | brand         | ID   | Reaction (kN/mm/rail) | Clamping force (kN) | sprople / | name /type | width (mm) | spacing (mm) | mass (kg) | Type/quality /stiffness             | Thickness (mm) | Type / material    | Contact surface with rail (mm²) | Thickness (mm) | Static | Dynamic S Hz |
| LOWNOISEPAD 1    | LOWNOISEPAD 1 | 1,435           | 100%                    | 2007               | 2007                                    | 1000x100 | 1000x100        | LOWNOISEPAD 1 | 1000 | 1000                  | 1000                | 1000      | 1000       | 1000       | 1000         | 1000      | 1000                                | 1000           | 1000               | 1000                            | 1000           | 1000   | 1000         |

| Railpad properties               |  |  |  |  |                                                 |  |  |  |  |                                                           |                      |  |  |  |                              |  |                    |  |  |                                          |  |  |  |  |                        |  |  |  |  |               |  |  |  |  |              |  |  |  |  |                  |  |  |  |  |                                           |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                              |  |  |  |  |                                        |  |  |  |  |                                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |  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| Composition/dimensional          |  |  |  |  | Mechanical Stiffness (test bench under preload) |  |  |  |  |                                                           | Acoustical stiffness |  |  |  |                              |  | Acoustical Damping |  |  |                                          |  |  |  |  |                        |  |  |  |  |               |  |  |  |  |              |  |  |  |  |                  |  |  |  |  |                                           |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                              |  |  |  |  |                                        |  |  |  |  |                                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |  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| Internal technical specification |  |  |  |  | Tests required according to the homologation    |  |  |  |  | contact under rail + rail width x length under rail (mm²) |                      |  |  |  | Contact in contact with rail |  |                    |  |  | estimated surface % in contact with rail |  |  |  |  | composition / material |  |  |  |  | Whisker class |  |  |  |  | Date of sale |  |  |  |  | Test procedure   |  |  |  |  | STIFFNESS (N/mm or MN/m)                  |  |  |  |  | Test procedure 1         |  |  |  |  | STIFFNESS (N/mm or MN/m) |  |  |  |  | Test procedure 2         |  |  |  |  | STIFFNESS (N/mm or MN/m) |  |  |  |  | General test section details |  |  |  |  | TDR VERTICAL (dB/m @1/3 octave values) |  |  |  |  | TDR HORIZONTAL (dB/m @1/3 octave values) |  |  |  |  | Test procedure 1         |  |  |  |  | Loss factor              |  |  |  |  | Test procedure 2         |  |  |  |  | Loss factor              |  |  |  |  | TDR Single value         |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          |  |  |  |  |                          | 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Figure 3: LOWNOISEPAD database

## 2.2. MASTERCLASS ON HOW TO CARRY OUT TDR MEASUREMENTS

The TDR measurements were crucial for each step of the project. Part of the scope included details and discussions on how to measure and calculate the TDR. The procedure below covers both TDR measurement in horizontal and vertical direction, in accordance with EN 15461 [4]. For instance, an example is given below which clearly shows that changing a rail pad from very soft to very stiff has a significant effect on the vertical TDR (0.8 dB/m to 12dB/m at 1kHz), while there is only a minimal effect on the horizontal TDR (0.35 dB/m to 1.8 dB/m). In Figure 4, the dotted lines represent data for a soft rail pad, the full lines for a stiff rail pad. Therefore, the focus in this project was on the vertical TDR.



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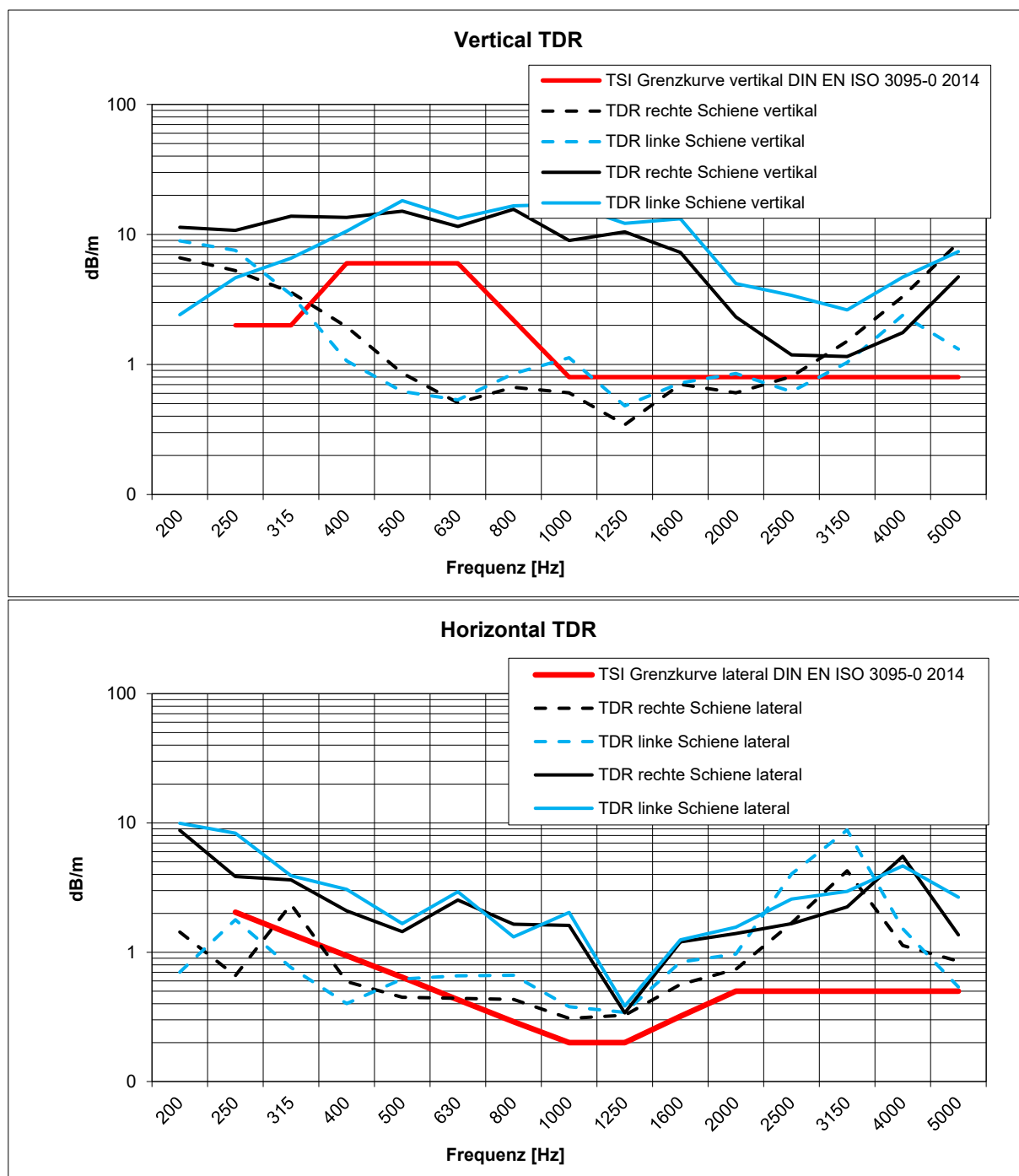


Figure 4: Comparison between Horizontal and Vertical TDR

TSI Grenzkurve vertikal DIN EN ISO 3095-0 2014:

TDR rechte Schiene vertikal:

TDR linke Schiene vertikal:

TDR rechte Schiene vertikal:

TDR linke Schiene vertikal:

TSI vertical limit curve DIN EN ISO 3095-0 2014

TDR right rail vertical

TDR left rail vertical

TDR right rail vertical

TDR left rail vertical

### 2.2.1. Following EN 15461: Characterisation of the dynamic properties of track sections for pass-by noise measurements

TDR calculations according to EN 15461 involve frequency response functions (*FRF*) measured on the rails of an unloaded track, as follows:

- a) Acquiring data on mechanical frequency response functions
- b) Processing measurement data to calculate the estimated vibration decay rates along the rails within the audible frequency range associated with rolling noise
- c) Comparing this estimate with the lower limits of the decay rates

To obtain the  $H_1 - FRF$ , [4] [5] the rails' responses are measured during an application of rail impulse forces, via an instrumented hammer, within a specific frequency range. Figure 5, taken from the standard, specifies the hammer's horizontal and vertical excitation points. Accelerometers are then fixed in Section 0, in both the horizontal and vertical directions. Three-channel data must be recorded for all excitation points, in the directions indicated by arrows "1" and "2". Alternatively, only one accelerometer may be used, with measurements first being made in the horizontal direction, and then in the vertical direction. However, the latter approach would double the required track access time.

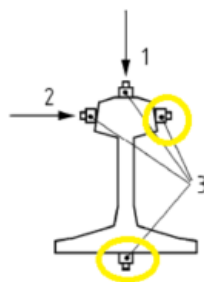


Figure 5: The hammer excitation points and the fixation of the accelerometers (Section 0, as shown in EN 15461, 1: Vertical force, 2: Transverse force, 3: Accelerometers)

### 2.2.2. Preparatory steps for performing an in-situ TDR measurement

A basic understanding of how to perform measurements for structural dynamics, including knowledge regarding sensors, data-acquisition systems, and data processing, is required.

- Prepare the necessary equipment: ideally having a battery powered handheld data acquisition system, 2 accelerometers for mounting on the rail (sensitivity between 100m/s<sup>2</sup>/V and 1000m/s<sup>2</sup>/V), an instrumented impulse hammer (sensitivity around 1000N/volt), and an extension cable for the accelerometers (2x 40m).
- Verify the impulse force and accelerometer response on a free accessible track to determine the frequency range. The combination of tip hardness, hammer weight and thus impulse duration will determine the excited frequency range. The hammer excitation must not go below 5kHz. A coherence function can be used to verify data quality.
- Select a standard track section, with no irregularities which could cause an increase in noise emissions (e.g., welds, joints, switches, etc.) and which is free from traffic for at least 1 hour.

- Measure both the ambient (inc. humidity and wind) and rail temperature during the TDR measurements.
- Mount accelerometers horizontally and vertically in rail Section 0 as indicated on Figure 5. They should be in the middle of the distance between the two sleepers. The positions circled in yellow can be used when the measurement with a running train is carried out. The horizontal accelerometer should then be positioned at the outer side of the rails. If magnets are used, it is important to take the weight of the sensors and force of the magnet into consideration, ensuring that no resonance from mounting occurs in the frequency range of interest. The contact stiffness is extremely important, as is the use of electrically isolated connections when mounting the sensors on the rails.
- Perform measurements with at least 8 hammer excitations in the vertical direction (Section 0) with the response being recorded each time. The averaged frequency dependent  $H_1 - FRF$ , the auto power spectra from the force and acceleration, and the coherence function are to be calculated for each measurement series. These should be directly interpreted to verify the quality of the measurement. They should also be repeated at three-positions to verify the dynamic stability of the test track.
- Perform all measurements (vertical, horizontal) and carry out on-site quality control checks to detect any potential signalling issues caused by cable movements or connections. All measurements should be stored, and the timestamps recorded. A quality control check on all measurement data is to be performed, preferably onsite, as, for example, cable movements and faulty connections can cause misalignments between the timestamps and the recorded data.
- Convert fine band measurements ( $H_1 - FRF$ ) to one-third (1/3) octave bands and calculate TDR for each band using the provided formula. From these FRFs, TDR as a function of the 1/3 octave bands can be calculated, to be repeated for every 1/3 octave band, where  $A(x)$  corresponds to the amplitude of an FRF in a 1/3 octave band at a point on the rail head at  $x$ , and  $\Delta x_n$  corresponds to the interval between the points situated at a half-distance between the measuring positions on either side of the excitation point.

$$TDR = \frac{4,343}{\sum_{x=0}^{x_{max}} \frac{|A(x_n)|^2}{|A(x_0)|^2} \Delta x_n}$$

Equation 1: Track Decay Rate according to EN 15461 [4]

### 2.2.3. Performing Indirect versus Direct TDR measurements

There are two methods for performing TDR measurements in railway applications: direct TDR according to EN 15461 [4] and indirect TDR according to CEN/TR 16891 [6]. The direct TDR method involves unloading the track and using an impulse hammer to excite the rail. Whereby for the indirect method, the excitation results from a train passing by, and the rail only has accelerometers on it. In this method, the track is partially loaded, which results in a compression of the substructure and, in some cases, differences when compared with the unloaded track. Examples are also given in CEN/TR 16891, and the two methods are compared in certain cases.

In **WP5: Measurements**, a suggestion was made to apply the comparative technique to measure the rail accelerations in pass-bys to learn more about the differences in unloaded track TDR (EN 15461) and loaded track TDR (CEN/TR).

## 2.2.4. TDR as a single parameter

To describe TDR as a single parameter, the following steps were suggested for the project:

- An initial definition was proposed, based on analysis of the measured vertical TDR curves and their relationship with the insertion loss (IL) of measured noise emissions. As explained in section 2.2, horizontal TDR is effectively not affected by rail pad changes, so this was not used during the project.
- Initial data showed that the dominant effect of the TDR change on noise emission was limited to a specific bandwidth. It is proposed to take four 1/3 octave bands into account: 630Hz, 800Hz, 1000Hz, 1250Hz
- The ISO3095 limits for 630Hz, 800Hz, 1000Hz, 1250Hz are subtracted from the TDR values for the vertical direction (see in 2.2): 6dB/m, 2.19dB/m, 0.8dB/m and 0.8dB/m respectively. This leads to negative values if the TDR values are lower than the reference values.

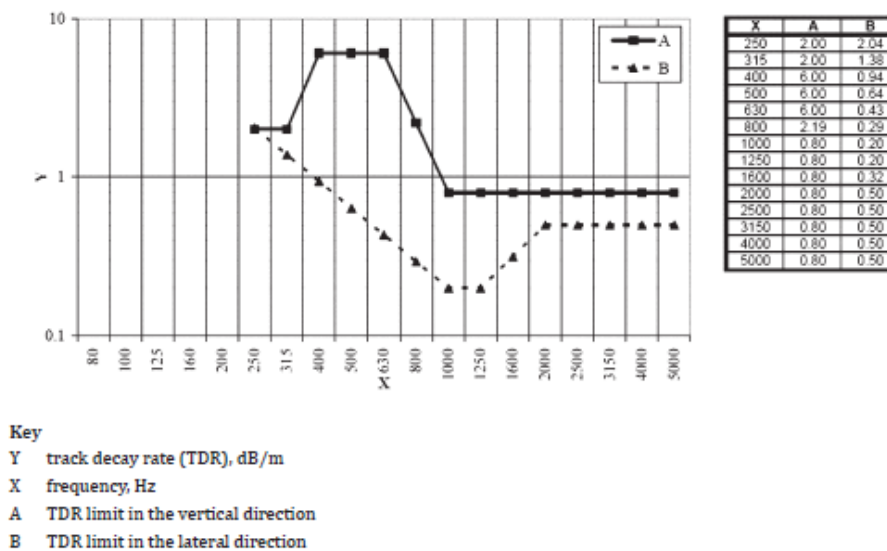


Figure 6: Default lower limit curves for TDR [7]

- The A-weighted values were subtracted so that their contribution to noise emissions could be seen
- The energetic mean value is calculated for the four 1/3 octave bands
- This leads to values that were well matched with the noise emission differences in dB(A) to be expected

$$TDR \text{ single value} = 10 * \log_{10} \left( \sum_{f1=630}^{f4=1250} 10^{\frac{(TDR(f) - TDR_{ref}(f) + A_w(f))}{10}} \right)^{1/4}$$

Equation 2: Single value TDR derived from only vertical TDR

The validation process is explained using the following practical example for a monoblock sleeper, with rail clip and a 60E1 rail with different rail pads:

- An initial correlation between the values (Batch 1) was established, with further calculations

being made once additional data became available (Batch 2)

- The approach will be applied to the measurement data from WP5

Figure 7 illustrates the variation in TDRs based on specific rail pads, such as PRORAIL EVA and other stiff rail pads, which yield high single value TDRs ranging from between 15 and 20 dB/m.

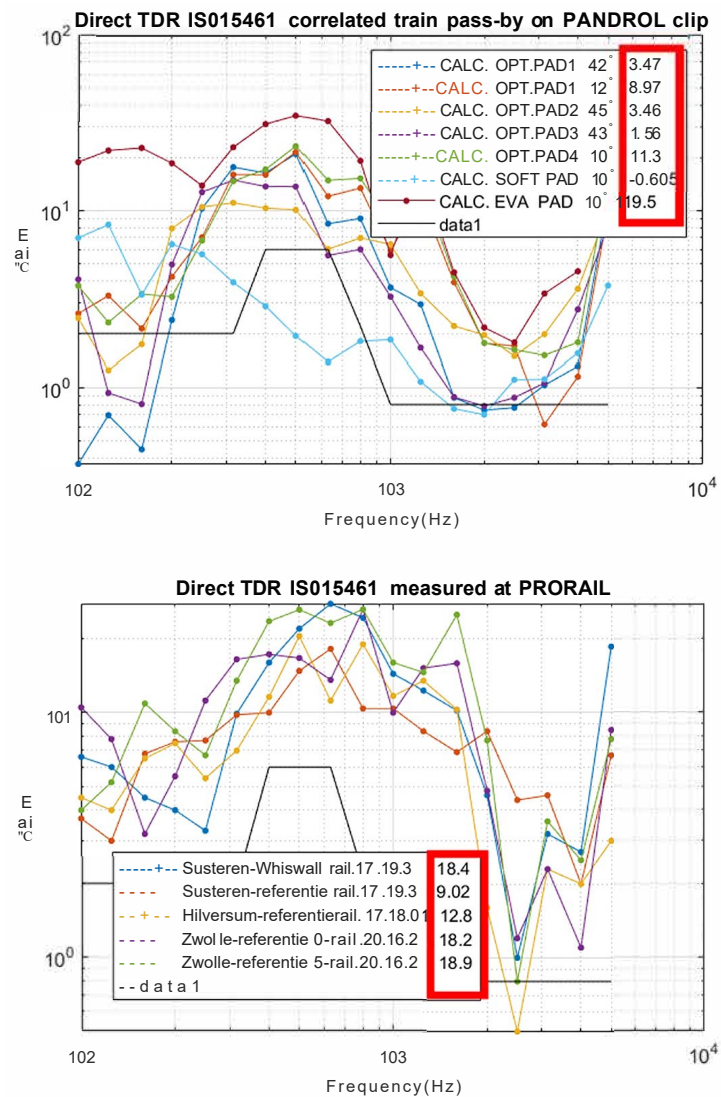


Figure 7: Examples of Direct TDRs

Table 2: Relationship between single value TDR and measured noise reductions

| Single value TDR | Noise reduction on LAeq, tp |                       |
|------------------|-----------------------------|-----------------------|
|                  | Batch1: Limited data        | Batch2: Extended data |
| -2.5             | 0                           | <0                    |
| 0                | 1                           | 0                     |
| 5                | 2.5                         | 1.2                   |
| 10               | 4                           | 2.2                   |
| 15               | (6)                         | 3.5                   |
| 20               | (7.5)                       | 4.4                   |

Batch 2, also with the establishment of an initial correlation, showed an acceptable relationship between the single value TDR and the expected noise reduction when compared to soft rail pads. However, to further support these findings, additional measurement data is required. The further corroboration process is explained in **WP5: Measurements**.

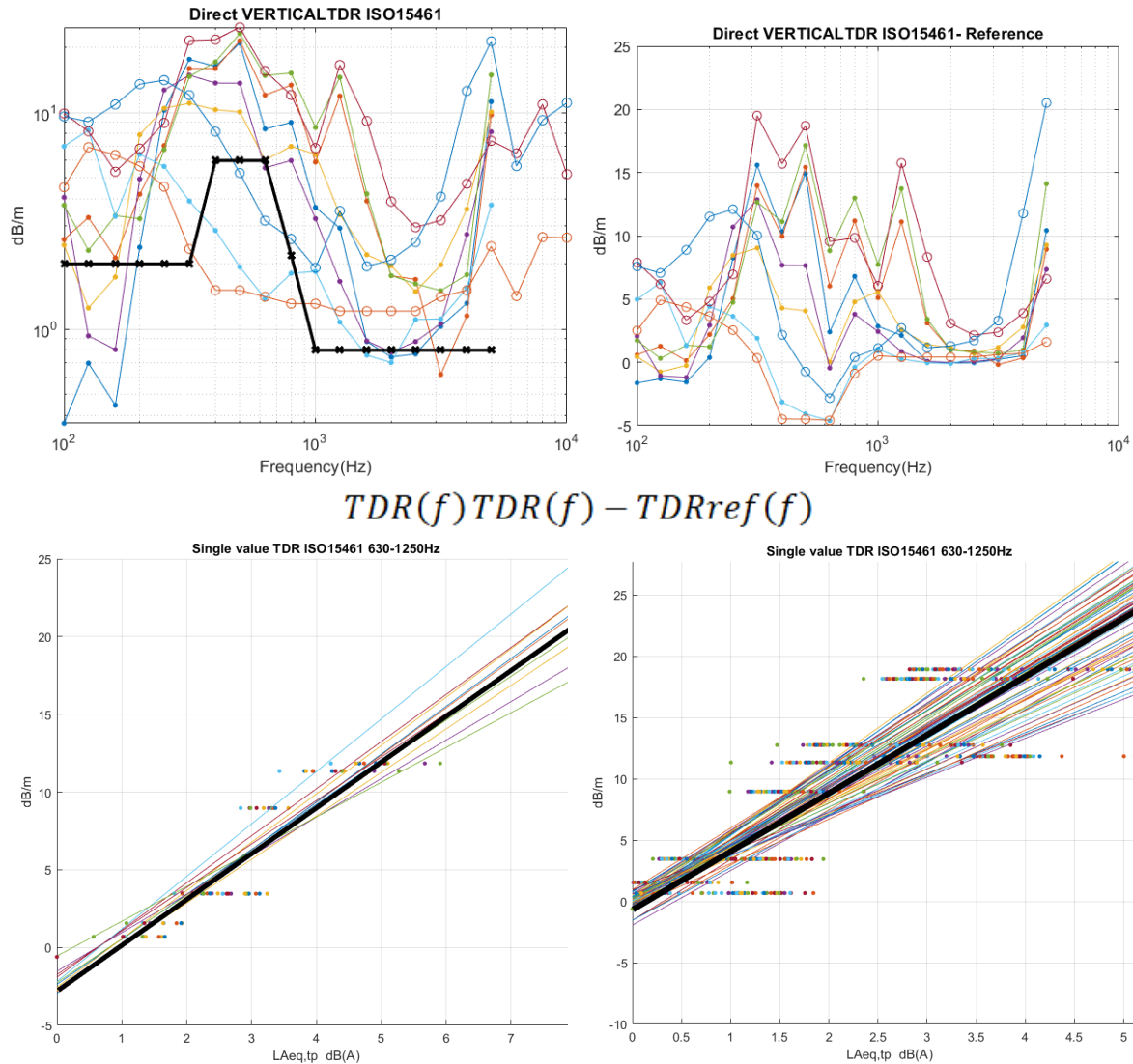


Figure 8: Single value TDR versus a weighted noise reduction with a very soft rail pad as reference (left: batch 1, right: batch 2)

## 2.3. CONCLUSIONS

The results obtained from the LOWNOISEPAD Track Database constituted the backbone of the LOWNOISEPAD project. These results were used in WP3 for selecting and/or optimising the reference rail pad and the rail pad to be tested in WP5. Furthermore, these results are expected to serve as valuable input for other projects and research, contributing to a reduction in overall noise emissions and nuisance from railways, by enhancing future efforts to make railways a better neighbour. The single value TDR was then used and confirmed in **WP5: Measurements**, and **WP6: Data processing and dissemination** and compared with the real measured noise reduction results (see section 8.1.3).

### 3. WP3: SELECTION OF RAIL PADS TO BE TESTED

Based on the information from the LOWNOISEPAD Track Database established in WP2, the rail pad(s) to be used for the measurements were selected, according two possibilities:

- Testing and comparing existing rail pads, or
- Optimising an existing rail pad, which has been additionally ordered by the PPs, in line with the project length

To assess the changes in the rail pad and TDR, a new semi-empirical methodology was developed, which combines theoretical aspects with available pass-by measurements. It is detailed below.

#### 3.1. METHODOLOGY

##### 3.1.1. Theory in combination with available pass-by measurements

In line with Equation 1 [3], the theory of the  $-10\log_{10}\Delta$  correction in combination with available train pass-by measurements allows for the calculation of noise emissions. This correction accounts for differences in TDR ( $-10\log_{10}(\frac{TDR2}{TDR1})$ ). However, additional corrections were necessary due the

wheel's increasing contribution to railway noise emission, due to the separation between the wheel and the rail, particularly from frequencies of 2kHz and above.

$$L_w \approx 10\log_{10}\left(4.343\rho_0 c_0 P \frac{v_{ref}^2}{W_{ref}}\right) + 10\log_{10}\sigma + 10\log_{10}\left(\frac{|v(0)|^2}{2v_{ref}^2}\right) - 10\log_{10}\Delta$$

*Equation 3: The sound power level is related to the radiation index, velocity level, and the decay rate [3]*

In this project, the focus was on utilising TDR2 and TDR1 measurements, along with their corresponding  $L_{pAeq,tp}$  for TDR1 and TDR2, obtained from the PPs' tracks (for example tension clamp or rail clip). The objective was to assess the influence of TDR on  $L_{pAeq,tp}$  using 1/3 octave band data. This approach offered a simpler alternative to the complex TWINS modelling, which typically requires train-by-train analysis for detailed wheel/rail source separation. Instead, two additional correction factors were determined and applied, leveraging the existing database of train pass-by  $L_{pAeq,tp}$  1/3 octave data. These correction factors were derived from measurements conducted on at least two different rail pads, accounting for various types of rolling stock and train speeds. The flow-charts below (Figure 9 and Figure 10) provide a visual representation of this proposed method.

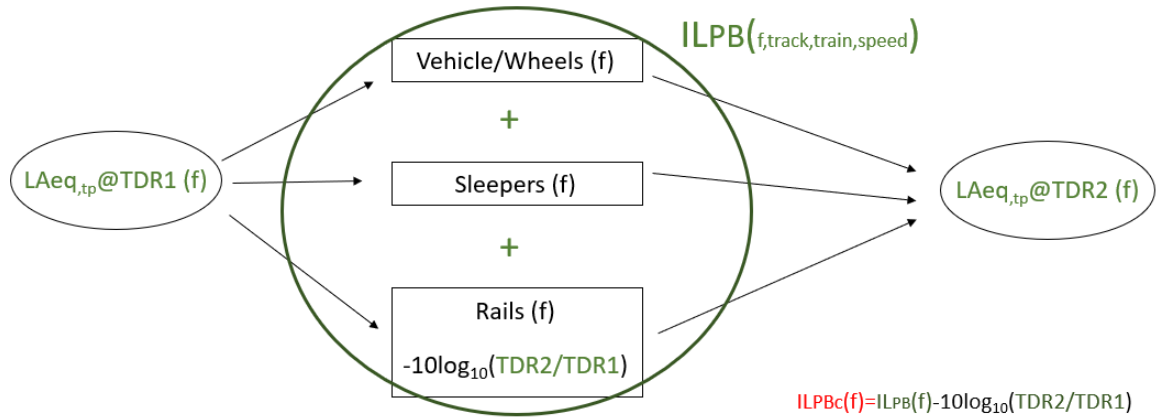


Figure 9: Flow chart in line with Equation 3 – prepared for the LOWNOISEPAD project

The correction factors are as follows:

1.  $IL_{PBc}$  - calculated based on the actual measured direct noise insertion loss  $IL_{PB}$  in 1/3 octave bands using measurements from at least two rail pads. This correction factor takes the excitation of the system into account, regardless of it being caused by rough or smooth wheels. It represents the difference between the in-situ measured IL and the theoretical formula  $(-10\log_{10}(\frac{TDR2}{TDR1}))$ .

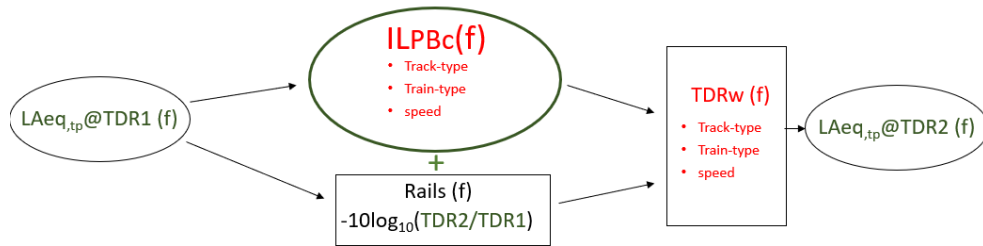


Figure 10: Flow chart to define the two correction factors used in the project

2.  $TDR_w$  – involves adding a weighting function to the 1/3 octave bands, which focuses the influence of TDR on a specific frequency range to ensure realistic results. The adjustment of this factor is based on available pass-by measurements.

Equation 4, which considers all parameters within the 1/3 octave bands ranging from 100Hz to 5kHz, is used to calculate the noise emission difference for different rail pads:

$$L_{Aeq,tp@TDR2} = L_{Aeq,tp@TDR1} - \left( 10\log_{10} \left( \frac{TDR2}{TDR1} \right) \right) + IL_{PBc} + TDR_w$$

Equation 4: Calculated noise emission difference for different rail pads

Once measurement data is available, the  $IL_{PBc}$  and  $TDR_w$  values are determined and validated for a typical track, train type and operating speed, with several simulations being able to be conducted. These include:

- Assessing the influence of temperature on noise emission through direct TDR measurements at different temperatures.
- Predicting the effect of noise emission on other track locations by using direct TDR measurements.

It is crucial to focus on similar track types at different locations to ensure that realistic predictions are made.

- Making predictions between countries if there is sufficient similarity in track design, rolling stock (e.g., SNCB NMBS-Desiro in Belgium and ÖBB-CityJet in Austria), and temperature values during the measurements.

### 3.1.2. Validation for a track with rail clip

The authorisation to benefit from INFRABEL RRP project (2017) data played a vital role in conducting a thorough validation of the proposed approach above. The measurement data obtained from a standard INFRABEL track (which includes concrete monoblock sleepers, 60E1 rails, rail clip, various rail pads, and diverse rolling stock), served as a solid basis for the validation process.

Approximately 340 train pass-bys, encompassing different types and speeds on the INFRABEL track with rail clip, were analysed to confirm the effectiveness of this approach. The results demonstrated that the methodology worked well, and with a high degree of accuracy, as changes in overall pass-by noise emission were assessed within a margin of  $\pm 1$  dB. This level of precision was achieved through cross-checks using available pass-by data, allowing the correction factors, such as  $IL_{PBc}$  and  $TDR_W$ , to be fine-tuned.

Figure 11 illustrates typical examples for  $IL_{PB}$  and  $IL_{PBc}$  for three different types of rolling stock at a speed of 160km/h. These examples further support the validity and effectiveness of the approach, showcasing the correlation between the measured noise insertion loss (NIL) and the derived correction factor for the different train configurations.

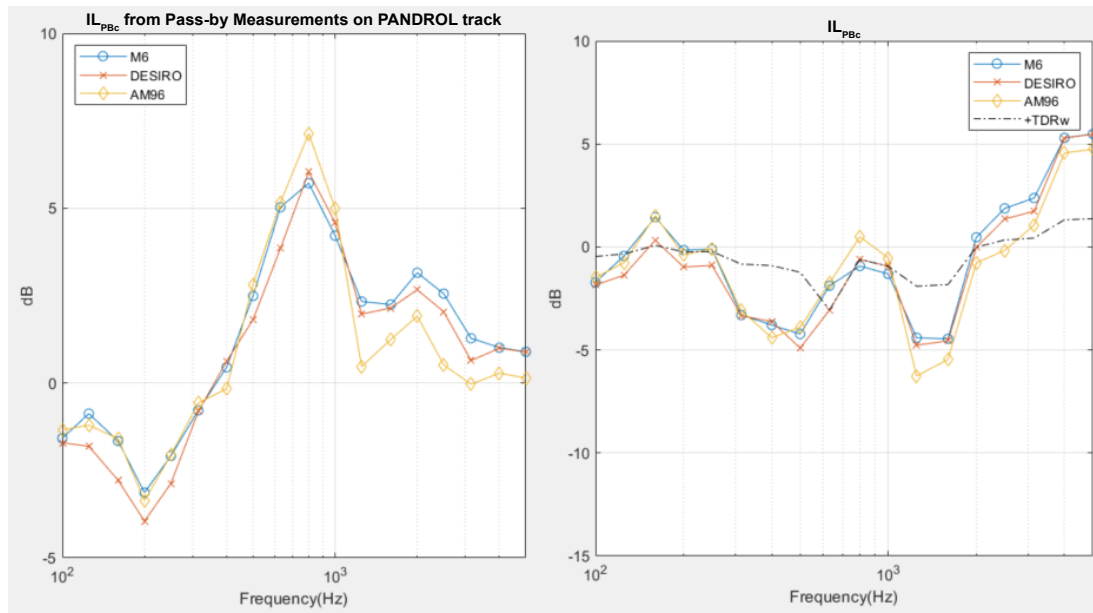


Figure 11:  $IL_{PB}$  and  $IL_{PBc}$  for 3 different types of rolling stock on a track with rail clip at a speed of 160km/h

### 3.1.3. Validation for a track with tension clamp

To gain a better understanding of the contribution of rail fasteners to rail noise emission in the Belgian example above, a similar approach was applied using pass-by data measured on the ÖBB standard track equipped with concrete monoblock sleepers, 60E1 rails, and W14 tension clamp. This additional data enhanced the analysis and provided valuable insights into the influence of rail fasteners on noise emissions. Initial analysis of approximately 50 train pass-bys, involving different train types and rolling stock speeds on the ÖBB tracks with SKL tension clamp, confirmed the effectiveness of this approach. Changes in overall pass-by emissions were successfully assessed within a margin of  $\pm 1$  dB. Figure 13 shows the  $IL_{PB}$  obtained from pass-by measurements on a track with tension clamp at a speed of 120km/h, further supporting the validity of the approach.

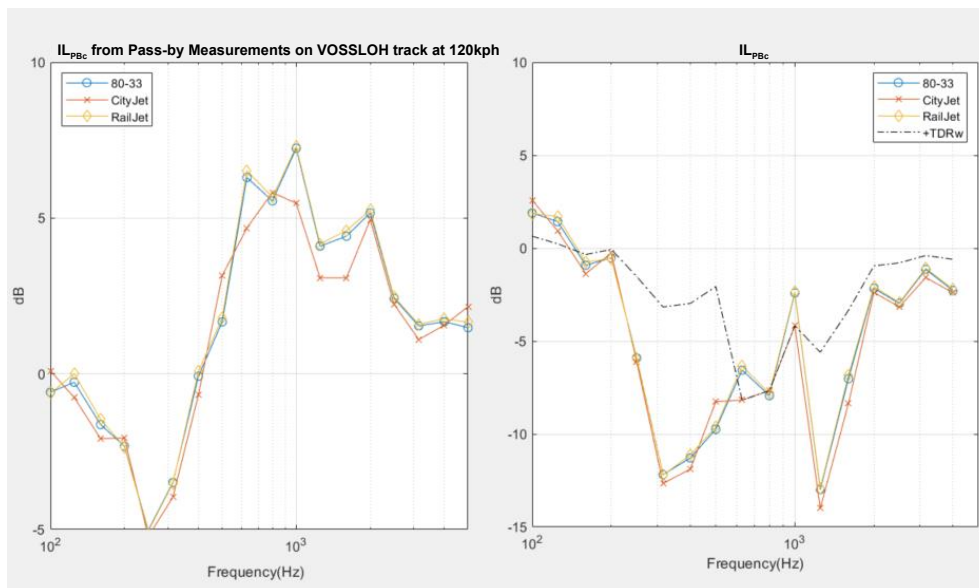


Figure 12:  $IL_{PB}$  from pass-by measurements on a track with tension clamp at 120km/h

### 3.1.4. Conclusion

In conclusion, the proposed approach of using the two  $IL_{PB_c}$  and  $TDR_W$  correction factors was successfully applied to assess the influence of rail fasteners on rail noise emissions. The combination of the correction factors  $IL_{PB_c}$  and  $TDR_W$ , along with the available pass-by data, allowed for informed decision-making regarding the selection of rail pads for further testing within the project.

- $IL_{PB_c}$  is to be determined for a **typical rail fastening system** and **rolling stock**
- $TDR_W$  is to be determined for **specific speeds** and **similar rolling stock**

The final analysis planned to include data from both clip and tension clamp, obtained from standard tracks with concrete monoblock sleepers and 60E1 rails. The validation of the WP3 approach was conducted using extensive pass-by data from INFRABEL and ÖBB tracks, considering various types of rolling stock and different speeds. The preference for real measurement data validation over expensive modelling ensures a more accurate representation of the effects on noise emissions. To conclude, the proposed approach offers a practical and reliable method for assessing and predicting noise emissions in rail systems, considering factors such as rail fasteners, rolling stock, and speed. Ongoing validation and analysis during WP6 aimed to further refine and strengthen the applicability of this approach in the final stages of the project.

### 3.2. LESSONS LEARNED AND CONCLUSIONS DRAWN

The proposed approach for selecting rail pads to be tested in relation to noise reduction constituted a significant milestone in the project. The selection process involved close collaboration between track engineers, acoustics engineers, and UIC, together with the subcontractor. Criteria such as static/dynamic stiffness, differences in the distribution of stiffness, and pad dimensions were taken into consideration during the selection process. Furthermore, available TDR measurements (following EN 15461 standards) and pass-by measurements played a crucial role in the decision-making process.

One of the critical aspects of the project was reaching a final decision on the chosen rail pads, with a particular focus on the differences in TDR. In cases where the quality of existing TDR measurements was found to be insufficient, new TDR measurements were carried out to ensure that the data was accurate. The selection of rail pads was essential in preparing for WP4, where detailed testing and analysis would take place.

Overall, the rail pad selection process was successfully completed, setting up the investigations and evaluations in the subsequent phases of the project.



## 4. WP4: TEST SITE SELECTION + RAIL PAD INSTALLATION

### 4.1. TEST SITE SELECTION

Following the methodology outlined in IRS 75717 Section 2.1 [2], a test site was carefully selected for the test phase of each PP. The primary objective was to vary only one component (the rail pad) across adjacent test sections, while keeping other factors such as track type, rail fastening, and rail roughness consistent throughout the entire test section. Each PP thoroughly examined any potential discrepancies between the reference and test sections. This approach allowed for a precise assessment of the impact of rail pads on noise reduction, enabling observed differences in noise emissions to be directly attributed to the differences in rail pads. More detailed information and specific measurement results for each PP can be found in Chapter 6.

### 4.2. RAIL PAD INSTALLATION

Preloading has a significant influence on dynamic rail pad properties that affect the dynamic responses of railway tracks. Therefore, this is expected to have an influence on the TDR. For clips, the effect remains relatively constant, as it is determined by the deformation of the fasteners, which are maintained at a consistent level. However, for tension clamp, preloading on the pad is determined by the torque applied to the fixation bolts. It was crucial to verify that the preloading was identical in both the reference and test sections, necessitating a thorough verification process.

### 4.3. LESSONS LEARNED AND CONCLUSIONS DRAWN

Estimating the time and cost for installing the rail pads was the responsibility of each PP and was financed accordingly. The required effort varied depending on the type of rail fastening used, and whether the installation was done manually or with the assistance of machinery. For instance, the replacement of rail pads for a 100-meter track equipped with rail clip could be completed overnight, involving approximately 15 man-hours and the use of a rail crane. It was also important to note that a track closure had to be organised in accordance with the operational regulations of each PP. Additionally, rail roughness measurements were performed across the entire test section.

Each PP made a final decision on the site, considering all relevant factors. The selected site was then equipped with microphones and rail accelerometers (in line with IRS 75717 Section 2.2.1 and detailed in Chapter 5 of this report), facilitating the collection of data for further analysis and evaluation.



## 5. WP5: MEASUREMENTS

In WP5, the twelve European PPs organised and took measurements on their respective railway networks to compare the noise emission differences between the test section, with a different rail pad configuration, and the reference section, with the original rail pad. The purpose was to compare the differences in noise emissions on tracks in service, specifically the noise emission insertion loss (IL) of the rail pad in the test section, using the rail pad in the reference section as the reference pad.

Following the methodology outlined in Sections 2.2 to 2.4 of IRS 75717 [2], each PP carefully selected a test site for the measurements. The relevant standards were also taken into consideration in line with the IRS and all requirements and recommendations were fulfilled [4] [8] [7] [2].

Each PP took responsibility for carrying out the measurements within their allocated budget. The measurement plan, including sensor sensitivity and other relevant parameters, was verified for each PP to ensure consistency and reliability across the different railway networks. All information about the test set-up is described in detail in the following chapters of IRS 75717 [2]:

### 2.2. Parameters to be measured

- 2.2.1. Installing equipment
- 2.2.2. Measurements with running trains
- 2.2.3. Measurements requiring access to tracks

### 2.3. Setting up for pass-by measurements

### 2.4. Equipment required for pass-by measurements

### 2.5. Sensor calibration and sensitivity



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## 6. WP6: DATA PROCESSING AND DISSEMINATION

WP6 focused on analysing and processing the collected data to evaluate the impact of rail pad optimisation on noise reduction of each PP. The following key steps were carried out:

- **Dataset:** A comprehensive dataset was obtained, consisting of raw data from both accelerometers on the rail and microphones. The dataset included approximately 1200 train pass-bys, resulting in a substantial amount of data to process (approximately 34 gigabytes).
- **Processing protocols:** Detailed and harmonised processing protocols were established as guidance for data analysis, ensuring a consistent and systematic evaluation across all twelve PP test sites.
- **Automated batch processing:** To streamline the analysis, a multicore automated batch processing approach was deployed, which enabled the efficient processing of all train pass-bys in a systematic manner.
- **Parameters analysed:** In addition to the 1/3 octave analysis of the data, various parameters were processed, including the number of axles, train length, train speed, and combined wheel-rail roughness and indirect TDR.
- **Synchronisation and correlation:** The simultaneous collection of rail accelerations and microphone data, linked with a time stamp, allowed for accurate correlation with known train types during pass-bys. This synchronisation facilitated the investigation of noise emissions in relation to specific train characteristics.

Following the methodology outlined in Section 2.6 of IRS 75717 [2], the data to be collected from each PP was carefully defined. The relevant standards were also taken into consideration in line with the IRS and all requirements and recommendations were fulfilled [4] [8] [7] [2]. All information regarding the data analysis process is available in detail in the following sections of IRS 75717:

2.6. The data to be collected

2.7. Decay rate and rail roughness data

### 6.1. PROCESSED DATA

The final project report provides detailed technical analysis based on the 1/3 octave band spectra. By considering the measured noise insertion loss in these bands, the spectral insertion loss  $IL_{PB}$  can be calculated. This parameter enables the reduction in noise emissions to be estimated, including specific factors such as:

1. The rail-fastener configuration
2. The reference rail pad
3. The rail pad being tested
4. The type of rolling stock
5. The speed
6. The temperature

To compare, disseminate, and publish the results amongst the 12 PPs, six influence parameters can

be considered for each  $IL_{PB}$ . Once data is available, this results in six scripts (indexes) for data post-processing and the sample naming should be as follows:  $IL_{PB,Vossloh,ZW900,Semp6,AM96,120kph,20^{\circ}C}$ . For instance, in the case every analysed pass-by within the INFRABEL project, data is presented in Figure 13 and is labelled as  $IL_{PB,Pandrol,Soft,Optimised,various\ trains,80-160kph,15^{\circ}C}$ .

|               |                                       |
|---------------|---------------------------------------|
| v             | 134.46                                |
| type          | '1X3AM96+1X3AM96+1X3AM96'             |
| ttot          | 8.4016                                |
| tp            | 6.4204                                |
| time          | 336x1 double                          |
| projectname   |                                       |
| okt3t         | 35x5 char                             |
| leqvstime     | 336x4 double                          |
| G             | 2401x1 double                         |
| file          | 'SVAN0007'                            |
| Fcorr         | 1x33 double                           |
| F             | 1x33 double                           |
| Dsel          | [109.0929;105.9845;113.5236;108.4314] |
| directory     |                                       |
| dataoutoktmax | 4x33 double                           |
| dataoutoktleq | 4x33 double                           |
| chunitstxt    | 16x1 cell                             |
| chunits       | 16x1 double                           |
| chlabel       | 16x1 cell                             |
| answer        | ' 19-Sep-2016 15:47:25'               |

Figure 13: Example from the INFRABEL RRP project – post-processing data and sample naming

Examining the plots from the INFRABEL RRP project in Figure 14, the following observations were made:

#### ■ Plot 1: Spectral insertion loss (SIL)

- The plot displays the SIL from 200Hz to 12.5kHz, considering both noise and the midspan rail vibrations (i.e., the middle of the distance between the two sleepers).
- Notably, the maximum noise insertion loss occurs just before the pin-pin frequency.
- The NIL shows only slight variations with speed and excitation/train type (cast iron or disc brakes).
- The rail insertion loss exhibits a distinct dip in the pin-pin frequency region, coinciding with the noise insertion loss.

#### ■ Plot 2: Overall values as a function of train speed

- The plot illustrates the calculated overall values from 200Hz to 12.5kHz for both noise and midspan rail vibration, as a function of train speed.
- At higher speeds, the differences between the overall noise and vibration values become more pronounced.
- These differences can also be observed in the SIL for noise, particularly around the 2kHz-3.15kHz frequency range.

These findings provide valuable insight into the relationship between various parameters, such as speed, noise, and vibration, in the context of rail pad optimisation. The analysis in Figure 14 highlights the significance of the pin-pin frequency region and emphasises the influence of train speed on noise and vibration levels. These technical details contribute to a comprehensive understanding of the project's outcomes and support the development of effective noise reduction strategies in future railway track designs.

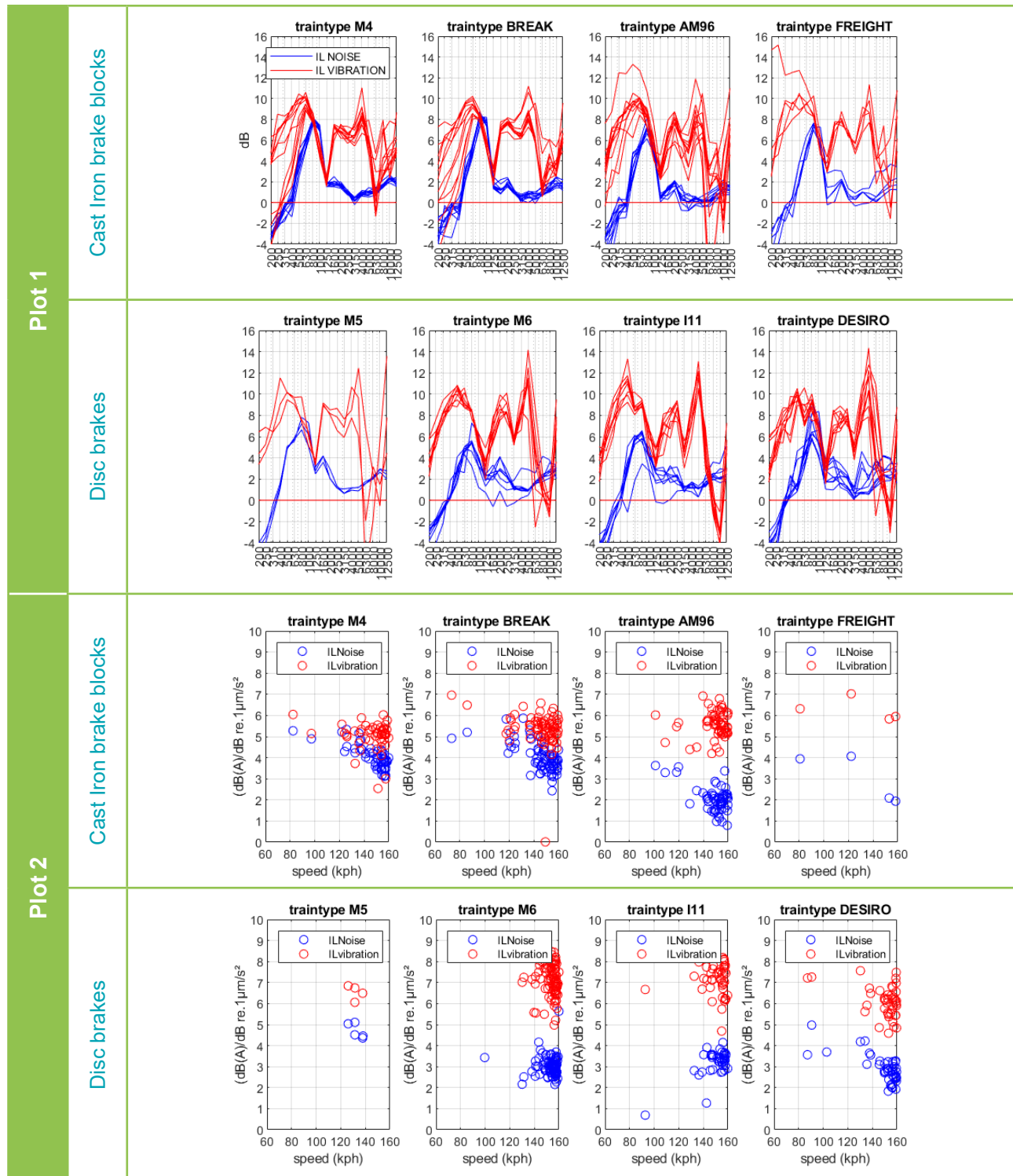


Figure 14: Example from the INFRABEL RRP

## 6.2. CONCLUSION

The outcomes of WP6 contribute to the broader goal of reducing noise emissions in railway operations. The ability to evaluate noise reduction, provide design recommendations, and develop a simulation tool enhances the understanding of the relationship between rail pad optimisation and noise mitigation. These findings have the potential to inform future infrastructure projects and facilitate the development of quieter and more sustainable railway systems.

The automated batch processing approach and the correlation of synchronised data provided valuable insight into the relationship between noise reduction and the multiple factors influencing it. Analysis of the processed data gave rise to the following conclusions:

- **Evaluation of noise reduction**

The measurement data obtained through  $IL_{PB}$  analysis allowed noise reduction, specific to the 12 PPs sites, to be evaluated, taking their unique track characteristics, rolling stock, speed, and temperature conditions into consideration. The results indicate that noise reduction is influenced by various factors, including rolling stock and speed, rail fastening systems, temperature, and country-specific variations. These findings contribute to the development of effective strategies for noise mitigation in railway operations and rail pad optimisation will play a significant role in noise reduction.

- **Recommendations for rail pad design**

The WP6 findings serve as a basis for generating recommendations for future rail pad design, including their properties and geometry. These recommendations aim to provide clear quantifiable guidelines for achieving low-cost noise reduction in future railway track fastener designs.

- **Software tool development**

The availability of the project's measurement data presented an opportunity to develop a software tool. The tool uses the collected data and can be deployed to simulate the effect of rail pads/TDR on train noise. This tool would enable noise reduction outcomes for different rail pad configurations to be predicted and would facilitate the design optimisation process.



## 7. WP6: MEASUREMENTS

This chapter provides a comprehensive overview of the project's site descriptions, measurement setups, installed pads, and initial results for each PP. While a limited number of selected results are presented in this section, more extensive analysis can be carried out using the LOWNOISEPAD software tool, allowing for visualisations based on country, train type, rail pad type, and speed. For more information, see **Annex A: Graphic Reference Guide**, which contains additional detailed plots for 8 of the PPs.

Note: Information such as the current track data or track roughness measurements for four of the PPs (BaneNor, Network Rail, ProRail and SNCF) will be detailed during the next revision of the document and the results will be updated and included in the final version of the LOWNOISEPAD report.

The post-process procedure can be summarised as shown in Figure 15, which outlines the steps undertaken to analyse and interpret the collected data. Pass-bys were rejected if they fell outside defined synchronisation and quality limits, which may occur due to poor quality or disrupted accelerometer and microphone signals.

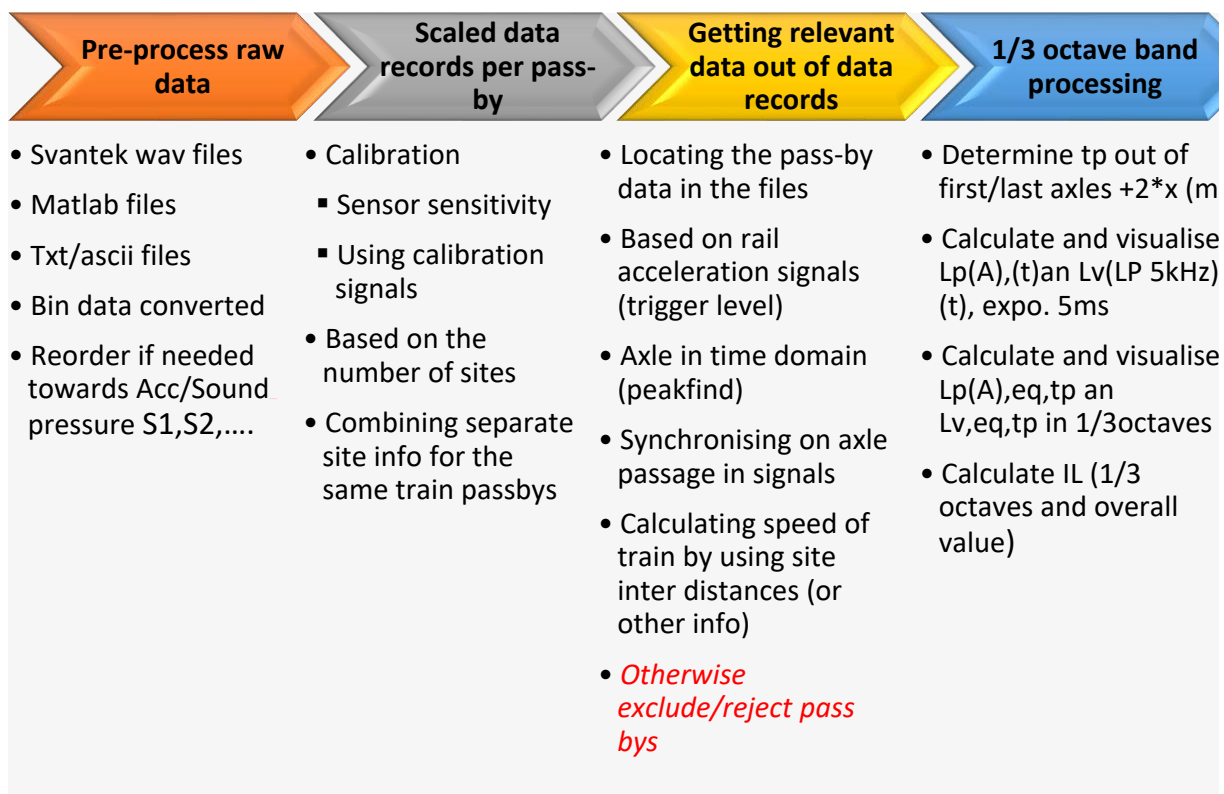


Figure 15: The basic data processing flow for analysing a "typical" pass-by

Figure 16, taken from **Annex A: Graphic Reference Guide**, provides an example of detailed analysis of a pass-by, in line with the process given in Figure 15, and a detailed explanation is given below. Each individual train pass-by within the project is accompanied by a similar plot, given in **Annex A: Graphic Reference Guide**.

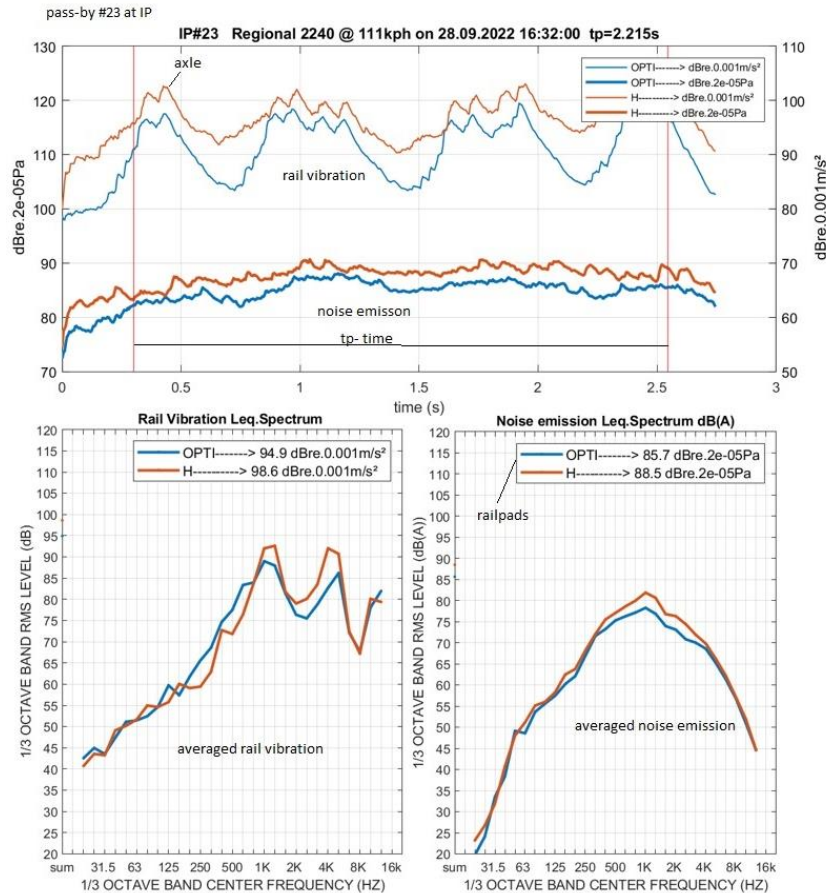


Figure 16: A typical pass-by, available for every pass-by in the project

- Different rail pads are represented by different colours
- Amplitudes are calculated in dB, time is measured in seconds, and frequencies are displayed in 1/3 octave bands
- Clear differences in noise and vibration levels at 1/3 octave bands can be observed in the plots above
- The IL can be calculated and used for further analysis
- Information about each PP's type of train, date, and timestamps can be provided at the top of the plot (example from IP, Portugal)
- Synchronisation checks shall be conducted, for example, to ensure that the passage of the axles over the different pads is aligned (detailed in Figure 17 and problem areas are shown with a red circle)
- Variations in train speed can be monitored
- The exponential time averaging was set to 5ms, allowing for the detection of short-term issues

Following the pass-by analysis, several examples of microphone, accelerometer, and rail discontinuity related problems are presented in the figures below. These visual representations and data processing protocols serve as valuable resources for understanding the project's findings and provide a foundation for further research and investigation. Each figure's title describes the specific problem encountered. Based on predefined limit values, these pass-bys were automatically rejected.

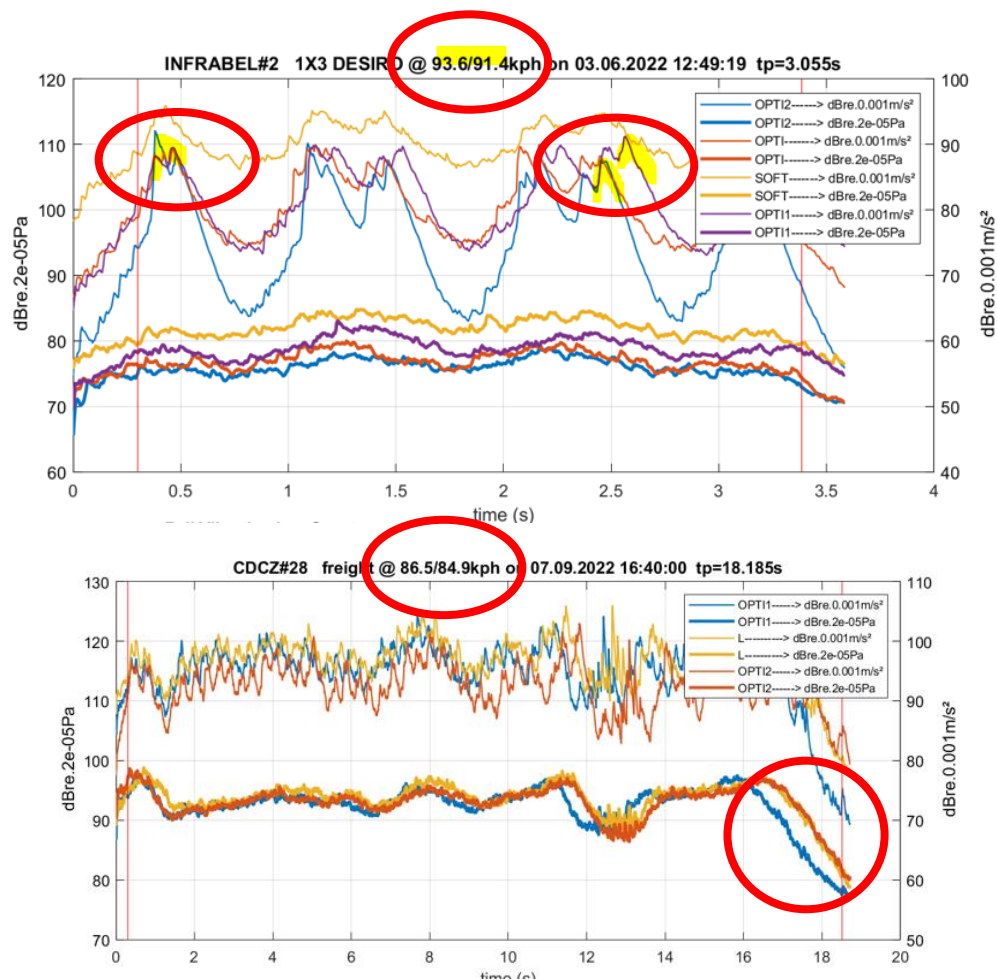


Figure 17: A minor speed change was observed between different sections  
Top graph from INFRABEL; Bottom graph from SZCZ

- Example from INFRABEL: A minor speed change was observed between different sections across INFRABEL's four sites. The speed decreased from 96.3km/h at the first site to 91.4km/h at the second site, resulting in a synchronisation error.
- Example from SZCZ: Similarly, a minor speed change was observed between different sections across SZCZ's three sites. The speed decreased from 86.5km/h at the first site to 84.9km/h at the second site, leading to a synchronisation error, which is indicated by the blue curves.

These examples highlight how variations in speed between different sections can affect the synchronization of measurements, emphasising the importance of maintaining consistent speed for accurate data analysis.

In Switzerland at two sites with similar stiff rail pads, before a rail pad change, it was observed that the rail acceleration was the same. However, the railway noise emitted was different, as indicated by the presence of blue bold curves showing jumps in Figure 18. This indicates a track defect that systematically occurred for numerous trains. In Austria, a wheel flat was identified, as shown in Figure 18 for the ÖBB graph, where it affected the accelerometer signals, but not the normal high frequency response of the 3 microphones. These findings provide valuable insight into the challenges and potential sources of noise on railway systems.

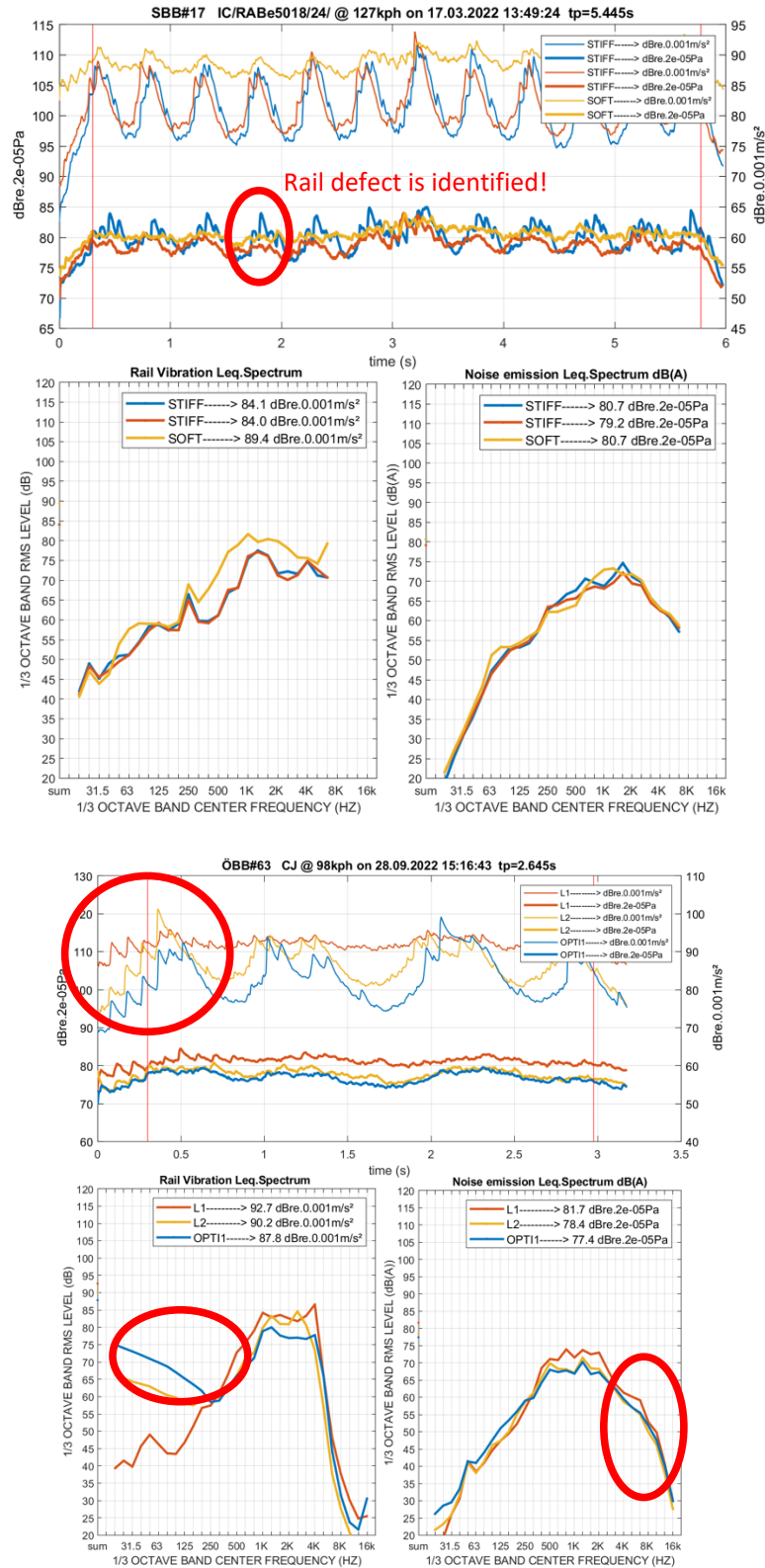


Figure 18: Analysis of pass-bys in Switzerland and Austria

Top: Noise emitted despite similar rail acceleration indicates the presence of a track defect  
 Bottom: Impact of a wheel flat on accelerometer signals while maintaining a normal response from the microphones

At ÖBB-Infar's test site "L1", shown in Figure 19, it was observed that the microphone exhibited unstable behaviour above 2.5kHz. However, this issue was not consistently present for all pass-bys and at all sites. This finding indicates a specific problem with the microphone's performance at site L1, specifically in the higher frequency range. Identifying and understanding such issues is essential for ensuring the accuracy and reliability of the measurement data. By documenting and analysing these anomalies, appropriate measures can be taken to improve the measurement process and obtain more accurate results in future studies.

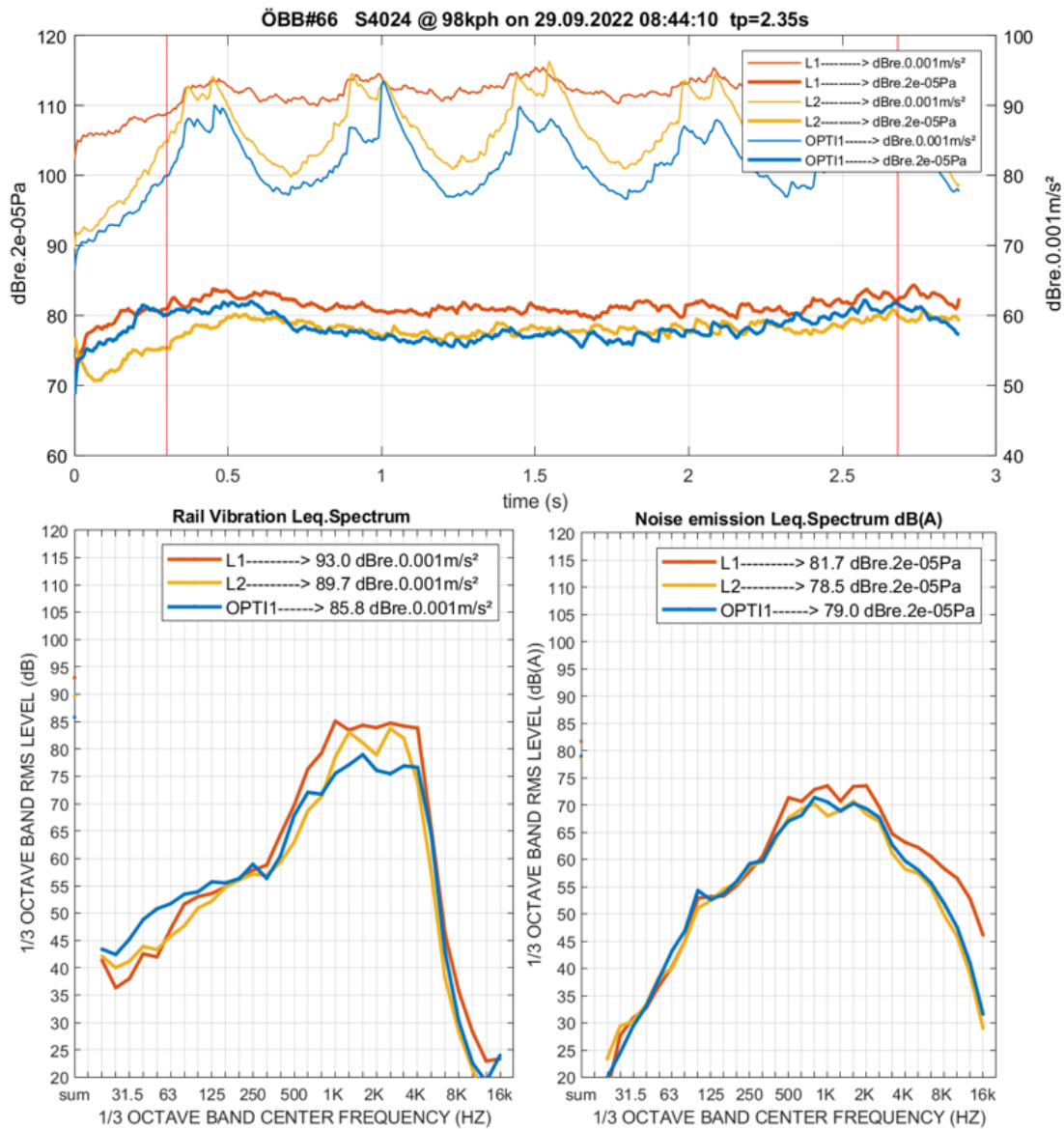


Figure 19: Unstable microphone behaviour above 2.5kHz at ÖBB site soft rail pad (L1)  
Please note, it is not systematically present for all pass-bys and all sites

## 7.1. SBB MEASUREMENTS, SWITZERLAND

During the measurements taken at SBB, conducted by EMPA in March, April, and May 2022, important details were identified. From analysis of the collected pass-by data, TDR, and roughness measurements, the key outcomes were:

- March 2022: Despite the expectation that pass-bys under the same conditions should cause the same noise levels, detailed analysis of the measurement data revealed a discrepancy. It was discovered that there was a noise-emitting welding in the section with optimised pads. This welding created a discontinuity in the running band of the rail, changing the emitted noise levels. Therefore, to draw accurate conclusions, the LOWNOISEPAD project only selected the trains that did not pass over the welding for analysis (due to a different contact line with the rail). Therefore, the recommendation was to repeat the measurements after removing the discontinuity, or to install the pads on another location. Consequently, SBB installed the rail pads in a railway field laboratory in May 2023, to monitor noise and track mobility. The laboratory consists of a 1km long track section where both noise and rail acceleration are continuously monitored. Given that the database contains pass-bys from both before and after the installation of the optimised pad, the pass-bys from SBB cannot be averaged within the software tool.
- April and May 2022, rail acceleration measurements were not always available, hindering their use in the software tool's analysis as the procedure for all PPs is based on rail acceleration. However, TDR measurements were verified, and improvements were advised for measurements on stiff rail pads. The final measurements obtained were deemed to be of acceptable quality.

### 7.1.1. Site description

The test track located in Nottwil consisted of three rail pads for comparison, a standard stiff pad, a soft rail pad, and an optimised rail pad (not the EPFL-designed rail pad, but a custom-made design by Semperit for the project). The test track consisted of concrete monoblock B91 sleepers with a USP of 0.3N/mm<sup>3</sup>, 60E2-R260 rails, and W14 tension clamp. More detailed information about the rail pads can be found in Table 14, Table 15 and Table 16.



Figure 20: SBB test site: Left: an overview of the test site. Right: the track's surroundings.

### 7.1.2. Measuring equipment

Pass-by vibrations on the rail were measured using the PCB M352C18 accelerometer, with a sensitivity of 10mV/g. For noise emissions, IEPE membrane microphones (B&K 4189) with a sensitivity 50mV/Pa were used. The multichannel sampling equipment was the NI DAQ card (PXIe-4499, 24 bits) with 16 synchronous recording channels. The data was simultaneously sampled at 100kHz, and there was an automatic anti-aliasing filter in place. Roughness measurements were conducted to verify the stability of the rail roughness across the three test sections, although no noise-emitting welding was identified. The results of the roughness measurements were not transferred to LOWNOISEPAD.

### 7.1.3. Rolling stock & speeds tested

Various passenger and freight trains were used for testing as part of the project, with speeds ranging from 70 to 160km/h. Detailed information about the train types and speeds can be accessed through the software tool, along with images being available in **Annex B: Rolling stock - Visual Reference Guide**. Since the track was in normal operation during the measurements, there was minimal variation in speed among trains of the same type. The data for SBB train noise emissions cannot be averaged in the software tool as the database contains data from before and after the rail pad change. The following passenger and freight rolling stock types were tested in the project:

*Table 3: Types of SBB trains stored in the database*

|                 |                            |                            |
|-----------------|----------------------------|----------------------------|
| Passenger train | EC/RABe501 8/24/           | EC/RABe501_8/24/           |
| Freight train   | GZ/Re620/GW4Ax_2DG         | GZ/Re620/GW4Ax_2DG         |
| Passenger train | IC/RABe501_8/24/           | IC/RABe501_8/24/           |
| Passenger train | IR/RABe526_8/20/           | IR/RABe526_8/20/           |
| Passenger train | IR/Re460/DOSTO_IC2000_HALL | IR/Re460/DOSTO_IC2000_HALL |
| Passenger train | IR/Re460/EW4_HALL          | IR/Re460/EW4_HALL          |
| Freight train   | LE/Re620/                  | LE/Re620/                  |
| Passenger train | RE/RABe521_4/10/           | RE/RABe521_4/10/           |
| Passenger train | S/RABe521_4/10/            | S/RABe521_4/10/            |

### 7.1.4. TDR

The TDR measurements were taken according to the CEN15461 and CEN TR 16891 standards, with the possibility of comparing the two methods via the software tool. The TDR raw measurement data was obtained, with both of UIC's subcontractors, SD&M and EMPA, doing the calculations. The results obtained by the two entities yielded similar values. As shown in Figure 21, the optimised rail pads exhibited higher damping behaviour than the stiff EVA pad.

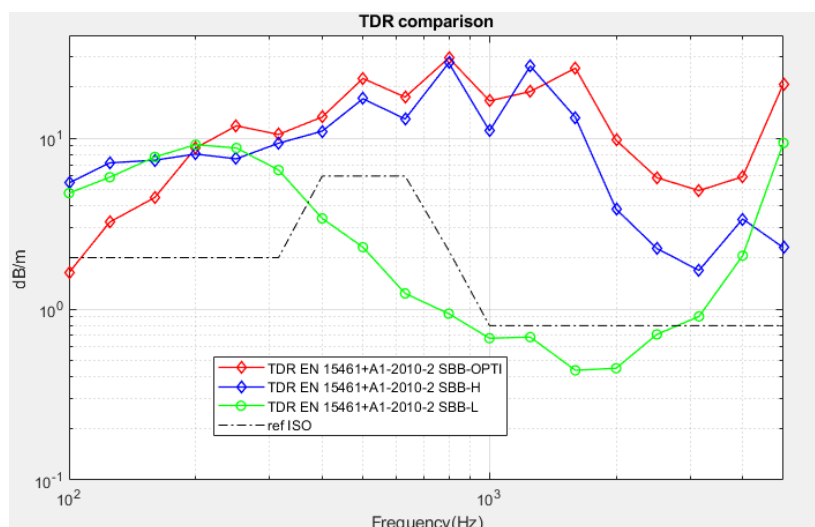


Figure 21: Measured TDR according to CEN15461 at SBB

### 7.1.5. Temperature during testing

During the measurements in March, the rail temperature was 7°C, while in April, it was 32°C.

### 7.1.6. Raw data received

The raw data was provided in MATLAB files and was then pre-processed and renamed by EMPA, based on the type of the rolling stock.

### 7.1.7. Database information received

All required information was delivered to the database, with further information being available on the software.

### 7.1.8. Results in the database

A total of 66 pass-bys were selected for analysis. Seventeen pass-bys were rejected due to, for example, speed differences, low quality rail acceleration measurements, and the inability to synchronize pass-bys across the three different sections. The processing information and any processing errors have been logged in the database for reference. It is important to note that the **pass-bys affected by the rail defect in the section with the optimised pads are included in the database**, meaning that they are to be reviewed with caution. Detailed plots of the processed data can be found in **Annex A: Graphic Reference Guide**. In future versions of the software tool, these issues can be addressed in detail, including the selection of averages within specified dates.

### 7.1.9. Noise insertion loss

Figure 22 illustrates the noise insertion loss (NIL) curves. For SBB, since the data cannot be averaged as described in Section 7.1, a limited number of individual trains were selected to avoid the rail welding in the optimised pad section having an influence when the data was compared with that of the stiff rail pad (H) with the optimised pad (OPTI pad). Similarly, individual trains were selected when comparing the soft rail pad (L) pad with the H pad. The noise insertion loss for the latter case was smaller than that of other PPs. Rail roughness measurements were taken by SBB but were not integrated into the LOWNOISEPAD software tool and therefore not verified.

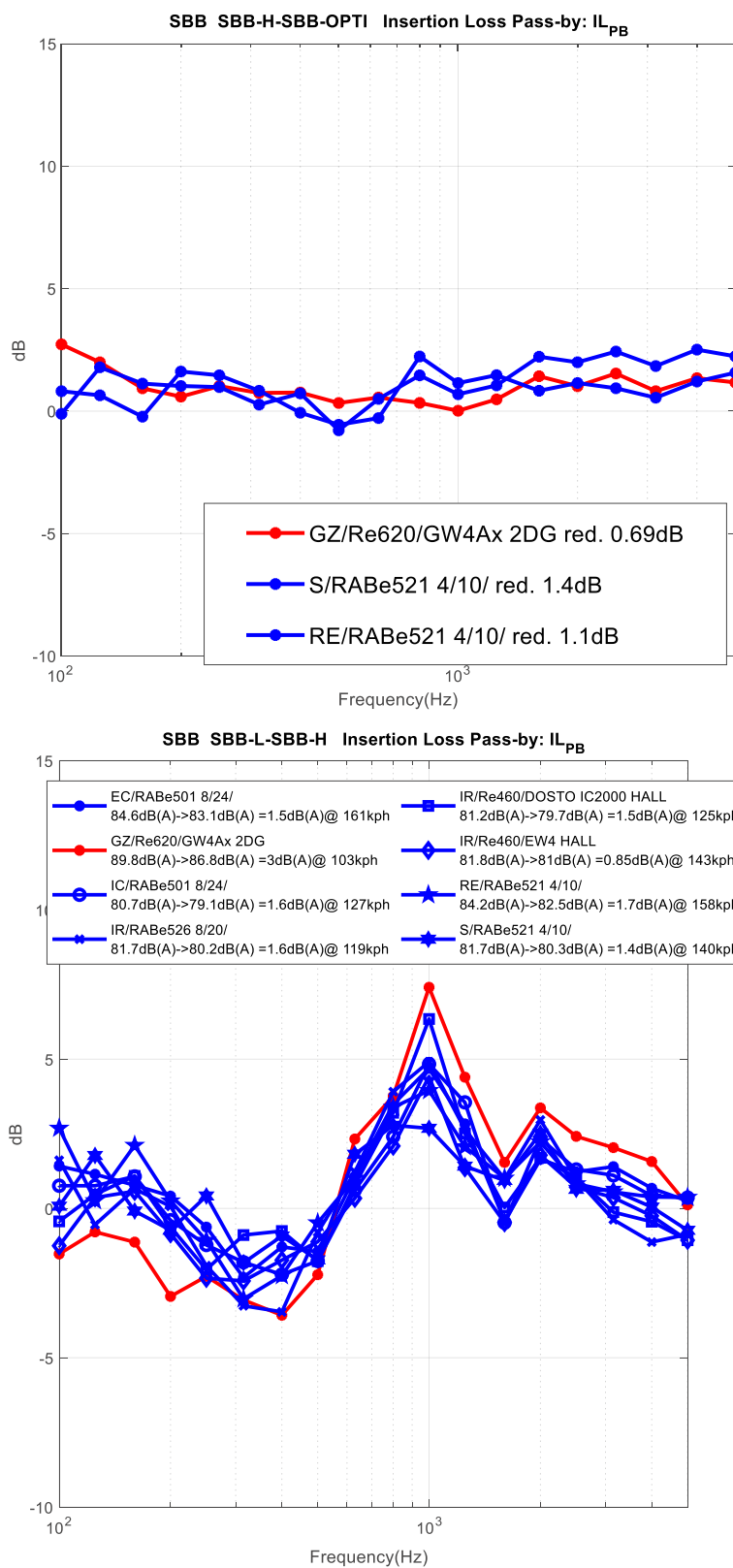


Figure 22: Top: detailed noise insertion loss for the OPTI pad, with the H pad for reference. Analysis for individual trains that were not affected by the weld.

Bottom: noise insertion loss for the H pad with the L pad for reference. Analysis also limited to individual trains

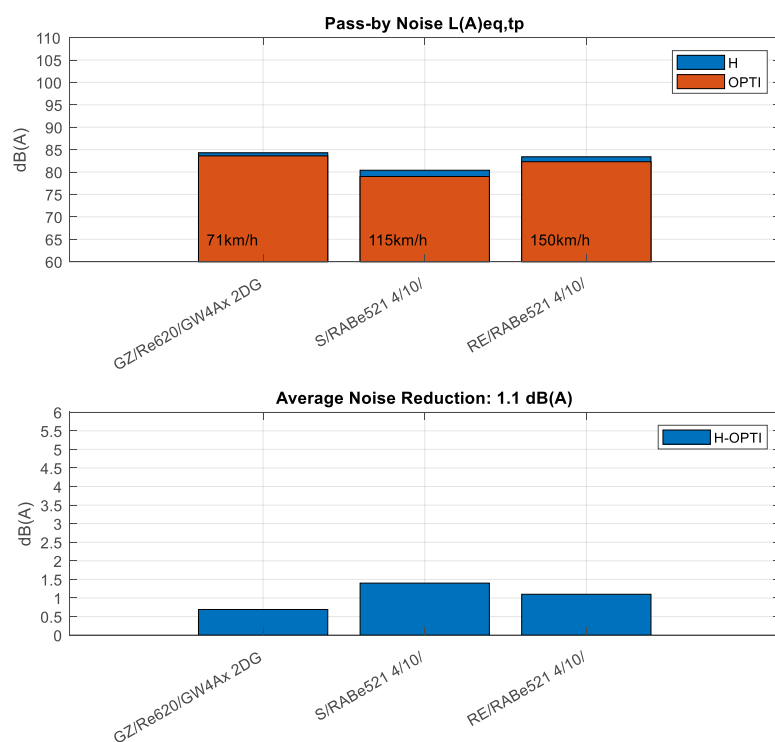


Figure 23: Pass-by noise and noise reduction for the OPTI pad, with the H pad for reference. Analysis for individual trains not affected by the weld

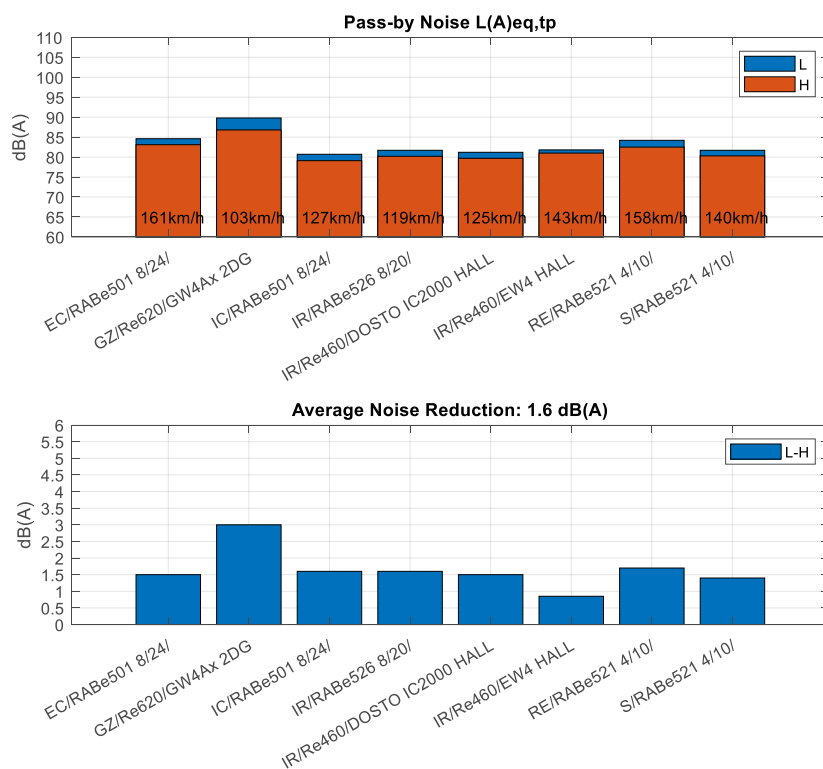


Figure 24: Pass-by noise and noise reduction for the H pad with the L pad for reference. Analysis for individual trains not affected by the weld

## 7.2. DB MEASUREMENTS, GERMANY

DB-Systemtechnik conducted pass-by, TDR, and roughness measurements over several days. The data from 4-6 October 2022 was sent and verified, and the final measurements were then taken.

### 7.2.1. Site description

The test track consisted of concrete monoblock B70 sleepers, 60E2 rails, and W14 tension clamp. Three rail pads were installed for testing: soft, stiff, and optimised pads (custom made design by Semperit for the project). Additional details about the rail pads can be found in Table 14, Table 15 and Table 16. The measurement site is illustrated in Figure 25.



Figure 25: Overview of the DB measurement site

### 7.2.2. Measuring equipment

The measurements were conducted using equipment compliant with DIN EN ISO 17025 standards. The M-BBM PAK system was used for noise and vibration measurements, the SINUS sound book for TDR measurements, and the M-BBM trolley for rail roughness measurements. Figure 25 (right image) indicates that the microphone at a distance of 7.5m was tripled, and measurements at 25m in the field were also taken.

It is important to mention that there was a difference in the rail roughness for the reference pad when compared to the two other sections. Due to the substantial difference in the measured rail roughness between the test section and the reference section, it is not possible to compare the rolling noise results from the reference section and test sections.

### 7.2.3. Rolling stock & speeds tested

The project involved testing various types of passenger and freight rolling stock, as shown below:

Table 4: Types of DB trains stored in the LOWNOISEPAD database

|                              |                   |                   |
|------------------------------|-------------------|-------------------|
| Passenger train              | ET429_3T/FLIRT3T  | ET429_3T/FLIRT3T  |
| Passenger train              | ET429_4T/FLIRT4T  | ET429_4T/FLIRT4T  |
| Passenger train              | ET462_4T          | ET462_4T          |
| Passenger train              | ET462_4T+ET462_4T | ET462_4T+ET462_4T |
| Freight train                | GZ                | GZ                |
| Passenger train - High Speed | IC                | IC                |

The ET passenger trains were observed to travel at speeds of between 150 and 160km/h, while the GZ (freight trains) ran at speeds between 90 and 100km/h. On the other hand, the IC trains were recorded to be operating at speeds of between 170 and 200km/h. Detailed information about the train types and speeds can be accessed through the software tool, along with images being available in **Annex B: Rolling stock - Visual Reference Guide**. Since the track was in normal operation during the measurements, there was minimal variation in speed among trains of the same type. However, based on the measurement results, the DB ET429 flirt trains are assumed to have high traction noise at approximately 1kHz, even when running a higher speed (150-160km/h). The source of this noise was identified in the spectrogram and appeared to originate from the first and last bogies of the train. These traction noise sources could mask the effects of the rail pad changes, resulting in different NIL values to other trains, as demonstrated in Figure 26.

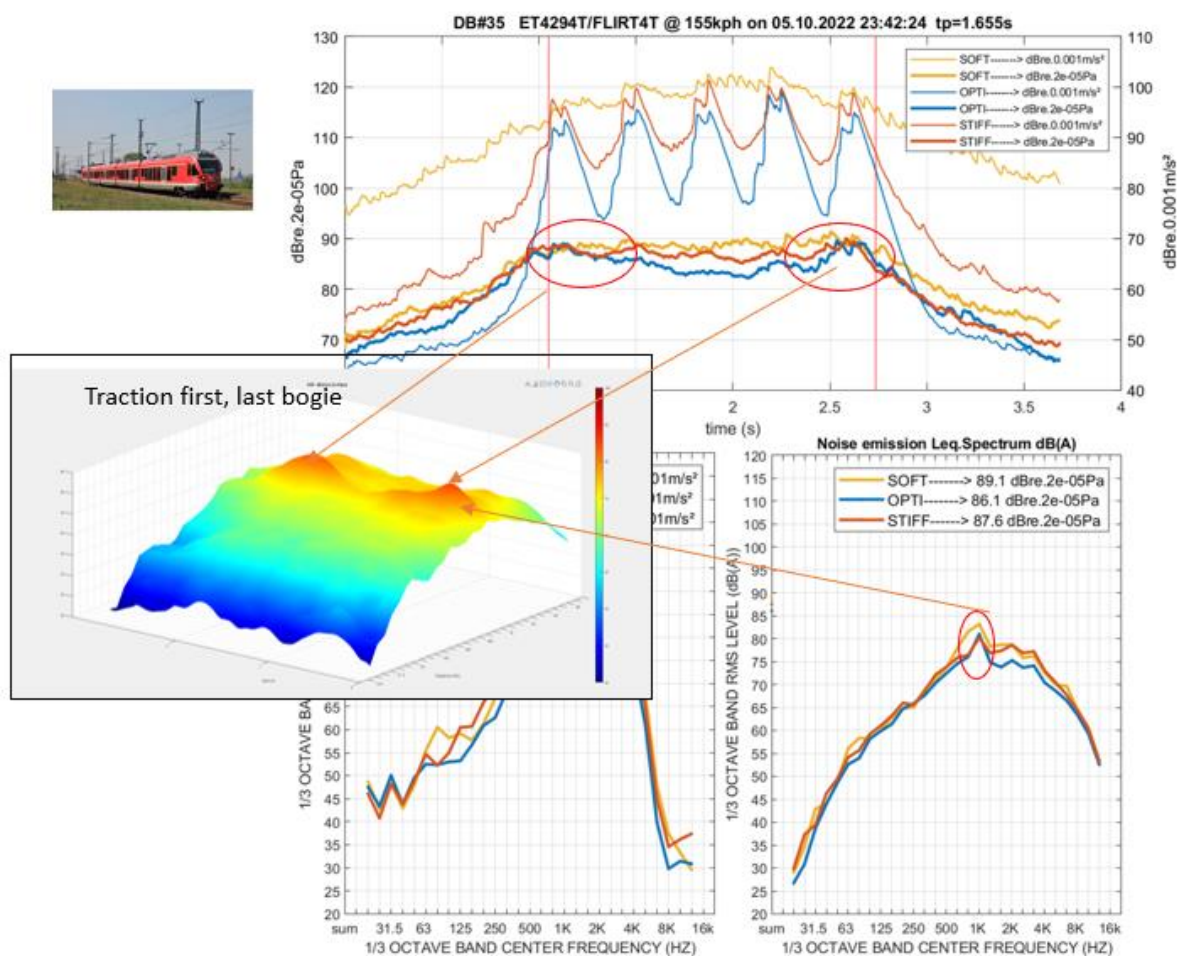


Figure 26: Identification of traction noise during pass-bys of the DB FLIRT 429 trains

#### 7.2.4. TDR

TDR measurements were taken according to the CEN15461 and CEN TR 16891 standards, with the possibility of comparing the two methods via the software tool. Based on the raw data calculations obtained from DB and SD&M, the TDR for the reference section was compared with the and the TDR results from the left side of the track beings given as an example in Table 5. The results obtained by the two entities yielded similar values.

Table 5: Calculations by SD&M and DB using the raw data

| 1/3 octave frequency (Hz) | TDR vertical at reference section (dB/m) |                  |
|---------------------------|------------------------------------------|------------------|
|                           | DB-calculation                           | SD&M-calculation |
| 100                       | 7.05                                     | 6.98             |
| 125                       | 8.90                                     | 8.85             |
| 160                       | 9.35                                     | 9.35             |
| 200                       | 11.36                                    | 11.33            |
| 250                       | 10.76                                    | 10.75            |
| 315                       | 13.83                                    | 13.83            |
| 400                       | 13.51                                    | 13.49            |
| 500                       | 15.08                                    | 15.1             |
| 630                       | 11.51                                    | 11.5             |
| 800                       | 15.61                                    | 15.61            |
| 1000                      | 8.7                                      | 8.7              |
| 1250                      | 12.95                                    | 12.95            |
| 1600                      | 7.27                                     | 7.21             |
| 2000                      | 2.32                                     | 2.26             |
| 2500                      | 1.19                                     | 1.18             |
| 3150                      | 1.15                                     | 1.13             |
| 4000                      | 1.76                                     | 1.8              |
| 5000                      | 4.72                                     | 4.71             |

Figure 27 shows the results according to CEN15461 as an example:

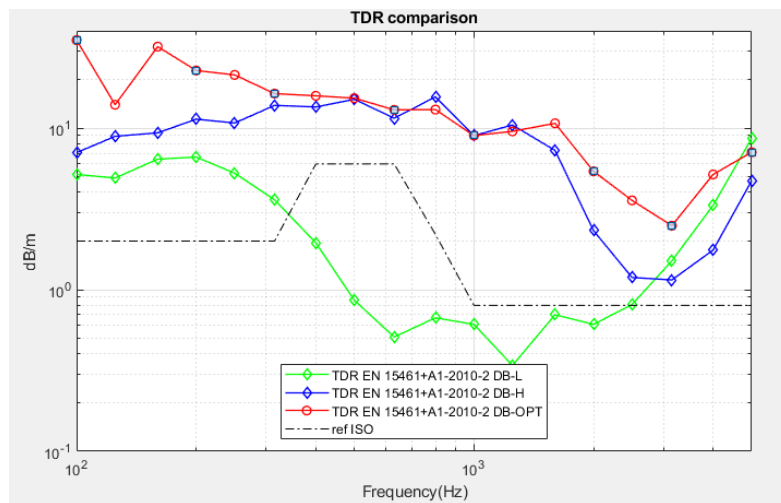


Figure 27: Measured TDR according to CEN15461 at DB

### 7.2.5. Temperature during testing

Both the rail and ambient temperatures were recorded for each train pass-by, with variations approximately ranging between 10 and 20°C.

### 7.2.6. Raw data received

The raw data, provided in MATLAB files, was pre-selected based on the type of train. All the necessary information for the database was sent, including the tp time and train lengths, which were separately recorded by the MBBM system of DB-Systemtechnik. The verification process confirmed that the procedures followed by LOWNOISEPAD, using rail acceleration, resulted in similar pass-by times (tp).

### 7.2.7. Results in the database

A total of 114 pass-bys were selected for analysis, while 15 pass-bys were rejected due to, for example, speed differences, low-quality rail acceleration measurements, and the inability to synchronize pass-bys across the three different sections. The processing information and any processing errors have been logged in the database for reference.

Due to a difference in roughness between the stiff pad reference section and the other two sections, DB-Systemtechnik suggested that the IL compared to the reference stiff rail pads not be included in the analysis and that limited conclusions for that specific site be drawn. Given the uncertainty of the difference in roughness, the following conclusion was proposed by DB-Systemtechnik: "Under the given conditions at the test site and considering the uncertainty in the measurements taken, the rolling noise at the test site with the optimised rail pad is comparable to the rolling noise at the site with a stiff EVA rail pad."

### 7.2.8. Noise insertion loss

The noise insertion loss curves are presented as averages per type of train only if more than one pass-by measurement is available for that specific train type. Figure 28 displays the difference in noise levels between the soft rail pad (L), as a reference, and the optimised rail pad (OPTI pad). By averaging the pass-by measurements for each train type, the IL curves provide a comprehensive overview of the noise reduction achieved with the OPTI pad when compared to the L pad, across different train types. These curves allow for a direct comparison of the performance between different train types, highlighting the effectiveness of the OPTI pad in reducing noise levels during pass-by events. However, it should be noted that the IL for the DB ET429 Flirt trains are limited due to the masking effect from the previously discussed traction noise. Only four IC trains are given in the database, with speeds recorded at 199km/h, 189km/h, 187km/h, and 167km/h, resulting in an average speed of 185km/h. This limited number of IC trains and the slight speed variation can introduce some uncertainty in the calculated IL values.

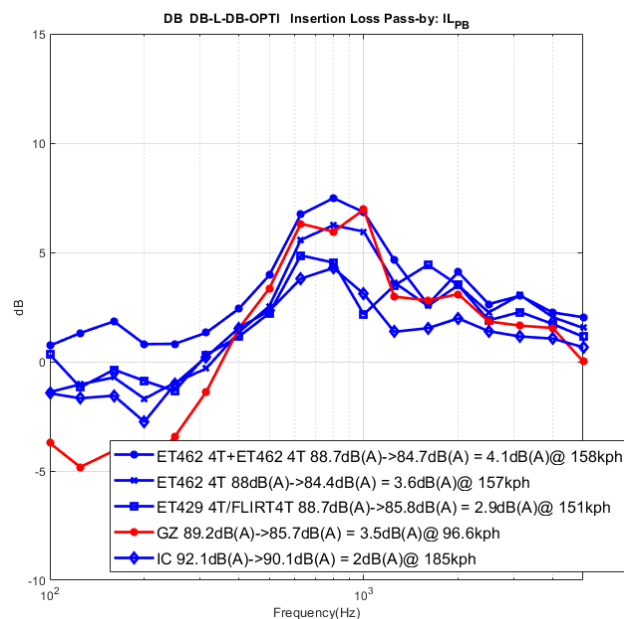


Figure 28: Averaged noise insertion loss per train type for the OPTI pad using the L pad for reference

Figure 29 illustrates the averaged pass-by noise levels and noise reduction for the OPTI Pad using the L Pad for reference. The graph depicts the average noise levels for various types of trains and shows the noise reduction achieved by using the OPTI pad over the L pad. The data presented in Figure 29 also gives insight into the effectiveness of the OPTI pad in reducing noise during pass-bys. By comparing the noise levels between the OPTI pad and the L pad, the graph demonstrates the potential benefits in terms of noise reduction offered by the OPTI pad.

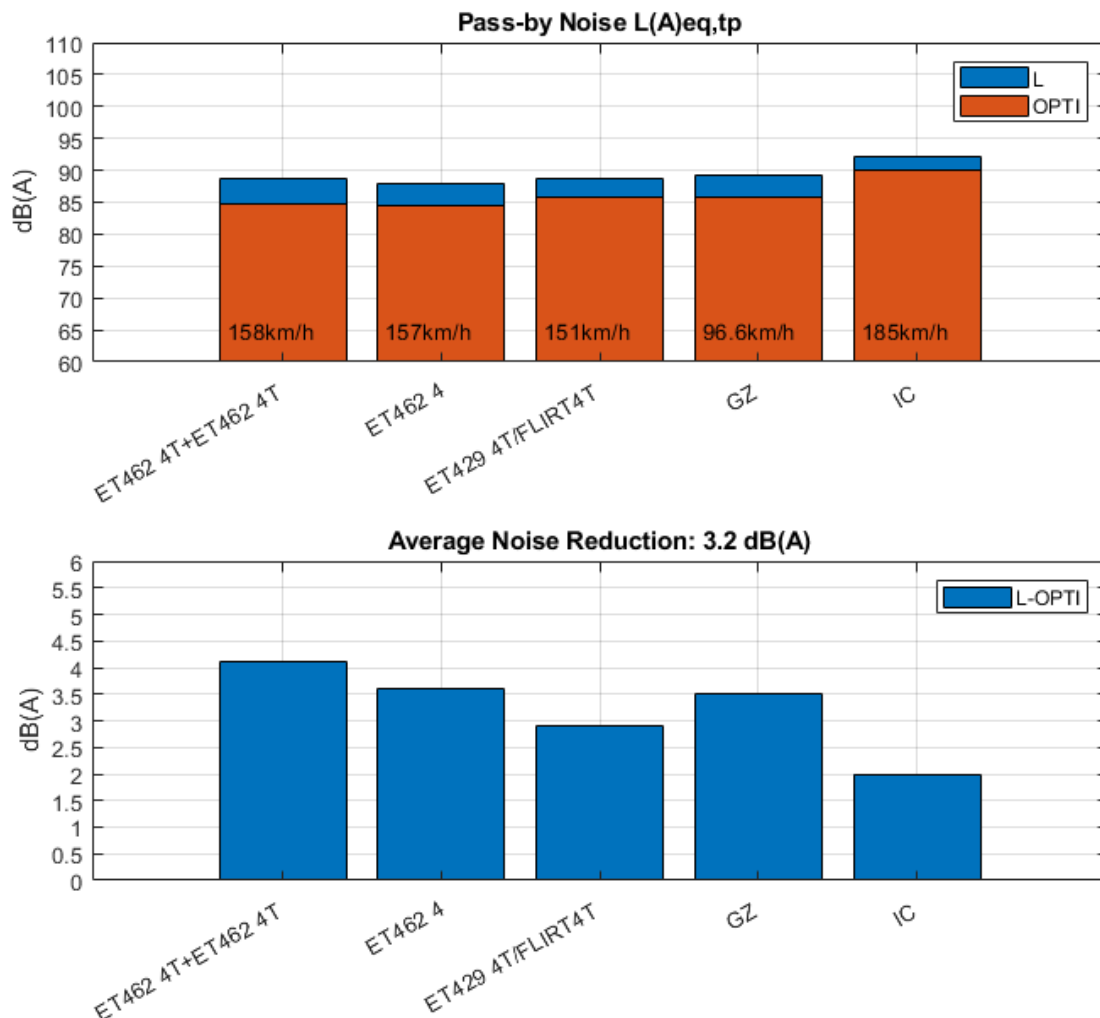


Figure 29: Averaged pass-by noise levels and noise reduction for the OPTI pad using the L pad for reference

### 7.2.9. Brief analysis on the DB ILENA project for noise insertion loss

During the LOWNOISEPAD project, data from the ILENA project carried out by DB were also analysed. Averaging data from the same train types (as shown in Figure 30), but from different individual trains, was shown to lead to uncertainty in the noise insertion loss values. For example:

Figure 30: Identical trains (from the same type) showed consistent and stable differences between the soft and stiff rail pads for three different train types.

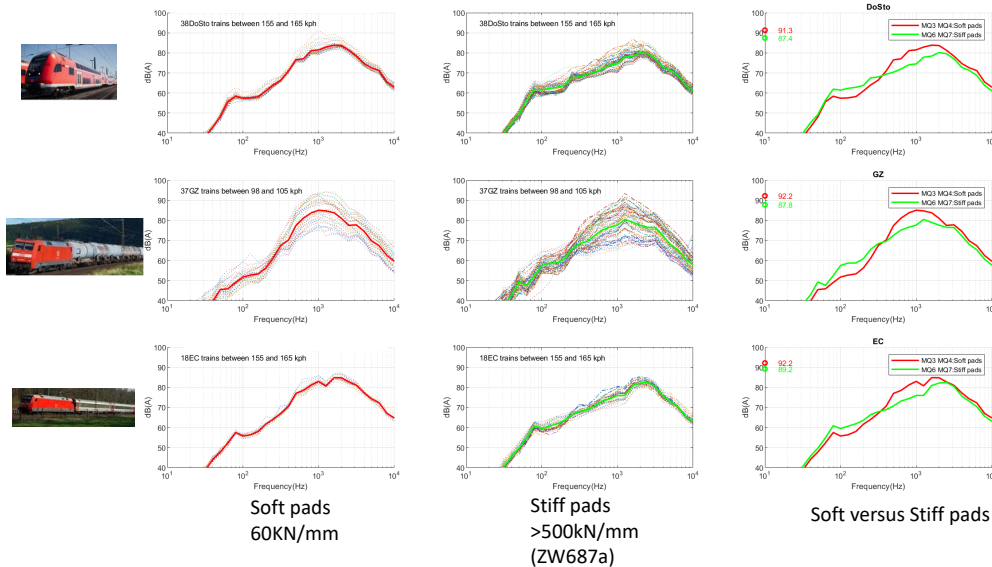


Figure 30: External example (DB ILENA project) for averages of the same train types, with the same individual trains

Figure 31 shows that averaging data across a non-identical but similar train leads to spectral differences between the soft and stiff rail pads, caused by different wheel roughness, or potentially wheel flats, etc. This differs significantly from the analysis shown in Figure 30, particularly for freight trains. The comparison of DoSto trains also revealed a difference in the overall level, with 3.9dB(A) for the same trains and only 2.5 dB(A) for a non-identical similar train. These findings highlight that uncertainty is introduced when averaging data across different individual trains within the same train type. Consistency in selecting trains is therefore crucial to ensure reliable results in noise insertion loss comparisons between rail pads.

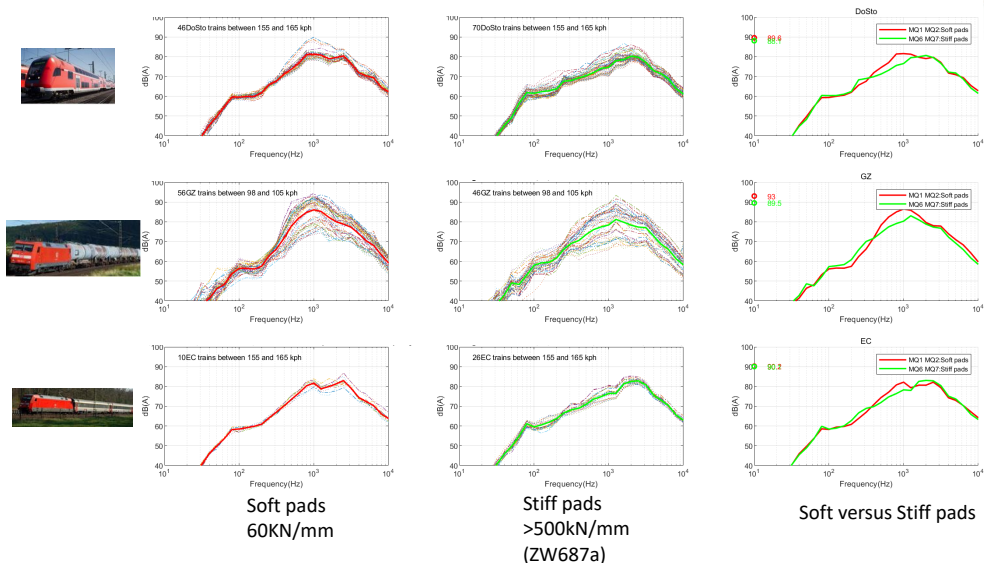


Figure 31: External averages (DB ILENA project) over a non-identical but similar train

### 7.3. ÖBB-INFRA MEASUREMENTS, AUSTRIA

At ÖBB-Infrastruktur AG, a total of six different rail pads across 6 different sites were installed for comparison during pass-bys and for TDR measurements, performed by psiacoustic GmbH. The measurements were carried out over three separate phases, with each one consisting of a different set of sites and individual trains (the constraints related to this method are outlined in Section 7.2.9 for the DB ILENA project), as it was not possible to measure all of the sites all simultaneously. Each phase consisted of three, three, and two sites respectively. Nevertheless, it was still possible to compare each rail pad to the reference section/pad within each phase.

Due to the unique approach used at ÖBB, the software tool takes this specificity into account. Depending on the selected pass-by number, the database will show the different rail pads based on the corresponding measurement campaign. To ensure accuracy and prevent errors, the software tool excludes the averaging of trains of the same type for the ÖBB data. The database contains a carefully selected set of measurements conducted by psiacoustic GmbH in September and October 2022.

#### 7.3.1. Site description

The data used in this project was obtained from the test track located at the Pottendorfer line. The test track section underwent complete renewal, including the ballast, and has the standard ÖBB L2 monoblock sleeper with USP, 60E1 rails and SKL14 tension clamp. There were six measurement sections (MQ1-MQ6), each approximately 200 meters in length, equipped with different rail pads (see Figure 32). More detailed information about the rail pads can be found in Table 14, Table 15 and Table 16.

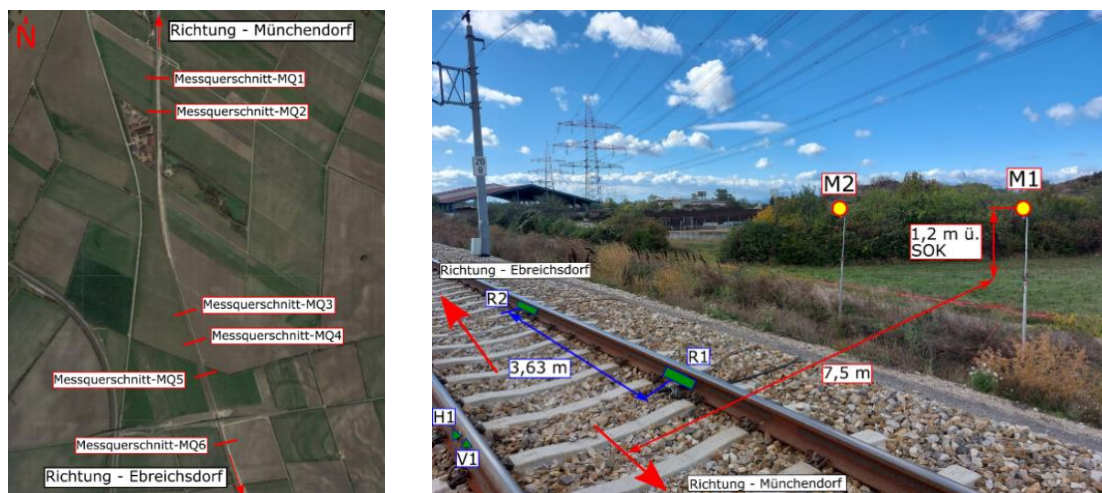


Figure 32: The six measurement sites at ÖBB-Infra and photo showing the test set-up

#### 7.3.2. Measuring equipment

The measurements in this project were taken using three psiacoustic GmbH - acramos® systems. Figure 32 illustrates those 2 microphones at a distance of 7.5m were used, and the speeds were recorded using accelerometers. However, specific information regarding the type of microphones and accelerometers used was not provided. Additionally, roughness measurements were carried out, with the observation being made that both rails on all test sites remained below the ISO 3095 limit value, as shown in Figure 33).

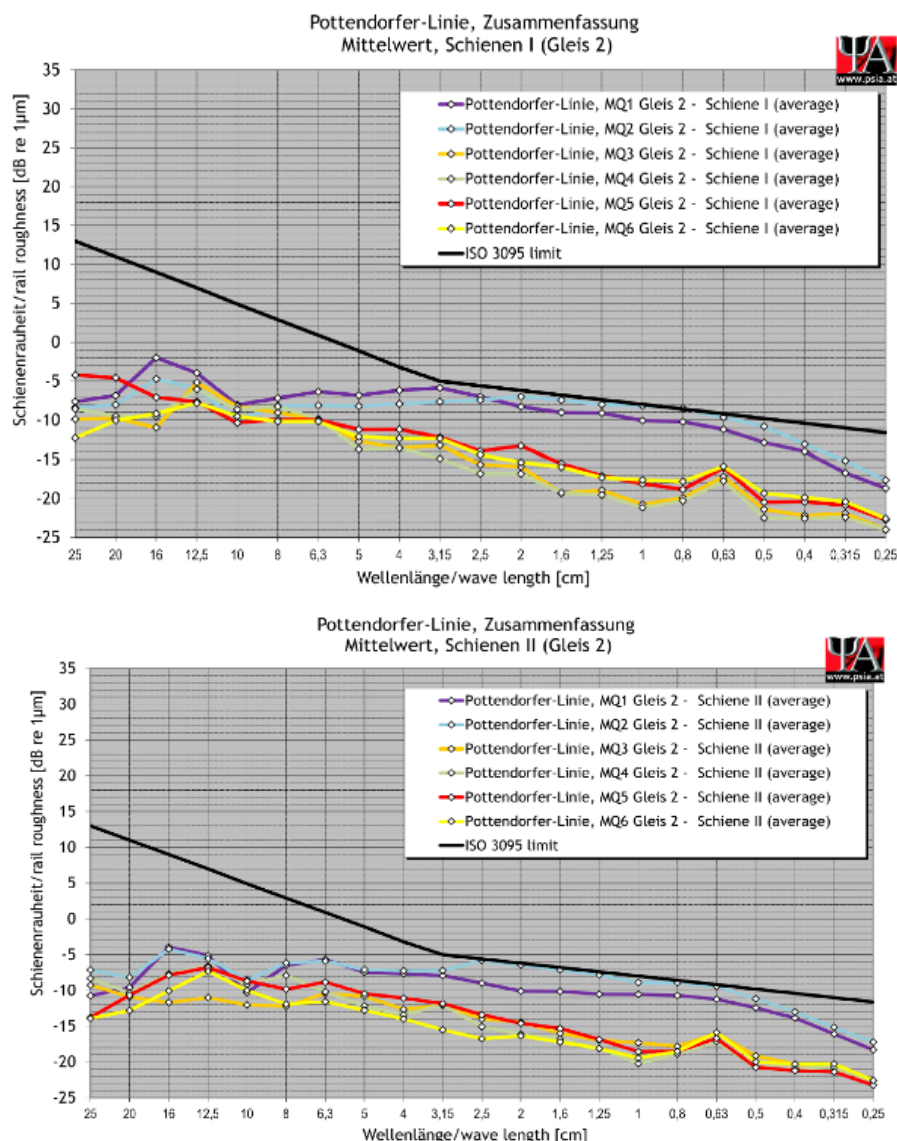


Figure 33: Acoustic rail roughness at ÖBB test sites - below ISO 3095 limit value

### 7.3.3. Rolling stock & speeds tested

Various passenger and freight trains were used for testing as part of the project, with all ÖBB trains operating at approximately 100km/h. Detailed information about the trains can be accessed through the software tool, along with images being available in **Annex B: Rolling stock - Visual Reference Guide**. Since the track was in normal operation during the measurements, there was minimal variation in speed among trains of the same type.

Table 6: Types of ÖBB trains stored in the LOWNOISEPAD database

|                 |       |       |
|-----------------|-------|-------|
| Passenger train | CJ    | CJ    |
| Freight train   | GZ    | GZ    |
| Passenger train | RZ-mx | RZ-mx |
| Passenger train | S4024 | S4024 |

### 7.3.4. TDR

The TDR measurements were taken according to the CEN15461 and CEN/TR 16891 standards, and a comparison between the two methods was carried out. A noticeable difference between the two methods was observed, with CEN15461 showing lower TDR values for the soft rail pads. The TDR raw measurement data was obtained, with both SD&M and psiacoustic GmbH doing the calculations. The results obtained by the two entities yielded similar values. Figure 34 (top) presents the measured TDRs according to CEN15461 and TR 16891 for two rail pads, while Figure 34 (bottom) displays the measured TDRs according to CEN15461 for all six rail pads tested. The bottom graph also shows the TDR results for both of the prototype optimised rail pads (OPTI1 and OPTI2).

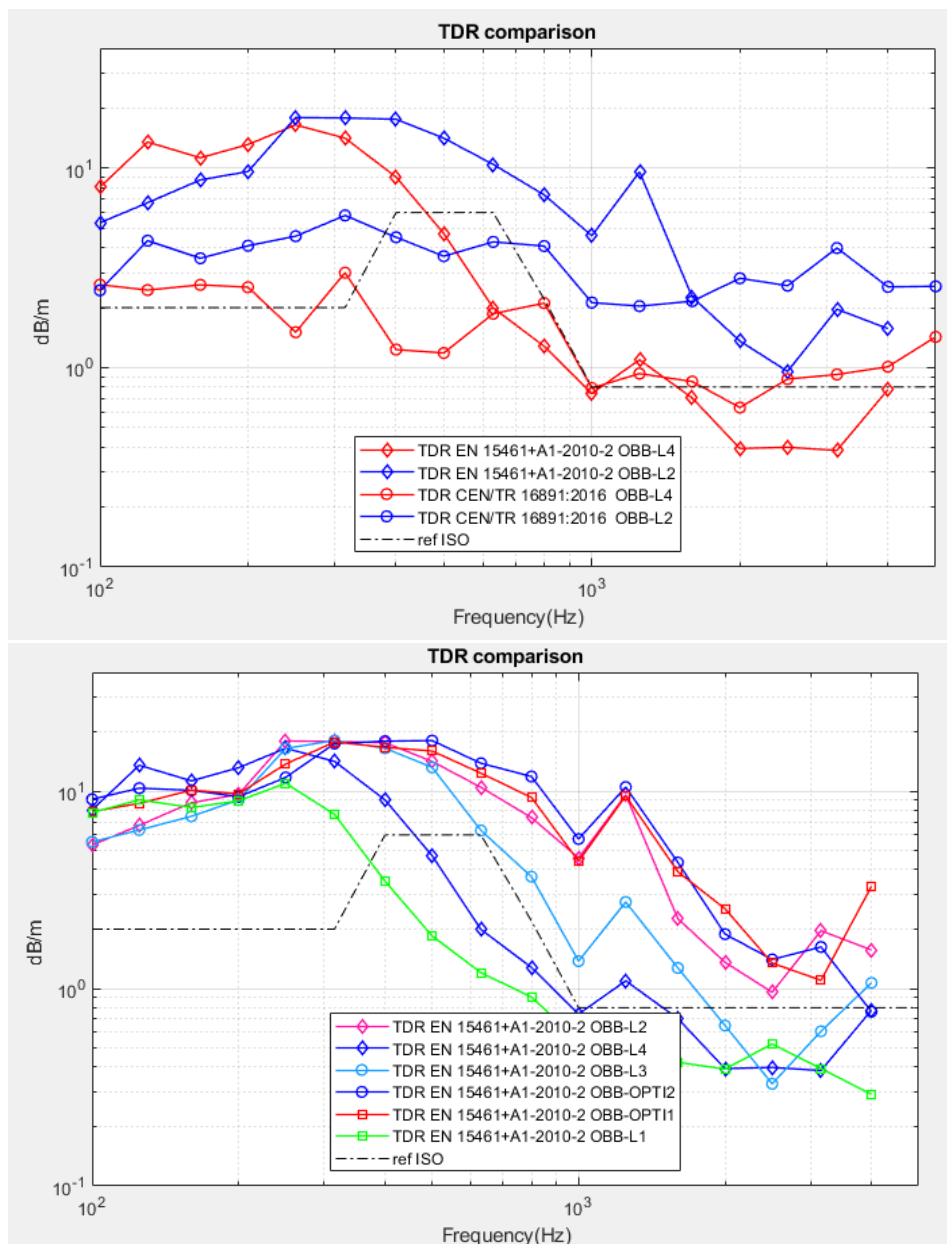


Figure 34: Top: measured TDR according to CEN15461 and TR 16891 at ÖBB for 2 tested rail pads, Bottom: measured TDR according to CEN15461 at ÖBB for the 6 tested rail pads

### 7.3.5. Temperature during tests

Temperature measurements, including rail and ambient temperatures, were recorded during the tests but were not communicated in time for data analysis.

### 7.3.6. Raw data received

The received raw data was provided in WAV files per measurement MQ section, categorised by timestamps and measurement campaigns.

### 7.3.7. Information received for database

Excepting the temperature data, all other required information is available in the database.

### 7.3.8. Results in the database

A total of 77 pass-bys were selected for analysis, with nineteen pass-bys being rejected due to, for example, speed differences, low-quality rail acceleration measurements, and the inability to synchronise pass-bys across different sections. The processing information and any processing errors have been logged in the database for reference.

### 7.3.9. Noise insertion loss

Noise IL comparisons for the six rail pads tested at ÖBB offer various combinations for analysis, and all of these possible combinations are available in the software tool. Detailed results for both of the prototype optimised rail pads (OPTI1 and OPTI2) are given in **Annex A: Graphic Reference Guide**.

It is important to note that the effectiveness of the optimised rail pads in reducing noise is closely linked to the specific reference pad chosen for comparison. In the Austrian context, two standard pad types were used, with the "acoustic" pad serving as a reference. When the optimised pad was compared to the reference pad, a substantial noise reduction of 4.3dB was observed, making it a promising choice for demonstration purposes (Table 16, OPTI1 compared to L1). However, when the optimised rail pad (OPTI1) was compared to the second standard pad (L2), the reduction in noise was considerably lower, only measuring 1dB. Thus, the project's findings suggest that the noise reduction achieved with the optimised pads can vary from 1-2dB when compared to stiff pads and from 3-5dB when compared to soft pads. It is important to bear in mind that the choice of reference pad significantly influences these outcomes. Figure 35 shows the IL per train type, using the OPTI1 pad with the L1 as the reference pad, for individual selected pass-by. Figure 36 presents the pass-by noise levels and noise reduction for the same pad combination, again for individual selected pass-by. The overall reduction is given in **WP6: General project output and results** of this report.

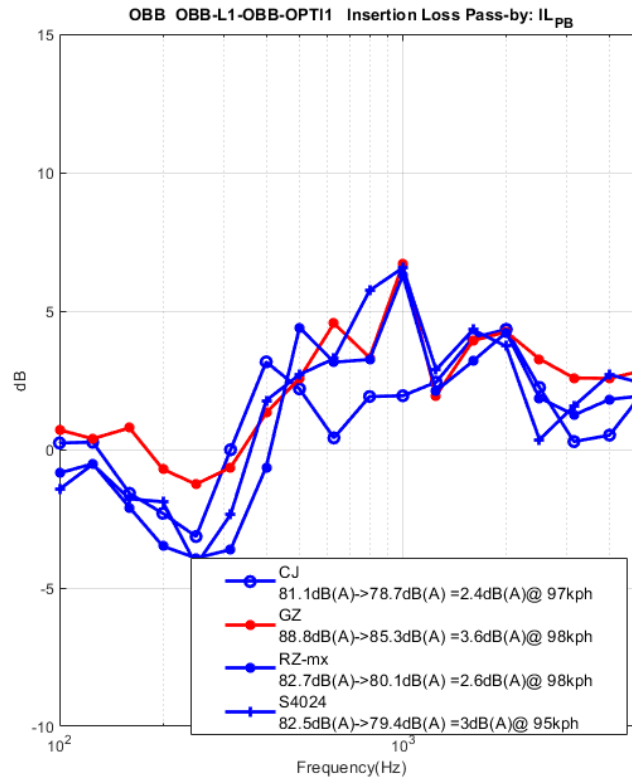


Figure 35: Noise IL per train type for the OPT11 pad with the L1 pad as the reference, for some individual selected pass-bys

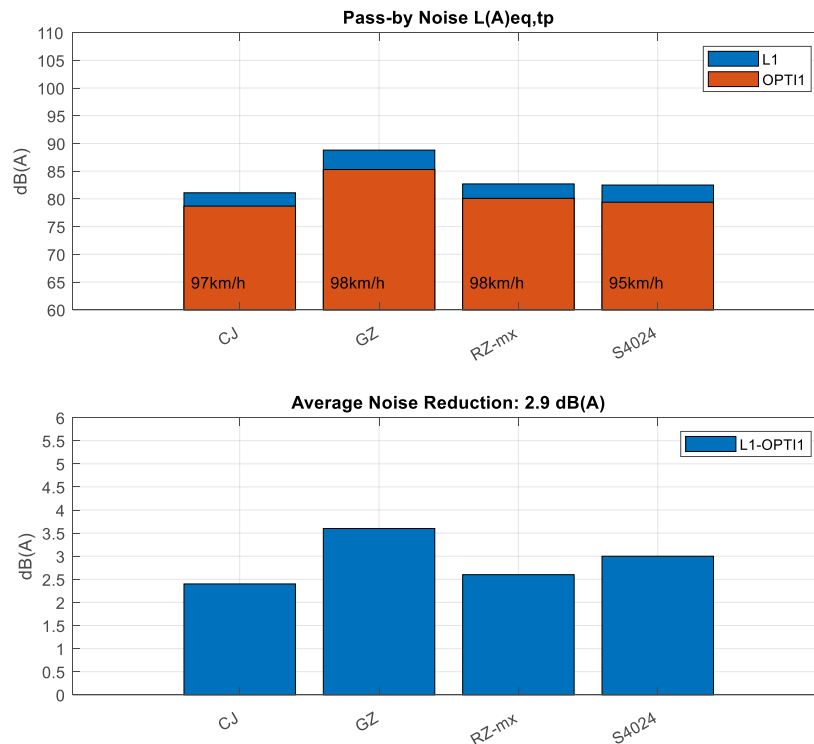


Figure 36: Pass-by noise and noise reduction for the OPT11 pad with the L1 pad as the reference for individual selected pass-bys

## 7.4. INFRABEL MEASUREMENTS, BELGIUM

The pass-by, TDR, and roughness measurements at INFRABEL were taken in multiple campaigns by the measurement team. The measurements took place between May and June 2022. The TDR measurements were verified and fine-tuned by INFRABEL to align with the approaches used in other countries.

### 7.4.1. Site description

The test track, situated near Dendermonde, consisted of four 80m sections where four different rail pads were compared. These included a softer rail pad (formerly the standard pad pre-2018) and three optimised rail pads, two of which fulfil the INFRABEL rail pad specification (L63 - 2018) from two different suppliers, and with one additional optimised pad being tested specifically for this project. Detailed rail pad information can be found in Table 14, Table 15 and Table 16.

The track used standard monoblock concrete M41 sleepers with 60E1 rails and rail E-clip. Further details and photos can be found in Figure 37. The rail pads were placed during track renewal works with the new versions of the sleeper and rail types listed above being used for the entire track.

Speed differences were automatically calculated due to the presence of four accelerometers over a 400m distance. The test track was located in a zone where some trains brake and accelerate, and therefore these were automatically excluded from the measurement.



Figure 37: Top: overview of the test track at INFRABEL,  
Bottom: a microphone at the opposite side of the test track at INFRABEL

### 7.4.2. Measuring equipment

The measuring equipment used at INFRABEL consisted of 2 Svantek 958 dataloggers, 4 Class 1 microphones (Svantek SV12L preamplifiers with Microtech Gefell MK 255 microphones), 4 accelerometers (Vibrasens 108.01-3-4, 10mV/g), and an MBBM rail trolley for rail surface analysis. The rail roughness measurements indicated no significant difference between the 4 test sites.

### 7.4.3. Rolling stock & speeds tested

Various passenger and freight trains were tested as part of the project, with speeds ranging from 80 to 120km/h. Detailed information about the train types and speeds can be accessed through the software tool, along with images being available in **Annex B: Rolling stock - Visual Reference Guide**. Since the track was in normal operation during the measurements, there was minimal variation in speed among trains of the same type.

Table 7: Types of INFRABEL trains stored in the LOWNOISEPAD database

|                 |                                |                                  |
|-----------------|--------------------------------|----------------------------------|
| Passenger train | IX3 BREAK                      | 1X3 BREAK                        |
| Passenger train | IX3 DESIRO                     | 1X3 DESIRO                       |
| Passenger train | DESIRO0 1X3 DESIRO             | 1X3 DESIRO 1X3 DESIRO            |
| Passenger train | DESIRO0 1X3 DESIRO0 1X3 DESIRO | 1X3 DESIRO 1X3 DESIRO 1X3 DESIRO |
| Freight train   | FREIGHT                        | FREIGHT                          |
| Passenger train | M6 T18(8)                      | M6 T18(8)                        |

Additional information for Table 7: 1X3 means 3 EMU cars (12 axles). M6 are double-deck sets, pulled by a TSI compliant locomotive. The “BREAK” train category is an old type of passenger train with cast-iron brake blocks, therefore with high wheel roughness. And finally, the freight trains used varied in length, wagon and load type.

### 7.4.4. TDR

The TDR measurements were taken according to the CEN15461 and CEN/TR 16891 standards. The TDR raw measurement data was obtained, with both SD&M and INFRABEL doing the calculations. The results obtained by the two entities yielded similar values. Figure 38 shows the TDR results according to CEN15461 for the 4 rail pads tested, highlighting the improved decay rate of the OPTI3 rail pad compared to the OPTI1 pad, particularly in the 1kHz, pin-pin region.

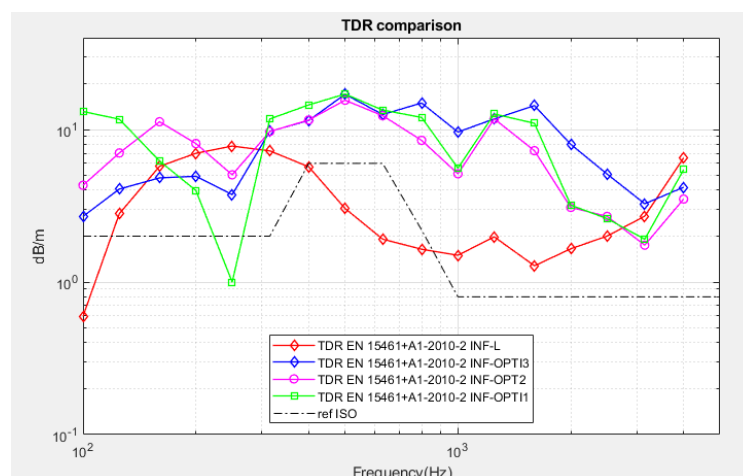


Figure 38: Measured TDR according to CEN15461 at INFRABEL

#### 7.4.5. Temperature during tests

The temperature during the tests was reported to be 20°C.

#### 7.4.6. Raw data received

Raw waveform files were automatically recorded using two 4-channel Svantek 958 devices during the measurements. Each pass-by generated a calibrated file containing 8 channels (4 accelerations and 4 microphones) for further post-processing.

#### 7.4.7. Information received for the database

All required data was included in the database.

#### 7.4.8. Results in the database

A total of 359 pass-bys were selected for analysis, while 143 pass-bys were rejected due to, for example, speed differences, low-quality rail acceleration measurements, and the inability to synchronise pass-bys across different sections. The processing information and any processing errors have been logged in the database for reference.

#### 7.4.9. Noise insertion loss

If there was more than one pass-by per train type, the noise insertion loss (NIL) curve is presented with the average per train type. Figure 39 shows the results for the OPTI3 rail pad with the soft rail pad (L) as the reference, showing comparable IL curves for most trains, except for freight trains which operate at different speeds and cause different excitations due to having different wagon formations. The maximum reduction of 5dB(A) in the A-weighted level across all members in the project were achieved here.

Figure 40 gives the averaged pass-by noise and noise reduction for the OPTI3 pad using the L pad for reference. Further comparisons between rail pads can be made using the LOWNOISEPAD software tool.

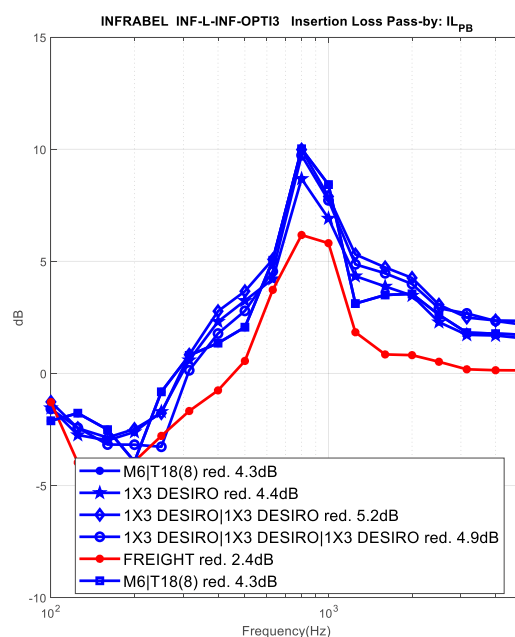


Figure 39: Averaged noise insertion loss per train type for the OPTI3 pad using the L pad for reference

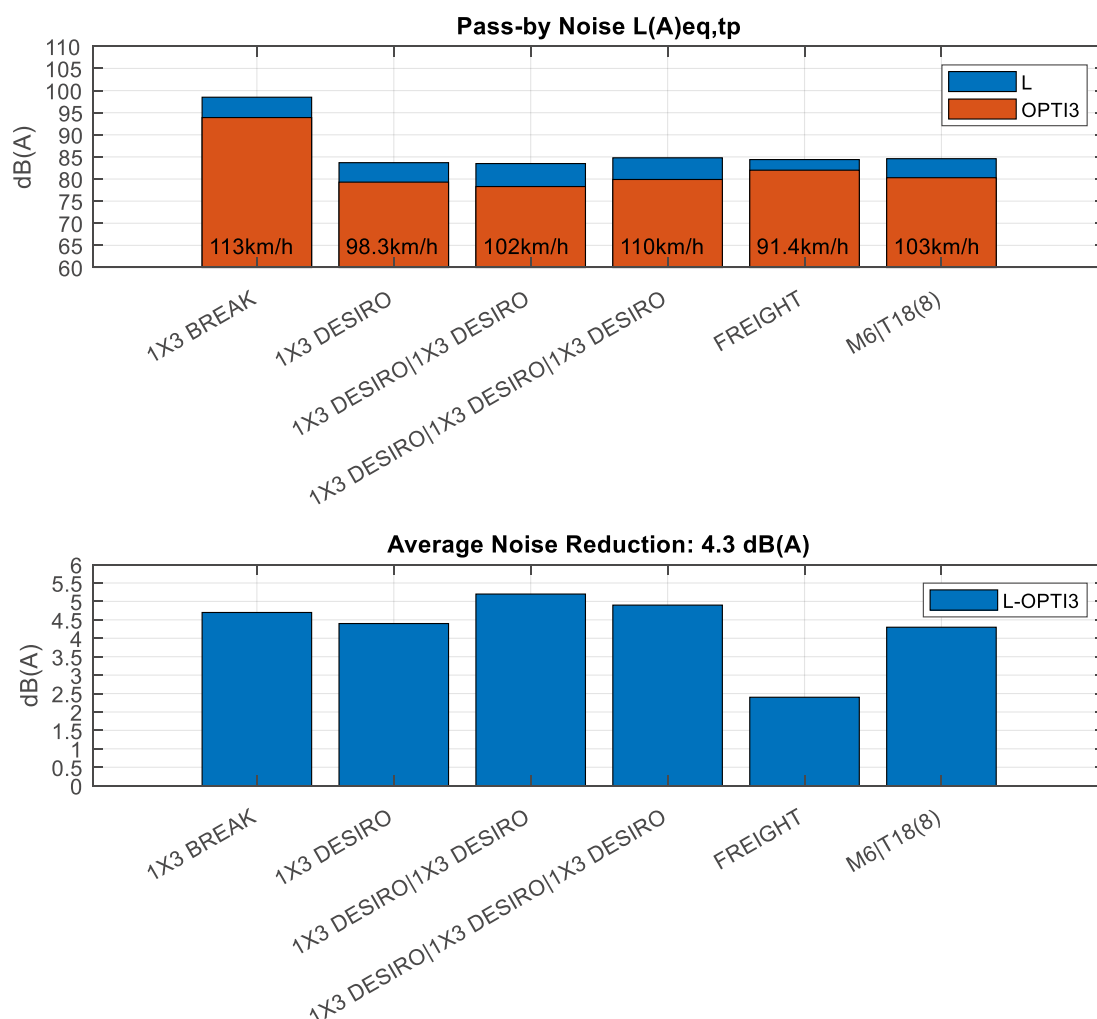


Figure 40: Averaged pass-by noise and noise reduction for the OPTI3 pad using the L pad for reference

#### 7.4.10. Additional information: Analysis of the relationship between rail pad changes and the Life Cycle Cost (LCC) and track maintenance in Belgium

Note: This section represents the position of INFRABEL I-AM.23, with the content being approved by INFRABEL, not all LOWNOISEPAD project members as it was not discussed during LOWNOISEPAD project meetings.

Despite consulting various UIC LOWNOISEPAD project PPs and other experts, a simple question remains unanswered: “What is the effect on maintenance and LCC of changing a rail pad with a stiffness of, for example,  $k_{SP}$  80kN/mm to a rail pad of 160kN/mm?”

This question is relevant for a standard ballast track and seeks answers regarding minor changes in rail pad stiffness within the relatively “soft” stiffness range, excluding specific cases like curves, tunnels, or slab tracks. The stiffness values mentioned in this document refer to the static stiffness  $k_{SP}$  as per EN13146-9:2020 [9]. To gain insight from an experienced and valuable source, Paul Godart, former Head of the Track Engineering Division at INFRABEL, and former Chair of the UIC Track Expert Group, was contacted due to his extensive knowledge of track design and maintenance.

## Background

Track maintenance and LCC can be managed in two ways:

1. Involves minimal maintenance after complete track renewal, followed by complete track replacement at the end of its planned lifespan.
2. Regular maintenance activities are planned to extend the track's lifespan before complete renewal.

The frequency of maintenance activities can vary for specific track components, based on factors such as cost and availability. On the INFRABEL network in Belgium, both extremely stiff and soft rail pads were in use in track designs across more than 6,000km of track, providing an ideal basis for detailed analysis. The decision to use soft pads was made in the early 1990s, primarily to protect sleepers against high dynamic loads, with noise reduction being of lesser importance at the time. Due to the favourable performance of these pads, in 2010, INFRABEL decided to widely implement the use of the M41 concrete sleeper with soft pads, mainly for logistical reasons.

## Track degradation analysis

Analysis conducted by the INFRABEL Track Measurement Division in 2015 examined track degradation (vertical track position D1, according to EN 13848-5 [10]) over a 10-year period for two extreme cases on a similar track representing a factor of 10x the difference in stiffness:

- M31 monoblock concrete sleepers with rail E-clips and extremely stiff EVA rail pads (kSP > 1000kN/mm)
- M41 concrete sleepers equipped with very soft rail pads (kSP between 50-100kN/mm).

The analysis, carried out on over 1,900km of track in 20m sections, revealed a difference in track degradation of less than 0.1 mm/year. The value is quite small, and other factors such as ballast and formation quality, track load according to UIC classifications, rolling stock variations, changes in rolling stock maintenance practices, and overall improvements in wheel and rail roughness over time also influence the study's outcome. Thus, changing rail pad stiffness within a factor of 2 in the soft stiffness range is not expected to significantly impact LCC or maintenance.

In conclusion, a change in the softness of a rail pad by a factor of 2 is not expected to affect the LCC or maintenance, especially given the fact that no difference was attained when a difference of 10 was tested.

## Godart's experiences

There was no evidence of increased track maintenance requirements for tracks equipped with stiff pads compared to soft pads. Additionally, maintenance activities have consistently been similar for both types of tracks. At INFRABEL, the average tamping interval is approximately 4 years, based on the rate of track geometry degradation. Regarding substructure protection, cases of concrete monoblock sleeper cracks were reported, but these were always attributed to issues with the concrete quality of the delivered sleepers, independent of rail pad stiffness.

The optimal elasticity of ballast track issue remains unresolved despite numerous studies and track elasticity remains an open question in the EU-TSI Infrastructure [11].

Stiff rail pads are preferable in curves to prevent the failure of rail clips. They exhibit better behaviour in relatively sharp curves ( $R < 400\text{m}$ ) by limiting horizontal movement at the rail head and reducing stress on the fastenings.

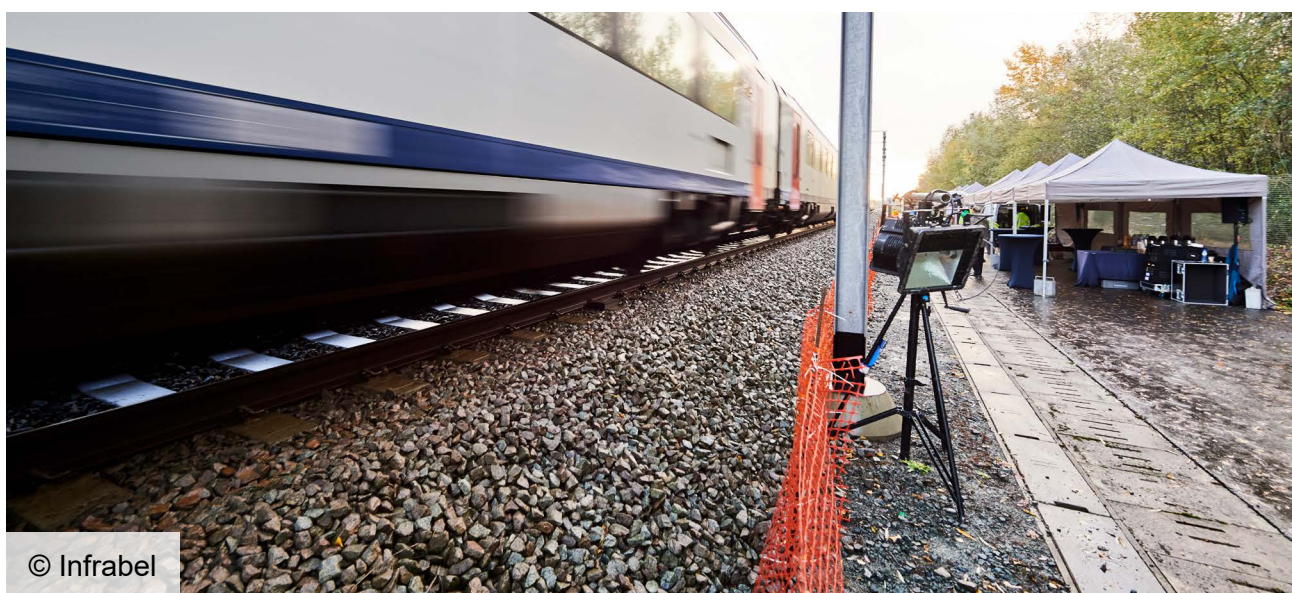
## Conclusions

Before concluding, emphasis should be placed on the fact that optimised rail pads are designed to be as soft as possible in a given scenario (in accordance with specified requirements and specifications) within the track engineering frequencies ( $< 20\text{Hz}$ ). However, they exhibit increasing stiffness and damping in higher frequency ranges ( $> 500\text{Hz}$ ) to absorb rail vibrations and reduce rail noise when trains pass by. Within the scope of this investigation the design was shown to have an average noise reduction of 3dB during train pass-bys.

Optimised rail pads can be designed with a stiffness range from very soft ( $60\text{kN/mm}$ ) to relatively stiff ( $230\text{kN/mm}$ ), depending on the producer, material, type, and cost.

Based on the INFRABEL case study:

- Detailed track degradation analysis over a 10-year period at INFRABEL showed no differences between extremely soft and extremely stiff rail pads ( $> 1,900\text{km}$  of track analysed).
- No differences in maintenance and life cycle costs were observed or reported at INFRABEL over a 40-year period for the two extreme rail pad stiffness values ( $100\text{kN/mm}$  and  $1000\text{kN/mm}$ ).
- Since 2018, optimised rail pads ( $250\text{kN/mm}$ ) have been installed as the new standard at INFRABEL, to be retrofitted on existing tracks and installed on new tracks. No issues related to track substructure degradation were reported. The noise reduction achieved by these rail pads is consistently included in the CNOSSOS noise mapping calculations and validated as an effective noise mitigation measure.
- Based on the above information, there is no apparent reason to consider track maintenance or life cycle costs as issues when installing optimised rail pads.



## 7.5. IP MEASUREMENTS, PORTUGAL

The pass-by and TDR measurements at IP were performed by SD&M in September 2022, before and after the rail pads were replaced. The calibration aimed to ensure consistent emission measurements under comparable conditions. The results, as illustrated in Figure 41, for a regional train running at 106km/h, show nearly identical levels within a range of  $\pm 1$  dB across most frequency bands. The overall noise levels emitted remained consistent.

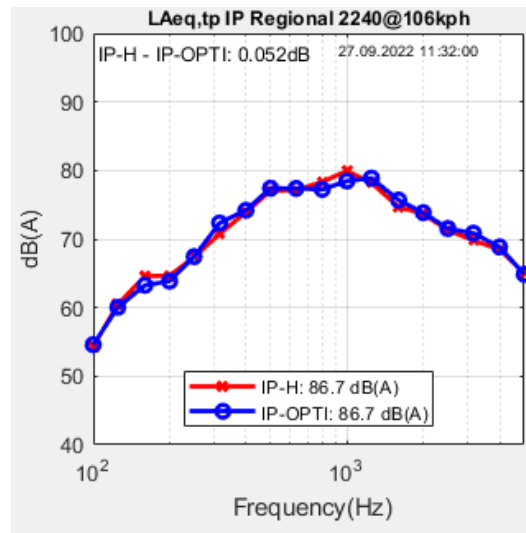


Figure 41: Results from the calibration

### 7.5.1. Site description

The test track was located on the Linha do Norte, approximately at marker 42,000 in Vila Nova da Rainha. Two rail pads were compared: the standard stiff pad and an optimised rail pad, as shown in the diagram below.



Figure 42: Overview of the measurement site at IP

The track used concrete monoblock DW60 sleepers, 60E1 rails and the W14 tension clamp. Further details on the rail pads can be found in Table 14, Table 15 and Table 16.

Images of the measurement site at IP are shown below. Two, approximately 100-metre sections were carefully selected, excluding areas with rail defects after a few pass-bys were listened to. The site was a free-field zone (meaning that had no reflecting objects), and the ballast blanket was similar on both sites.



Figure 43: Pictures of the measurement site at IP

### 7.5.2. Measuring equipment

The equipment used included 1 Svantek 958 datalogger, 2 Class 1 microphones (Svantek SV12L), and 2 accelerometers (Vibrasens 108.01-3-4, 10mV/g). Roughness measurements were not performed as calibration was used to ensure similar noise emissions before the rail pads were changed.

### 7.5.3. Rolling stock & speeds tested

Various passenger and freight trains were used for testing as part of the project, with speeds ranging from 105 to 220km/h. Detailed information about the train types and speeds can be accessed through the software tool, along with images being available in Annex B: Rolling stock - Visual Reference Guide. Since the track was in normal operation during the measurements, there was minimal variation in speed among trains of the same type.

Table 8: IP Types of trains stored in the LOWNOISEPAD database

|                              |                     |                     |
|------------------------------|---------------------|---------------------|
| Freight train                | Freight LOC 4700    | Freight LOC 4700    |
| Passenger train – High speed | High speed CPA 4000 | High Speed CPA 4000 |
| Passenger train              | Intercity LOC 5600  | Intercity LOC 5600  |
| Passenger train              | Regional UTE 2240   | Regional UTE 2240   |
| Passenger train              | Urban UQE 2300      | Urban UQE 2300      |
| Passenger train              | Urban UQE 3500      | Urban UQE 3500      |
| Passenger train              | Urban UQE2300 new   | Urban UQE2300 new   |

#### 7.5.4. TDR

The TDR measurements were taken according to the CEN15461 and CEN/TR 16891 standards. The TDR raw measurement data was obtained, with SD&M doing the calculations. Details between the two methods can be found and comparisons can be carried out in the software tool, alongside the general table in Chapter 6.

The results below, based on CEN15461, serve as an example for the two rail pads tested. It is evident that the optimised rail pad (OPTI) exhibits similar TDR amplitudes up to 800Hz. For frequencies above 800Hz, the optimised rail pad (OPTI) shows significantly better damping, including in the 1kHz pin-pin region.

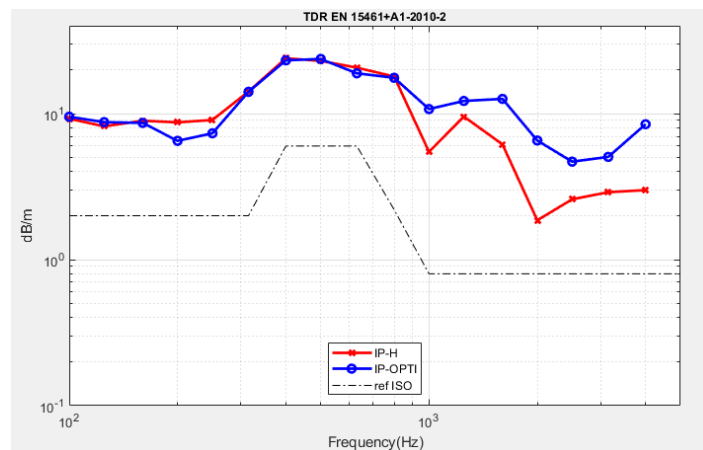


Figure 44: Measured TDR according to CEN15461 at IP

#### 7.5.5. Temperature during tests

The rail temperature varied from 17°C in the morning to a maximum of approximately 33°C around 14h30.

#### 7.5.6. Raw data received

The measurements were taken using the 4-channel SVANTEK 958 device, storing raw WAV files for post-processing. Calibrated files were created, containing 4 channels (2 accelerations and 2 microphones) for each pass-by.

#### 7.5.7. Information received for the database

All necessary data was received and is available in the database.

#### 7.5.8. Results in the database

A total of 26 pass-bys were selected for analysis, with 2 pass-bys being excluded due to, for example, speed differences and low-quality rail acceleration measurements. The processing information and any processing errors have been logged in the database for reference.

### 7.5.9. Noise insertion loss

If there was more than one pass-by per train type, the noise insertion loss (NIL) curve is presented with the average per train type. Figure 45 illustrates the results for the optimised pad (OPTI) compared to the stiff rail pad (H) as the reference. Detailed comparisons can be made using the LOWNOISEPAD software tool. Notably, the IL loss curves for all trains exhibit similar patterns, while the optimised pad promisingly demonstrates a reduction of 2.8dB(A) in the A-weighted level compared to a stiff EVA rail pad, surpassing the results observed at SBB.

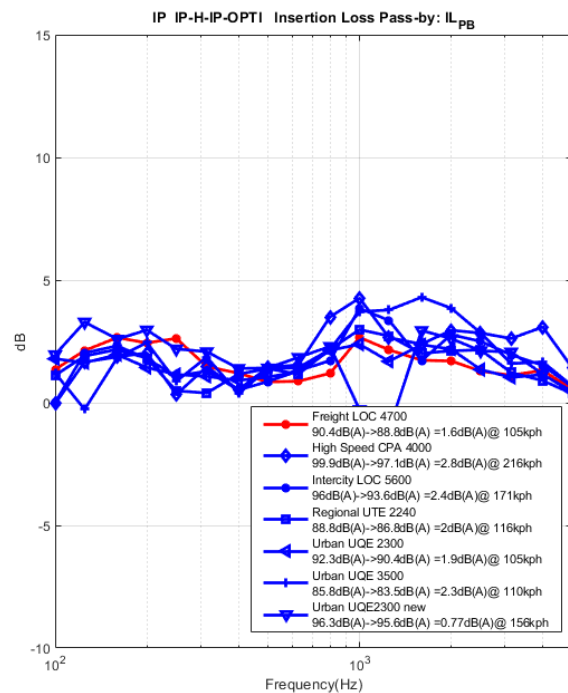


Figure 45: The results for the optimised pad (OPTI) with the stiff rail pad (H) as the reference

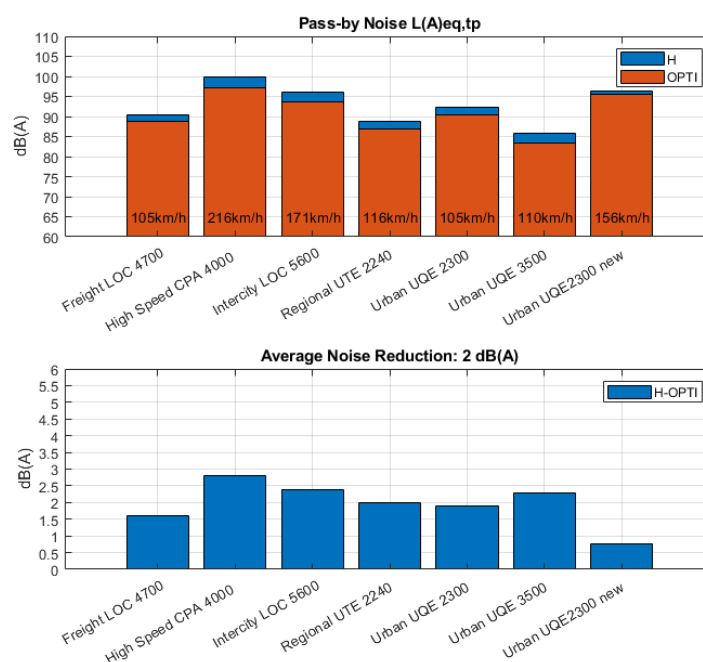


Figure 46: Averaged pass-by noise and noise reduction for the OPTI pad using the H pad for reference

## 7.6. TRAFIKVERKET MEASUREMENTS, SWEDEN

The pass-by and TDR measurements at Trafikverket were taken by the Luleå University of Technology between 31 October 2022 and 1 November 2022. The measurement site, located in Sävast/Boden, Sweden, offered unique conditions with below zero temperatures, going as low as  $-10^{\circ}\text{C}$ . Although the temperature differed throughout the day, the consistently low temperatures in comparison to other PPs' test sites could contribute to the exceptionally high TDR values observed for the tested rail pads.

### 7.6.1. Test track and tested rail pads

The measurement took place on a test track with concrete Trafikverket standard monoblock sleepers, 60E1 rails, and rail E-clips. Two rail pads were compared: a standard soft pad and an optimised rail pad. Detailed information about the rail pads can be found in Table 14, Table 15 and Table 16.

### 7.6.2. Site description

Figure 47 provides images of the test site. Two carefully selected sections, each approximately 80 meters in length, were used for the measurements. The site offered an open field environment with a similar ballast bed on both sections.

### Installation of pads in track 119, Sweden

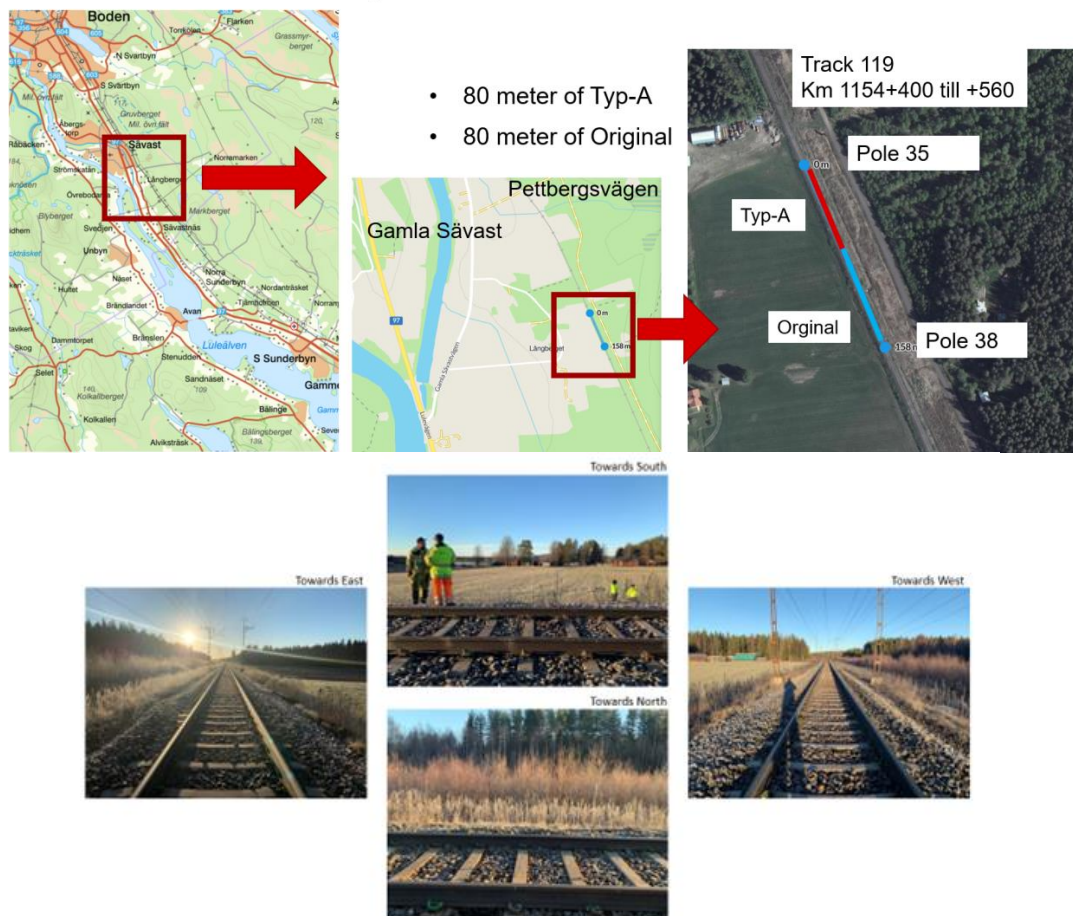


Figure 47: Overview of the Trafikverket measurement site

### 7.6.3. Measuring equipment

The measuring equipment used at the Trafikverket site included a Svantek 958 datalogger, two Class 1 microphones (Svantek SV12L), and two accelerometers (Vibrasens 108.01-3-4) with a sensitivity of 10mV/g. The setup for both pass-by measurements and TDR measurements is depicted in Figure 48. However, it should be noted that roughness measurements were not included in the data collection process.

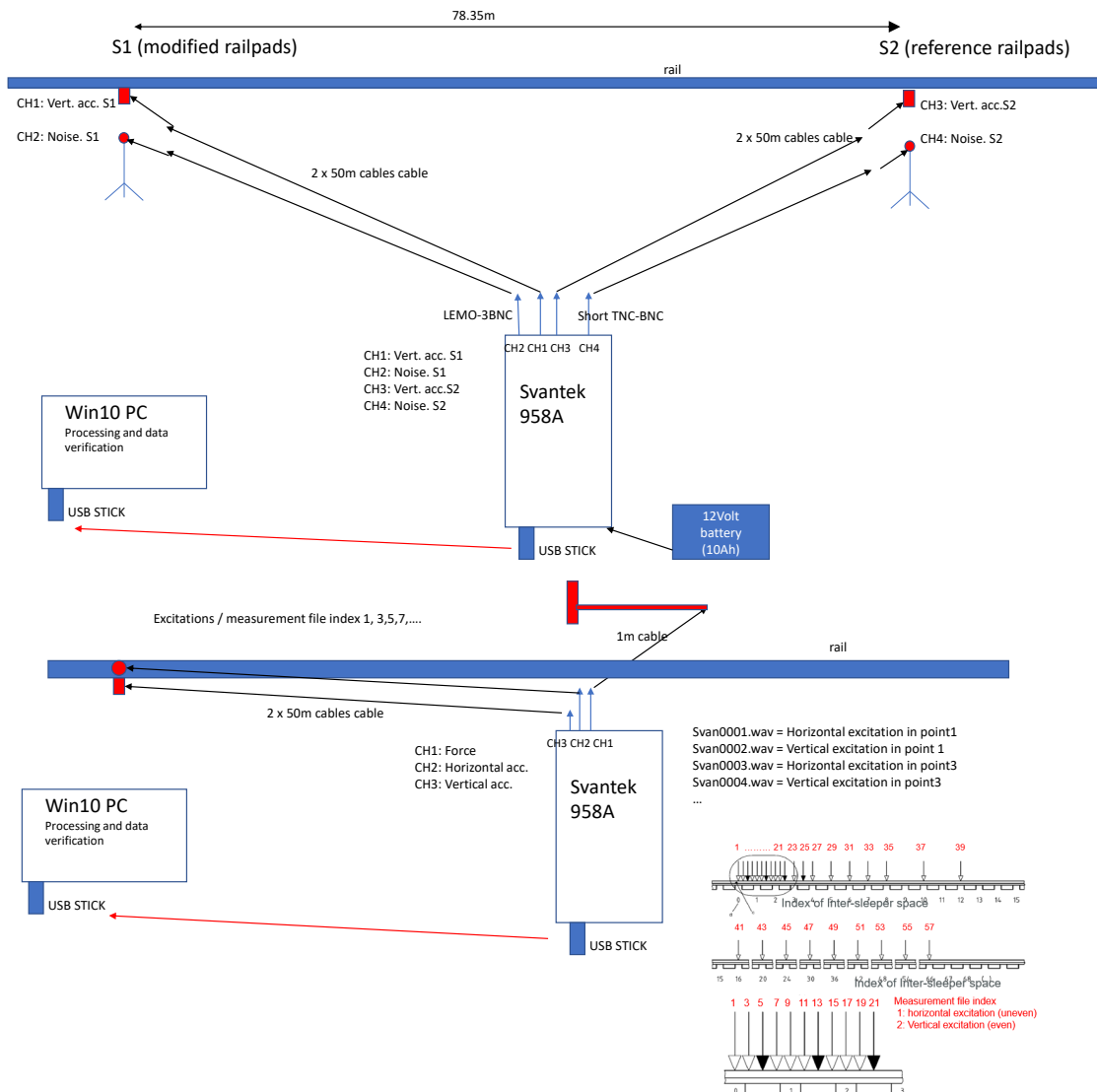


Figure 48: Setup of the system to take pass-by and TDR measurements

### 7.6.4. Rolling stock & speeds tested

Various passenger and freight trains were used for testing as part of the project, with speeds ranging from 105 to 120 km/h. Detailed information about the train types and speeds can be accessed through the software tool, along with images being available in **Annex B: Rolling stock - Visual Reference Guide**. Since the track was in normal operation during the measurements, there was minimal variation in speed among trains of the same type.

Table 9: Types of Trafikverket trains stored in the LOWNOISEPAD database

|                 |                                 |                                 |
|-----------------|---------------------------------|---------------------------------|
| Freight train   | Freight train, iron ore train   | Freight train, iron ore train   |
| Freight train   | Freight train, steel pendulum   | Freight train, steel pendulum   |
| Freight train   | Freight train1                  | Freight train1                  |
| Passenger train | Passenger train, EMU Regina     | Passenger train, EMU Regina     |
| Passenger train | Passenger train, RC1 locomotive | Passenger train, RC1 locomotive |
| Passenger train | Passenger train, RC2 locomotive | Passenger train, RC2 locomotive |

### 7.6.5. TDR

The TDR measurements were taken according to the CEN15461 and CEN/TR 16891 standards. Details of the two methods can be found and comparisons can be carried out in the software tool, alongside the general table in Section 8. The raw TDR measurement data was obtained, with calculations being carried out by both SD&M and the Luleå University of Technology.

Figure 49 presents the results based on CEN15461 for the two rail pads tested. It should be noted that both TDR curves exhibit higher values than expected due to the low temperatures experienced when the measurements were taken.

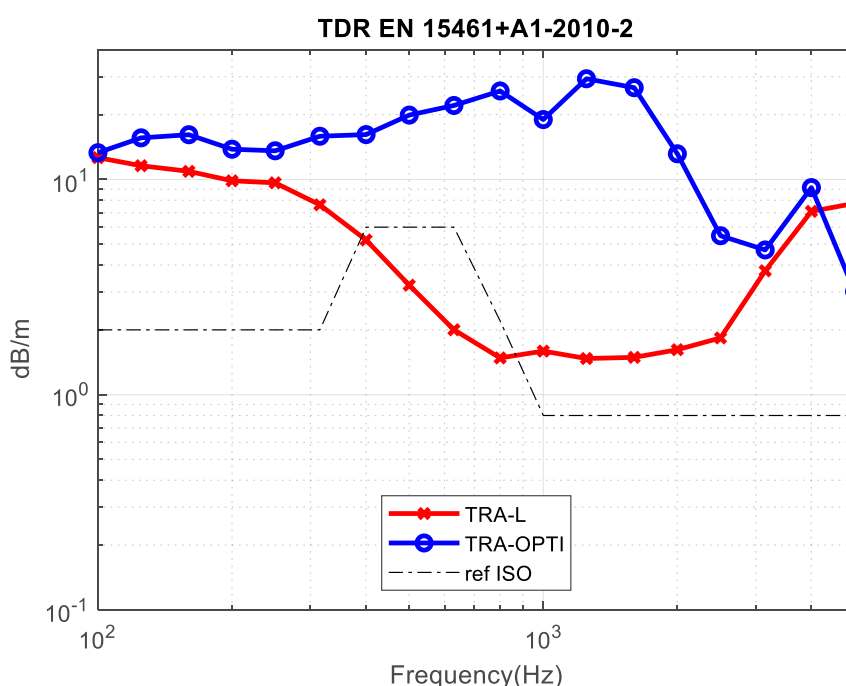


Figure 49: Measured TDR according to CEN15461 at Trafikverket

### 7.6.6. Temperature during tests

The temperature variation during the pass-by tests is displayed in Figure 50.

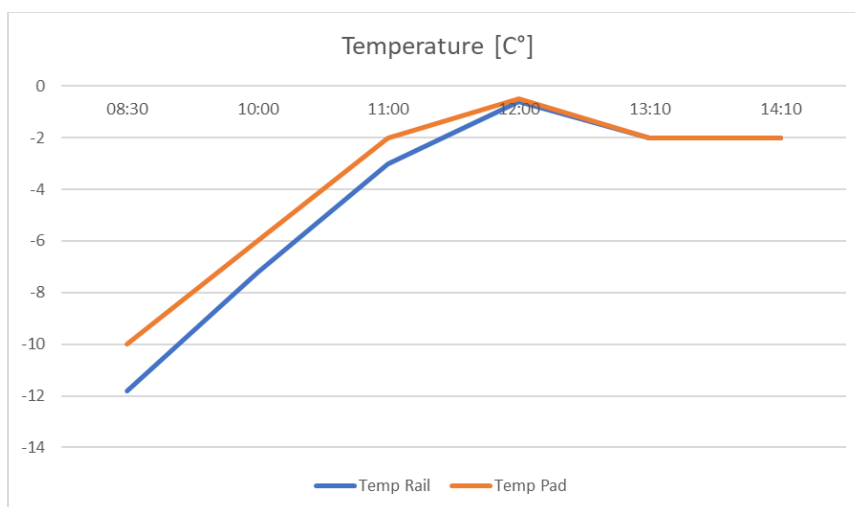


Figure 50: Temperature during the pass-by tests at Trafikverket

Additionally, detailed temperature variations were recorded during the TDR measurements, as follows:

Temperature at the start of the day on the rail: -12.3°C

- Type A left rail
  - Before measurement: -7.2 °C
  - After measurement: 6.1 °C
- Type A left rail
  - After measurement: 0.5°C
  - No measurement
- Type Original left
  - Before measurement: 4.1 °C
  - After measurement: 3.3 °C
- Type Original right
  - After measurement: -1.3 °C
- Type A right
  - After measurement: -6.5 °C

#### 7.6.7. Raw data received

Raw WAV files from the 4-channel SVANTEK 958 device were automatically stored during the measurement campaign and made ready for postprocessing. Calibrated files containing 4 channels (2 accelerations and 2 microphones) were created for each pass-by.

#### 7.6.8. Information received for the database

All necessary data was successfully obtained and is available in the database.

### 7.6.9. Results in the database

After the pads were installed, the measurements were carried out over a single day and therefore, there was a limited number of pass-bys available for analysis. Out of the total of 14 pass-bys selected, 1 pass-by was excluded. The processing information and any processing errors have been logged in the database for reference.

### 7.6.10. Noise insertion loss

If there was more than one pass-by per train type, the noise insertion loss (NIL) curve is presented, with the average per train type. Figure 51 illustrates the results for the optimised pad (OPTI) compared to the soft rail pad (L) used as a reference. Detailed comparisons can be performed using the LOWNOISEPAD software tool. The maximum observed noise reduction throughout the entire set of measurements was 3.3dB(A).

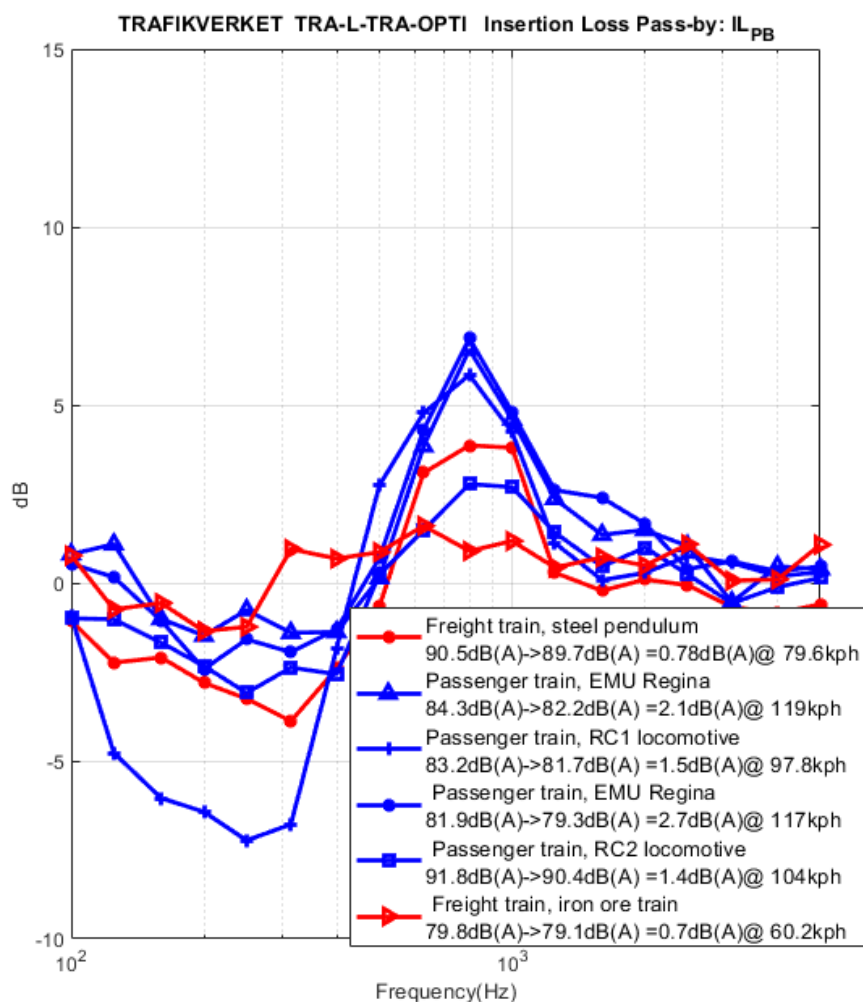


Figure 51: Averaged noise insertion loss per train type for the OPTI pad using the L pad for reference

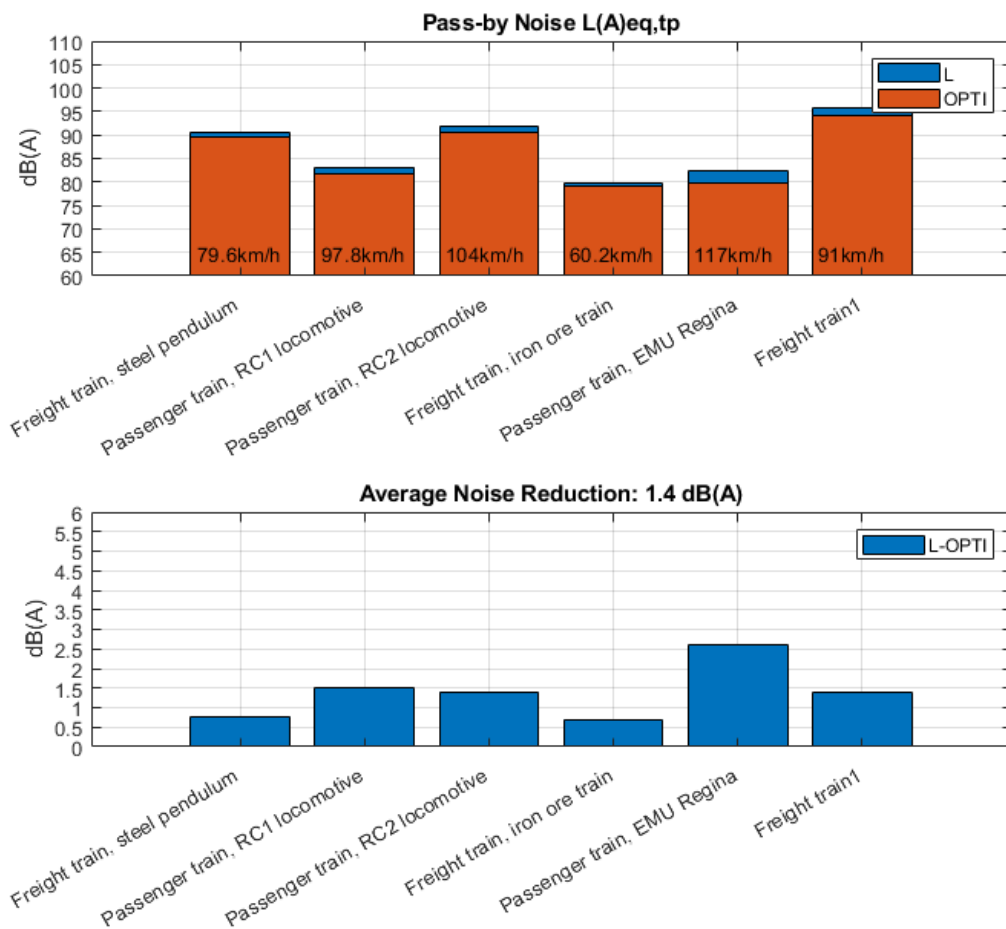


Figure 52: Averaged pass-by noise and noise reduction for the OPTI pad using the L pad for reference



## 7.7. SZCZ MEASUREMENTS, CZECH REPUBLIC

The pass-by and TDR measurements at SZCZ were taken by the VUZ test laboratory in September 2022. SZCZ selected a site in a curve with a radius of 800m to enable alternative rail pads to be installed for testing within the project parameters. Although this site was different to the others, the results obtained are interesting.

As the measurements were taken in a curve, increased rail roughness values needed to be taken into account. Hence, the measured roughness at the three sites within the curve was verified and is depicted in Figure 53 below.

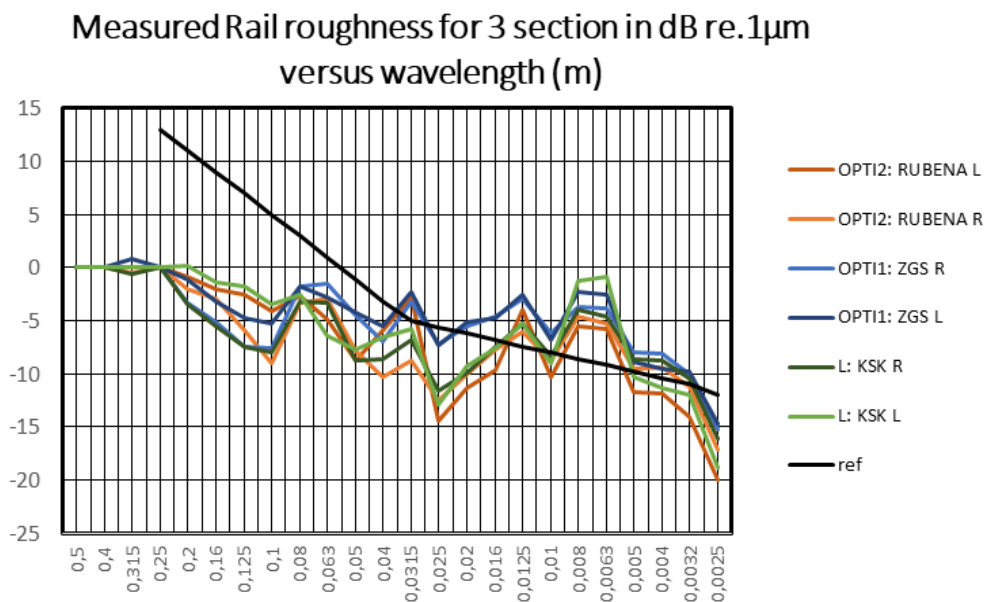


Figure 53: Measured roughness at the three sites in the curve

In the test curve at SZCZ, no prominent high-amplitudes due to corrugations were observed. However, the sections with the optimised rail pads (OPTI) exhibited slightly higher rail roughness at specific wavelengths than the section with the softest rail pad (L), with a wavelength of 2.5cm corresponding to approximately 1kHz at a speed of 100km/h. This slight difference in rail roughness can result in slightly higher noise levels in the optimised sections (OPTI1 and OPTI2) if the wheel-rail contact in the curve is comparable during roughness measurements. Based on this observation, there is a risk that any noise reduction from the optimised rail pads may be masked and minimised by the difference in rail roughness which generates more noise.

### 7.7.1. Site description

The site for the measurements was located in Přelouč. Three rail pads were compared, each with similar static stiffness (kSP) but different dynamic stiffness. The track used type B91S concrete monoblock sleepers, 60E2 rails, and W14 tension clamp. More details about the rail pads can be found in Table 14, Table 15 and Table 16. The test site consisted of three selected sections, each approximately 80 meters in length, as shown in Figure 54.

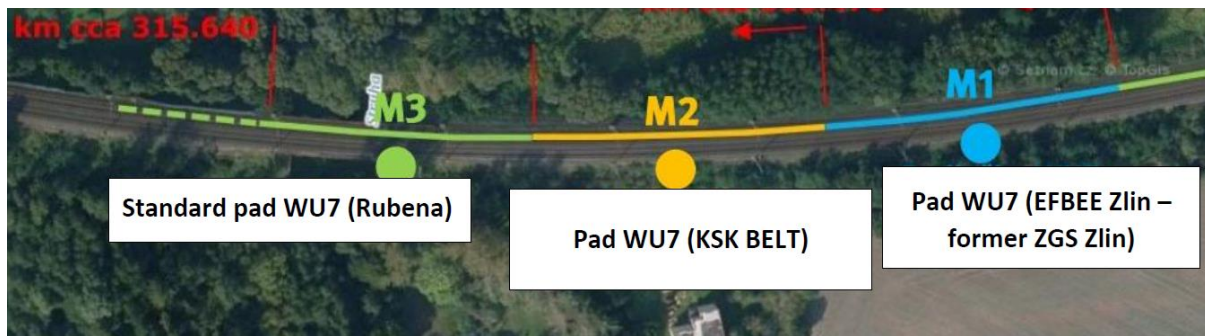


Figure 54: Overview of the SZCZ measurement site

### 7.7.2. Measuring equipment

For the measurement setup at SZCZ, a multi-channel Bruel&Kjaer PULSE system was used for taking the measurements. The sensitivity values for the accelerometers were as follows:

- M1: 0.9447 mV/ms<sup>-2</sup>
- M2: 0.9737 mV/ms<sup>-2</sup>
- M3: 10.4 mV/ms<sup>-2</sup>

These sensitivity values indicate the conversion factor between the measured acceleration and the corresponding voltage output of the accelerometers.

For the microphones, separate wave files were provided with a 94dB signal to verify their sensitivity. This procedure allowed the microphone signals to be accurately calibrated and ensured that the sound pressure levels were reliably measured during the tests.

### 7.7.3. Rolling stock & speeds tested

Various passenger and freight trains were used for testing as part of the project, with speeds ranging from 80 to 136 km/h. Detailed information about the train types can be found in Table 10 and speeds can be accessed through the software tool, along with images being available in Annex B: Rolling stock - Visual Reference Guide. Since the track was in normal operation during the measurements, there was minimal variation in speed among trains of the same type.

Table 10: SZCZ Types of trains stored in the database

|                 |                                  |
|-----------------|----------------------------------|
| Freight train   | freight                          |
| Passenger train | intercity passenger EMU          |
| Passenger train | intercity passenger loco+coaches |
| Passenger train | regional passenger loco+coaches  |

### 7.7.4. TDR

The TDR measurements were taken in accordance with the CEN15461 and CEN/TR 16891 standards. Details of the two methods can be found and comparisons can be carried out in the software tool, alongside the general table in Chapter 8. The TDR raw measurement data was obtained and analysed by both SD&M and the VUZ test laboratory. Figure 55 presents the results according to CEN15461 for the three rail pads tested. The rail pad with the lowest TDR and lowest dynamic stiffness is labelled as L, while the other two are referred to as OPTI1 and OPTI2.

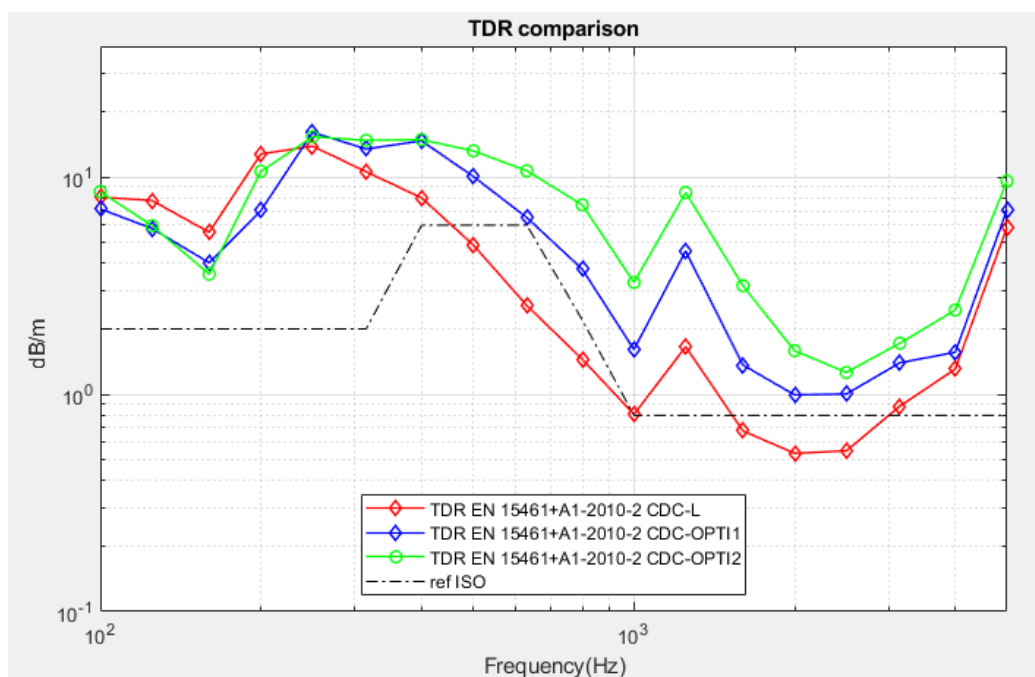


Figure 55: Measured TDR according to CEN15461 at SZCZ

### 7.7.5. Temperature during tests

During the pass-by measurements at SZCZ, the ambient temperature ranged between 23 and 25°C.

### 7.7.6. Raw data received

The raw data for the measurements was generated by the measurement system and stored in 6-channel WAV files. Calibration signals at 1 kHz with a sound level of 94 dB were used for system calibration.

### 7.7.7. Information received for the database

All the necessary data was obtained and is available in the database.

### 7.7.8. Results in the database

Since there was only one measurement day planned after the rail pad installation, the number of pass-bys available for analysis was limited. Out of a total of 19 pass-bys, 7 were rejected due to, for example, speed differences, low-quality rail acceleration measurements, and the inability to synchronise pass-bys across different sections. The processing information and any processing errors have been logged in the database for reference.

### 7.7.9. Noise insertion loss

If there was more than one pass-by per train type, the noise insertion loss (NIL) curve is presented, with the average per train type. Figure 56 depicts the results for the optimised pad (OPT12) using the soft rail pad (L) as the reference. A detailed comparison can be performed using the LOWNOISEPAD software tool.

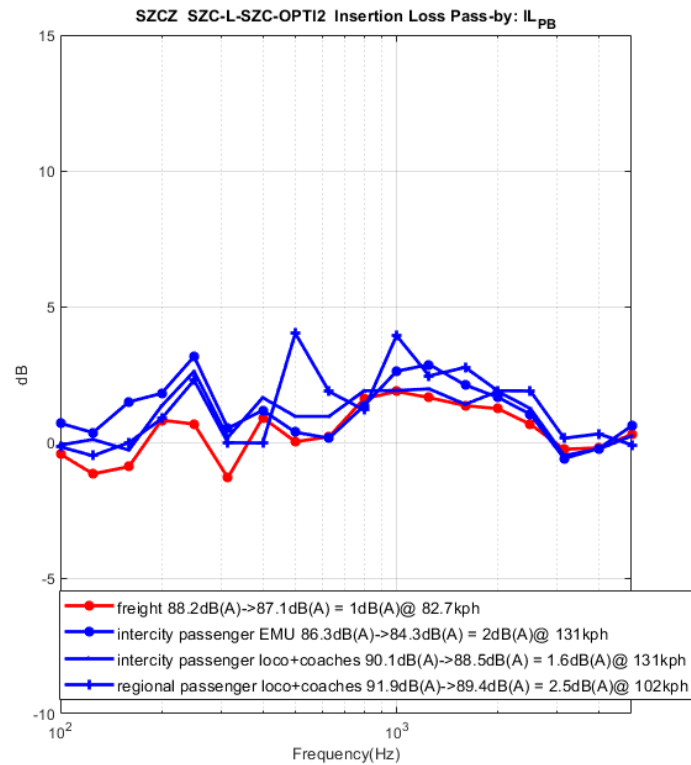


Figure 56: Averaged noise insertion loss per train type for the OPTI2 pad using the L pad for reference

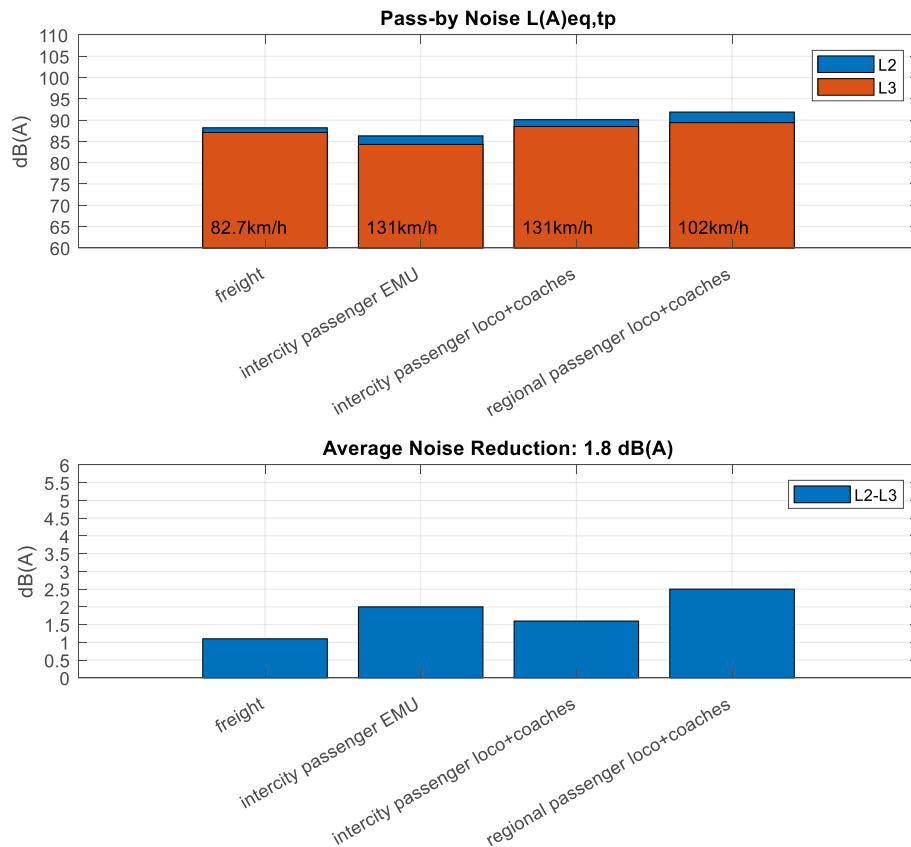


Figure 57: Averaged pass-by noise and noise reduction for the OPTI pad using the L pad for reference

## 7.8. RFI MEASUREMENTS, ITALY

The pass-by and TDR measurements were conducted at RFI from 4-7 October 2022. From the project's outset, RFI had stated that changing a track component would require extensive laboratory testing, which was not feasible within the project's timeframe. Consequently, a single section of a typical track with standard components was selected for taking the measurements.

### 7.8.1. Test track and tested rail pads

The measurement site was located on the Roma-Livorno line, tratta Quercianella-Castiglioncello, specifically between pk 12+925 and pk 12+665. The track was equipped with type RFI240 concrete monoblock sleepers, 60E1 rails, and W14 tension clamp. An EVA rail pad with a static stiffness of 200kN/mm was also used. Further rail pad details can be found in Table 14, Table 15 and Table 16.

### 7.8.2. Site description

Due to the presence of trees and plants alongside the track, which prevented the free field (no reflecting object) conditions from being fulfilled, only one measurement section was available for comparison with other test sections.

The microphone was installed on the opposite side of the track and the train type and speed were captured using specialised devices. Additionally, a road was situated approximately 40m from the track. Figure 58 provides images of the site.



Figure 58: Picture of the sensor set-up at RFI

### 7.8.3. Measuring equipment

The measuring equipment used for the project included the Sinus Noise PAD, a portable spectrum analyser capable of vibration and noise measurements on 4 channels. It was paired with a microphone sensitivity of  $> 20 \text{ mV/Pa}$  and an accelerometer sensitivity of  $99.4 \text{ mV/m/s}^2$ .

#### 7.8.4. Rolling stock & speeds tested

Various passenger and freight trains were used for testing as part of the project, with speeds ranging from 80 and 105km/h. Detailed information about the train types and speeds can be accessed through the software tool, along with images being available in **Annex B: Rolling stock - Visual Reference Guide**. The train names are detailed, including various subtypes that may differ in locomotor position and/or number of wagons.

Table 11: Types of RFI trains stored in the database

|                  |                      |                      |
|------------------|----------------------|----------------------|
| Diagnostic train | DGN E652+E652        | DGN E652+E652        |
| Freight train    | FRG E 189            | FRG E189             |
| Freight train    | FRG E191             | FRG E191             |
| Freight train    | FRG E494             | FRG E494             |
| Freight train    | FRG E652             | FRG E652             |
| Passenger train  | PAX Ale642           | PAX                  |
| Passenger train  | PAX Ale642 (1M + 1R) | PAX Ale642           |
| Passenger train  | PAX Ale642 (1M + 2R) | PAX Ale642 (1M + 1R) |
| Passenger train  | PAX E401             | PAX Ale642 (1M + 2R) |
| Passenger train  | PAX E414+E414        | PAX E401             |
| Passenger train  | PAX E464np+E464np    | PAX E414+E414        |
| Passenger train  | PAX ETR460           | PAX E464np+E464np    |
| Passenger train  | PAX ETR485           | PAX ETR460           |
| Passenger train  | PAX ETR521 (old)     | PAX ETR485           |
|                  |                      | PAX ETR521 (old)     |

#### 7.8.5. TDR

The TDR measurements were taken according to the CEN/TR 16891 standard, and calculated from rail acceleration data obtained during the pass-bys. Results from the alternative method using an impulse hammer (CEN15461) were not compared, as with other PPs, due to difficulties in carrying out the test and potential non-compliance with the standard. Repeating these measurements may be considered by RFI. Figure 59 presents the TDR results according to CEN/TR 16891 for the tested rail pad.

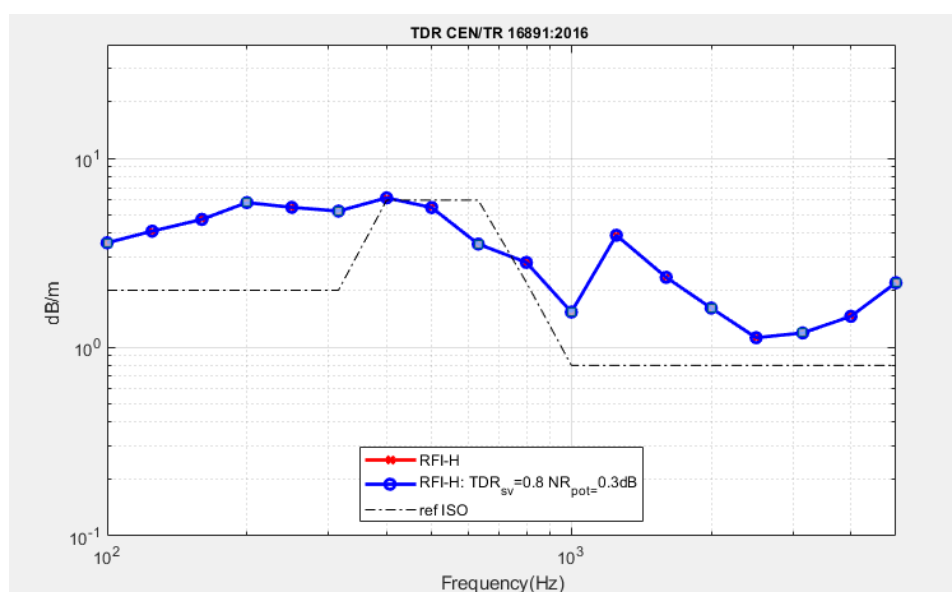


Figure 59: Measured TDR according to CEN/TR 16891 at RFI for the rail pad tested

### 7.8.6. Temperature during tests

Table 12 summarises the temperatures recorded during the pass-by measurements at RFI.

*Table 12: Temperatures during the pass-by measurements at RFI*

|                     | 04/10/2022                      | 05/10/2022                      | 06/10/2022                      |
|---------------------|---------------------------------|---------------------------------|---------------------------------|
| Ambient Temperature | Avg 18 °C, min 13 °C, max 24 °C | Avg 19 °C, min 13 °C, max 25 °C | Avg 18 °C, min 12 °C, max 25 °C |
| Rail Temperature    | 21,8 °C at 10 AM                | 22,8 °C at 10 AM                | 22,9 °C at 10 AM                |

### 7.8.7. Raw data received

Raw data files in an ASCII format were delivered, refined to increase precision, and translated for processing.

### 7.8.8. Information received for the database

Only one rail pad is included in the database.

### 7.8.9. Results in the database

Out of a total of 65 pass-bys, 35 pass-bys were excluded due to, for example, speed differences, low-quality rail acceleration measurements, and the inability to synchronise pass-bys across different sections. The processing information and any processing errors have been logged in the database for reference.

### 7.8.10. Noise insertion loss

As only one rail pad was measured, direct calculations of the NIL were not possible. However, simulations may be created later on using other rail pads from the project via the software tool.

## 7.9. CONCLUSION

Data from a total of 30 pads, including 18 optimised pads at 10 test sites, and 12 reference pads at 12 test sites, were collected and stored in the LOWNOISEPAD software tool.



## 8. WP6: GENERAL PROJECT OUTPUT AND RESULTS

### 8.1. OVERVIEW OF THE INSTALLED RAIL PADS AT LOWNOISEPAD

#### 8.1.1. Project statistics and creating the LOWNOISEPAD database for the installed rail pads

The LOWNOISEPAD project tested 31 different rail pads for their acoustic performance using pass-by (ISO3095) and TDR measurements (CEN15461 and CEN/TR 16891:2016). The pads included reference pads, optimised pads, and various train types on different track sections. The project involved multiple partners and will incorporate additional data in the future. The rail pads tested included:

- 15 country-specific reference rail pads with varying levels of softness and stiffness, using EVA pads
- 18 acoustically optimised rail pads from 4 different suppliers
- 2 rail fastening systems, namely tension clamp and clips (Fast- and E-clip)
- A mix of over 60 different train types, including passenger and freight trains
- 12 different types of country-specific monoblock sleepers
- Speeds ranging from 60 to 220km/h
- Ambient temperature ranging from -11°C to 25°C

Raw data from 8 project partners was processed in an identical manner. In the later stages of 2023, raw data from 4 other project partners (BaneNor, Network Rail, ProRail and SNCF) will be added and processed. Furthermore, in the summer of 2023, Trafikverket will repeat the measurements to better understand how temperature may have an influence. This additional data can also be incorporated into the project's database and software tool.

The processed data, including selected pass-by information and calculated TDR values, is stored in a database. An example of a typical scenario using an imaginary train is given in Table 13. This data was used to validate the LOWNOISEPAD procedure for the speed and tp time calculations.

In the project, crucial information such as tp-time and speed was always recalculated using rail accelerometers positioned in the middle of each section. If there were more than two sections, the variation in speed during the pass-by was also able to be calculated. This standardised approach was applied to all of the PPs' measurements.

In the subsequent step, during the calculation of pass-by data in batches, in both the time and frequency domains, the data from all measurement sites were stored in the final LOWNOISEPAD database, along with the corresponding TDR data. The database consisted of 32 fields for each pass-by, as illustrated in Figure 60 below. These fields included character-type (**ch**), and **cell {}** type data, as well as multidimensional matrices of doubles or single doubles. While most, but not all, of these records were accessed by the LOWNOISEPAD software tool and were visible in the BETA version of the software, additional parameters could be included in the software upon request. This information and data management process ensured the accurate and comprehensive storage of pass-by information, facilitating further analysis and assessments within the LOWNOISEPAD project.

Table 13: Example with available individual pass-by information for final database

| Parameter                 | EXAMPLE                       |
|---------------------------|-------------------------------|
| Data/location             | Londerzeel/Belgium            |
| Filename                  | rec01.wav                     |
| Filetype                  | wav                           |
| Location                  | Strecke 1760-1 Hannover-soest |
| S1 (pad name)             | L                             |
| S2 (pad name)             | OPT11                         |
| S3 (pad name)             | OPT12                         |
| ... (In order of pass-by) | ...                           |
| Linename                  | L89                           |
| Railtype                  | 60                            |
| File ID                   | 1                             |
| Track                     | A                             |
| Direction                 | Brussel                       |
| Type of train             | AM96                          |
| Length(m)                 | 120                           |
| Tp(s)                     | 5.1                           |
| Tpax1(s)                  | 0.25                          |
| Tpax2(s)                  | 5.25                          |
| Speed mean (km/h)         | 100                           |
| Speed min(km/h)           | 99                            |
| Speed max(km/h)           | 101                           |
| Axles                     | 40                            |
| Temperature (°C)          | 22                            |
| Press                     | 1048                          |
| Humidity                  | 65                            |
| Windspeed1 (m/s)          | 4.2                           |
| Winddirection1            | NZ                            |
| Rain(mm)                  | 0.2                           |
| Rail temperature (°C)     | 34                            |

| Fields | written                | calculation | fileID | Operator | passbynumber | channellabels | accelch | noisech | speed    | sfq   |
|--------|------------------------|-------------|--------|----------|--------------|---------------|---------|---------|----------|-------|
| 1      | '18-Feb-2023 12:03:57' | 'accepted'  |        | 9"IP"    | 1            | 1x4 cell      | [1,3]   | [2,4]   | 106.3316 | 48000 |

| Fields | refp | timedatdB    | timedata     | freqdatdB   | freqdata    | location        | tp     | traintype       | track     | rail    | date         | time       | length |
|--------|------|--------------|--------------|-------------|-------------|-----------------|--------|-----------------|-----------|---------|--------------|------------|--------|
| 1      | 4    | 568x4 double | 568x1 double | 4x31 double | 1x31 double | 'Northline V... | 2.3050 | 'Regional 22... | 'Vossloh' | 'UIC60' | '27.09.2022' | '11:32:00' | NaN    |

| Fields | axles | temp | railtemp | Ftdr        | TDRd        | TDRpb       | TDRtemp | traintypes | traintypei |
|--------|-------|------|----------|-------------|-------------|-------------|---------|------------|------------|
| 1      | NaN   | 21   | 33       | 1x18 double | 18x2 double | 18x2 double | 15      | 8x1 cell   | 8          |

Figure 60: Overview of the fields in the database

### 8.1.2. Technical specifications for the installed rail pads: comparison

In order to facilitate a comparison between the rail pads, the PPs were requested to provide rail pad stiffness values in accordance with DIN EN 13481-2:2022-11 and EN13146-9:2020. The following stiffness parameters were collected:

- kSA: static stiffness of assembly [MN/m]
- kLFA: low-frequency dynamic stiffness of assembly [MN/m]
- kLFPf: low-frequency dynamic stiffness of the pad at a specific frequency [MN/m]
- kLFPmean: mean of pad low-frequency dynamic stiffness measurements at 5Hz, 10Hz and 20Hz [MN/m]

Based on the discussions among the PPs, a standardised colour scheme and standardised rail pad names were agreed upon. A static stiffness of 200kN/mm was initially used to distinguish between low and high stiffness. For practical purposes, all optimised pads were identified as “OPTI” on the plots. More detailed information can be found in Table 14, Table 15 and Table 16.

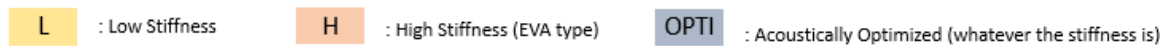


Figure 61: Colour scheme and rail pad names

A comprehensive summary of all of the project data has been compiled in an Excel Sheet. This sheet serves as the basis for generating the tables presented in Section **WP6: General project output and results** of this report. Each PP has given their agreement on the values and parameters to be included in the tables. The final table header is displayed in Figure 62.

| project database |        |    | Railpad properties |      |                      |                 |          |     |           |             |             |                      |
|------------------|--------|----|--------------------|------|----------------------|-----------------|----------|-----|-----------|-------------|-------------|----------------------|
| dBase            | PAD id | PP | Rail Fastener      | type | name in LNP software | internal naming | Producer | kSP | kLFPf 5Hz | kLFPf 10 Hz | kLFPf 20 Hz | kLFPmean (5-10-20Hz) |
|                  |        |    |                    |      |                      |                 |          |     |           |             |             |                      |

| Measured Noise reduction |           |     |     | TDR- CEN15461     |                   | CEN TR 16891      |                   |
|--------------------------|-----------|-----|-----|-------------------|-------------------|-------------------|-------------------|
| reference                | at speeds | min | max | TDR <sub>sv</sub> | Nr <sub>pot</sub> | TDR <sub>sv</sub> | Nr <sub>pot</sub> |
|                          |           |     |     |                   |                   |                   |                   |

Figure 62: Excel Sheet header with all of the project data

The Excel Sheet serves as a comprehensive repository of track engineering information, including details about the rail pad producers and other relevant data. It offers a more comprehensive overview of the rail pads in relation to the measured noise reduction, specifically for **TDR<sub>sv</sub>** and **NR<sub>pot</sub>**, both based on EN15461 [4] for unloaded tracks, and TR16891 [6] for loaded tracks.

Table 14 below presents the available data as of September 2023. It is important to note that not all stiffness values are definitive and may be subject to refinement. This is particularly the case for very stiff pads (EVA), as significant variation can occur based on the stiffness of the measurement setup and the specific laboratory where the tests are conducted, as the stiffness of the measurement equipment often becomes a crucial factor.

Table 14: Rail pad properties: available data as of 23/03/2023

| Project database         |        |                         | Rail pad properties |                        |                      |       |           |             |             |                      |
|--------------------------|--------|-------------------------|---------------------|------------------------|----------------------|-------|-----------|-------------|-------------|----------------------|
| Integrated into database | PAD ID | Name of Project Partner | Rail fastener       | Type                   | Name in LNP software | kSP   | kLFPf 5Hz | kLFPf 10 Hz | kLFPf 20 Hz | kLFPmean (5-10-20Hz) |
| No <sup>1</sup>          | 1      | BANENOR                 | Clip                | Optimised              | OPT1                 | 140   | 210       |             |             |                      |
| No <sup>1</sup>          | 2      | BANENOR                 | Clip                | Reference              | L                    | 130   | 140       | 140         |             |                      |
| Yes                      | 3      | SZCZ                    | Tension Clamp       | Optimised              | OPT11                | 119.8 |           |             |             | 156.8                |
| Yes                      | 4      | SZCZ                    | Tension Clamp       | Optimised              | OPT12                | 121.3 |           |             |             | 162.6                |
| Yes                      | 5      | SZCZ                    | Tension Clamp       | Reference              | L                    | 114.4 |           |             |             | 128.9                |
| Yes                      | 6      | DB                      | Tension Clamp       | Optimised <sup>2</sup> | OPT1                 | 165   | 220       |             |             |                      |
| Yes                      | 7      | DB                      | Tension Clamp       | Reference              | L                    | 60    | 79        |             |             |                      |
| Yes                      | 8      | DB                      | Tension Clamp       | Reference              | H                    | 600   |           |             |             |                      |
| Yes                      | 9      | INFRABEL                | Clip                | Optimised              | OPT13                | 200   | 300       |             |             |                      |
| Yes                      | 10     | INFRABEL                | Clip                | Optimised              | OPT12                | 200   | 300       |             |             |                      |
| Yes                      | 11     | INFRABEL                | Clip                | Reference              | L                    | 55    | 65        |             |             |                      |
| Yes                      | 12     | INFRABEL                | Clip                | Optimised              | OPT11                | 200   | 300       |             |             |                      |
| Yes                      | 13     | IP                      | Tension Clamp       | Reference              | H                    | 1100  | 1300      | 1400        |             |                      |
| Yes                      | 14     | IP                      | Tension Clamp       | Optimised              | OPT1                 | 230   | 340       |             |             |                      |
| No <sup>1</sup>          | 15     | Network Rail            | Tension Clamp       | Reference              | L                    | 100   | 110       |             |             |                      |
| No <sup>1</sup>          | 16     | Network Rail            | Tension Clamp       | Optimised              | OPT1                 | 190   | 290       |             |             |                      |
| Yes                      | 17     | ÖBB                     | Tension Clamp       | Reference              | L2                   | 100   | 134       |             |             |                      |
| Yes                      | 18     | ÖBB                     | Tension Clamp       | Reference              | L1                   | 103   |           | 123         |             |                      |
| Yes                      | 19     | ÖBB                     | Tension Clamp       | Optimised              | OPT11                | 84    |           | 237         |             |                      |
| Yes                      | 20     | ÖBB                     | Tension Clamp       | Optimised              | OPT12                | 134   |           | 379         |             |                      |
| Yes                      | 21     | ÖBB                     | Tension Clamp       | Optimised              | L3                   | 195   | 212       | 217         | 224         | 218                  |
| Yes                      | 22     | ÖBB                     | Tension Clamp       | Optimised              | L4                   | 106   | 116       | 118         | 122         | 119                  |
| Yes                      | 23     | SBB                     | Tension Clamp       | Reference              | L                    | 83.3  |           |             |             |                      |
| Yes                      | 24     | SBB                     | Clip                | Reference              | H                    | 700   |           |             |             |                      |
| Yes                      | 25     | SBB                     | Clip                | Optimised              | OPT1                 | 162   | 225       |             |             |                      |
| No <sup>1</sup>          | 26     | SNCF                    | Tension Clamp       | Reference              | L                    | 90    | 110       | 120         |             |                      |
| No <sup>1</sup>          | 27     | SNCF                    | Tension Clamp       | Optimised              | OPT1                 | 210   | 310       |             |             |                      |
| Yes                      | 28     | Trafikverket            | Clip                | Optimised              | OPT1                 | 170   | 240       |             |             |                      |
| Yes                      | 29     | Trafikverket            | Clip                | Reference              | L                    | 50    | 55        | 60          |             |                      |
| Yes                      | 30     | RFI                     | Tension Clamp       | Reference              | H                    | 200   | 310       | 325         | 355         |                      |
| No <sup>1</sup>          | 31     | PRORAIL                 | Tension Clamp       | Reference              | H                    | 700   |           |             |             |                      |

<sup>1</sup> to be updated in 2024: The LOWNOISEPAD database will be updated in 2024 together with the data of the members who have not included in the system and will be presented in the final report.

<sup>2</sup> Optimized values for reference only based on one time measurement.

### 8.1.3. Acoustic properties of the installed rail pads: single value TDR results

The definition of the single value TDR performance is detailed in Section 2.2.4 of this report, where the relationship between  $TDR_{sv}$  and  $NR_{pot}$  is proposed, primarily based on the CEN15461 TDR measurement data. However, the report also includes values calculated according to the CEN/TR 16891 standard. It is worth noting that these values may differ significantly in certain cases, especially for very low TDR values. Consequently, these discrepancies can be attributed to the varying  $NR_{pot}$  values for the two methods. Should the need arise later on, an update based on new measurement data may be accommodated, upon request.

Table 15: Acoustic properties of the installed rail pads: TDR-performance-single value

| Project database         |        |                         | Rail pad properties |                        | TDR-CEN15461         |                   | CEN TR 16891      |                   |                   |
|--------------------------|--------|-------------------------|---------------------|------------------------|----------------------|-------------------|-------------------|-------------------|-------------------|
| Integrated into database | PAD ID | Name of Project Partner | Rail fastener       | Type                   | Name in LNP software | TDR <sub>sv</sub> | NR <sub>pot</sub> | TDR <sub>sv</sub> | NR <sub>pot</sub> |
| No <sup>1</sup>          | 1      | BANENOR                 | Clip                | Optimised              | OPT1                 | -                 | -                 | -                 | -                 |
| No <sup>1</sup>          | 2      | BANENOR                 | Clip                | Reference              | L                    | -                 | -                 | -                 | -                 |
| Yes                      | 3      | SZCZ                    | Tension Clamp       | Optimised              | OPT11                | 1.7               | 0.4               | 3.2               | 0.8               |
| Yes                      | 4      | SZCZ                    | Tension Clamp       | Optimised              | OPT12                | 5.2               | 1.2               | 3.6               | 0.9               |
| Yes                      | 5      | SZCZ                    | Tension Clamp       | Reference              | L                    | -                 | -                 | -                 | -                 |
| Yes                      | 6      | DB                      | Tension Clamp       | Optimised <sup>2</sup> | OPT1                 | 8.5               | 1.9               | 6.1               | 1.5               |
| Yes                      | 7      | DB                      | Tension Clamp       | Reference              | L                    | -                 | -                 | -                 | -                 |
| Yes                      | 8      | DB                      | Tension Clamp       | Reference              | H                    | -                 | -                 | -                 | -                 |
| Yes                      | 9      | INFRABEL                | Clip                | Optimised              | OPT13                | 10.1              | 2.2               | 6.5               | 1.5               |
| Yes                      | 10     | INFRABEL                | Clip                | Optimised              | OPT12                | 7.7               | 1.7               | 4.7               | 1.2               |
| Yes                      | 11     | INFRABEL                | Clip                | Reference              | L                    | -                 | -                 | -                 | -                 |
| Yes                      | 12     | INFRABEL                | Clip                | Optimised              | OPT11                | 9                 | 1.9               | 3.5               | 0.9               |
| Yes                      | 13     | IP                      | Tension Clamp       | Reference              | H                    | -                 | -                 | -                 | -                 |
| Yes                      | 14     | IP                      | Tension Clamp       | Optimised              | OPT1                 | 12.3              | 2.9               | 5.5               | 1.3               |
| No <sup>1</sup>          | 15     | Network Rail            | Tension Clamp       | Reference              | L                    | -                 | -                 | -                 | -                 |
| No <sup>1</sup>          | 16     | Network Rail            | Tension Clamp       | Optimised              | OPT1                 | -                 | -                 | -                 | -                 |
| Yes                      | 17     | ÖBB                     | Tension Clamp       | Reference              | L2                   | 5.9               | 1.3               | 4.8               | 1.2               |
| Yes                      | 18     | ÖBB                     | Tension Clamp       | Reference              | L1                   | -1.4              | -0.6              | 0.3               | 0.1               |
| Yes                      | 19     | ÖBB                     | Tension Clamp       | Optimised              | OPT11                | 6.5               | 1.5               | 2.8               | 0.6               |
| Yes                      | 20     | ÖBB                     | Tension Clamp       | Optimised              | OPT12                | 8                 | 1.8               | 5.7               | 1.3               |
| Yes                      | 21     | ÖBB                     | Tension Clamp       | Optimised              | L3                   | 0.8               | 0.1               | 0.6               | 0.1               |
| Yes                      | 22     | ÖBB                     | Tension Clamp       | Optimised              | L4                   | -0.1              | -0.5              | -0.9              | -0.5              |
| Yes                      | 23     | SBB                     | Tension Clamp       | Reference              | L                    | -                 | -                 | -                 | -                 |
| Yes                      | 24     | SBB                     | Clip                | Reference              | H                    | -                 | -                 | -                 | -                 |
| Yes                      | 25     | SBB                     | Clip                | Optimised              | OPT1                 | 21.5              | 4.8               | 1.9               | 0.4               |
| No <sup>1</sup>          | 26     | SNCF                    | Tension Clamp       | Reference              | L                    | -                 | -                 | -                 | -                 |
| No <sup>1</sup>          | 27     | SNCF                    | Tension Clamp       | Optimised              | OPT1                 | -                 | -                 | -                 | -                 |
| Yes                      | 28     | Trafikverket            | Clip                | Optimised              | OPT1                 | 24.4              | 5.8               | 8.2               | 1.8               |
| Yes                      | 29     | Trafikverket            | Clip                | Reference              | L                    | -                 | -                 | -                 | -                 |
| Yes                      | 30     | RFI                     | Tension Clamp       | Reference              | H                    | -                 | -                 | -                 | -                 |
| No <sup>1</sup>          | 31     | PRORAIL                 | Tension Clamp       | Reference              | H                    | -                 | -                 | -                 | -                 |

Table 16 presents the IL for all of the “optimised” pads examined in the project. It should be noted that the negative values observed for ÖBB are a result of variations in the setups and measurement sites. Therefore, it was not possible to use the same reference for all the rail pads.

Table 16: Measured noise reduction - the insertion loss (IL) for all “optimised” pads in the project

| Project database         |        |                         | Rail pad properties |                        |                      | Measured noise reduction |          |      |      |
|--------------------------|--------|-------------------------|---------------------|------------------------|----------------------|--------------------------|----------|------|------|
| Integrated into database | PAD ID | Name of Project Partner | Rail Fastener       | Type                   | Name in LNP software | Reference Pad            | At speed | min  | max  |
| No <sup>1</sup>          | 1      | BANENOR                 | Clip                | Optimised              | OPTI                 |                          |          |      |      |
| No <sup>1</sup>          | 2      | BANENOR                 | Clip                | Reference              | L                    |                          |          |      |      |
| Yes                      | 3      | SZCZ                    | Tension Clamp       | Optimised              | OPTI1                | L                        | 81-136   | 0.5  | 1    |
| Yes                      | 4      | SZCZ                    | Tension Clamp       | Optimised              | OPTI2                | L                        | 81-136   | 1    | 2.5  |
| Yes                      | 5      | SZCZ                    | Tension Clamp       | Reference              | L                    |                          | 81-136   |      |      |
| Yes                      | 6      | DB                      | Tension Clamp       | Optimised <sup>2</sup> | OPTI                 | L                        | 90-200   | 2    | 4.1  |
| Yes                      | 7      | DB                      | Tension Clamp       | Reference              | L                    |                          | 90-200   |      |      |
| Yes                      | 8      | DB                      | Tension Clamp       | Reference              | H                    |                          | 90-200   |      |      |
| Yes                      | 9      | INFRABEL                | Clip                | Optimised              | OPTI3                | L                        | 90-110   | 2.4  | 5.2  |
| Yes                      | 10     | INFRABEL                | Clip                | Optimised              | OPTI2                | L                        | 90-110   | 2.1  | 4.4  |
| Yes                      | 11     | INFRABEL                | Clip                | Reference              | L                    |                          | 90-110   |      |      |
| Yes                      | 12     | INFRABEL                | Clip                | Optimised              | OPTI1                | L                        | 90-110   | 1.1  | 3.3  |
| Yes                      | 13     | IP                      | Tension Clamp       | Reference              | H                    |                          | 105-220  |      |      |
| Yes                      | 14     | IP                      | Tension Clamp       | Optimised              | OPTI                 | H                        | 105-220  | 1.6  | 2.8  |
| No <sup>1</sup>          | 17     | ÖBB                     | Tension Clamp       | Reference              | L2                   | L1                       | 100      | 1.4  | 3.3  |
| No <sup>1</sup>          | 18     | ÖBB                     | Tension Clamp       | Reference              | L1                   |                          | 100      |      |      |
| Yes                      | 19     | ÖBB                     | Tension Clamp       | Optimised              | OPTI1                | L1                       | 100      | 2.6  | 4.3  |
| Yes                      | 20     | ÖBB                     | Tension Clamp       | Optimised              | OPTI2                | L2                       | 100      | 0.5  | 1.5  |
| Yes                      | 21     | ÖBB                     | Tension Clamp       | Optimised              | L3                   | L2                       | 100      | 1    | 2.1  |
| Yes                      | 22     | ÖBB                     | Tension Clamp       | Optimised              | L4                   | L2                       | 100      | -4.2 | -2.7 |
| Yes                      | 23     | SBB                     | Tension Clamp       | Reference              | L                    |                          | 70-160   |      |      |
| Yes                      | 24     | SBB                     | Tension Clamp       | Reference              | H                    |                          | 70-160   |      |      |
| Yes                      | 25     | SBB                     | Tension Clamp       | Optimised              | OPTI                 | H                        | 70-160   | 1    | 1.9  |
| Yes                      | 28     | Trafikverket            | Clip                | Optimised              | OPTI                 | L                        | 80-120   | 1    | 2.6  |
| Yes                      | 29     | Trafikverket            | Clip                | Reference              | L                    |                          |          |      |      |
| No <sup>1</sup>          | 30     | RFI                     | Tension Clamp       | Reference              | H                    |                          |          |      |      |
| No <sup>1</sup>          | 31     | PRORAIL                 | Tension Clamp       | Reference              | H                    |                          |          |      |      |

## 8.2. OVERVIEW OF THE DEVELOPED METHODOLOGIES AT LOWNOISEPAD

### 8.2.1. $IL_{PB}$ with or without the $IL_{PBc}$ correction factor

The methodology, explained in Chapter 3.1, involves calculating the IL of the rail pads with or without applying the  $IL_{PBc}$  correction factor. The variation in different speeds is limited, thus requiring limited correction factors. The accuracy of the calculation results is highly dependent on the quality of the TDR measurements.

Theoretically, the calculations can be performed using TDR values calculated according to either CEN 15461 [4] or CEN/TR 16891 [6]. However, only CEN/TR 16891 should be used in the software for calculations, since the results obtained with CEN 15461 have a large variation. Observations from the project showed that there are significant differences in the results obtained by applying these two methods.

### 8.2.2. Separating data by iteration at 2 measured sites

This methodology, illustrated in the flow chart shown in Figure 63, is based on available data from pass-by and TDR measurements on two different rail pads. The plotted curve is iterated until the noise emission for at least one pad can be calculated within a 1dB margin. This should allow the vehicle's contribution in terms of pass-by noise levels to be estimated. This can then be used to estimate the total pass-by noise emissions, after simulating a TDR change by using another rail pad. The results obtained are also influenced by the choice of TDR calculation method. The methodology developed in this project is based on the assumption that the vehicle's contribution does not change between two measured sites with different TDRs.

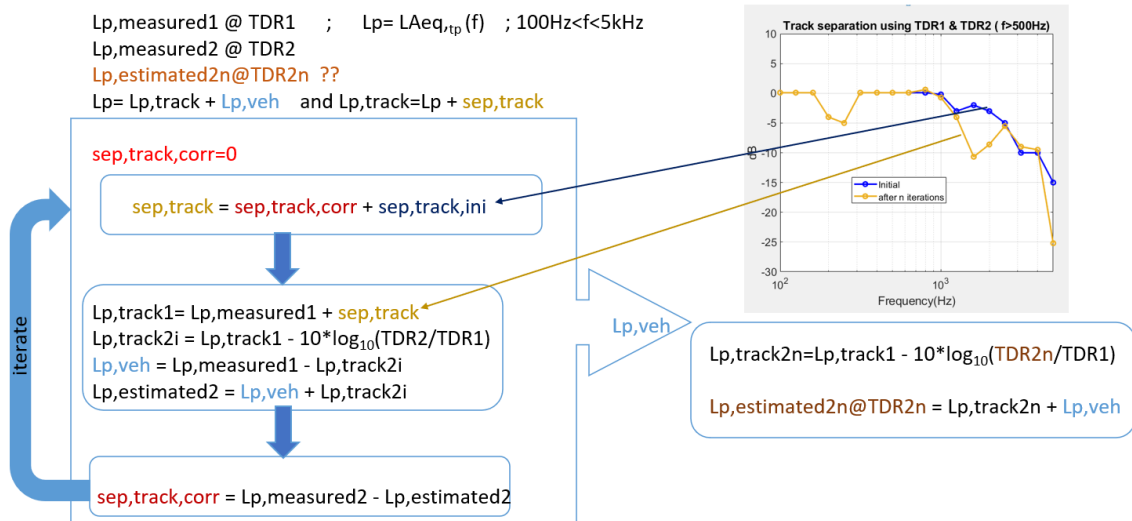


Figure 63: Separating data by iteration at 2 measured sites

### 8.2.3. LOWNOISEPAD software tool

The software tool was developed and fine-tuned during the project to easily view the project results and estimate changes in noise levels when rail pads are replaced using different TDR values. It uses data from the project's measurement database and is packaged in a single executable file (\*.exe). The software is currently in its initial BETA version and has been reviewed based on feedback from the PPs. Based on interest and on future needs, further refinement may be required.

The software tool is compatible with Windows systems, is password protected, and features self-explanatory menus for easy installation and use. The initial version focuses on evaluating rail pad changes and their impact on pass-by noise emissions. The software could then be expanded to view and compare other mitigation measures such as grinding, noise barriers, and track changes (e.g., sleepers, USP). This tool will initially only be available to project members, but UIC aims to work on developing a more user-friendly interface with input from the remaining PPs and to make the software available for UIC members in the coming years based on interest and need.

The software tool serves two main functions:

1. **COMPARE** and visualise measurements (pass-by and TDR). It allows for the comparison of trains and tracks between different countries using an overlay functionality.
2. **CALCULATE** changes in noise emission levels. It enables virtual scenarios, which were tested in another country, to be analysed regarding rail pad replacement, by using the methodologies described in Sections 8.2.2 and 8.2.3. However, caution must be exercised to ensure that these scenarios are carried out for **the same type of rail fastener system**.

Certain considerations should also be taken into account for the calculation method:

1. Poor TDR quality can lead to incorrect results in certain 1/3 octave bands.
2. Calculating extreme differences in rail pad-TDR values is not advised.
3. The database includes data predating optimised rail pad installation for some countries (IP, SBB, ÖBB). This data can be used for comparing and evaluating test sites. Therefore, when calculating averages, care must be taken to avoid averaging train pass-bys with and without optimised rail pads. ÖBB's situation is even more complex, as explained in Section 6.2 ÖBB measurements.
4. The software tool offers two calculation modes:
  - a)  $IL_{PB}$  method (with or without applying the  $IL_{PB_c}$  correction)
  - b) Method of separating the influence of wheels and the track

These methods yield different outcomes, and precision is dependent on TDR quality, as calculations should only be made with TDR values from a loaded track (CEN/TR 16891 [6]), as there are relative calculation differences despite having the same pass-by and TDR measurement data.

A user manual with examples and best practices for making the calculations can be developed based on interest and need. Additionally, **Annex B**, which is a database of images of the rolling stock, is available as a pop-up window to facilitate the recognition and comparison of train types. The following screenshots provide examples of the software tool's functions.

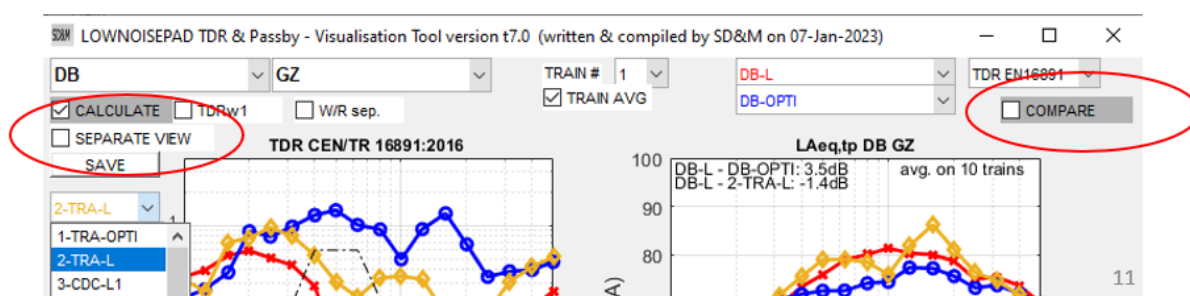


Figure 64: Calculation and comparison mode

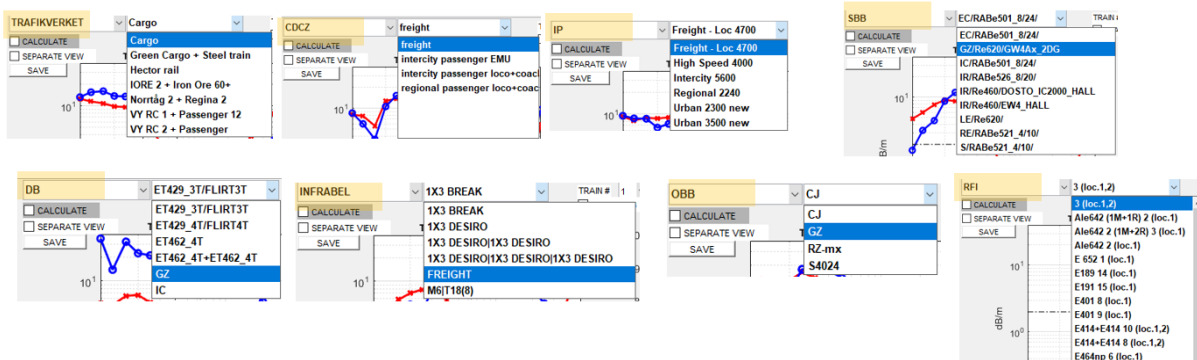


Figure 65: Different types of rolling stock

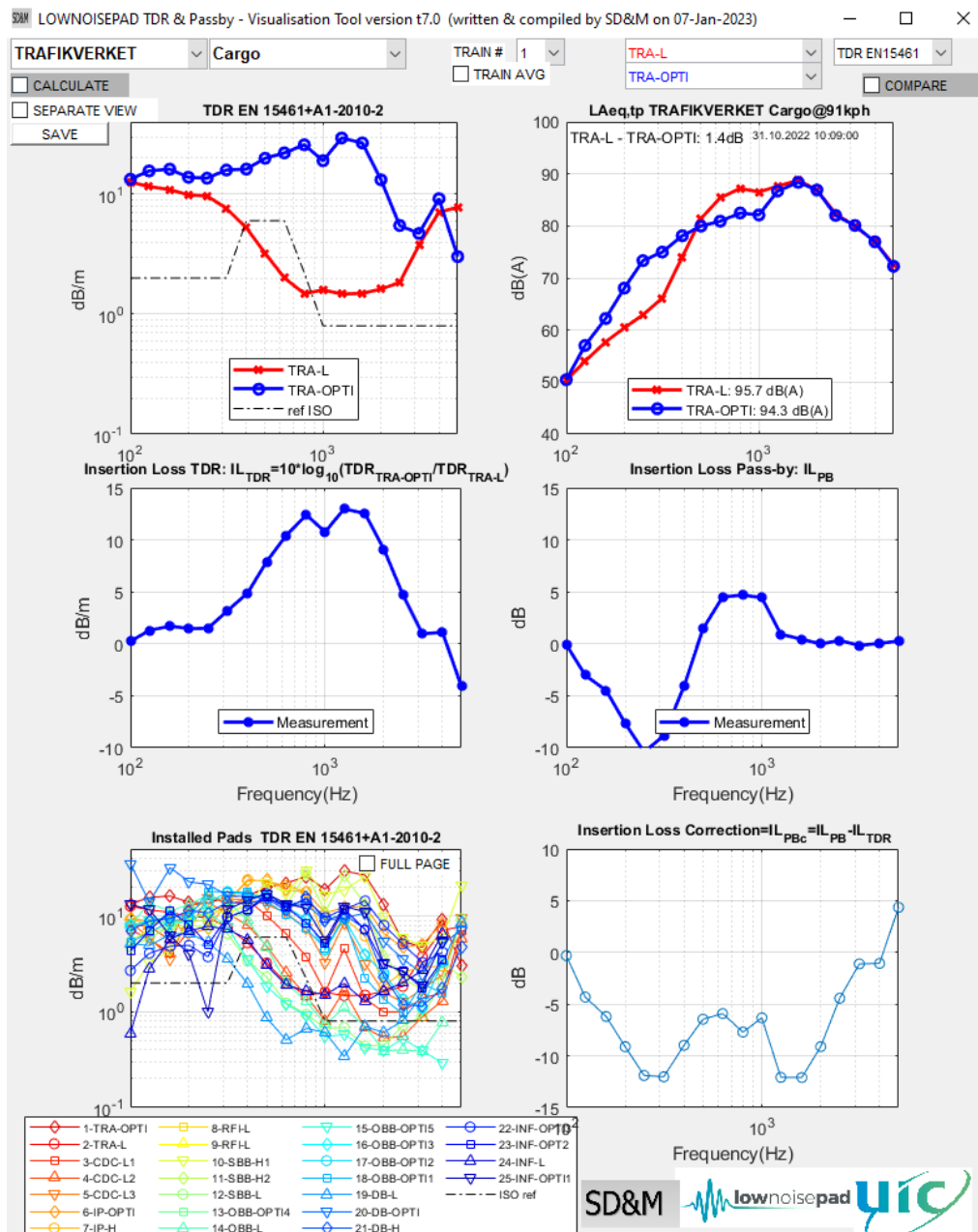


Figure 66: General overview from the software tool (Trafikverket data)

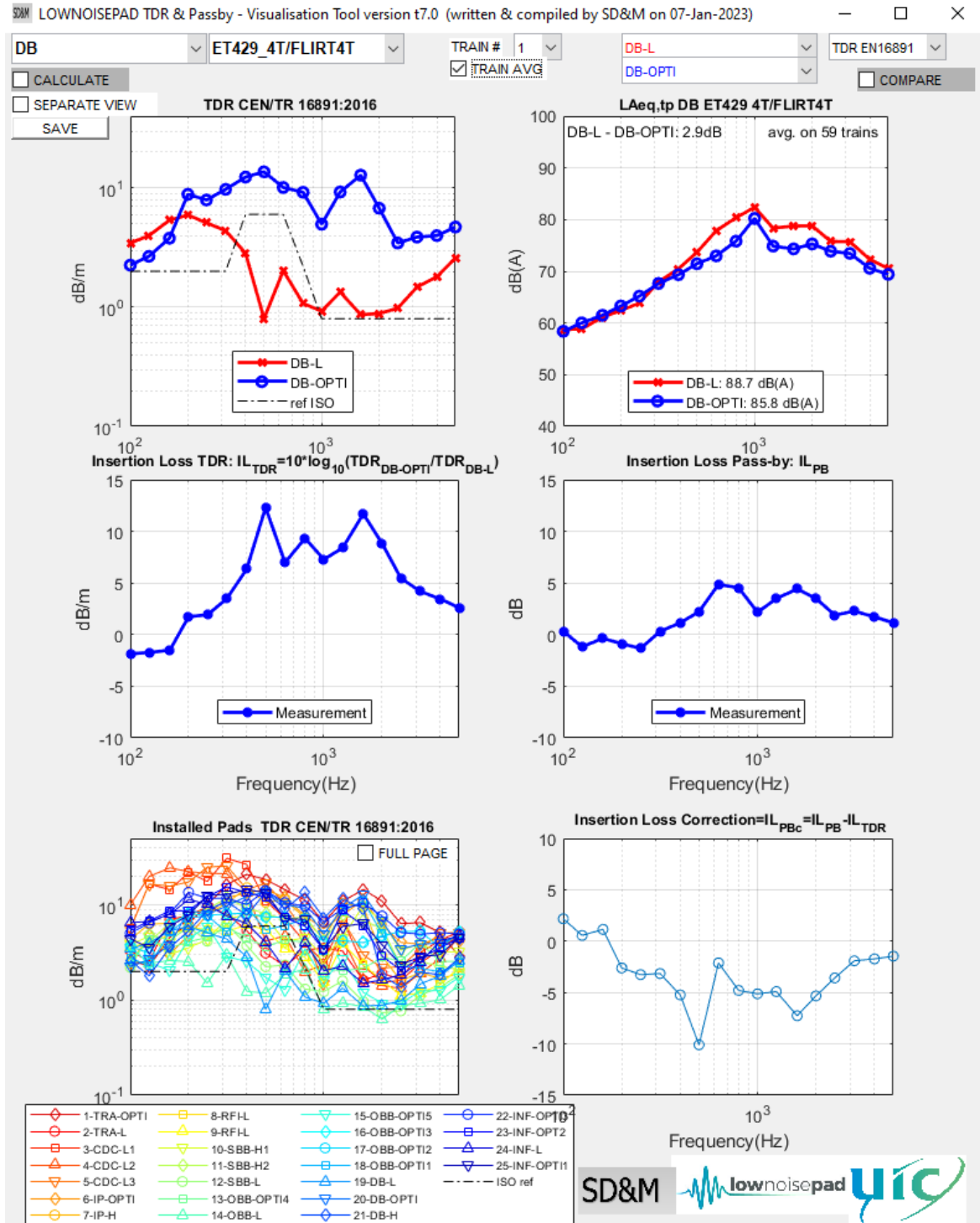


Figure 67: General overview from the software tool (DB data)

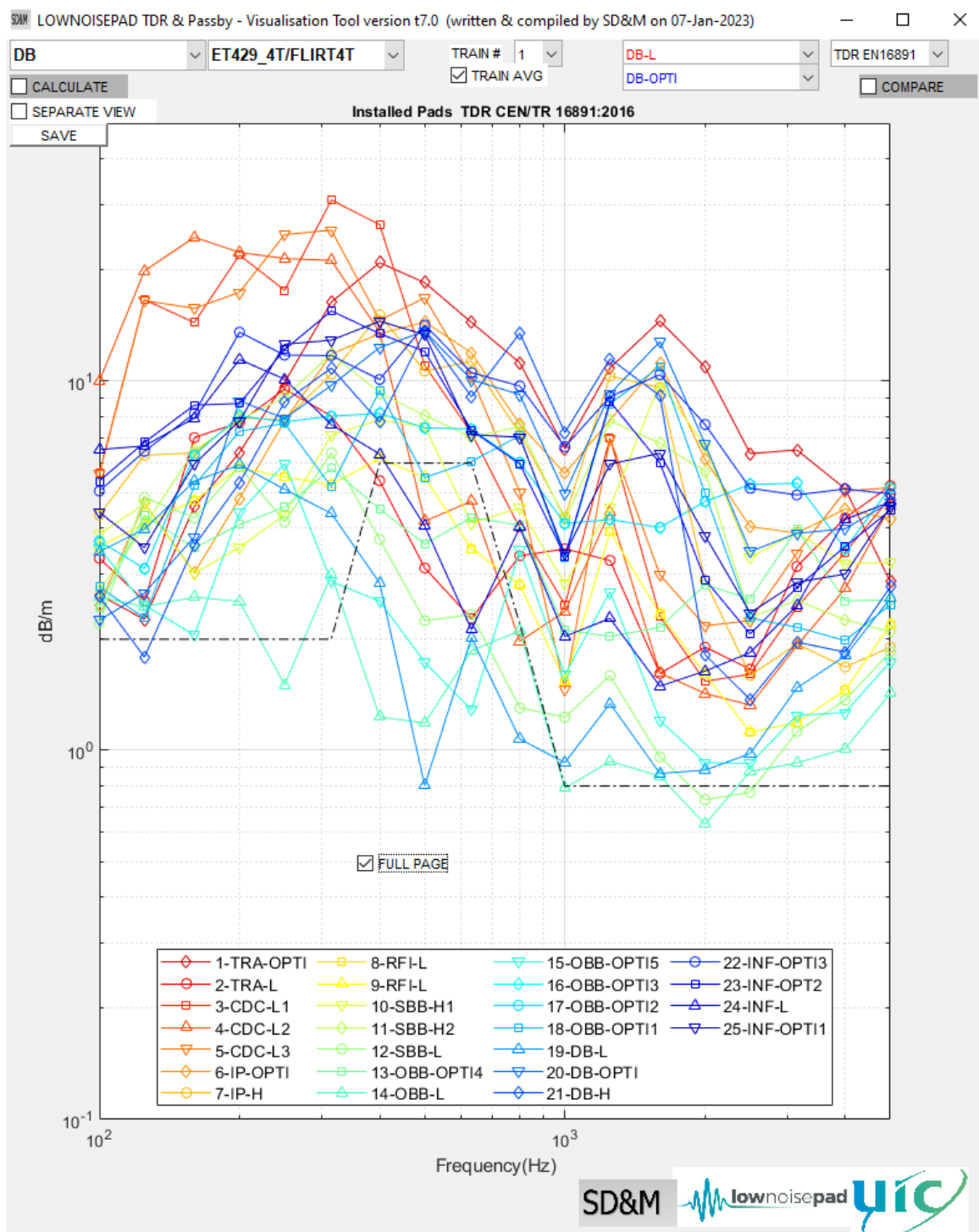


Figure 68: Full page view of all the measured TDR values calculated using the CEN/TR 16891 method

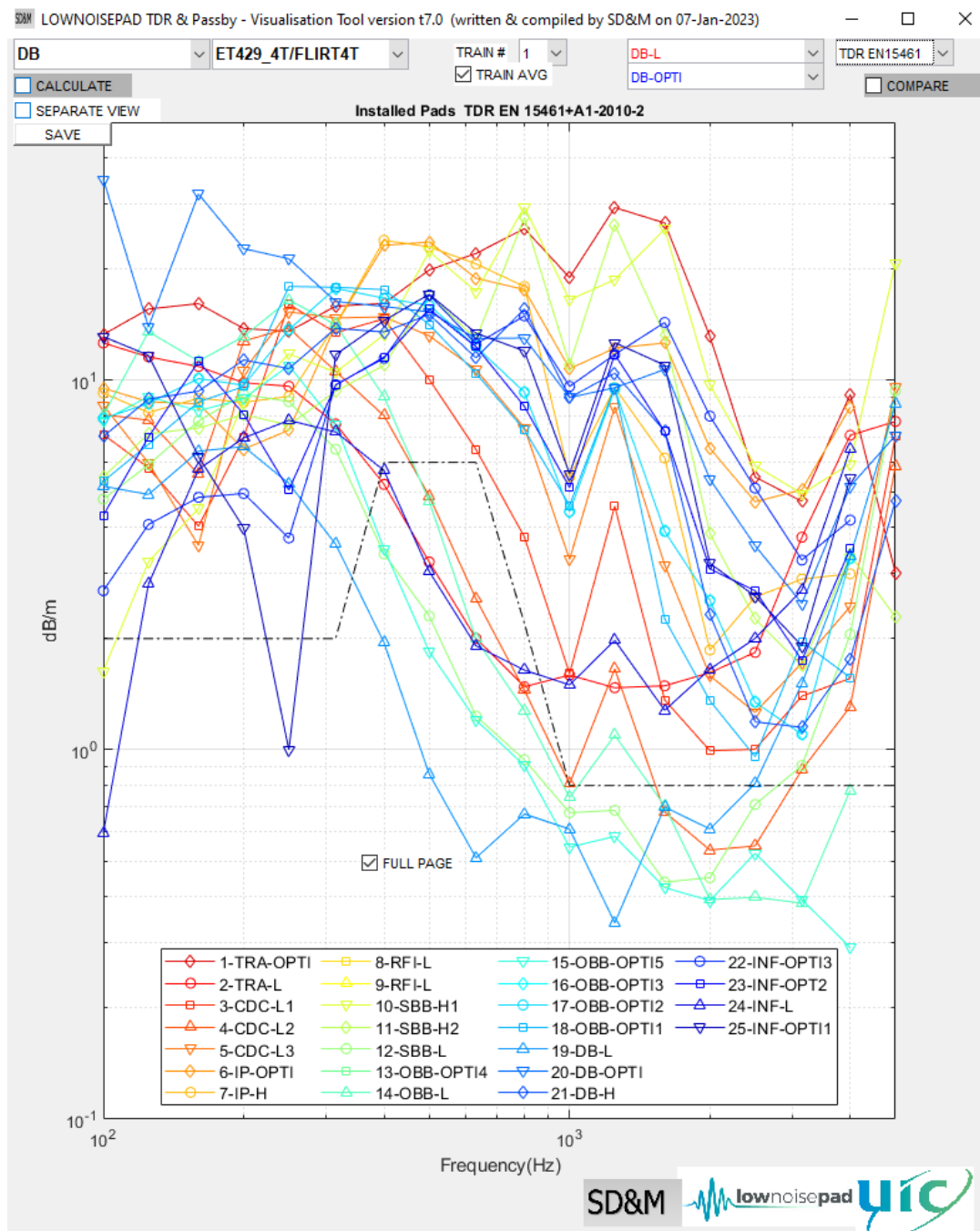


Figure 69: Full page view of all the measured TDR values calculated using the EN 15461 method

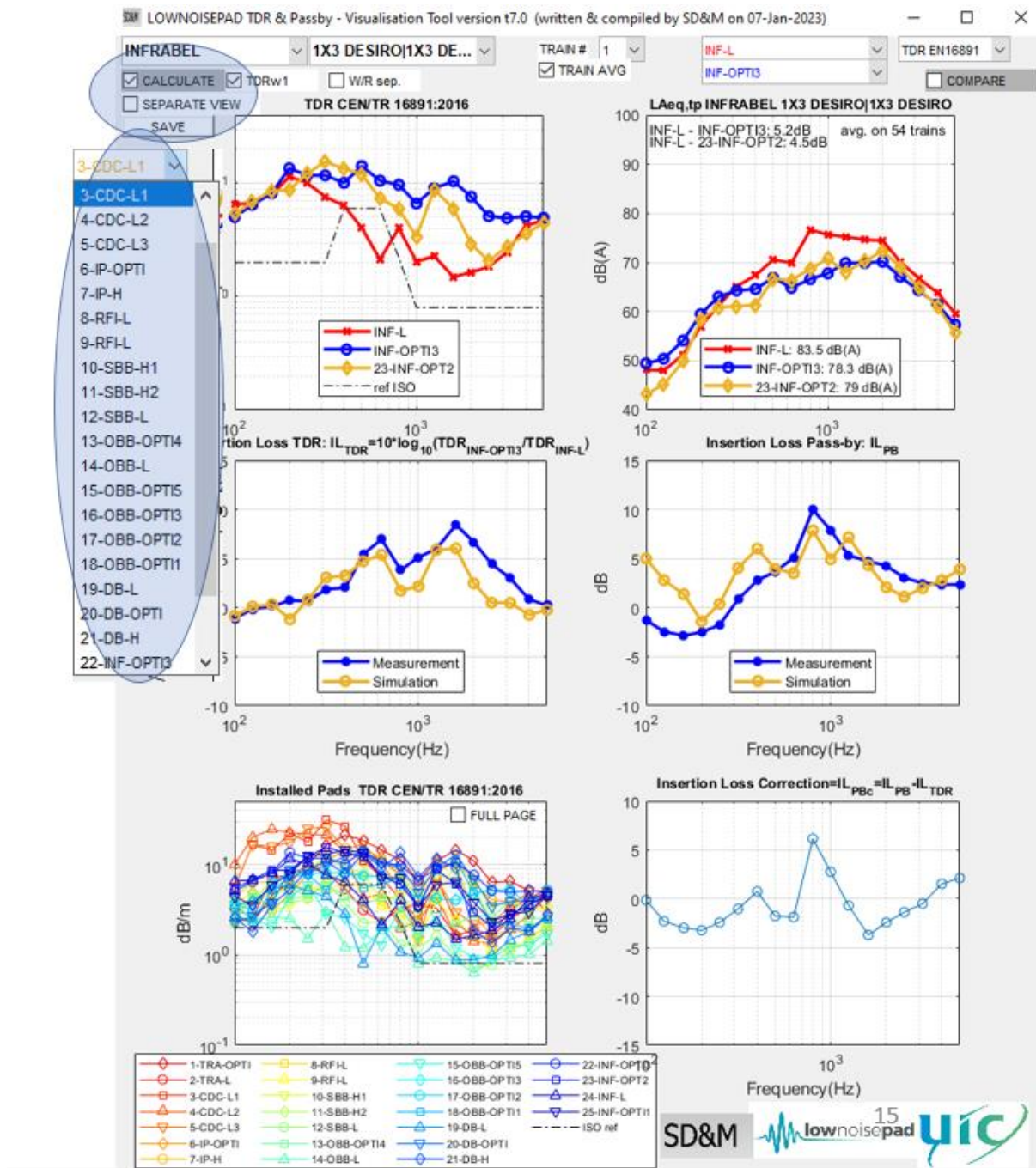


Figure 70: Calculation mode when changing a rail pad

### 8.3. POSSIBLE ON-SITE MEASURED NOISE REDUCTION AND INSERTION LOSS

Noise reduction and insertion loss has already been detailed in Section 6.2 for each PP that delivered the raw measurement data. The influence of various factors on noise reduction and insertion loss is discussed below:

#### 8.3.1. Influence of rolling stock (type, brake-blocks/wheel roughness)

The effect of changing the rail pad/TDR, and therefore the contribution of the rail to noise level, is influenced by the acoustic properties of the train components. Factors such as wheel roughness and high-frequency traction noise (noticed for several DB–ET429 and SBB trains), and the contribution of sparks on the catenary line in below zero-degree environments (noticed at Trafikverket) can impact the results. The software tool is useful for analysing these effects and showing the measured insertion loss curve. Table 14, Table 15 and Table 16 provide an overview of the minimum and maximum noise reductions calculated on average for similar trains, with the exception of ÖBB and SBB. Some of the negative values for ÖBB are due to the different references used, as measurements were conducted across three campaigns with different sets of sites, although one site was kept as the reference site throughout the measurements. The reference pads at ÖBB (a standard ÖBB rail pad) already had high TDR values.

Figure 39 shows an example for the INFRABEL passenger trains. INFRABEL's BREAK trains with cast iron brake blocks have noise emission levels 15dB higher than the DESIRO trains with disc brakes. As a result, the noise reductions for similar train types were observed to be approximately 4dB.

#### 8.3.2. Influence of temperature

The dynamic properties and TDR amplitudes for rail pads change with temperature. In Sweden, Trafikverket took measurements at negative temperatures, which had a different effect on both the reference and optimised pads. Lower temperatures result in higher TDR values, and vice versa, which can impact the measured IL. Consequently, this may be lower than expected when compared to other countries as the softer rail pad may have stiffened more than the optimised one. Trafikverket decided to repeat the measurements in summer to provide a clearer conclusion regarding the influence of temperature on the installed rail pads. Measurements have been taken, but not yet analysed and detailed information will be shared in the final updated report (to be published in 2024).

#### 8.3.3. Influence of combined wheel/rail roughness

Drawing a definitive conclusion on this is challenging but comparing the noise IL at INFRABEL for passenger trains with low wheel roughness (disc brakes) and high wheel roughness (cast iron brake blocks) shows similar insertion loss (Figure 40).

#### 8.3.4. Noise reduction for soft rail pads used as the reference pad

Soft rail pads have low TDR values, resulting in higher pass-by noise. Optimised rail pads, designed for higher TDR, consistently demonstrate positive IL and lower pass-by noise. Detailed illustrations of this can be found in Section 6.2. Therefore, the A-weighted noise reduction achieved, using soft rail pads as the reference pad, ranged from 1.5 to 4.5dB.

### 8.3.5. Noise reduction for stiff (EVA) pads used as the reference pad

Stiff EVA rail pads already have high TDR values. Some optimised pads were specifically designed to have a higher TDR than the EVA, especially for frequencies above 1kHz. These optimised pads provide additional damping to the overall system. At three test sites (IP, SBB, and DB), stiff EVA rail pads were used as the reference pad, although, even in these cases, no noise increase was observed after the optimised rail pads were installed. Analysis of the TDR differences gives clear reasons for this. In Germany, DB has already installed EVA rail pads but has not used the measurements for comparison. This will be addressed in the LOWNOISEPAD report to be published in 2024. Figure 71 shows the TDR of the optimised rail pad in blue and the TDR for the stiff EVA rail pad in red. The noise reduction for IP is in the range of 1.6 to 2.8 dB and for SBB in the range of 1 to 1.9 dB.

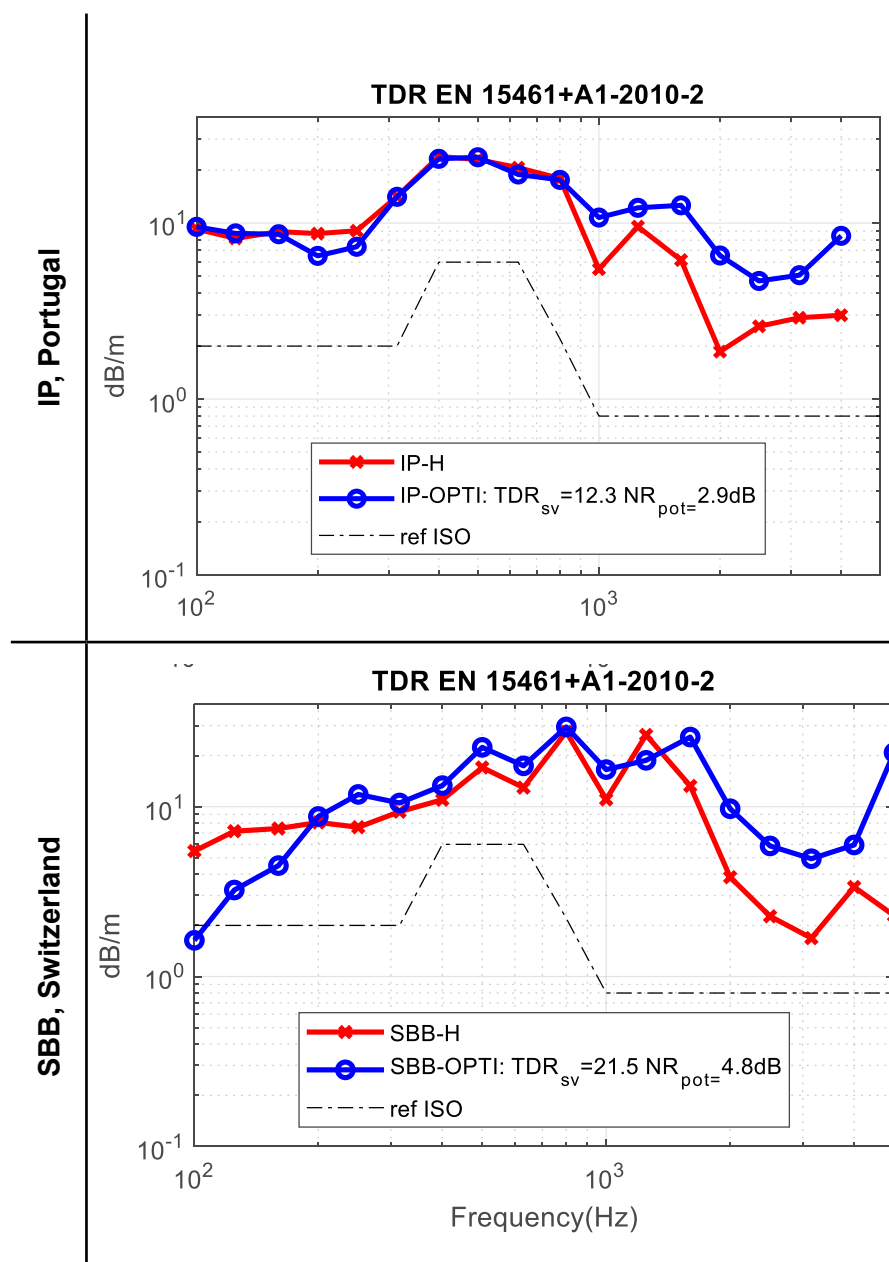


Figure 71: Measured TDR according to EN15461 for stiff and optimised rail pads at IP and SBB, clearly showing that “soft” optimised pads can have higher TDR than stiff EVA pads

## 8.4. SHOWING NOISE REDUCTION: TECHNICAL AND ACOUSTIC CONCLUSIONS

The noise reduction attained can be represented in various ways. The following figures show different methods of presenting the technical results, specifically the potential noise reduction. The value of this project lies in the fact that these results were obtained through on-site measurements conducted by the various PPs, rather than being calculated through models like TWINS. Figure 72 shows an overview of the minimum and maximum noise reduction achieved by comparing the optimised rail pads with the standard rail pads. These values represent the range of noise reduction outcomes obtained by comparing the optimised and standard rail pads used for each company. As a result, maximum noise reductions of up to 5dB for INFRABEL DESIRO trains using a soft rail pad for reference were observed.

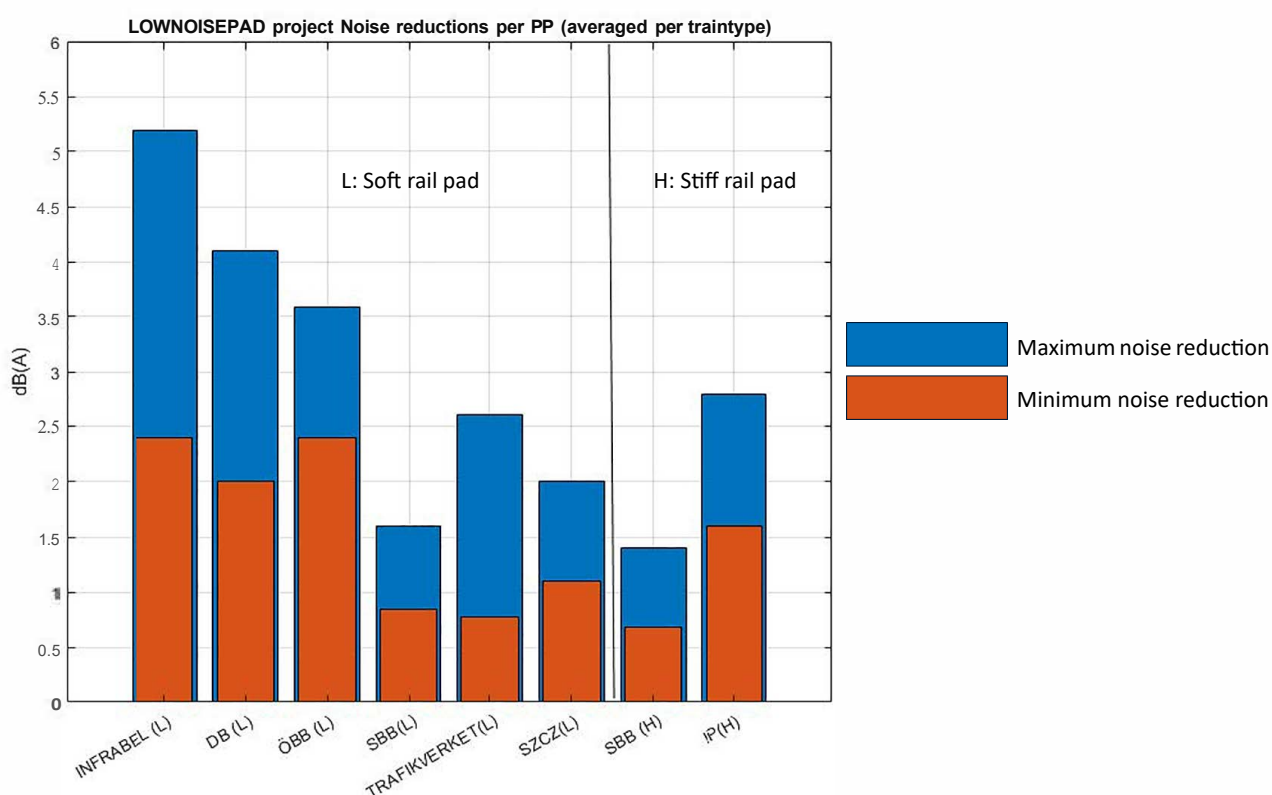


Figure 72: Overview of the achieved minimum and maximum noise reduction by comparing the optimised rail pads with the standard rail pads  
(L): soft rail pad, (H) stiff rail pads

It should also be noted that the minimum and maximum noise reduction values can vary across different train types and speeds, with more detailed information being given in the Figure 73, and the results are presented per PP for different standard rail pads. The results for passenger trains are shown in blue in the top figure and for freight trains in red in the bottom figure, with the results for the different reference pads being separated and given in the areas shown by L and H. In summary, it is difficult to draw a general conclusion in terms of speeds within this project, as each PP took measurements based on their own operating speeds on their own test sections.

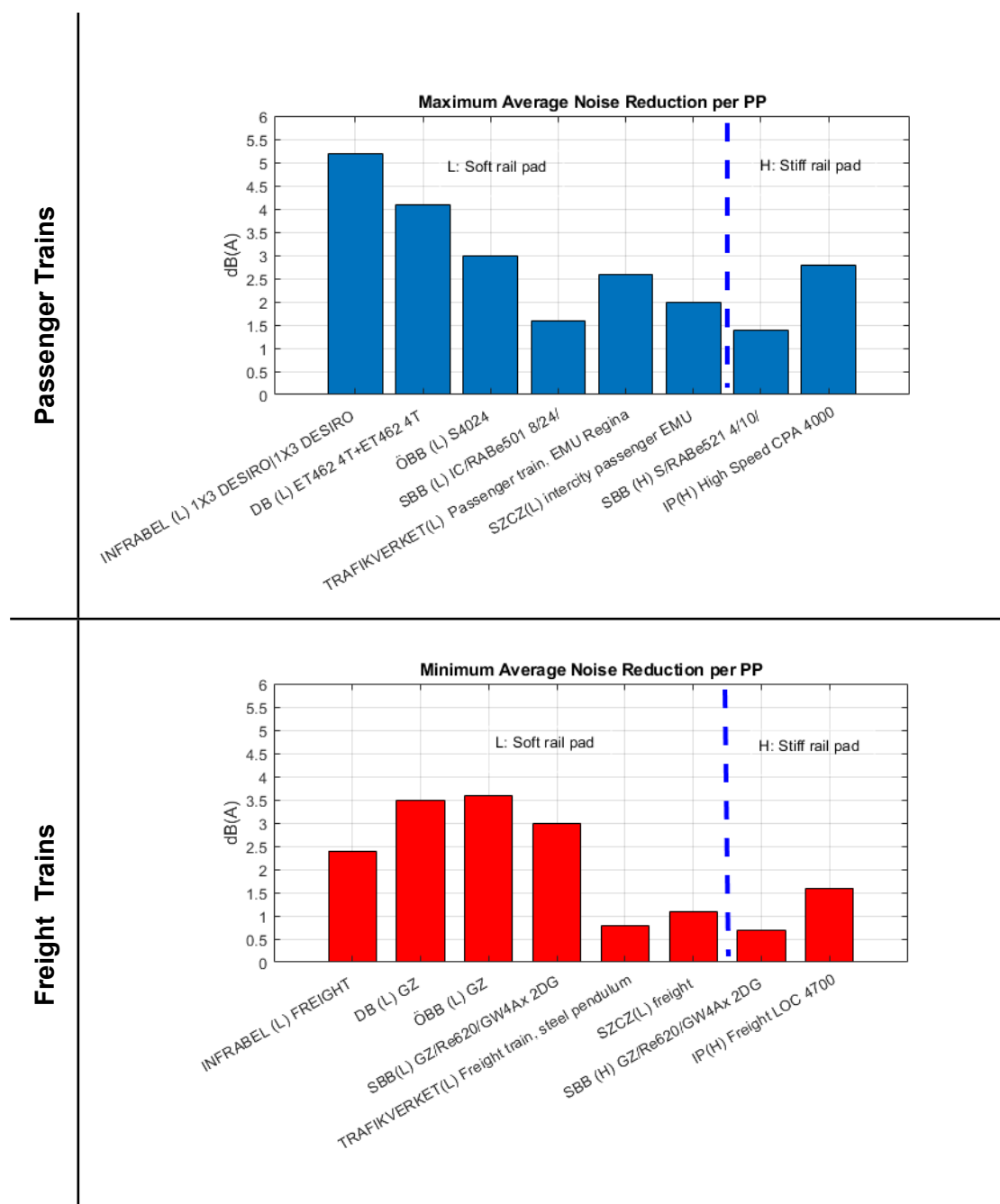


Figure 73: Details for specific train types of the achieved minimum and maximum noise reduction by comparing the optimised rail pads with the standard rail pads

Figure 74, Figure 75 and Figure 76 show the noise reduction per train type, taking the variations in rail pads, train types, and operating speeds in each country into account. These figures provide a detailed comparison of the noise reduction attained for different train types across multiple countries. The effectiveness of the optimised rail pads in reducing noise levels is significantly influenced by the choice of reference pad, as reference pads and speeds are known to differ from country to country. Therefore, the figures present the general outcomes of the LOWNOISEPAD project, and detailed analysis can be carried out for each country using the software tool.

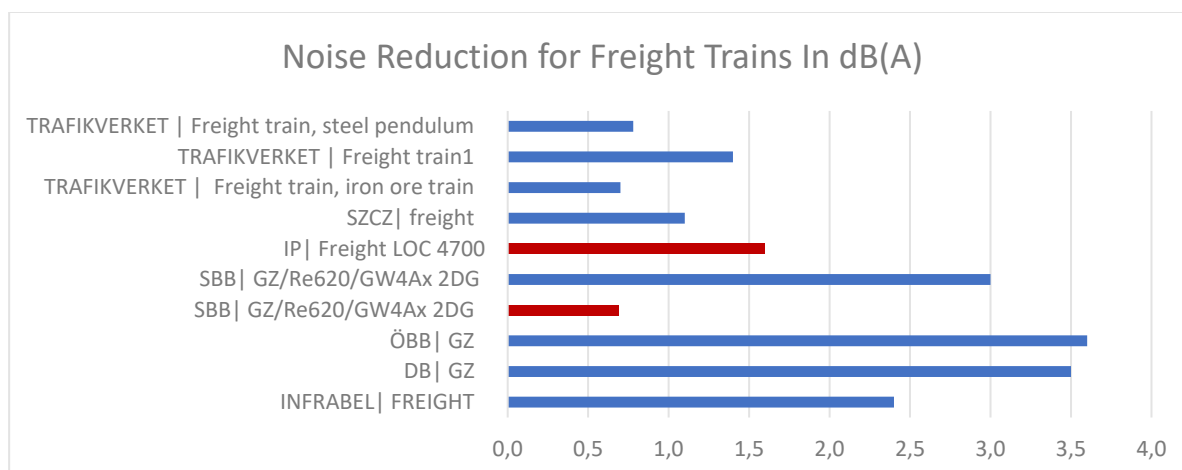


Figure 74: Averaged noise reductions for freight trains per PP - different reference rail pads and speeds  
L: soft rail pad - blue; H: stiff rail pads - red

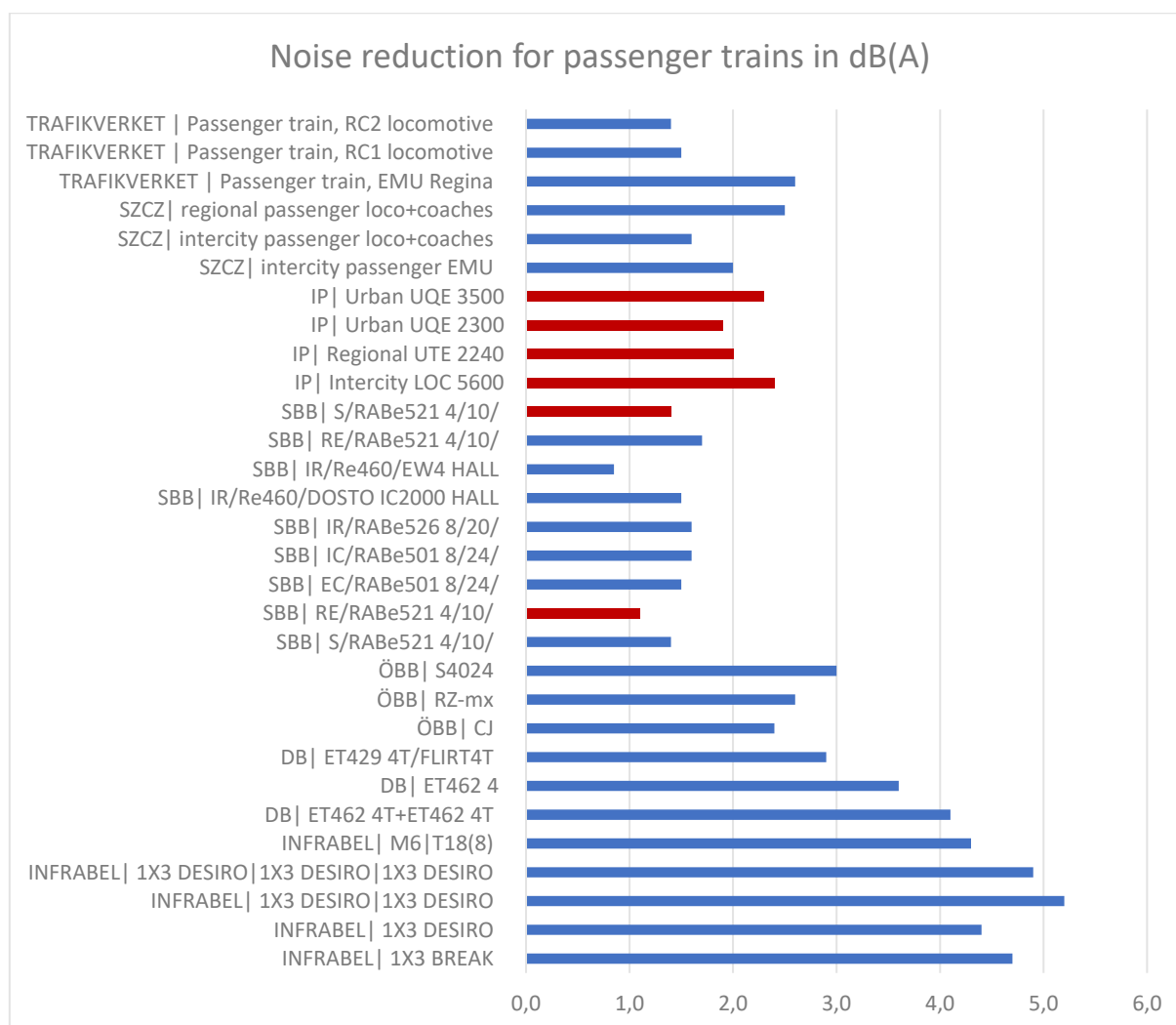


Figure 75: Averaged noise reductions for passenger trains per PP - different reference rail pads and speeds  
L: soft rail pad - blue; H: stiff rail pads - red

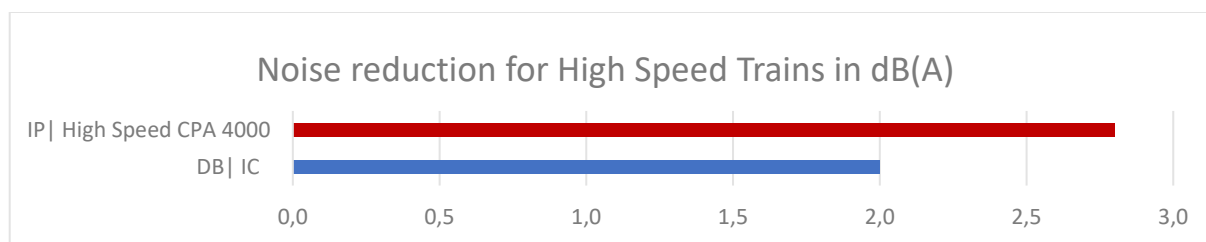


Figure 76: Averaged noise reductions for high(er) speed trains (> 185km/h) per PP - different reference rail pads and speeds; L: soft rail pad - blue; H: stiff rail pads – red

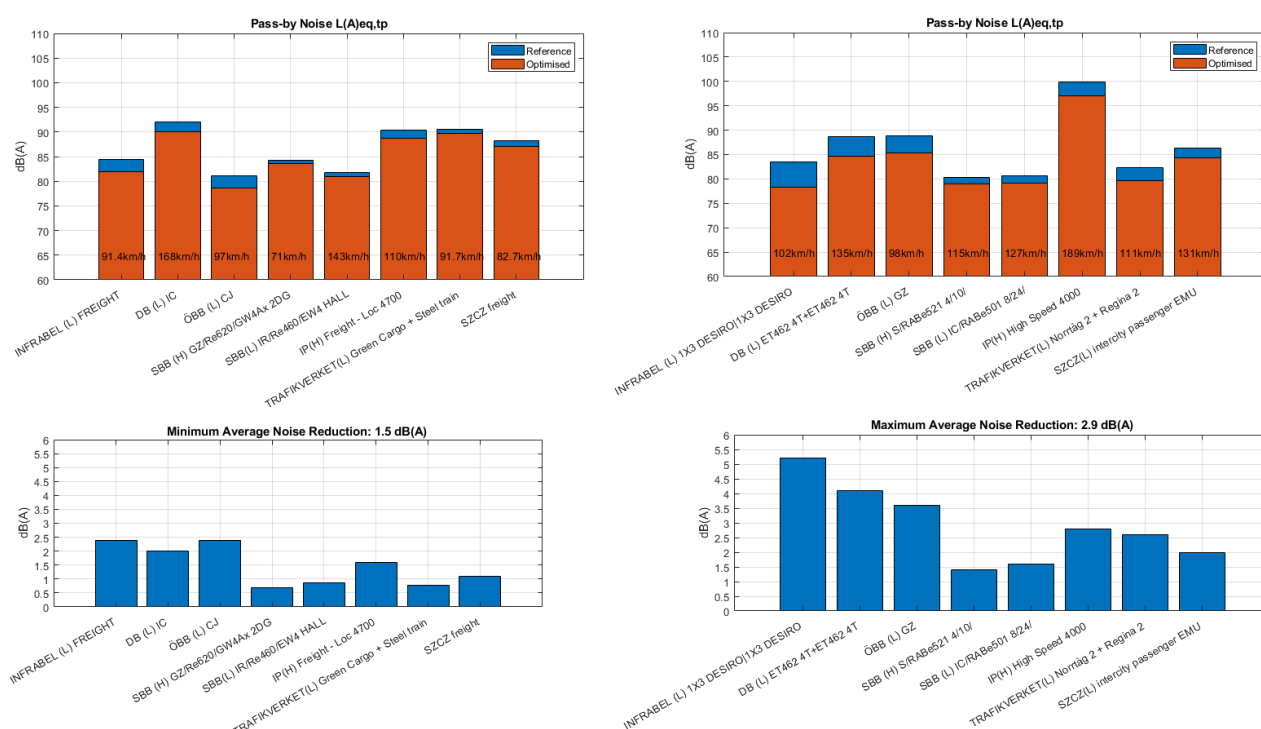


Figure 77: Details regarding minimum and maximum noise reduction for specific train types, by comparing the optimised rail pads with the standard rail pads, including their individual noise emission levels

Figure 78, below, provides an approximate indication of  $NR_{pot}$ , which is calculated using a very soft rail pad as the reference pad, as a function of static rail pad stiffness.  $NR_{pot}$  gives an underestimation of about 1dB compared to the actual measured noise reduction. The potential for noise level reduction previously identified and shown in Table 15 appears to be 1dB lower than the actual measured noise reduction within the project. This confirms the accuracy of the methodology applied and shows that there was no “overestimation”. It is important to exercise caution when interpreting this data, as it represents a mixture of different rail pads, fastening systems, train types, and operating speeds. Therefore, the information presented in the figure only demonstrates a rough estimation. Considering the above issues, the curve may need to be adjusted, particularly for low stiffness values. Moving further up the curve to account for all stiffness levels (i.e. the higher the curve the better, which means higher noise reduction for the same stiffness) poses a challenge for future designs and the production of new rail pads.

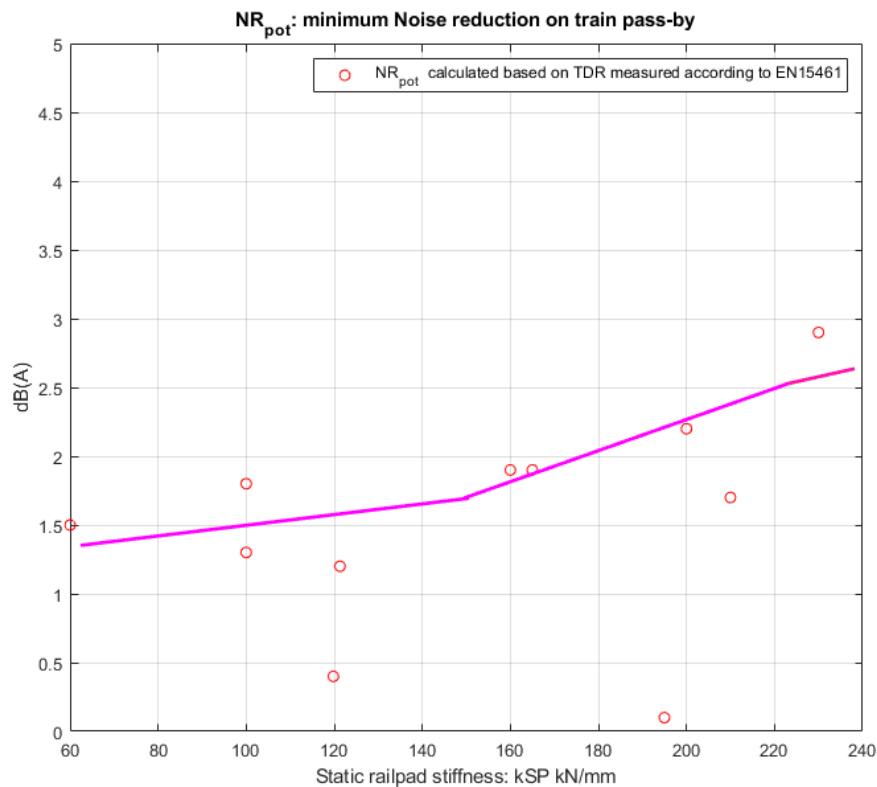
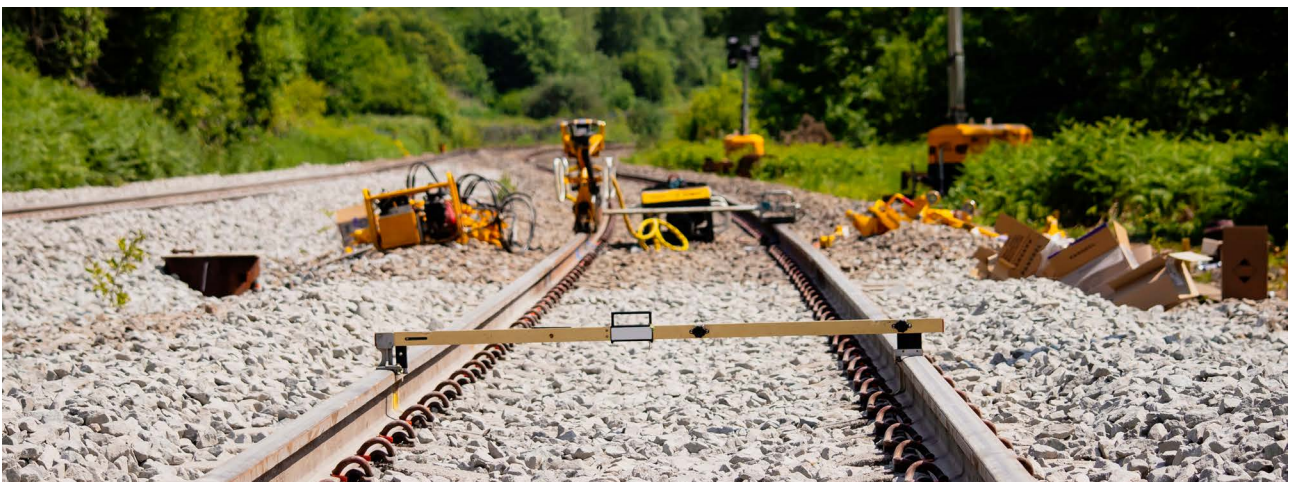


*Figure 78: Minimum potential noise reduction as a function of static rail pad stiffness kSP*

Furthermore, after verifying the available data, a decision was made not to include higher kSP values in Figure 78, as most PPs would avoid using extremely stiff rail pads as a solution for noise reduction and so the decision was made to only focus on optimised rail pads. Furthermore, it was also decided that insufficient data could be misleading. The conclusion drawn were that the best solution for noise reduction would be to select the softest rail pad possible in a given scenario and further recommendations are given in Chapter 8.5.5.



## 8.5. RECOMMENDATIONS

### 8.5.1. Additional dynamic property measurements for all of the rail pads in the project

Taking additional measurements of the acoustic stiffness of all the rail pads tested for LOWNOISEPAD, according to EN 17495:2022 [12], will provide a more comprehensive understanding of the dynamic properties of the rail pads. Furthermore, the influence of pads optimised for acoustic purposes on other relevant parameters, such as impact attenuation performance according to EN13146-3, should be investigated. These parameters have implications for sleeper design criteria and track maintenance. Evaluating the LCC of ballast is also another factor which should be taken into consideration. IM should continue to apply and disseminate the knowledge gained from this project to prepare and implement noise mitigation measures in operation.

### 8.5.2. Further testing for optimised rail pads

The optimised rail pads should continue to be studied, tested, and compared for the following reasons:



#### **Building a broader knowledge base for decision making**

Further research will provide a more comprehensive understanding of the performance of various rail pads, enabling better-informed decisions to be made regarding rail pad replacements in the future.



#### **Acoustic properties**

Conducting tests, according to the EN 17495 standards [12] (as explained in IRS 75717 [2]), will allow for a comprehensive assessment of the acoustic properties of different rail pads, leading to improved noise reduction strategies.



#### **Substructure Protection**

Exploring the impact of rail pad damping properties, in accordance with EN 13146-3 [13], will provide insight into their effectiveness in protecting the substructure, helping to enhance the overall durability and longevity of the track system. One goal should be to quantify the life cycle cost (LCC).



#### **Software Tool Enhancement**

Including new measurements from other project partners (BaneNor, SNCF, ProRail and Network Rail) and conducting extra tests at different sites and at different temperatures (Trafikverket) will contribute to the refinement and enhancement of the software tool used in the project.

The IM should actively consider integrating optimised intermediate layers (such as rail pads) into existing rail systems where possible. This approach not only enhances decision-making but also contributes proactively to reducing noise disturbances. Additionally, it is recommended that a new project focusing on the impact of rail pad stiffness on LCC and track maintenance be launched. Collaboration with the UIC Interfaces and Interaction between Infrastructure Subsystem and Rolling Stock (TTI) Network and the UIC Track Expert Group (TEG) would be beneficial, in order to this research, alongside acoustics engineers. Engaging different stakeholders to participate in long-term studies on these effects is challenging. However, expanding collaboration and involving additional experts will provide more comprehensive insight into the long-term effects of rail pad stiffness on LCC and track maintenance. This will enhance decision-making processes and contribute to the overall improvement of rail infrastructure.

### 8.5.3. Further testing to supplement existing data

Some PPs have already planned to take additional measurements, as within this project, pass-bys for the same track and rolling stock at different speeds were not systematically measured, due to the operational services requiring different speeds. In the meantime, results from the INFRABEL RRP project, where trains operated at different speed on the test sections, demonstrate the dependency of speed for different types of rolling stock (Figure 79). It is recommended to plan and coordinate with railway operators and other relevant stakeholders to conduct further testing with actual rail pads under different conditions, including using various sites, rolling stock, temperatures, and speeds. This will enhance the understanding of the performance of the rail pads in real-world scenarios and enable the project outcomes to be exploited to minimise railway noise impacts.

### 8.5.4. Further testing with the existing rail pads on the same or new sites

To gather a more comprehensive dataset for making informed decisions regarding rail pad changes as a noise mitigation measure, it is recommended that the tests be repeated and continued on a per-project basis, at additional test sites. The parameters such as speed, rolling stock types, and temperatures, should also be varied, as mentioned above. The LOWNOISEPAD software tool has the flexibility to easily incorporate additional data through a four-step procedure:



**Import new raw data**



**Calculate spectral information**



**Perform quality control checks (both visual and audio)**



**Add the data to the database**



**Processing the new TDR measurements**

The next phase aims to expand the project database by including data from 4 members (BaneNor, Network Rail, ProRail and SNCF), which have not been analysed by September 2023. It is also expected that some of the members participating in the project will undertake similar initiatives for comparative evaluation in the future (e.g. Trafikverket to validate the impact of temperature). However, there is also the possibility that some IM, considering the positive conclusions of this project, might try similar initiatives. Therefore, this collaborative strategy will not only improve the dataset, but will also play an important role in advancing engineering practices that promote effective noise mitigation strategies on railway systems.

### 8.5.5. Next steps for optimising rail pads

Rail pad manufacturers are encouraged to further optimise rail pads, in order to achieve increased softness in a given scenario, targeting kSP values of 100kN/mm or less, while preserving track elasticity and ensuring high TDR values. PPs have taken a collaborative and future-oriented approach by developing rail pads with the required softness values in a given scenario to reduce noise. Based on the knowledge gained during the project, it is also important that IM are able to obtain both financial and organisational support for the implementation of optimised pads to contribute to effective noise mitigation.

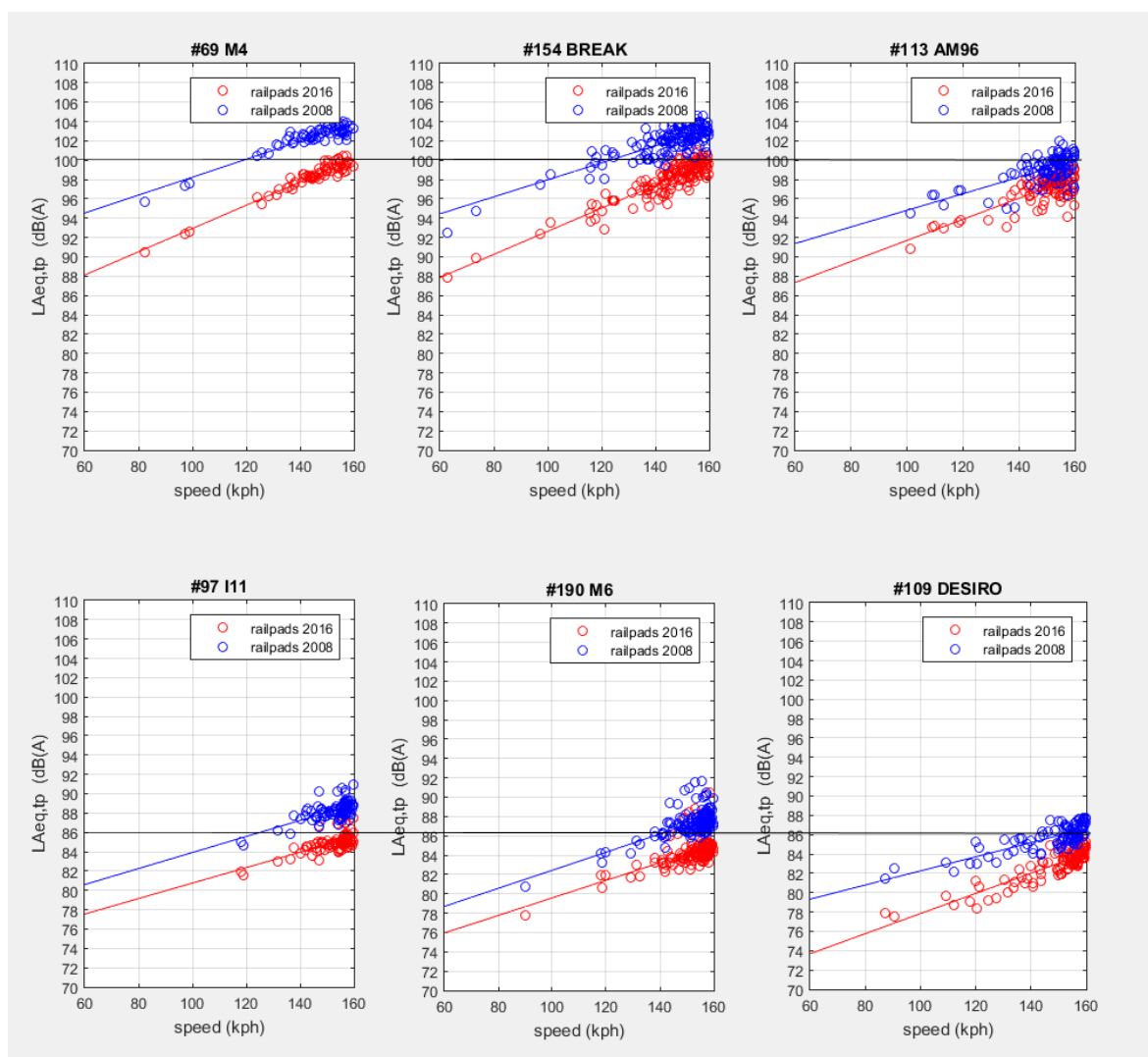


Figure 79: The dependency of speed for different types of rolling stock (data from the INFRABEL RRP project)



## 9. CONCLUSIONS

### *A much quieter railway: tangible noise reduction*

The project's technical findings confirm that substantial noise reduction was achieved through the installation of optimised rail pads when both soft and stiff (EVA) pads were used as the reference pad. The project demonstrated that optimised pads could lower overall noise levels by 1-2dB when compared to stiff pads and 3-5dB when compared to soft pads. Given these promising results, it is advisable to consider further investigation on the retention of “soft” qualities usually associated with better track protection. Further studies on rail pads could examine these issues in more detail. These results were made possible through the skilled use of various noise monitoring techniques, including harmonised methodologies. On-site measurements, meticulously taken by 10 project partners, provided tangible evidence of the project's success in reducing noise emission levels during train pass-bys. The noise reduction measured serves as a testament to the effectiveness of rail pad optimisation as a practical and efficient measure to mitigate noise generation in railway operations. Outcomes derived from the LOWNOISEPAD software tool, complemented by the inputted figures, serve to reinforce the fundamental importance of implementing optimised rail pads and contribute to a comprehensive understanding of their impact on noise reduction.

### *A case study in collaboration between railways to promote innovation*

The LOWNOISEPAD project serves as a remarkable example of combining innovation and networking to optimise an essential track component, the rail pad, with minimal costs involved. Through extensive networking efforts involving numerous meetings with project partners and technical experts, the project successfully fostered collaboration among acoustical and track engineers at national and international levels. This collaboration not only addressed the common challenge to reduce noise production, but also provided an opportunity for knowledge sharing and networking on broader railway issues.

The pragmatic approach and robust support for the project allowed 12 EU railway IM to install optimised rail pads and conduct on-site measurements under actual operating conditions. The customisation of the rail pad optimisation process based on individual partner requirements, including input from track engineers, contributed to a collaborative and effective approach throughout the project's implementation. Furthermore, the project's standardised procedures for installing, measuring, and data processing have been converted into harmonised guidelines (IRS 75717), providing a common understanding and methodology for measuring and comparing noise emissions during train pass-bys. These guidelines are now accessible to all sector stakeholders, allowing them to measure changes in noise levels by replacing a single-track component, such as a rail pad. The installation of optimised rail pads substantially reduced noise levels in comparison to both soft and stiff (EVA) pads, offering a viable solution for track engineers whose IM is seeking to mitigate railway noise and to contribute to being a better neighbour. In summary, the acoustically optimised rail pad design provided a reliable solution for noise mitigation.

### *Driving change: optimising the track in terms of noise, vibrations and LCC*

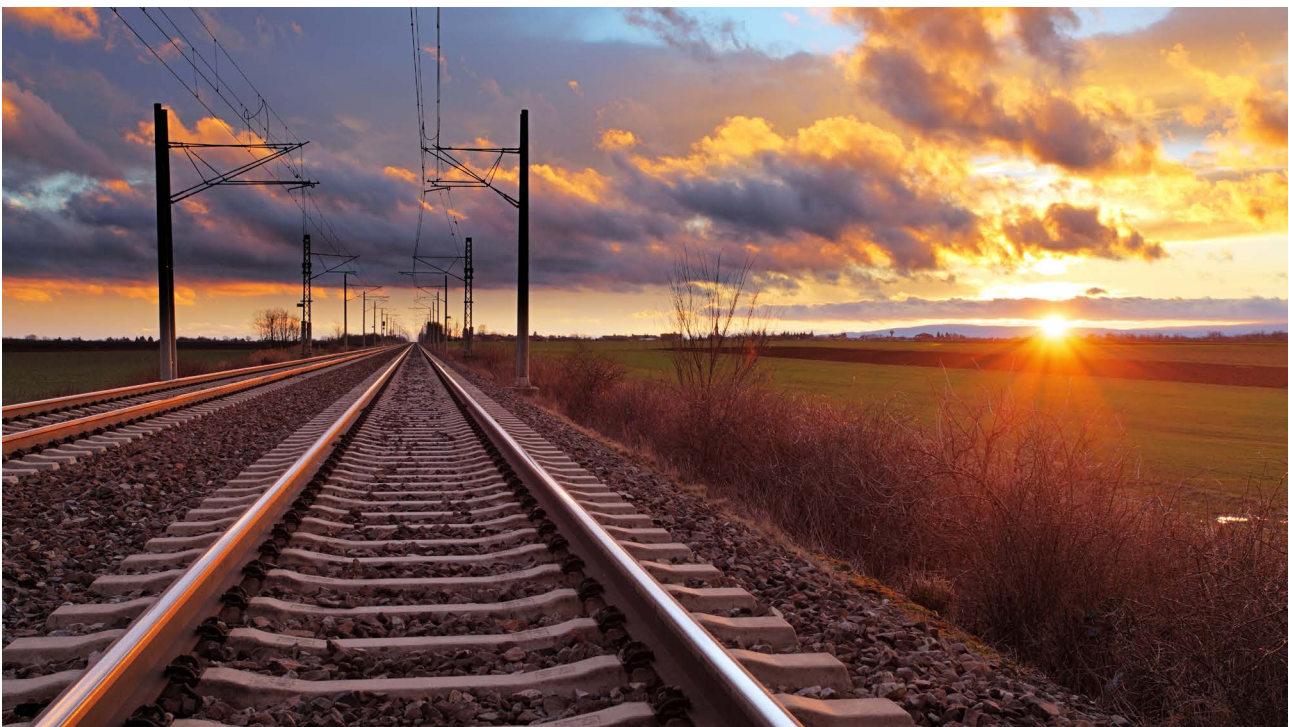
Addressing transport noise, including railway noise, is crucial for the health and well-being of communities along the railway network. By implementing effective noise mitigation measures, we can create quieter and more liveable environments, contributing to a sustainable transport system and promoting social cohesion. Collaboration between track and acoustical engineers is key to developing tailored solutions that effectively reduce railway noise while also considering the technical and practical constraints. Most importantly, ways must be found to quantify the effect of changes to track components on their LCC.

The aim should be to create a track system that is optimised in terms of noise, vibrations and LCCs. To support these efforts, national and international organisations need to play a pivotal role in supporting these collaborative efforts. Incentives should be created for IM to invest in both monitoring programmes and mitigation measures, so that they are better equipped to move forward in their efforts to be a quieter and better neighbour. Long-term monitoring programmes can assess the effectiveness of noise reduction measures as well as LCC, driving continuous improvement and further research in the field of railway noise reduction.

### *Forging ahead: advancing innovation and collaboration*

The LOWNOISEPAD project is a catalyst for future innovation and collaboration in railway noise reduction. Ongoing collaboration among research institutions, railway IM, and stakeholders is crucial for driving innovation, sharing knowledge, and developing comprehensive noise mitigation strategies. Integrating noise reduction measures such as rail grinding and noise barriers into existing software tools, as well as partnering with relevant organisations, can enhance the practical implementation of the project's findings and ensure their widespread applicability. Moreover, rail pad manufacturers can significantly contribute to noise reduction efforts by optimising rail pad designs to achieve greater softness and low kSP values while maintaining track elasticity and high TDR values.

In conclusion, the LOWNOISEPAD project demonstrates the effectiveness of rail pad optimisation as a practical and potentially cost-effective measure for reducing railway noise. It fosters collaboration, generates valuable insight, and provides a standardised framework for assessing rail pad performance. By prioritising innovation, collaboration, and incentives for measurements and maintenance, the railway sector can work towards the common goal of reducing noise and addressing concerns within the community, leading to a healthier and more harmonious coexistence between railways and the communities they serve.

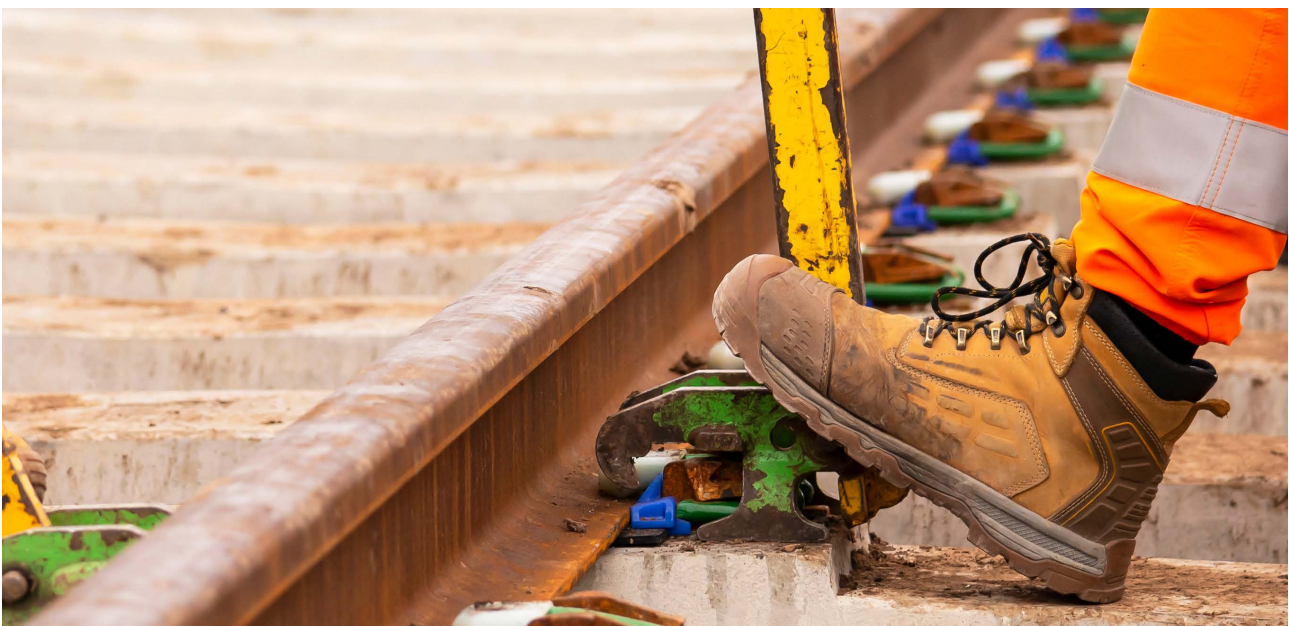


## 10. ANNEX A: GRAPHIC REFERENCE GUIDE

This annex [14], provided in a separate document, gives a detailed and graphic overview of the pass by data collected from each project member throughout the project. All results showing the noise reduction and detailed pass-by analysis, calculated on the basis of the data available in the LOWNOISEPAD software tool, are shown in a graph format for each type of rolling stock, given in an individual section for each PP (alongside Chapter 7 of this report). This annex should be used alongside the information gathered as part of the project carried out by UIC and the 12 project participants. It is not recommended to carry out analysis without first having reviewed the LOWNOISEPAD final report and the **Annex B: Rolling stock - Visual Reference Guide**, and also without consulting and receiving authorisation from the project participants and UIC.

## 11. ANNEX B: ROLLING STOCK - VISUAL REFERENCE GUIDE

This annex [15], provided in a separate document, aims to show images of each type of rolling stock for which data was collected during the project, including the specific nomenclature used within each company and the nomenclature used in the LOWNOISEPAD software tool. Furthermore, it aims to facilitate the comparability of the data obtained from different types of rolling stock, which might be considered to have similar characteristics, despite the nomenclature within each member company being different. For instance, the INFRABEL Desiro, ÖBB Cityjet and DB ET462 appear to be similar (disc brake, low noise emission). This annex should be used alongside the information gathered as part of the project carried out by UIC and the 12 project participants. It is not recommended to carry out analysis without first having reviewed the LOWNOISEPAD final report and the **Annex A: Graphic Reference Guide**, and also without consulting and receiving authorisation from the project participants and UIC.



## 12. ACKNOWLEDGEMENT

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