UIC SUSTAINABILITY

Nuisance and Health Impacts of Railway Noise

Noise and Vibration Technical Advice (NOVITÀ) Project

September 2022

NOVITÀ
NOISE AND VIBRATION
TECHNICAL ADVICE

INTERNATIONAL UNION
OF RAILWAYS

Citation style
International Union of Railways (UIC), Sustainability, *Nuisance and Health Impacts of Railway Noise* (NOVITÀ project), 2022.

ISBN 978-2-7461-3209-2

Contents

Tables

Figures

Foreword

If we want to decarbonise mobility and make it more sustainable, one thing is clear: we are going to need more trains! In fact, we will need 50% more by the end of this decade. Significant growth is expected in both high-speed passenger and freight rail traffic across Europe and the rest of the world. It is however essential that this growth does not come at the expense of those living and working near railways. We recognise that there is a public health and socio-economic welfare burden caused by transportation noise. Reducing noise emissions, from freight trains in particular, is the key to substantially reducing the undesirable impact of railway noise. The health effects of exposure to environmental noise are becoming better understood, including how exposure may cause nuisance, sleep disturbance as well as longer-term physiological conditions including cardiovascular disease. Despite noise levels being reduced through railway innovation and mitigation measures being implemented, evidence shows that there has been a potential increase in the number of people affected by railway noise. The number of complaints received about railway noise still remains high. UIC is committed to understanding the driving factors that trigger individuals to complain about railway noise and to improve outcomes for all stakeholders. This study represents a step forward in our understanding of the relationship between noise exposure and the impact on our neighbours. UIC will continue to strive to identify appropriate cost-effective noise mitigation measures.

François DAVENNE
Director General

Executive summary

The **nuisance and health impact of railway noise preliminary study of** the UIC **Noise and Vibration Technical Advice (NOVITÀ)** project aims to demonstrate that an understanding of the health effects of noise through high-quality research will support better-informed decision-making. This scoping study presents the nuisance effect of rail noise, its impact on human health in European railways and the next steps for the global railway community. The study provides evidence on this for UIC participation in European Commission meetings to inform funding and legislation decisions.

The study has found that there is an expanding evidence base on a variety of cardiovascular, metabolic and other critical outcomes and risk indicators associated with noise. The **self-reported** effects of noise on **sleep** and **annoyance** are two current key indicators for evaluating health outcomes and are relevant to health, policy and stakeholder engagement. Noise **complaints** from communities along railways are an active expression of dissatisfaction with the noise environment. A complaint may not always link directly to noise exposure but can be a function of the "**arousal**" effect - a conscious recognition of a change from an unusual noise stimulus.

Noise indicators such as L_{den} or L_{night} may limit associations between noise at night and some health outcomes such as **awakening reactions**. The increased probability of awakenings from events affects quality of life. There is a link between intermittent noise events at night and the likelihood of "arousals" leading to complaints. The **judgement of acceptability** depends on several factors including the maximum noise levels. Of indicators considered supplementary to long-term indicators, $\mathbf{L_{Amax}}$ is the most commonly used. It is used to evaluate short-term sleep effects, representative of "arousal" responses and appropriately reflects the intermittent and variable nature of railway operations. To set appropriate target values, L_{Amax} could be defined with reference to its frequency of distribution, and descriptors accounting for noise **characteristics**.

Recent studies have indicated that exposure-response relationships no longer favour railway noise over other transportation sources and suggest that the number of people annoyed by railway noise may have increased. Global exposure response curves are not an optimal tool for **managing local issues** along the railways and designing **mitigation**. Local acoustic and non-acoustic factors should be considered when investigating issues and the measures to address them.

Future methods to reduce impacts from noise will need to combine the conventional mitigation efforts with innovative ways to more specifically address annoyance/complaints caused by railways. Railway infrastructure managers and operators will need to work together to achieve cost-effective mitigation; however, the established ways of monetising noise impacts are based on long-term exposure and do not recognise short-term impacts from atypical events. This may be a limiting factor in identifying the benefit or value-for-money of mitigation measures. Monetisation tools currently exclude productivity losses, impacts to ecology and indirect effects, and the need to be regularly updated to include new evidence on health effects.

A key part of the study has been to acquire a representative picture of the nuisance effect of railway noise for European railways. This has been undertaken by issuing a questionnaire to UIC members about noise complaints on their network, including how they are investigated, managed and resolved. The questionnaire was completed by 18 stakeholders accounting for 64% of the total railway length in Europe. Legal noise limits or other Regulatory Controls are in place across the rail sector to minimise the emission of noise from railways. Legal limits are typically different for new and existing railways and do not differentiate between freight and passenger services, although separate limits for some high-speed railways do exist.

Noise complaints received are generally monitored well and recorded in a way to enable meaningful analysis. Fewer than half of respondents indicated that they have legal requirements to act on noise complaints, and investigating complaints is partly shaped by stakeholder pressure and a desire to minimise reputational risk. Most respondents stated noise monitoring is never or rarely used to investigate complaints. Some of the most frequently used noise indicators for complaints have limitations in assessing awakening reactions and arousals.

Freight trains during the night were the most common cause of noise complaints. Although noise complaints from changes to infrastructure and operations are also common, 33% of respondents perceived an increase in complaints where there has been no change to the railway noise. Only one operator stated high-speed trains were a common cause of noise complaints. Research findings show noise complaints are a result of the arousal effect of exposure to atypical high-noise events, which may also lead to short-term sleep disturbance.

The outcomes of this study have identified a number of knowledge gaps and opportunities for future research that can be considered in the next phase of the project. These opportunities include research into complaints from high-speed rail, factors affecting exposure-response relationships, monetisation of short-term noise annoyance, and practical noise indicators to better represent the characteristics of railway noise.

1. Introduction

1.1. Purpose of the report

The International Union of Railways (UIC) is the worldwide organisation responsible for promoting rail transport and developing the railway system to support the strategies of its members. As part of the UIC Sustainability Platform, its noise and vibration sector promotes the effective management of railway noise and vibration in the context of sustainable development.

There is a perception within the sector that the rate of complaints from communities living along parts of the railways remains high, despite evidence that noise levels are decreasing as a result of a range of innovations and mitigation measures being employed across Europe.

The **nuisance and health impact of railway noise preliminary study** of the UIC **(NOVITÀ)** [1] project aims to demonstrate that an understanding of the health effects of noise through high-quality research will support better-informed decision-making. This research will support more effective policy and efficiently direct resources to improve noise and vibration management.

The objectives of this scoping study are as follows:

1. To acquire a representative picture of the nuisance effect of rail noise and its impact on human health in European railways in 2022 and to prepare a proposal to determine the next steps and make suggestions for the global railway community.

2. Provide an evidence basis on the impact of noise nuisance on human health for UIC participation in the European Commission meetings with the aim that it will inform EU or national governments' funding and legislation decisions.

This report for the UIC describes the state of research on noise nuisance and the health impact situation for European railways and includes a literature review, a critical assessment of the quality of the research and a description of the knowledge gaps and suggestions for further work. The key target audiences for this report are individual railway companies, the EU Commission and national governments, as this study provides information to facilitate discussions on the noise nuisance situation as well as evidence for decision-making.

1.2. Definition of terms

The key terms used as part of this study are defined below.

Nuisance

Although the term “nuisance” can have a specific meaning in law, in this study it is referenced in a general sense as a particular noise exposure resulting in a **community** or an **individual** response, in the form of either a health effect or a complaint. These responses may vary for different railway noise sources and the perceptions of noise may differ between population groups and countries.

Health

World Health Organisation’s Constitution (1946) [2] defines health as “*a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity*”. In the context of noise, the WHO Guideline Development Group (GDG) [3] clarified further that “*…documenting physical health does not present a complete picture of general health; and being undisturbed by noise in all activities, including sleep, constitutes an asset worthy of protection. Therefore, in accordance with the above definition, the GDG regarded (long-term) annoyance and impaired well-being, as well as self-reported sleep disturbance due to noise, as health outcomes.”* It goes on to explain that “*…The importance of considering both annoyance and self-reported sleep disturbance as health outcomes is further supported by evidence indicating that they may be part of the causal pathway of noise-induced cardiovascular and metabolic diseases.*” In this report, a “health effect” or a “health outcome” is used when describing research findings on the potential impact of noise on humans. Health outcomes could further be distinguished in the literature as objective/subjective or short-term/long-term or auditory/non-auditory, etc.

Complaint

In this report, a complaint is a written or verbal expression of dissatisfaction with the noise environment experienced, made by or on behalf of individuals or a community (e.g. action group) to the responsible authority (e.g. railway operator or infrastructure manager), with an expectation that the issue raised will be dealt with. A complaint may not always be directly linked to noise exposure.

1.3. Scope of the report

The scope of this study covers conventional rail traffic, including both passenger and freight services, and high-speed rail traffic. It also includes a literature review of published material on noise-related health and nuisance effects from railway noise, the applicability of different noise and health indicators, mitigation measures and economic considerations. This study provides a critical review of the current evidence base to support the EU Commission, national governments and individual railway companies with their decision-making, and to help them describing the noise nuisance situation to their counterparts in each type of organisation.

A key part of the study has been to acquire a representative picture of the nuisance effect of railway noise for European railways. This has been undertaken by issuing a questionnaire to UIC members about noise complaints on their network, including how they are investigated, managed and resolved. The questionnaire responses were critically reviewed alongside the key outcomes from the literature review to identify knowledge gaps, discrepancies and topics to focus on for future phases of this project.

Noise related to construction activities at railways, depots and fixed stationary noise sources at stations are outside the scope of this study. Excluded noise sources at depots and stations include Public Address systems, idling trains, and heating ventilation and air conditioning (HVAC) systems serving the depot or station. Further information on noise from stationary sources is presented in a separate parallel study commissioned by UIC.

1.4. Document structure

In order to address the key areas of focus for the study, this report is structured as follows:

- Chapter 2 - description of the “big picture” in relation to railway noise in Europe;
- Chapter 3 - discussion and review of the reported impacts from railway noise, including an overview of health and annoyance effects, complaints pathways and noise metrics for assessing impacts;
- Chapter 4 - overview of methods for reducing railway noise impacts;
- Chapter 5 - overview of the economic effects from railway noise approaches taken to monetise adverse and beneficial noise impacts in Europe;
- Chapter 6 - a discussion on the situation in European Railways based on outcomes from a survey issued to the UIC membership; and
- Chapter 7 - conclusions of the scoping study research including an overview of the knowledge gaps identified and recommendations for future phases of the project.

Key research papers linked to guidance published by the World Health Organization and case studies linked to the complaints questionnaire are provided in Appendix B of this report.

2. The big picture

The first item in UIC's mission is *to promote rail transport at world level with the objective of optimally meeting current and future challenges of mobility and sustainable development* [4]. Following the introduction of the European Commission's Green Deal in December 2019, there is a clear requirement for a transition to greener mobility and the acknowledged benefit of the increased use of railways for freight and passenger transportation over roads and aircraft.

The European Commission's Sustainable and Smart Mobility Strategy [5] proposes that by 2030 high-speed rail traffic will double and by 2050 rail freight traffic will double across Europe. In addition, the Trans-European Transport Network (TEN-T) action plan for cross-border passenger rail traffic [6] is expected to be fully operational by 2050.

Alongside the anticipated future increase in railway traffic is the recognised public-health and socio-economic welfare burden caused by transportation noise from railways which the rail sector and UIC has been working to address. An objective of the European Commission's zero-pollution action plan is that the share of people chronically disturbed by transport noise will be reduced by 30% by 2050. In 2022, the Commission will determine which kind of legislative measures are necessary to achieve this goal. The United Nations Environment Programme (UNEP) has recently identified noise pollution as a top environmental risk as cities grow, recognising that high levels of noise impair human health and well-being [7]. UNEP highlights the importance of desirable soundscapes and the role of urban planners to incorporate noise abatement measures in urban spaces to protect public health [7].

In January 2021, the UIC Sustainability Unit published 'Railway Noise in Europe - State of the Art Report' [8]. This report was an update to a previous 2016 review [9], triggered by several major developments regarding railways and environmental noise in the past five years. The State-of-the-Art report [8] describes recent railway noise developments and provides an overview of the activities that the railway sector is undertaking to improve the railway noise situation. The report specifically integrates the latest publications from the World Health Organisation (WHO) and the European Environment Agency (EEA) to reflect the latest European developments and policies regarding noise from railways and the measures being implemented to reduce railway noise. These measures provide a holistic approach for European railways that considers the European Green Deal, the Zero Pollution Action Plan and the Strategy for Sustainable and Smart Mobility.

2.1. Characteristics of railway noise

Sources of railway noise include rolling noise from the rail-wheel interaction, traction noise from locomotive engines and auxiliary equipment, and aerodynamic noise from turbulent air flow as the train is moving. Additional sources of noise can include tonal squeal from the interaction between the rail and wheel in narrow curves and brake squeal emitted during braking. Each noise source will have its own acoustic characteristic and the noise level contribution of individual sources can vary depending on factors including track-bed design, braking system, train composition/length and train speed. Additionally, the maintenance and condition of both the train and the track will affect the noise emissions, for example increased rail roughness or wheel flats will result in increased rolling noise. The community response to noise can therefore be influenced by both individual sources and the cumulative overall railway noise level.

The source characteristics and noise and vibration emissions of freight trains varies from that of passenger trains. This is because freight typically utilises older rolling stock with more primitive tread brakes and suspension systems than those often found on passenger trains, which are more refined for passenger comfort. Generally, freight trains are also heavier, longer trains hauling large volumes of cargo that traditionally require strong diesel locomotive engines to gain momentum (although electric traction is becoming more common). It is also the case that freight trains tend to use the railway network more during the night-time when fewer passenger trains are in service and there is more capacity on the network.

It is anticipated that the shift to rail as a green mode of transportation will increase the demand for freight to be carried by rail rather than by road and air, which will see a rise in global freight train noise across the railway network and possibly disproportionate increases in night-time railway noise emissions. The White Paper on Innovative Rail Freight Wagon 2030 [10] recognises that freight wagons are key to substantially reducing the undesirable impact of rail traffic noise. While innovative noise-reduction concepts include low-noise wheelsets, brakes and running gear, there are no technically and commercially mature designs for rail freight wagons which sufficiently reduce noise emissions. The industry ambition is to design freight trains in a way that the overall noise emissions are no greater than those from passenger trains by 2030.

Traditionally, most noise assessment methods and limit values in national railway noise legislation are based on long-term equivalent levels such as L_{den} and L_{night}. Long-term noise indicators are typically dominated by rolling noise arising from the interaction of rail and wheel over a wide range of speeds, which is a well-understood mechanism. Most of the research on noise and health is also based on these long-term indicators. However, there is concern that these indicators do not adequately represent the intermittent nature of railway operation or specific railway features, which may be important in describing the impacts of noise on people. A recent study by Poisson and Guerrero [11] indicates that very short-term indicators such as the L_{Amax} may not be appropriate due to the high variability of data and concludes that a short-term indicator representing the total single pass-by, such as the Sound Exposure Level (SEL) or Transient Exposure Level (TEL) is more relevant than a very short-term indicator. Further research is therefore required to provide a strong evidence base for the adoption of alterative indicators in environmental noise legislation, if this is considered appropriate.

2.2. Health effects and complaints

A report by the EEA in 2020 [12] concluded that noise is a major environmental problem in Europe where 20% of the EU population are living in areas where transportation noise levels are harmful to health and noted that railway noise is the second most significant source after road traffic noise. For comparison, the overall number of people exposed to long-term day-evening-night noise levels of at least 55 dB(A) is estimated to be 113 million for road traffic noise and 22 million for railway noise.

The health effects of exposure to environmental noise are well researched and include annoyance, sleep disturbance and longer-term physiological conditions including cardiovascular health effects. There is clear evidence that a significant number of people are annoyed by railway noise and that the number of significantly annoyed people increases with higher noise levels. Historically, research into environmental noise annoyance had indicated that exposure response functions for the percentage of the population highly annoyed was lower for rail compared to other transportation sources such as road. This conclusion has led to many countries allowing higher noise levels from railways than for road traffic when determining noise limits. A Noise Annoyance Correction Factor (NACF) is applied in approximately 20% of European countries to relax the limits for railway noise, often referred to as a “railway bonus”. However, more recent studies have conflicting conclusions, with the WHO’s Environmental Noise Guidelines [3] now presenting an exposure-response function indicating that the railway noise response curve should be higher than road traffic noise. This emerging research and the potential removal of the “railway bonus” may have the consequence of showing an increase in the population reported to be exposed to railway noise levels that would cause annoyance, sleep disturbance and other adverse health outcomes.

UIC acknowledges that more research is needed into why the new WHO exposure-response function is higher than the previous curves, why the perceived preferable attitude towards rail noise with respect to road noise has been eroded, and whether this assumption is sufficiently scientifically proven and justified [8]. The applicability of these global response curves also requires further investigation as the noise exposure responses in research studies varies between different groups of people where conflicting factors or route-specific features may have influenced the survey responses (such as exposure to other sources of noise, socio-demographic variables, local features affecting noise propagation, varying exposure to freight versus passenger trains or other localised specific features not necessarily picked up by long-term indicators describing the noise exposure). Additionally, it may be appropriate to consider supplementary health indicators (for example distinct short-term effects such as physiological awakenings) when considering the human response to railway noise to more comprehensively define the exposure response and to ensure appropriate resources are directed to mitigate impacts.

As alluded to above, recent research indicates that attitudes to railway noise, as measured by the percentage of population annoyed and sleep disturbed, may have become more adverse over the years. As highlighted in Chapter 1, there is a perception that the rate of complaints from communities living along parts of the railways remain high, despite evidence that noise levels are decreasing as a result of a range of innovations and mitigation measures being employed across Europe. The driving factors that trigger individuals to complain about railway noise exposure have not been addressed in previous UIC studies, nor is there data on the number and nature of complaints to draw any correlations.

2.3. Noise reduction strategies and measures

There are a wide range of measures currently being implemented by European railways to reduce the noise levels, often driven by EU policy and legal requirements implemented by individual Member States. The European Commission's zero pollution action plan is targeting a 30% reduction in the number of people chronically disturbed by transportation noise by in the EU by 2030, which if successful, could benefit approximately 1 million people who are highly annoyed by railway noise [13].

The Environmental Noise Directive (END) [14] aims to define a common approach to avoiding, preventing or reducing the harmful effects of environmental noise and to increasing the public awareness of noise exposure. The directive requires that Member States publish strategic noise maps and action plans every five years. The purpose of the action plans is to strategically target prevention and reductions in environmental noise where necessary and particularly where exposure levels induce a harmful effect to human health. The PHENOMENA project report will be the basis of the revision of the END starting from 2022 [15].

In 2015, the European Commission adopted the Commission Implementing Regulation 2015/429 on the Noise Differentiated Track Access Charge (NDTAC) [16]. This sets out a legal framework for EU Member States to implement NDTAC, which is a financial incentive scheme that provides a range of financial bonuses for railway operators to use quieter trains and/or issues financial penalties to them for running noisier trains on European railways. Similar methods already exist for aircraft, for example, using noise-differentiated landing and take-off fees. The NDTAC is a voluntary scheme intended to run until 31 December 2021. NDTAC has been implemented by Germany, Austria, the Netherlands and the Czech Republic.

It is recognised at UIC [8] that freight wagons with cast iron brake blocks or tread blocks are currently the most significant issue in railway noise, and many of the initiatives to reduce noise emissions currently focus on retrofitting and improving braking systems on freight wagons or the complete ban on cast iron brakes such as being implemented in Switzerland and Germany, where the entire fleet of freight wagons is now retrofitted with composite brake blocks. However, rail freight wagons equipped with cast iron brake blocks still represent about 40% of all the European freight wagon fleet [17].

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The Technical Specification for Interoperability relating to the subsystem “rolling stock - noise” (TSI Noise) [18] sets out the optimal level of harmonisation for specification on the rolling stock subsystem with the aim of limiting the noise emission of railway systems of the European Union. From 8 December 2024, wagons with cast iron brake blocks will be banned on “Quieter Routes”, defined in the TSI Noise as sections of the railway network with a minimum length of 20 km, on which the annual averaged daily operated number of freight trains during night-time is higher than twelve trains [8]. There is an expected wider benefit of the Quieter Routes scheme as low-noise wagons used on Quieter Routes are inherently used more widely across the network. There are a number of exclusions and exceptions to the Quieter Route scheme (such as the Channel Tunnel) and there are some reported problems with composite brake performance in winter conditions leading to a backstop clause granting dispensation where testing proves safety concerns.

The Connecting Europe Facility (CEF) for Transport is the funding instrument for realising the European transport infrastructure Policy. The CEF supports investments in new and existing infrastructure in Europe and provides funding for 20% of the eligible costs for retrofitting wagons with quieter composite brake blocks. UIC estimated that 200,000 freight wagons have been retrofitted through CEF [8].

On a local level, other measures are implemented by infrastructure managers to deal with isolated potential noise issues, including the construction of noise barriers or the application of rail dampers on the track.

In considering noise mitigation whether locally, nationally or at the EU level, it is important that the overall cost of such measures should not reduce the competitiveness of the railways over other modes of transportation. Additionally, European policy makers should not only consider the costs of noise mitigation measures but also their secondary influence on traffic capacity or trade-offs against other factors such as maintenance. In addition to the overall cost of noise mitigation, the cost effectiveness should also ensure the measures represent a value for money in terms of health and/or socio-economic welfare outcomes. Examples of this include the cost-benefit analysis undertaken in the UK on large infrastructure projects where the whole-life cost of noise barriers (comprising installation, maintenance and replacement over a 60-year period) is compared to the monetised health benefits from reduced noise levels. UIC states that the cost-benefit aspect of railway noise reduction and the possible effects on the modal shift to rail requires further research before implementation of the latest WHO recommendations [8].

There are a number of innovative future solutions in noise mitigation currently being developed. These include studies into barriers featuring diffracting tops, which are being trialled in the Netherlands, Germany and the UK. There is also a move towards more sustainable and green solutions. For example, the application of “green” noise barriers which are made from sustainable or recycled materials. Additionally, hybrid, hydrogen and battery powered trains are being trialled, which tests indicate can reduce noise emissions by up to 5 dB compared to conventional versions when running, with even greater benefits when stationary (e.g. shunting yards) [19]. The development of the technology is ongoing to achieve full TSI compliance and this presents an opportunity to achieve further noise reductions at source, particularly from the cooling units of hydrogen cells. The UIC Train Track Interaction Sector’s White Paper [20] lists several ideas for future research, which includes topics such as the monitoring of curve squeal noise, subjective perceptions and psychoacoustics indicators, and the annoyance of low-frequency noise.

2.4. Summary: the big picture

There is a clear requirement for increased rail transportation across Europe to meet environmental pollution goals, with a significant growth expected in both passenger and freight rail traffic over the coming years. Future development of rail sector will need to proactively consider the impacts of noise on public health and socio-economic welfare and implement adequate levels of protection against noise.

Noise from railways is a combination of a number of individual sources, including those with distinctive acoustic characteristics. The source characteristics and noise emissions of freight trains vary from that of passenger trains. Due to the expected increase in freight train traffic, it is recognised that reducing noise emissions from freight trains in particular is key to substantially reducing the undesirable impact of railway noise.

Traditionally, noise from trains has been assessed using long-term acoustic indicators. However, there is emerging research showing that additional short-term indicators can be used to better describe certain characteristics of railway noise and the resulting impacts of noise on human health.

The health outcomes of exposure to environmental noise are well researched and include annoyance, sleep disturbance and longer-term physiological conditions including cardiovascular health effects. Recent studies have indicated that exposure-response relationships no longer favour railway noise over other transportation sources and suggest that the numbers of people annoyed by railway noise may have increased. Additionally, the number of complaints received about railway noise are high despite evidence that noise levels are decreasing due to the implementation of a range of noise mitigation measures and innovative solutions. The driving factors that trigger individuals to complain about railway noise exposure are not well understood.

Understanding the main sources and characteristics of railway noise, and the relationship between noise exposure and health/complaint outcomes is key to identifying appropriate cost-effective noise mitigation measures that can help reduce the number of people disturbed by railway noise.

3. Impact of noise from railways

This chapter of the report provides a critical overview of the main health outcomes from exposure to railway noise and other transportation noise sources where relevant. It highlights the potential limitations of using community response curves in managing local issues encountered along the railways and for designing mitigation. The discussion includes a critical review of potential pathways to complaints. The chapter identifies supplementary health and noise indicators for better evaluating the impact of noise from railways. The robustness of various studies and approaches is addressed, in relation to their applicability to rail transport.

3.1. Overview

This section provides an overview of potential health impacts of exposure to environmental noise, particularly from transportation sources.

The Environmental Noise Guidelines for the European Region published by WHO [3] is a key document providing an evidence-based assessment of health impacts of exposure to environmental noise. The public health advice provided in the Guidelines has shaped policy and practice in recent years. WHO Systematic Reviews are a comprehensive source of reference for robust and relevant research undertaken in the field between 2000 and 2014. Self-reported sleep disturbance and annoyance are two of the key priority health outcomes for transportation noise with a robust evidence base. The document also considers the evidence base on cardiovascular disease, cognitive impairment, metabolic outcomes, hearing impairment and tinnitus, quality of life, well-being and mental health. Recent reviews published in 2020 [21] [22] [23] further evaluated how the evidence base for noise effects on health has changed following the WHO reviews.

There have been a number of studies into the health effects of transportation noise. For example, **SAPALDIA** (**S**tudy on **A**ir **P**ollution **A**nd **L**ung **D**isease **I**n **A**dults) is a long-term cohort investigation undertaken between 1991 and 2021 (ongoing) into the effects of lifestyle and environment (including noise) on the chronic diseases and aging in adults in the general population in Switzerland [24] [25] [26] [27].

NORAH (Noise Related Annoyance, Cognition and Health) is a multidisciplinary research project undertaken in Germany between 2011 and 2015 on the effects of air, road and rail traffic on the health and life quality of residents in the vicinity of airports [28]. Although the main focus of the project is on the potential effects of aircraft noise, comparisons are made with the effects of noise from road and rail.

Another interdisciplinary research project is the **SiRENE** study (Short and Long-Term Effects of Transportation Noise Exposure) undertaken in Switzerland between 2014 and 2020 with an objective to investigate the effects of road, rail and aircraft noise on annoyance, sleep, metabolism and cardiovascular diseases as well as mortality of the Swiss population [29] [30] [31]. A further recent large nationwide cohort study in Denmark [32], looked at the increased risk of all causes of dementia and dementia subtypes, especially Alzheimer’s disease associated with transportation noise from road traffic and railways.

The **FAMOS** (**FA**ctors **MO**derating people's **S**ubjective reactions to noise) project [33], which is currently underway in Denmark, Germany and Norway, aims to improve understanding on subjective reactions of communities to road traffic noise. The project points out that two-thirds of “annoyance” responses are determined by non-acoustic factors and only one-third are caused by the level of noise. The aim of the study is to quantify how different factors modify people’s subjective reactions to road traffic noise.

There is an expanding evidence base on a variety of cardiovascular, metabolic and other critical outcomes and risk indicators associated with noise. Currently, the **self-reported** effects of noise on **sleep** and **annoyance** are two of the key indicators for evaluating health outcomes along railways. The significance of these two indicators can be summed up as follows;

1. **Health** - There is clear evidence that they represent critical health outcomes. These health outcomes affect a wider segment of the general population compared with other health outcomes. They can be used as a proxy for managing the overall community impacts of noise including cardiovascular, metabolic and other critical outcomes, which are considered higher risk but have a lower incidence rate among the population. Use of L_{den} and L_{night} are shown to be suitable for assessing long-term health effects.

2. **Policy** - The indicators lend themselves to meaningful and policy-relevant ways of measuring the community impacts. The concepts of "percentage of the population highly sleep-disturbed" (%HSD), and "percentage of the population highly annoyed" (%HA) are well-established. They can be assessed objectively according to common protocols set by the International Commission on Biological Effects of Noise (ICBEN). Both can be assessed using a standardised scale, typically evaluated via social surveys using a 5-point (1 to 5) or an 11-point (0 to 10) scale.

3. **Stakeholder** - The indicators support studies seeking to examine the causes of noise "issues" (subjective) along the railways, rather than noise "exceedances" (objective). Therefore, using indicators that stakeholders can relate to and involving the communities affected by railway noise in the identification of issues would help determine effective noise mitigation measures. It would also be a demonstration of positive community engagement in a socially and environmentally responsible manner.

The following areas have been identified as deserving further attention as part of this study to better understand the **underlying reasons** for the apparent worsening in critical **health outcomes** and perceived high rates of **complaints** along railways. This review aims to identify **aspects of railway noise** which elicit adverse subjective responses.

1. **Global response curves** - A critical review, including their applicability to managing local issues.

2. **Complaints** - Observations on a framework for assessing complaints and factors which drive complaints.

3. **Supplementary health indicators** - In addition to the well-established long-term health effects (and associated noise indicators), review of evidence on distinct short-term effects e.g. physiological awakenings which may be relevant.

4. **Alternative noise indicators** - Insofar as supplementary health indicators may be desirable, what alternative indicators or metrics are available to measure them, e.g. L_{Amax}, SEL, TEL or others.

3.2. Observations on global annoyance curves

WHO (2018) [3] defines noise annoyance "*…as a feeling of displeasure, nuisance, disturbance or irritation caused by a specific sound…*" in the context of long-term noise. What constitutes a noise annoyance may vary for different railway noise sources and perceptions of noise may differ between population groups and countries. In this context, consideration of non-acoustic confounding factors is relevant.

WHO [3] indicates that attitudes to railway noise, as measured by the percentage of population annoyed and sleep disturbed, have become more adverse over the years. However, there is also recent research which suggests annoyance reactions to road traffic noise [34] and aircraft noise [35] have been stable over the years, and that the observed differences in WHO curves may be a function of the size of data and the methodology used in the statistical analysis of data. A review by Brown and van Kamp [36] indicated that, in the case of road traffic, step changes in noise (such as those due to interventions at source or transmission path) could result in an "excess response" in annoyance, over and above those estimated using the exposure-response functions which represent steady-state conditions. The review does not identify research on the effects of step change or gradual change in railway noise on community annoyance or sleep disturbance.

The WHO Systematic Review on annoyance by Guski et al. [37] provides further background on the selected studies for annoyance. The evidence on the adverse effects of railway noise is rated moderate quality. However, there are a limited number of studies for railways related to noise effects and noise pollution. The list of annoyance studies on railway noise which have been considered in WHO Systematic Reviews are provided in **Appendix A**. The list includes both those sets included in and excluded from WHO Systematic Reviews.

In total, 10 studies (from 7 papers) were identified for the analysis of railway noise on self-reported annoyance. One of the studies related to the Shinkansen high-speed line and was omitted from analysis of the global curves due to observed distinct reactions in the study. Of the remaining 9 studies which contributed to the WHO (2018) [3] dataset, some key points to consider when comparing to the curves published by Miedema and Oudshoorn [38] are summarised below:

- 5 of the 9 studies are from Alpine valleys in Austria which is reportedly influenced by the so-called Alpine Valley effect (e.g. reflection effects in valleys, or U- or V-shaped valleys with "much wind" or "a lot of temperature inversion" [39]). The authors refer to previous research which has shown that annoyance responses are usually higher in Alpine areas than in non-Alpine areas at similar noise levels [40].
- 2 of the Alpine studies use the 5-point scale which may have contributed to an increased %HA. In the 5-point scale, the top 40% are considered as %HA (ratings of 4 and 5) as opposed to the top 27% using the 11-pt scale (ratings of 8, 9 and 10).
- The Alpine studies report "a high proportion of freight trains", but the number of events is not provided. There is research which shows freight trains are more annoying than passenger trains at the same vibration level [40]. There may be a confounding effect of vibration with noise particularly from freight trains where the number of freight trains is high.
- The Alpine studies report strong stakeholder involvement over extended periods of time (e.g. long-lasting issues with mixed sources with road and rail noise on a significant European route, tripling of heavy traffic over 25 years, increase of goods movement by two-thirds). It is possible that the strength of community sentiment may have affected the outcome of studies to some extent.

- One of the Alpine studies is reported to have installed noise barriers before the interviews with participants (Unterinntal, part of the ALPNAP study). Compared with the two environmental health impact studies (referred to as BBT studies) at Wipptal in Austria, the resulting %HA rates are distinctly lower at a given noise level. Indeed, an earlier study of the differences between the northern and southern areas within the Wipptal Valley [41] showed further significant differences due to the implementation of "counter-measures". This may point towards the modifying effect of proactive engagement with the community and action by the authorities (e.g. installation of mitigation).
- One study from Japan includes respondents living in mostly air-conditioned houses. It is also explained that Japanese houses are often built close to railway line and suffer from vibration issues. It is also possible that the type of construction is a contributory factor.
- Confidence Intervals (CI) of the WHO [3] aggregated dataset are not shown. However, there is a statement explaining that only 5th percentiles of the new curves are in the upper limit of CI for curves published by Miedema and Oudshoorn [38], suggesting the CI is wide. A relatively small number of samples at high noise levels may have affected the statistical distribution of data.
- The noise level ranges for the Alpine studies are not reported. It is possible that the levels encountered are at the high end of the range compared with other studies. Combined with strong public sentiment around noise in these areas, this could be a factor strengthening the link between exposure and annoyance.

Considering the coupling effect between self-reported annoyance and sleep disturbance at the upper end of the perception scale, a similar review is not provided here for sleep disturbance at night. However, a comparison of a recent Innsbruck study (2021) [43] with the SiRENE study (2019) [30], WHO (2018) [3] curve and the Miedema and Oudshoorn (2001) curve [38] is worthy of note. They all yield distinct exposure-response curves of "%highly sleep disturbed" (%HSD) with increased noise levels, as shown in Figure 1.

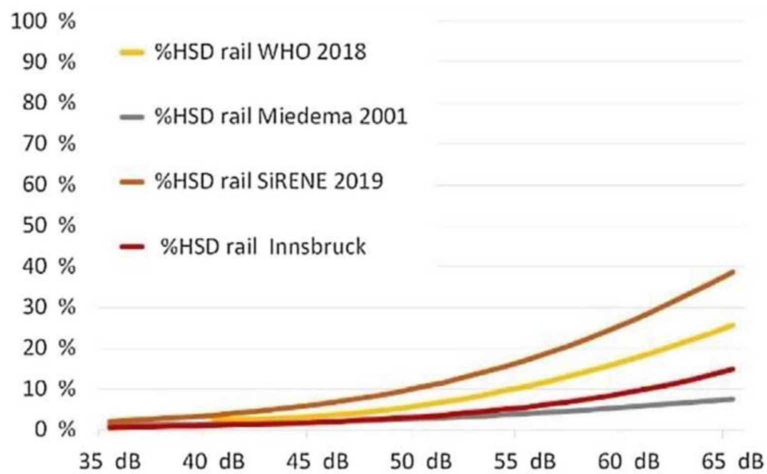


Figure 1: Comparison of different exposure-response curves for rail noise (from [43])

The studies all point to a general trend in the community attitude to rate railway noise less favourably compared with two decades ago. However, the strength of the responses appears to differ widely between studies. Another outcome of the Innsbruck study [43] relevant to this review is that road traffic noise at night is rated worse than rail traffic noise (in terms of %HSD), which appears to contradict the observations in WHO (2018) [3].

The review undertaken by Guski et al. [37] indicates that, due to the limited number of studies which were available for inclusion in the WHO analysis, some of the studies representing particular **local characteristics** may have contributed to an increased percentage of %HA, as well as **methodological differences** when analysing meta-data from social surveys,.

The general findings of this review are:

- **Individual sensitivity** - There is strong evidence that noise exposure explains only a small part of the variation in self-reported individual reactions. Individual sensitivity can be affected by non-acoustic factors (e.g. personal attitudes, age, education, other health indicators) and should be taken into account when assessing specific issues.
- **Community** - There may be local factors affecting community perception in different ways (e.g. common history, culture, politics, socio-economic indicators, availability and accessibility of information on noise impacts).
- **Local physical factors** - Specific sound propagation conditions including topography and meteorology can affect noise levels and community perception (e.g. noise propagation in a valley).
- **Confounding factors** - Noise in conjunction with vibration or other issues (e.g. air quality or wider environmental issues), as well as historic attitudes to the source and the operator may affect community perceptions.

Global exposure response curves may be desirable from the perspectives of policy and community **health** protection. However, they do not represent an optimal tool for **managing local issues** encountered along the railways and designing **mitigation**. The above review has shown that local acoustic and non-acoustic factors should be taken into account in the identification of issues and measures along the railways to address these issues. Further research is needed to better understand the influence of local acoustic and non-acoustic factors on dose-response curves.

3.3. Complaints

In addition to the annoyance and sleep disturbance effects of railway noise, the railway sector is faced with noise complaints from the communities living along the railways. As defined earlier in the report, a noise complaint is a written or verbal expression of dissatisfaction with the noise environment. There is a reasonable expectation on the railway sector to investigate and address complaints, as managing complaints is a consequence of noise emissions that railways must support themselves. A complaint may not always be linked directly to noise exposure.

This section provides a conceptual framework for assessing complaints and makes general observations on the nature of community complaints to noise. A detailed review of responses collected on complaints from UIC members through online surveys is discussed in Chapter 6.

3.3.1. Conceptual framework

Research on community complaints to noise shows that there are complex cognitive and psychological factors underlying a decision to complain [44] [45] [46]. A conceptual framework has been proposed by Luz et al [45], reproduced below.

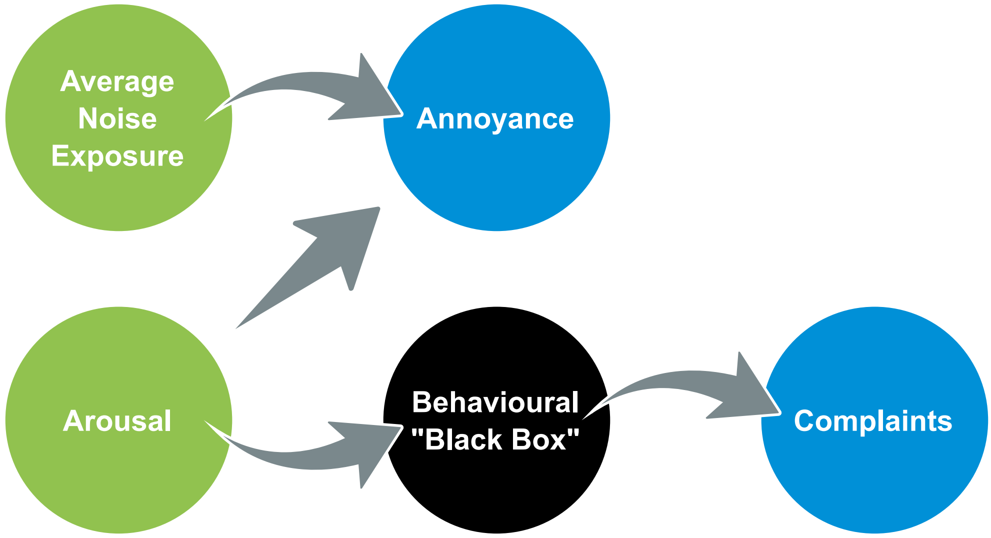


Figure 2: Conceptual framework for noise complaints (from Luz et al. 1983 [45])

According to this framework, "**annoyance**" is a function of both "**average noise exposure**" and "**arousal**", but "**complaints**" are a function of "**arousal**" only. The authors propose a further detailed model to describe the process governing complaints. The model assumes that the human brain has a "neural template" of what one expects to hear. When the brain is first exposed to a new stimulus, it responds with a series of reflexes designed to gather more information. If the stimulus is typical (has no good or bad meaning) and is repeated, the effects will be unconsciously integrated with past noise exposure. If an unusual noise has occurred, this results in a conscious recognition as a change and could be considered as an "**arousal**". This intrusion into conscious thought can be an annoyance and, depending on the meaning of the noise, the person will take steps to make sure it stops or is not repeated. To eliminate the noise, the individual chooses the behaviour that has been most reinforced in the past. If this behaviour alleviates or is perceived to alleviate the noise issue, it becomes more probable in the future. If noise remains an annoyance, the chosen action becomes less likely in the future.

Therefore, the act of "complaining" could be considered as a form of reaction and a coping mechanism to noise annoyance. Maziul et al. [47] showed that, in the context of airport noise, the level of noise was not the main factor affecting the decision to complain. The complaint behaviour appeared to be influenced by various factors (e.g. personal) and complaint data consequently did not provide an accurate measure of community annoyance. For example, there may be residents living in affected areas who do not complain, or residents living in areas with relatively low noise levels who do complain. There may be groups of people who declare being highly annoyed but do not lodge complaints.

A further airport noise study by Hume et al. [48] showed that the number of complaints were more clearly and positively coupled to the noise levels using L_{Aeq} and "perceived noise level" PNdB metrics. They pointed out that these results were to be expected since at higher noise levels more individuals would reach their "threshold of coping" with the nuisance in the noisiest areas and feel the need to complain. For example, on average they identified twice the number of complaints per movement at 110-114 PNdB (2 complaints) compared with 75-79 PNdB (1 complaint). For comparison, PNdB is approximately 13 dB higher than the maximum value of aircraft fly-by measured in dB L_{Aeq}. They also found a 24-hour pattern with night flights (23.00-06.00) causing on average nearly five times more complaints than the rest of the day (06.00-23.00). The time of the greatest tendency to complain about aircraft noise was between 01.00 and 02.00 (which corresponded to 30-35 complaints per 1,000 aircraft movements) and the lowest between 08.00 and 09.00. This could be due to event noise more readily resulting in an "arousal" reaction, particularly at night.

3.3.2. General observations

The following general observations can be made on the nature of community complaints to noise, based on past research.

- Spontaneous complaints are the end result of a process initiated by an annoying environmental event and influenced by several factors. Noise exposure is an indirect factor contributing to (e.g. via disturbances and annoyance), rather than a direct factor defining the complaint behaviour. At very high noise levels, a more direct relationship may be observed, for example due to the feeling of general disturbance being coupled with discomfort.
- A change in the stimulus is required for the brain to become aroused, leading to potential complaints.
- Often it is observed that complaints are generated by unusual rather than typical steady-state events or conditions, e.g. intermittent sounds which may not contribute to the statistical analysis of sound distribution over a day. In this context, intermittent events which are higher intensity or distinct in character are more likely to cause arousals.
- People are more likely to respond defensively to an addition of sound than to a deletion of sound.
- The most frequently mentioned effects of an acoustic nuisance are disturbances of rest at night. These are typically caused by activities which generate sound during the night and early hours of the morning.
- There is a weak correlation between long-term noise exposure and complaints.
- There is a weak correlation between community response as a whole and complaints.
- There are qualitative differences in the nature of complaints between different kinds of noise sources: for example, a comparison of blast and helicopter noise resulted in complaints about property, complaints associated with fear, and complaints about general nuisance. Freight trains were rated more annoying than passenger trains at the same vibration level [40].
- Perceptible vibration could elicit concerns about the structural integrity of a property. It is difficult to differentiate between complaints due to noise from those due to vibration or both noise and vibration.

Analysis of complaint data from airports showed that predictions of annoyance prevalence rates in airport communities are considerably improved when non-dose related factors, potentially including complaints, are taken into systematic consideration [49]. In the railway environment, it may be possible to use complaint data (as a non-dose related index) to improve dose-related reactions toward railways and railway noise, such as annoyance.

3.4. Supplementary health indicators

As highlighted above, noise complaints are frequently linked to disturbances of rest at night or in the early hours of the morning due to atypical events.

WHO [3] states that there is evidence rated moderate quality regarding an association between noise and polysomnography-measured outcomes (probability of additional awakenings) for road, rail and aircraft sources. However, the WHO largely disregards "objective" (physiological) indicators of sleep disturbance, such as the probability of awakenings or other polysomnography parameters due to the following reasons:

- Objective investigations (i.e. physiological) are complex and resource-intensive
- These investigations typically involve a small number of participants
- Participants often consist of healthy young volunteers (not representative of the community as a whole)
- The relationship between acute physiological reactions (micro-structure of sleep) and total sleep time (global sleep parameters) and long-term health remains unclear

WHO [3] acknowledges that self-reported sleep might differ considerably from objective sleep indicators. Elmenhorst et al. [50] also observe that objective sleep quality and noise annoyance are not related. Subjective sleep quality, on the contrary, appears to be moderated by noise annoyance. Currently there does not appear to be a robust reported link between short-term sleep effects and long-term annoyance/sleep disturbance outcomes.

Further investigations in this area would be desirable to address concerns about the size of datasets and the age distribution of respondents, before potential links to long-term effects can be defined better. For example, the polysomnographic studies conducted as part of the DEUFRAKO study to investigate the effect of railway noise on sleep included 33 individuals with an average age of 36 years [51]. This dataset ultimately shaped the advice contained in WHO [3] regarding the effect of rail noise on polysomnographically measured sleep. For comparison, research on self-reported annoyance from transportation noise (i.e. aircraft, road traffic, and railway noise) by Van Gerwen et al [52] shows a non-linear effect with age (inverted U-shaped pattern), with the largest number of highly annoyed individuals reported around the age of 45 years, and the lowest number of highly annoyed found in the youngest and oldest age categories.

Separate from discussions on long-term health effects, the increased probability of awakenings from events affects quality of life and could point to a link between intermittent noise events at night and the likelihood of "arousals" leading to complaints. This is further discussed in Chapter 6. The alternative noise indicators which may be relevant are explored further below.

3.5. Alternative noise indicators

WHO [3] acknowledges that the use of noise indicators such as L_{den} or L_{night} may limit the ability to observe associations between exposure to aircraft / railway noise at night and some health outcomes such as awakening reactions. In this instance, noise indicators based on the number of events (such as the frequency distribution of SEL or L_{Amax}) may be better suited, supplemented by additional descriptors. Sporadic noise events could require separate evaluation. The SNCF [53] bibliographic study provides a detailed review of a range of alternative noise indicators.

3.5.1. Intermittency of noise

The SiRENE study carried out throughout Switzerland emphasised the systematic analysis of noise characteristics, for example whether continuous noise has a different effect compared to widely varying noise events. To identify the effect of widely varying noise events, a new unit of measurement, the **intermittency ratio (IR)**, was developed in this study [30]. This indicator expresses the contribution in percentage of individual noise events (e.g. aircraft fly-bys or train pass-bys) to total noise pollution.

The study found that railway noise elicited a higher "percentage of highly annoyed" (%HA) persons than road traffic noise, possibly due to the "**intermittency**" of the source. They observed a marked difference of %HA for railway and aircraft noise as compared to the global response curves, corroborating findings that annoyance to these sources have increased over time. They also demonstrated that strong **non-acoustic factors** are highly relevant. They concluded that the "railway bonus" (the approach of rating railway noise more favourably compared with road traffic noise) does not find empirical support in this context. However, they noted that the intermittency ratio had the opposite effect on road traffic noise annoyance. The authors acknowledged that the occurrence of longer pauses in highly intermittent road traffic scenarios may have been one relevant factor for the reduced annoyance in situations where single events, even if perceived as loud, are followed **by periods of relative calmness**. The authors recommend further research to investigate the relative merits of intermittency and periods of calm.

Because of the low correlation between L_{den} and the intermittency indicator IR_{24h} in the case of road traffic noise, they concluded that the latter could offer a benefit as a complementary indicator in assessing the response to road traffic noise. The operation of rail and aircraft sources are intermittent by nature. They concluded that the predictive value of using this indicator in the modelling of %HA was less strong in the case of railway noise, and not linked to aircraft noise annoyance after full statistical adjustment.

3.5.2. Short-/very short-term indicators

Measurements and statistical analysis undertaken by Poisson and Guerrero [11] investigated the potential correlation between various noise indicators ($L_{eq,Tp}$, $L_{Aeq,Tp}$, SEL, TEL, L_{max}, L_{Amax}, and L_{PAFmax}) in characterising railway noise at different locations on the French railway network. For the suburban and regional traffic scenarios, the correlation between most of the indicators was high or very high. However, for the freight traffic scenario, correlation between long-term indicators and short-/very short-term indicators was found to be low. The authors point to the large variability in data for very short-term indicators (L_{max}, L_{Amax}, L_{PAFmax}), where differences of up to 19 dB were observed between the maximum and the minimum values. On this basis, the authors question the feasibility of adopting very short-term indicators as limit values to assess noise exposure. The study recommends assessing the relevance of these indicators in representing annoyance response as the next step.

The large variability in data for very short-term indicators and the observed lack of correlation for freight trains indicate that the prevalence of “maximum” noise levels at night, particularly from freight trains, could provide further insight into community response.

3.5.3. Level of noise and number of events

Recent research by Elmenhorst et al. [50] showed that the probability of awakenings at equal maximum A-weighted sound pressure levels (SPL) increased in the order aircraft < road < railway noise. They showed that the **maximum A-weighted SPL** and **Tr** were highly significant acoustical predictors for awakenings, where **Tr** represents the steepest slope of the event curve as the **rise time** of the maximum A-weighted SPL of a noise event **in dB/s**. The probability of awakenings increased with the **number of noise events per night** and the longer a **noise-free interval** lasted. Parameters of sleep were also shown to be important predictors (e.g. time spent asleep or time elapsed in the same sleep stage before the noise event occurred).

For example, in the UK, when assessing the impacts of noise on sleep, the overall noise levels at night measured using the $L_{Aeq,T}$ are typically supplemented by the L_{Amax} noise metric to account for the transient noise from the passage of individual trains. The practice is commonly applied to new residential developments near intermittent transportation sources, or when planning new railway infrastructure. The supporting evidence base is provided in relevant documents [54] [55]. Accordingly, a significant effect on sleep disturbance, e.g. behavioural awakening, is likely to occur where the maximum sound level at the façade of a building with partially open windows is 85 dB $L_{Amax,F}$. A lower value of 80 dB $L_{Amax,F}$ could be appropriate when the number of events is greater than 20 per night. The general premise of the assessment is that, for a smaller number of noise events, a higher maximum level dB L_{Amax} could be tolerated without adverse effects on sleep. This applies up to an upper limit, and with the proviso that the overarching noise level during the overall sleep period (e.g. $L_{Aeq,8hr}$) does not exceed a suitable threshold. At the opposite end of the scale, a case where noise events do not normally exceed 45 dB $L_{Amax,F}$ more than 10 times per night in noise-sensitive rooms at night (e.g. bedrooms) is considered good acoustic design.

Further applications of L_{Amax} in Europe are provided in the UIC State-of-the-Art review [8]. For example, the recommended maximum noise limit value for new lines in Norway is based on a statistical maximum level for L_{Amax} which excludes the top 5% of events (L5AF). The limit value is 75 L5AF and is applied when there are more than 10 noisy events on average during the night-time (23:00 hrs to 07:00 hrs).

3.5.4. Characteristics of noise and vibration

Elmenhorst et al. [50] refer to numerous research projects which may explain the difference in characteristics in sources leading to differences in reaction. This includes the spectral composition of noise which is shown to play an important role in the probability of awakening. For example, for railway noise, high frequency components are more likely to induce event-related arousals and increases in heart rate than low frequency events. The fluctuations in freight train sounds, the sharpness of the sound as well as the vibration characteristics of trains have been found to have an impact on people’s perception. Further review of psychoacoustic indicators and the spectral content of the noise source in relation to annoyance responses are provided in SNCF [53].

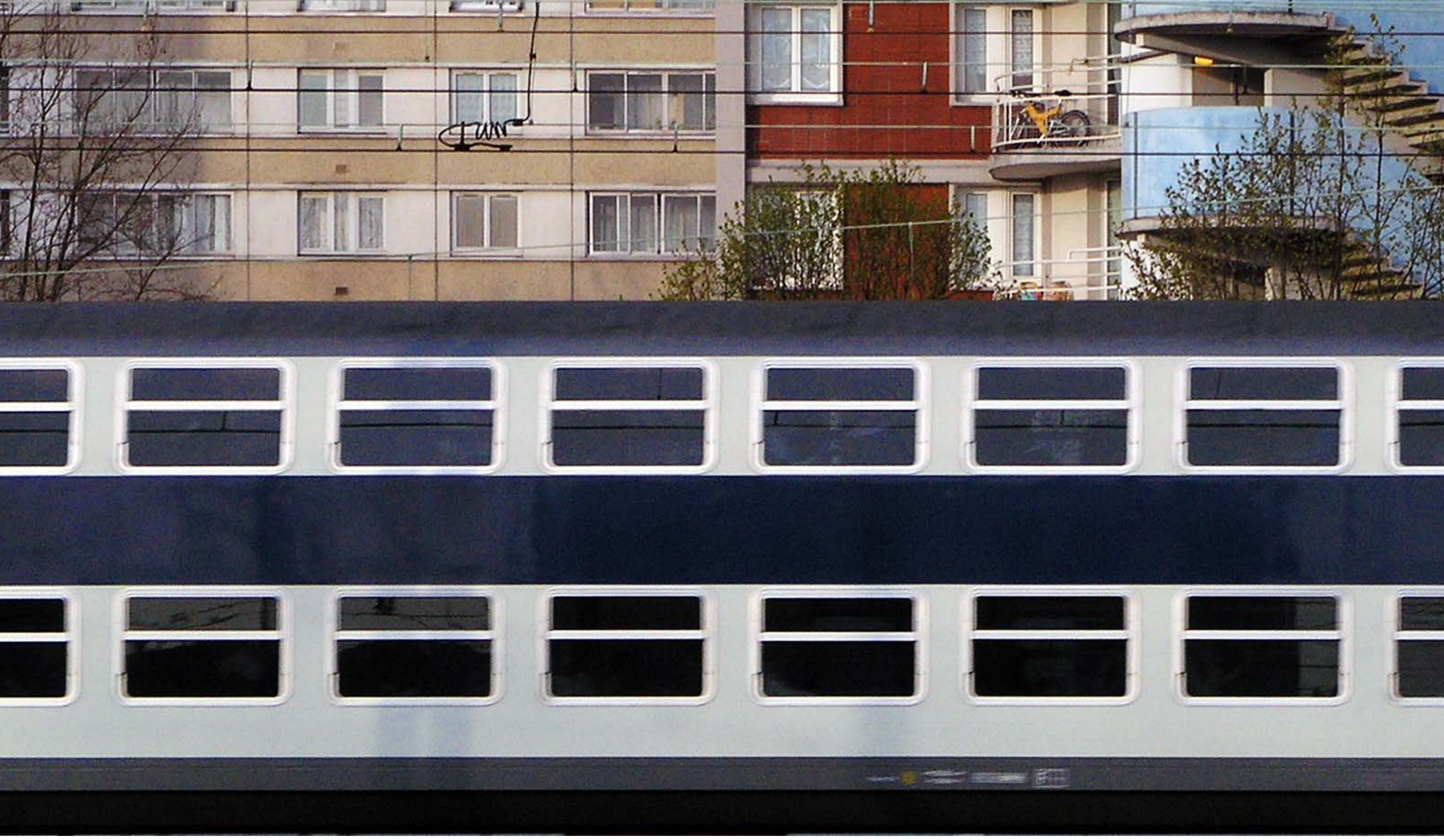
There are acoustic standards which recognise the importance of perceptions of sound when managing noise issues. Certain acoustic features can increase the significance of impact over that expected from a basic comparison between noise levels. For example, in the context of industrial and commercial noise (this definition includes some operations of railways), BS 4142 [56] makes allowances for **tonality**, **intermittency**, **impulsivity** and other **readily distinctive** sound characteristics. Originally (1997), the standard [57] was not based on substantive research and evolved from an experience-based method of assessing the likelihood of complaints. The current standard retains this experience accumulated over the years and allows for assessment of impacts more widely as well as the investigation of complaints in the described settings.

BS 4142 includes guidance on ‘subjective’ as well as ‘objective’ ways of determining acoustic character corrections based on research. Subjective methods may be applicable for example when a new source with known characteristics is proposed. As an illustration, the subjective penalties can be up to +6 dB for tonality, +9 dB for impulsivity and +3 dB for intermittency or other readily distinctive sound characteristics. Objective methods for determining the audibility of tones in sounds [58] or the prominence of impulsive sounds [59] are based on well-established methods. The “corrected” specific sound level (called rating level) is compared to the background noise level (dB L_{A90}) in the absence of the specific sound to enable an assessment of impacts to be made. Although not applicable to the operation of railways, the general approach and subjective/objective rating methods described in the standard could be relevant to identifying the impacts of atypical sounds. A key consideration would be establishing what is considered a typical railway operation as a baseline, in order to avoid prejudicing the intermittent operation of railways by nature.

When assessing complaints from helicopter and blast noise, it was found that a distinction between C-weighting (which measures both the audible and the low-frequency vibrational energy) and A-weighting (which measures only the audible energy) was a useful indicator in providing insights into the nature of complaints [45]. In this instance, it was found that many of the complaints were the result of noise-induced building vibration. In the railway environment, the use of C-weighting may be relevant for the assessment of relatively high-intensity sounds (e.g. impulsive sounds from trains over points) where humans are more sensitive to the lower frequencies or where ground-borne noise may be an issue (e.g. in the presence of substantial noise barriers or tunnels).

There are example approaches in the assessment of aircraft noise which could be applicable to railways. For example, the use of a “perceived noise level” PNdB indicator in assessing noise from aircraft operations aims to make an allowance for the specific nature of the source. In conjunction with the number of aircraft, “average peak” PNdB (logarithmic average of the highest levels of all overflights) has traditionally been used to derive a Noise and Number Index (NNI), which dates back to the Wilson Report [60] in 1963, to measure subjective annoyance to aircraft noise. When determining the subjective response to railway noise, the Swiss Federal Noise Abatement Commission assessment method applies noise level corrections to adjust for specific features, such as shunting noise and rail wheel squeal [61]. The application of the NACF to railway noise in Europe represents a similar approach to account for the characteristics of the source. This does not make a distinction between freight and passenger trains. Distinct vibration exposure-response curves between freight and passenger trains indicate that a similar differentiation may be desirable for noise to account more reliably for responses to different aspects of the railway [41].

There is a need for further research to identify robust and practical noise indicators which can represent the characteristics of railway noise more effectively.



3.6. Summary: impact of noise from railways

A review of recent key studies shows that there is an expanding evidence base on a variety of cardiovascular, metabolic and other critical outcomes and risk indicators associated with noise. Currently, the **self-reported** effects of noise on **sleep** and **annoyance** are two of the key indicators for evaluating health outcomes from different modes of transportation, including railways. These health outcomes are significant due to their relevance to health, policy and stakeholder engagement.

Various recent studies point to a general trend in the community to rate railway noise less favourably compared with two decades ago. However, the strength of the responses appears to differ widely between studies. The review undertaken by Guski et al. [37] indicates that some of the studies representing particular **local characteristics**, as well as **methodological differences** when analysing meta-data from social surveys, may have contributed to an increased percentage of %HA, due to the limited number of studies which were available for inclusion in the WHO analysis.

It is considered that global exposure response curves do not represent an optimal tool for **managing local issues** encountered along the railways and designing **mitigation**. The review has shown that local acoustic and non-acoustic factors should be taken into account in the identification of issues and measures along the railways to address these issues. Individual sensitivity, community perception, local physical characteristics as well as other confounding factors are relevant.

The railway sector is faced with noise **complaints** from the communities living along the railways, which is an active expression of dissatisfaction with the noise environment. There is a reasonable expectation on the railway sector to investigate and address complaints. A complaint may not always be directly linked to noise exposure but is typically a function of the "**arousal**" effect of noise. The review makes observations on the nature of community complaints to noise, based on past research. These are discussed further in Chapter 6.

The use of noise indicators such as L_{den} or L_{night} may limit the ability to observe associations between exposure to noise at night and some health outcomes such as **awakening reactions**. This has been identified as a supplementary health indicator. Although there is no robust reported link between “objective” (physiological) short-term sleep effects and long-term annoyance/sleep disturbance outcomes, the increased probability of awakenings from events affects quality of life. There is also a link between intermittent noise events at night and the likelihood of “arousals” leading to complaints. Further investigations in this area would be desirable to assess any potential relationship between long-term subjective sleep, short-term objective sleep and complaints at night.

Research indicates that the **judgement of acceptability** depends on the maximum noise levels as well as factors such as the type of source, number and the distribution, predictability and regularity of noise events. The parameters which could have significance as physiological sleep metrics for night-time noise protection include: number of noise events, maximum noise levels, event rise time in dB/s, length of noise-free period/relative calm and characteristics of noise.

Of the various noise indicators considered as a supplement to long-term indicators (e.g. L_{den}, L_{night}), it is noted that $\mathbf{L_{Amax}}$ is the indicator used most commonly in practice. It is used in the evaluation of short-term sleep effects, it is representative of “arousal” responses which may lead to complaints and it appropriately reflects the intermittent nature of railway operation and the large variability in emissions found in practice.

When considering appropriate target values during a reference time interval, L_{Amax} could be defined in a number of ways. The preferred way of expressing L_{Amax} would be with reference to its frequency of distribution, supplemented by additional descriptors to account for the **characteristics of railway noise**. There is a need for further research to identify robust and practical noise indicators which better represent the characteristics of railway noise.

The findings in Chapter 3 influence the approach to the identification of aspects of railway noise which elicit adverse subjective responses, and the methods to address them, as discussed in the next chapter.

4. Methods to reduce impacts from noise

The methods to reduce impacts from railway noise will depend on the nature of nuisance being addressed. As discussed in Chapter 3, self-reported effects, “objective” (physiological) sleep disturbance effects and complaints can be assessed using different indicators. This chapter provides an overview of main railway noise sources and operational parameters, as well as potential measures to address various impacts.

4.1. Sources of railway noise

In order to understand the nature of complaints generated by different aspects of railway noise, it is desirable to compare relevant studies that cover a range of railway situations - for example, busy railway lines with a combination of passenger and freight trains, low-traffic railways and high-speed railways with no freight trains.

The overview of the main health impacts shows that the social surveys forming part of the global response curves are focused on evaluating the perception of overall railway noise. Although noise from **high-speed** rail is reported separately due to its distinct characteristics, conventional **passenger** and **freight** services are typically considered as one. A case has been made in Chapter 3 for separate noise-exposure curves for passenger, freight or a combination of the two, following on from research which clearly shows higher annoyance responses to freight trains compared with passenger trains at the same vibration levels. In this sense, the application of a “railway bonus” might be more relevant to noise emissions from different railway noise situations, rather than the railways as a whole.

Commonly, complaint or social survey data is not reported in a way to allow an estimation of the relative contributions of passenger and freight trains (i.e. speed, number, type and composition of respective vehicle categories are not known in detail). In addition, the use of average noise indicators in standard calculation tools limits the ability to adequately quantify levels or to qualify characteristics of noise from certain aspects of railway operation, for example:

- general condition of the vehicle (e.g. wheel flats),
- general condition and level of maintenance of the track (e.g. corrugations) and
- some assets (e.g. squeal from tight curves, impact noise from joints, etc).

These features introduce additional uncertainty and variability to noise exposure data over and above the normally **intermittent** nature of railway noise.

Moreover, it is possible to make observations on the different components of railway noise which might give rise to community responses, by considering the operating speed of the line. A review of the main components of railway noise with operating speeds is provided in the UIC State-of-the-Art review [8]. It is well understood that the overall railway noise is dominated by **power/traction/auxiliary** noise at lower speeds (say <35kph), **rolling noise** at most operating speeds (35kph-250kph), and aerodynamic noise at higher speeds (>250 kph). Individually, each of these components displays a linear relationship with logarithmic train speeds. Acting as a whole, there is an interaction between different components, particularly at the cross-over speeds, to influence the overall noise from railways.

It was shown in Chapter 3 that noise effects associated with long-term exposure can be assessed better using the traditional L_{den} and L_{night} indicators. However, objective sleep disturbance effects and atypical aspects of railway noise which may be the cause for complaints could be characterised by L_{Amax}, supplemented by additional descriptors.

Typically, noise emissions from freight trains are more variable than passenger trains due to their make-up. Freight trains also result in higher noise levels in L_{Amax}, compared with passenger trains. In regular operational scenarios, where freight trains operate or where the speed of passenger trains is above 100kph, the maximum noise levels at 25m from the track are expected to exceed 80 dB L_{AFmax}. Taking into account more specific railway features (e.g. flanging, squeal from tight curves, impact noise from joints, train horns, wheel flats, etc), the levels could be significantly higher, more variable and tonal at certain locations.

Although it is not possible to robustly quantify maximum noise emissions in the railway environment (due to the great variability of operational parameters), it is useful to attempt a relative ranking of common noise sources to provide a relative risk of impact. The sources associated with the operation of railways and their likely noise contribution is presented in Table 1. The comparison is based on the range of L_{AFmax} which may be typically expected at a reference distance of 25m from the railway.

Table 1: Main Noise Sources under Different Operational Railway Scenarios

Operation Mode	Speed range kph	Main noise sources, L_{Amax} at 25m from track		
		Conventional Passenger Train	Freight Train	High-Speed Passenger Train
Stationary*	0	Idling engine and auxiliary Door alarm	Idling engine and auxiliary	Idling engine and auxiliary Door alarm
Low speed	<35	Traction noise Rolling noise	Traction noise Rolling noise	Traction noise Rolling noise
Normal driving**	80-140 (p) 50-100 (f)	Traction noise Rolling noise	Traction noise Rolling (wagons, cast-iron bakes) Rolling (wagons, composite brakes)	Traction noise Rolling noise
High speed	>250	N/A		Rolling noise Aerodynamic Pantograph (unmitigated) Pantograph (mitigated) Traction noise
Other	Various	Flanging, squeal from tight curves, impact noise from joints, train horns, wheel flats		
Legend	Red text: Typical noise emissions are above 85 dB L_{AFmax} Amber text: Typical noise emissions are 75-85 dB L_{AFmax} Green text: Typical noise emissions are below 75 dB L_{AFmax}			

* Noise from stationary sources is the subject of another UIC study currently in progress.
** (p) stands for "passenger" and (f) for "freight".

Table 1 highlights the general hierarchy of railway noise sources which need to be addressed to minimise nuisance and impacts on quality of life, in terms of long-term exposure (leading to self-reported health effects) and short-term effects (probability of awakenings) and the likelihood of "arousals" leading to complaints. A selection of measures to minimise impacts are discussed below.

4.2. Mitigation measures

There are three main approaches to noise mitigation:

- At source (infrastructure measures and quieter rolling stock),
- Propagation path (noise barriers) and
- At receiver (sound insulation treatments).

UIC [8] outlines the most common noise mitigation measures used on European railways. In addition, the PHENOMENA project [15] assessed the potential health benefits of noise abatement measures and the mitigation measures included in the EU Member States' noise action plans (NAP) submitted in accordance with the END.

Based on these studies, Table 2 summarises the most common mitigation measures and the associated estimated noise reductions.

Table 2: Common mitigation measures and associated noise reductions

<table>
<tr><th colspan="2" rowspan="2">Mitigation Measure</th><th colspan="3">Typical Noise Reduction (dB)</th></tr>
<tr><th>Freight</th><th>Conventional Passenger</th><th>High-Speed Train</th></tr>
<tr><td rowspan="7">At Source</td><td rowspan="2">Infrastructure measures
(rail grinding and milling, quieter rail pads, rail dampers or rail shielding)</td><td>Rail grinding 0-5 dB</td><td>Optimised rail pad 0-4 dB
Rail grinding 0-5 dB
Rail dampers 0-3 dB
Rail shielding 0-4 dB</td><td>Rail grinding 0-3 dB
Rail dampers 0-2 dB</td></tr>
<tr><td colspan="3">Avoiding having turnouts/crossovers with impulsive noise near sensitive receptors. Potentially 10 dB noise reduction, however could have significantly more beneficial effect due to removing the “annoying” characteristics.</td></tr>
<tr><td rowspan="3">Quieter rolling stock, including smooth, damped or optimized wheels and quieter powertrains</td><td>Similar to removing turnouts/crossovers close to receptors, eliminating curve squeal or flanging through rail friction modifiers may have similar effects.</td><td>Optimised wheel geometry 0-1 dB
Wheel dampers 1-3 dB
Bogie skirts 0-3 dB</td><td rowspan="2">Optimised wheel geometry 1-2 dB
Wheel dampers 1-5 dB
Pantograph design 0-4 dB
Bogie skirts 0-2 dB
For high-speed trains, a further reduction of 1-5 dB in aerodynamic noise is considered feasible by streamlining, in future years for new rolling stock.</td></tr>
<tr><td colspan="2">For electric and diesel locomotives and powered units a potential of 5 dB reduction in traction noise is estimated to be achievable for units older than 10 years.</td></tr>
<tr><td colspan="3">Additional benefit is that this mitigation takes effect throughout the whole network, in contrast to most other measures that only work locally.</td></tr>
<tr><td rowspan="2">Traffic management including re-routing, speed restrictions, access restrictions or noise access charging.</td><td>Noise-differentiated track access charges (NDTAC). Noise reduction is variable depending on the uptake by wagon owners and operators, indicatively 2-3 dB</td><td></td><td></td></tr>
<tr><td colspan="3">The UIC [8] advise caution against assuming noise reductions due to traffic planning such as speed reduction and traffic re-routing, because it would result in a reduced capability of the network in an already constrained situation.</td></tr>
<tr><td rowspan="3">Propagation Path</td><td rowspan="2">Noise barriers, standard or special, including absorbent and low barriers near the track</td><td>>10 dB</td><td>>10 dB</td><td>>10 dB</td></tr>
<tr><td colspan="3">The noise reduction strongly depends on the height of barrier and situation, but typically reductions of 10 dB and higher are found at the receiver relative to the near track. For close barriers the reduction is around 3-7 dB depending on the configuration. The effect is largest for barriers close to the source or to the receiver.
Barriers reduce all the main railway sources of rolling, traction and aerodynamic noise, but sufficient height is required to reduce higher sources such as exhausts, roof-mounted equipment, and aerodynamic sources such as pantographs and roof discontinuities.</td></tr>
<tr><td>Urban and spatial planning, increasing sound attenuation between source and receiver by buildings, urban layout, including renovation and reconstruction</td><td>>10 dB</td><td>>10 dB</td><td>>10 dB</td></tr>
<tr><td rowspan="2">At Receptor</td><td rowspan="2">Sound insulation of residential and communal buildings, including funding schemes for homeowners</td><td>>10 dB</td><td>>10 dB</td><td>>10 dB</td></tr>
<tr><td colspan="3">The noise reduction is only within the dwelling with windows closed, and from 10 dB up to around 40 dB depending on the glazing type and the inclusion of further façade insulation. The noise level at the façade, which is a crucial element of environmental noise legislation, is not affected.</td></tr>
</table>

The most commonly implemented mitigation measure for railway noise in most countries has traditionally been lineside noise barriers or façade insulation. However, the PHENOMENA study [15] shows that the most commonly specified noise abatement measure as part of the EU Members NAPs was rail/track improvements. This shows the changing emphasis over the years towards mitigating the source of the problem.

The modal shift from road and aircraft to rail, as a sustainable form of transport, could also act as a potential noise abatement measure [15], noting that this would reduce noise emissions from road and air traffic rather than on railways.

In practice, there are limitations to noise reductions achievable by the mitigation methods highlighted above. UNEP [7] describes noise abatement as a public health issue, highlighting the importance of desirable soundscapes. As a concept, this could encapsulate the creation of relatively quiet areas, encouraging natural sounds and reinforcing sounds we value in our cities. In the context of railways, it could represent an innovative approach to dealing with the characteristics of railway noise which may lead to annoyance/sleep disturbance and complaints, highlighted as a gap in Chapter 3. For example, the FAMOS study [33] currently in progress aims to assign benefits to non-acoustic factors responsible for community annoyance responses. These benefits will be expressed in terms of equivalent subjective decibel changes. In circumstances where actual reduction of noise levels may no longer be feasible, this approach could be used to reduce the adverse community impact of road traffic noise by addressing the non-acoustic moderators.

There is a need for research to combine the conventional mitigation efforts with innovative ways to more specifically address annoyance/ complaints caused by railways.

4.3. Working with communities

The range of mitigation measures described above provide typical noise reductions in decibels to minimise overall exposure to noise. However, this approach does not adequately deal with the “arousal” aspects of atypical high-noise events leading to short-term sleep disturbance and complaints, highlighted in Chapter 3. Experience in the mitigation of noise across other industries indicates “hard” and “soft” methods should be considered together to control the perception of sound along railways, particularly with regard to complaints. With potential worsening attitudes to railway noise, working closely with the communities is key to the sustainability of the rail sector.

A clear distinction needs to be made between new and existing railway lines in terms of the suitability of mitigation measures. In the case of a new railway line, it is feasible to plan, design and build multiple, effective noise-reduction measures to a high specification as an integral part of the overall infrastructure. In the case of existing railway lines, physical mitigation measures such as noise barriers may not be appropriate due to space restrictions or the retrofitting of track measures may be hugely disruptive to the operation of the railway. The reasons for the appropriate action taken need to be clear to enable public scrutiny.

Chapter 2 highlights the initiative of retrofitting freight wagon brakes across Europe. A recent review [62] estimated that 80% of the freight wagon fleet would be quieter by 2035. If a freight train partially comprises wagons with noisier brakes, this prevents the overall benefits from being fully realised. A similar focus will be needed to address specific issues which may need attention as part of ongoing maintenance (e.g. wheel flats, etc). This requires a concerted effort to maintain the existing state of the acoustic environment, rather than reducing noise exposure, which would be expected with a traditional “noise mitigation” measure.

This in turn requires having simple, transparent and effective processes in place to capture emerging concerns, take the required action, evaluate the effectiveness of actions and provide a feedback loop on lessons learned as part of continual improvement. Over the decades, liaison with the general public has become central to the management and control of construction noise, for example, and forms part of Best Practicable Means (BPM), which are defined in the UK legislation and can be a defence against prosecution under the law. BPM measures may include provision of a 24-hour hotline and a responsible point of contact to follow up on any issues raised.

The railway sector is very diverse in terms of its roles and responsibilities across geographic boundaries and types of assets. From a community perspective, whether a noise issue is related to the performance of a track or a train may not be particularly relevant beyond the nuisance caused. The overall perception is that this is a "railway"-related issue. Similarly, it is not desirable to put the burden on the community to identify the correct authority to resolve an issue. A review of previous studies indicates that a large proportion of complainants tend to complain multiple times, and if complaints are not dealt with in a timely fashion, the severity of the complaint could escalate (e.g. into a legal case) [63]. A local train operating company, a trans-national freight operating company and a track asset owner may all need to work together to tackle issues. This necessitates a proactive sharing of information, knowledge and experience across different sectors to identify the issues and take appropriate action. Further research is required to identify a suitable framework to assist ongoing management initiatives in the railway sector.

These considerations highlight the importance of active stakeholder communication with individuals, communities, action groups, local authorities and other interested parties. The feasibility and cost-effectiveness of mitigation measures along existing railways is a key consideration in identifying suitable measures, and should form part of these discussions when engaging stakeholders. The next chapter provides an overview of techniques to balance the costs of these measures with the community benefits as part of the whole life cycle of railway assets.

4.4. Summary: methods to address impacts due to noise

This chapter has highlighted the different types of noise sources typically associated with railway noise and their different characteristics. Table 1 provides a high-level summary of the general hierarchy of railway noise sources which need to be addressed to minimise nuisance and impacts on the quality of life.

The potential need for different measurement indicators to accurately capture the relative annoyance from different railway noise sources and their different characteristics was outlined with a reference back to the more detailed discussion in Chapter 3.

As discussed, it is believed that future mitigation will need to combine the conventional mitigation efforts with innovative ways to more specifically address annoyance/complaints caused by railways. Furthermore, it will be important for infrastructure managers and operators to work together to achieve cost-effective mitigation to further reduce railway noise.

5. Economic considerations

Health effects from railway noise can result in economic impacts on local and national scales through increased healthcare needs and productivity loss. Noise abatement measures to reduce railway noise levels and their associated health impacts involve capital expenditure and maintenance costs while also providing economic benefits from improved health of the noise-exposed population benefiting from these measures. The monetisation of noise costs and benefits can establish the scale of the noise impacts from railways and provide decision-makers with tools for taking appropriate action. This chapter provides an overview of the costs associated railway noise in Europe and the monetisation processes used appraise noise abatement measures.

5.1. Economic burden of railway noise in Europe

According to the EEA [64], approximately 16 million people in the EEA-32[1] (excluding Turkey) are affected by night-time railway noise in excess of 50 dB L_{night}. It is estimated that 4.3% of the population (22 million people) are affected by rail traffic noise levels that exceed the thresholds of the END during the day-evening-night period (55 dB L_{den}) and 3.4% (17 million people) during the night-time period (50 dB L_{night}), including contributions from passenger and freight services [12] [64].

The noise-induced health impacts from railways create external costs to society and the economy through increased healthcare pressures and requirements, loss of productivity and wider impacts to the environment due to noise such as noise-related impacts to ecological receptors [15]. Recent research tentatively indicates that approximately 1 million Disability Adjusted Life Years (DALYs) are lost every year due to health effects from environmental noise, namely annoyance, sleep disturbance, heart disease and cognitive impairment in children (aviation noise only for cognitive impairment) [12]. It is acknowledged that this figure may include double counting [12]. Road traffic noise and railway noise were responsible for 75% and 20% of this burden respectively [12]. The railway noise burden affected over 2.4 million people in urban areas and over 5.2 million people outside of urban areas in 2017 within the EEA-33[2] excluding Turkey [12].

The economic burden of railway noise is evaluated using a form of cost-utility analysis, which calculates impacts in public health units such as DALYs or Quality Adjusted Life Years (QALY) [65], from which financial values can be assigned as required [15]. For example, monetary values for DALYs can be assigned using the European Commission's handbook on the external costs of transport [66], where economic values in units of Euros/dB/person/year are provided and disaggregated by annoyance and health effects for each of the L_{den} noise bands used for strategic noise mapping [15]. However, the European Commission's handbook [66] does not allow monetisation or disaggregation for specific health effects such as sleep disturbance, which the European handbook classifies as "annoyance" [15]. Alternative sources for monetary values exist to represent costs for specific health effects, such as Vito [67], Defra [68], Department for Transport [69], the HEIMSTA project and Heatco [70]. Some tools used fixed costs: for example, Heatco assigns EUR 59 per annoyed/highly annoyed person per year for railway noise [70] whereas others use non-linear pricing to reflect the greater costs of high noise levels and the benefits of reducing them [69].

[1] Defined in [64] as the 32 member countries of the EEA as of 1 February 2020 (27 EU Member States plus Iceland, Liechtenstein, Norway, Switzerland and Turkey)

[2] Defined in [12] as the 33 EEA member countries of the EEA (28 EU Member States plus Iceland, Liechtenstein, Norway, Switzerland and Turkey)

The total cost of railway noise in the EU-28 was estimated to be approximately EUR 4 bn in 2016 [12]. Approximately 75% of the total cost is associated with conventional electric trains, which is attributed to the operation of these services in urban and metropolitan areas that have higher population densities and a greater population size that has the potential to be exposed to noise [64]. In terms of DALYs, the WHO [71] reported 32,080 to 384,960 DALYs in 2010 for highly annoyed people exposed to railway noise and 24,743 to 61,587 DALYs for sleep disturbance, both in agglomerations of 50,000 or more inhabitants[3].

The calculated DALYs or monetary costs of railway noise are likely to underestimate the true costs as health effects within populations exposed to railway noise levels below the 55 dB L_{den} and 50 dB L_{night} END noise bands are not considered [12]. Additionally, strategic noise mapping is limited to strategic transport routes and agglomerations, so it does not cover every railway and may not cover the entirety of a country's territory. Emerging noise-related impacts from other health conditions, such as breast cancer, respiratory disease and mental health problems, are generally not included in monetisation [12]. Costs related to productivity losses, noise impacts to ecology and indirect effects also tend to be excluded from such calculations [12] [65]. Further research is required in these areas to understand their impact pathways to allow monetisation to occur [68].

[3] The wide variation in DALYs reported in WHO (2011) is linked to the selection of disability weighting factors. The ranges presented cover the best- and worst-case outcomes in DALYs.

5.2. Monetisation of noise impacts for rail schemes and mitigation measures

5.2.1. General approaches to monetisation

Economic values can be assigned to railway noise to evaluate the economic sustainability of a rail scheme at project level (such as for preparing the business case for the project) and to justify the introduction of noise abatement measures at certain locations. Examples of monetising the costs and benefits of noise abatement measures for railway noise are provided in the PHENOMENA project, along with corresponding DALY figures with and without interventions [15]. It is important to understand the real-world noise problem affecting populations in proximity to railways prior to implementing noise abatement measures, to ensure that the most effective approach is used.

The EPA Interest Group on Traffic Noise Abatement [65] identified several methods for monetising noise costs and benefits, namely Cost Minimisation, Cost Effectiveness Analysis, Cost Utility Analysis, Cost Benefit Analysis and Multi-Decision Criteria Analysis. Current approaches to monetising noise costs and benefits are built on previous work undertaken in this area, such as EURANO [72], STAIRRS [73], UNITE [74] and the Heatco project. The European Commission's handbook on the external costs of transport [66] provides a specific approach on how noise from road, rail and aviation sources can be monetised. The proposed methodology uses a "bottom-up" approach based on 5 dB noise bands of the L_{den} metric with a lower limit of 50 dB and the population size exposed to each of those noise bands. The health costs (including annoyance) per capita are calculated using the harmonised environmental pricing and marginal economic costs stated in the handbook, which provides weighting factors and costs per vehicle kilometre for different modes of transport and vehicle sub-categories. The use of harmonised values enables like-for-like comparisons between different countries in Europe, but the absence of harmonised values for benefits does little to overcome the large variation between countries in their Willingness-To-Pay models. UIC [8] discusses the method stated in the handbook [66] in depth and acknowledges that the "5 dB rail bonus" is no longer included in the current pricing mechanism.

5.2.2. Monetisation approaches implemented in Europe

Research commissioned by the EPA Interest Group on Traffic Noise Abatement [65] was able to collate the approaches used for noise monetisation by a small number of European countries. It indicated that monetisation of noise is rarely a national legislative requirement and is most often undertaken as a decision-making tool for evaluating noise abatement measures.

To understand the decision methods and cost/benefits regarding noise abatement measures, the study issued a questionnaire through the Eionet network, which led to reporting detailed information for five countries: Belgium, Germany, the Netherlands, Switzerland, and the UK [65]. The questionnaire responses are summarised below:

- Belgium and Germany use flow charts for evaluating the ability of noise abatement measures to reduce noise levels below defined limit levels, with different approaches to pricing noise costs in each country.
- Hedonic pricing methods are used in Germany and the Netherlands to calculate noise costs, whereas Switzerland uses this method to monetise benefits.

- The Netherlands uses a Cost-Effectiveness Assessment method that includes "knock-out" criteria that may prevent a cost-effective noise abatement measure from being used, for example, if it blocks daylight. Costs and benefits are not expressed in direct monetary units and are not directly linked to public health.
- Switzerland and the UK use a Cost-Benefit Analysis to determine the appropriateness of noise mitigation measures and whether they meet certain cost-effectiveness or value-for-money criteria. Evidence of Swiss Railways SBB using other monetisation tools, such as Multi-Decision Criteria Analysis, was also reported.
- The UK's monetisation approach is based on health impacts from noise, where a DALY has a monetary value of £60,000 [74]. The appraisal worksheets use QALY valuations and Disability Weighting for daytime noise impacts and include a highly annoyed response function [75]. Night-time impacts are also assessed. The value of the noise changes from the mitigation measures or a new rail scheme are adjusted using Gross Domestic Product (GDP) deflators and the growth in GDP per capita to calculate a net present value [75].

The study found that there was not a consistent approach on what is included in the expression of costs or benefits among European countries, although use of noise reduction in dB combined with the population size benefitting from the noise abatement measure was widely reported [65]. Where health-related costs are appraised, the study found that these focussed on annoyance, sleep disturbance and heart conditions. None of the countries discussed in the study incorporated productivity costs and benefits in their monetisation.

5.3. Summary: economic considerations

A number of approaches exist for calculating the noise-related health costs of railways and for the economic appraisal of noise abatement measures. Although the methodology selected varies from country to country, strategic noise mapping and noise predictions provide a common starting point. The limitations of strategic noise mapping were reported to lead to underestimations of the size of the population exposed to railway noise, with knock-on effects on the monetised, noise-related health impacts.

As the body of research continues to grow on health effects that can be caused or exacerbated by noise exposure, it is necessary to ensure that monetisation tools are regularly updated to include new evidence on health effects. Monetisation tools currently exclude productivity losses, impacts to ecology and indirect effects, but should seek to include these factors when further information becomes available.

6. Situation in European railways

This chapter provides the outcomes of research undertaken by Atkins to further establish the specific railway assets and infrastructure on European railways leading to annoyance, noise impacts and complaints. Approaches used for investigating complaints and factors affecting the selection of noise abatement measures are also discussed, with examples of best-practice approaches provided.

6.1. Current information available

The general perception in the railway industry is that the noise levels are decreasing due to a range of innovations and mitigation measures being employed across Europe. However, the percentage of population annoyed and sleep disturbed at a given noise level, as reported in WHO Guidelines and other recent research highlighted in Chapter 3, have become more adverse over the years. There is a perception that the rate of complaints from communities living along parts of the railways remain high. The driving factors that trigger individuals to complain about railway noise exposure has not been addressed in previous UIC studies, nor is there currently available data on the number and nature of complaints, or how they are successfully resolved.

As discussed in Chapter 3.4, complaints are a reaction to noise annoyance [47]. To address current information gaps on complaints along European railways, Atkins prepared and issued a questionnaire. Further information on the themes covered in the survey and the survey methodology is provided in the sections below.

6.2. Survey methodology

An online questionnaire was issued to railway infrastructure managers and operators to better understand the causes of railway noise complaints linked to the infrastructure management, operation, and maintenance of railways across Europe [1] [77]. The questionnaire was prepared by Atkins and was managed through Microsoft Forms. The scope of the survey and the survey questions were reviewed and approved by UIC and the Steering Group. The survey included questions on the following topics: regulatory framework, general complaints management, noise indicators, mitigation measures and complaints history at hotspots on the participant's network. The survey was open for responses from 24 November 2021 to 22 March 2022 and was accessed through a link that was circulated among UIC members and other invited participants through an e-mail newsletter issued by UIC. Reminder e-mails were also issued to encourage participation. The survey focussed on the following aspects of noise complaints:

- What kind of complaints are generally received?
- How are complaints handled?
- What drives the actions to resolve complaints? Is it legislation driven, or goodwill driven?
- Noise metrics used to investigate complaints
- Factors influencing the selection of noise abatement measures and their efficacy once installed
- General feedback and experience

A range of specific case studies of complaints has been provided by survey respondents. They are replicated in full in Appendix B. The content of these case studies has been utilised in the following survey result discussions, whenever elements are relevant.

The data gathered from the survey has been used to provide context for the complaints encountered in Europe. The survey was used to identify the most frequently reported noise issues by the lineside population.

Noise complaints from construction activities, depots and fixed stationary sources at stations were outside the scope of this study. Excluded noise sources at depots and stations included Public Address systems, idling trains and HVAC systems serving the depot or station.

The main limitations of the survey are associated with the small sample size and that complaint statistics are based on operator/infrastructure manager interpretations of received complaints rather than a direct analysis of complaint records.

6.3. Survey results

The questionnaire was completed by 18 stakeholders from various European and international railways. The respondents included a mix of operators and infrastructure managers. Eleven of them were infrastructure managers (ten of which operate within a single country and one across Europe), two were operators (one operating within a single country and one operating internationally) and five were both (four operating within a single country and one internationally). Respondents representing a total of fifteen different countries participated in the study, including SBB (Switzerland), Trafikverket (Swedish Transport Administration), SNCF (France), Sydney Trains (Australia), IP (Portugal), ProRail (the Netherlands), SZCZ (Czech Republic), Network Rail (UK), Transport for London (UK), Serbian Railways (Serbia), Deutsche Bahn (Germany) and other respondents that wished to remain anonymous.

It is considered that this wide participation across the industry provides a robust basis for drawing conclusions about the overall picture regarding noise annoyance, noise impacts and complaints. The survey respondents represent countries accounting for 64% of the total length of railways in Europe based on 2019 data [78], amounting to over 150,000 km.

6.3.1. Regulatory framework on noise levels

The majority (15/18) of respondents acknowledged having legal noise limits for their operation (refer to Figure 3); two non-EU member countries did not have legal limits (Network Rail and Sydney Trains) and one Infrastructure Manager from EU did not know whether there were any legal limits that applied. Of the two respondents that did not have any legal limits of operation, one of these (Sydney Trains) is still obliged to investigate all complaints received and to outline the action taken in relation to the complaint. Sydney Trains is also required to submit monthly and annual reporting of complaints to the Environmental Regulator.

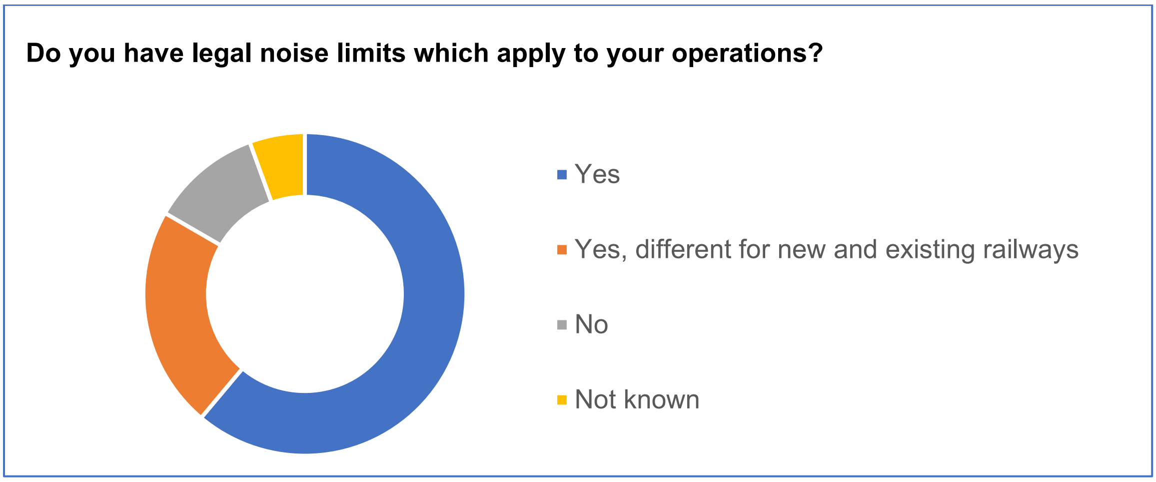


Figure 3: Questionnaire responses on the use of legal noise limits

Overall, the responses illustrate that the emission of noise from the railways is well regulated across the rail sector, either in the form of legal limits or other Regulatory Controls.

6.3.2. Train and infrastructure types

Of all the survey respondents who acknowledged having legal noise limits, the majority (11/15) declared that they had different laws and standards for the existing railway compared to new railways, see Figure 3. An example of how these are differentiated is having more stringent noise limits for new lines compared to existing lines (typically by 5-10 dB) or having limits for new lines additionally based on the change in existing ambient noise. Additionally, the majority (11/15) of respondents do not differentiate between passenger trains, high-speed trains and freight trains in relation to operational noise limits. Respondents that do differentiate between passenger trains and freight trains tend to include some of the larger European railway networks (representing about 25% of the total length of railways in Europe).

Differentiating between new and existing railway infrastructure acknowledges that a change in noise is perceived more annoying than an existing noise and demonstrates a pragmatic approach, by recognising that the opportunities for controlling noise emissions are far wider when designing new infrastructure. However, the “global response curves” do not make the distinction between new and existing networks. Similarly, global curves represent steady-state conditions, and step-changes in noise may not be reflected adequately. Furthermore, the treatment of passenger and freight traffic as a combined noise source in the majority of cases could prevent effective actions from being identified. This is compounded by the fact that “global response curves” do not differentiate between freight and passenger trains, even though high-speed trains (i.e. Shinkansen) are treated separately in the WHO exposure response curves for annoyance. A review of the research shows that freight trains at night represent a large part of the problem. There is also similar evidence emerging from industry responses below.

6.3.3. Regulatory framework on complaints

In contrast to above, only eight respondents out of eighteen have a legal requirement to act on complaints. Of these, one respondent clarifies that the legal obligation to act on complaints is only where the noise limits are breached, not due to the complaint itself. The courses of action could involve undertaking appropriate evaluation of the complaint received (e.g. compared to noise limits) and addressing the issue, either by mitigation or by appropriate response if limits are not exceeded or further mitigation is not possible/necessary in this case.

The industry response may go some way towards explaining the observation that complaints along parts of the network remain high even though the overall noise levels have been reduced over the years. As explained earlier in the report, complaint statistics are somewhat disconnected from noise emissions and not always linked to a certain noise level being exceeded. Having noise limit values may be desirable for transparency and the effective use of public funds for prioritising mitigation measures. However, on their own and without consideration of the subjective “arousal” effect of noise, the approach may have some limitations. This is an opportunity for the industry to manage complaints via sharing and the implementation of a framework of best practices, further highlighted in the sections below.

6.3.4. Number of complaints

One of the central questions in this study was whether the rate of complaints from communities living along parts of the railways remain high.

Half (9/18) of the respondents indicated that they received more than 1,000 noise complaints over the past five years, of which two received more than 5,000 complaints. The annualised complaint figures would be lower. There are no published data in the railway sector to act as a benchmark for these complaint statistics. However, relative to complaint statistics from a major airport, the figures seem favourable. For example, in 2020 and 2021, Heathrow Airport received one complaint for every five flights on average. This represents an intensification in complaints compared to 2018 and 2019 when one complaint was received for every six to seven flights (even though number of both the flights and the complaints were lower in 2020 and 2021). For a major railway with at least 30,000 train passages per year, 5,000 complaints over five years would represent a significantly lower intensity of complaints. When compared with the millions of people in the EU member countries affected by night-time railway noise in excess of 50 dB L_{night} (Chapter 5.1), complaint statistics seem modest.

The questionnaire did not seek clarity on whether a proportion of the complaint data may have resulted from repeat issues (i.e. number of complaints vs number of complainants). This analysis could provide a further evidence base for prioritising actions. In the case of Heathrow Airport, for example, 475 people complained once in 2021, and 6 people complained more than 1,280 times.

Generally, the number of complaints can be correlated to the size of the rail operator/network; however, there are some exceptions; where a relatively small network has a larger number of complaints (ProRail, Netherlands), and a relatively large network (Network Rail, UK) has a smaller number of complaints. This may be due to differences in the way complaint statistics are captured, or possibly indicates a direct connection with the density of population living along different networks.

6.3.5. Complaint management

The majority (14/18) of the respondents have a dedicated team to deal with noise complaints; the majority of these (10/14) maintain records of noise complaints on a central system. Of the four respondents that do not have a dedicated team to deal with noise complaints, two of these still maintain records of complaints on a centralised system. The responses show that noise complaints are generally monitored well and recorded in a way to enable future analysis. This practice is not always driven by an obligation to act on complaints (see 6.3.3). It is partly shaped by external stakeholder pressure and a desire to minimise reputational risk to the railway sector. It also demonstrates a strong sense of social and environmental responsibility.

In addition to the typical details regarding the time and location of the complaint collected by most respondents, it is also common to include information about the character or type of noise causing the complaint. Some respondents collected and recorded additional detailed information related to the complaints, including:

- Building or land usage, e.g. is the property used as and designated as a dwelling, how old is the building, is the property near old, upgraded or new tracks and the distance to the railway.
- Whether the noise emission is considered new or has been occurring for a while, and whether there have been more complaints in the same area.
- Whether noise mitigation measures have already been implemented in the area.
- Details of railway infrastructure, e.g. ballast type, sleeper type, fixation, rail type (including presence of joints) and track condition.

- Types and numbers of trains.
- The subjective character and intensity of the noise.
- The approximate noise levels from END noise mapping.
- An assigned priority level for addressing the complaint, based on likely noise reductions necessary.

Generally, a sufficient level of information is collected to enable meaningful analysis of complaints. There is some variation across the networks on the nature of data captured, some more comprehensive than others, which affects the depth of analysis possible. This is an opportunity for better sharing of best practices across networks to improve the complaint management process. The additional information described above could provide better context helping with the assessment of complaints. For example, the building details are not commonly documented. Referring to research in Chapter 3, this could provide an indication on whether vibration issues on certain types of buildings could be exacerbating noise complaints. As a further example, information on mitigation measures could identify if mitigation has improved the history of complaints in the area. Detailed knowledge of railway infrastructure could identify whether a change in the network leads to complaints over time.

6.3.6. Stakeholder communication

The most commonly used channels to register complaints were reported to be by e-mail, either directly from individuals or via an authority. It is clearly good practice to capture complaints formally in a written format. However, it may be desirable to consider whether standard online forms could streamline the initial process of data capture and analysis. This would make it easier to gather pertinent data in a consistent way for investigation, response and future reference, for example if the issue repeats itself. This would provide the noise complaint teams with more time to deal with the issue. In instances when the complaint may be linked to a number of issues, this would enable input from multiple specialist departments.

Effective communication is an integral part of tackling noise complaints, and it would be desirable for the teams to follow up the reported issue with the complainant over the phone, and where possible, face-to-face. This enables additional levels of information to be captured on the underlying causes of the complaint at a human level. The majority (12/18) of respondents collaborate with the complainant to address the complaint as far as reasonably practicable, and of those who do collaborate in addressing the complaint, the majority (8/12) further collaborate with the stakeholder regarding the evaluation or analysis of the complaint. One respondent stated that they collaborate with the stakeholders regarding the evaluation or analysis of the complaint but do not necessarily collaborate to address the complaint.

The methods for investigating complaints frequently include formal written responses, often based on noise assessments and modelling. One response noted that END noise mapping is relied on when investigating complaints from existing railways. The majority (11/18) of respondents stated that noise monitoring is never or rarely used to investigate complaints. The main exception for this was Network Rail UK, who indicated that noise monitoring is undertaken frequently to identify issues with the infrastructure or to quantify the scale of the noise problem at the location of complaints, so that mitigation can be planned and presented to residents. The most frequent method used for communicating results of investigated complaints is through a formal written response.

When a complaint (or group of complaints) is investigated and the noise levels are found to be compliant with national standards/laws/requirements, the majority (12/18) of survey respondents would not take further action on the complaint. A complaint could have the potential to escalate if the resident perceives that the authority is not positively engaging to help. The general disconnect between the nature of complaints and the noise levels has been highlighted in Chapter 3 of this report. Noise limits represent an aspiration to minimise long-term noise exposure (e.g. L_{den}, L_{night}). However, there are no exposure-response relationships for noise complaints. In this sense, a factual report linked to noise limits, without the consideration of complainant sentiment, may not resolve the complaint fully. The following are examples of good practice for addressing this further.

Five respondents noted that they would undertake further noise surveys and/or site visits despite the legal noise limits being met. Typically, these cases involve groups of highly disturbed complainants or potential track defects causing complaint, that require maintenance inspection but do not necessarily result in the noise level limits being exceeded. This represents the next level of engagement in the eyes of the public (i.e. being visible) to better communicate the issue, even if there are limited physical options available to the operator or infrastructure manager. This approach presents an opportunity to listen and to build a positive stakeholder relationship. For example, local noisy maintenance operations could be communicated to the neighbourhood via letter drops ahead of the work taking place, clearly explaining the nature of short-term disturbance, and providing background on the necessity of the works for safe operation of the railways. Another positive example emerging from the survey is engagement with the general public to provide clarity on the decision-making about how mitigation measures are prioritised where the noise levels are highest.

Frequently, it may not be possible to mitigate the underlying cause of the noise complaint. However, a better provision of information, communication and consideration of community sensitivities could help to address the frequency and severity of complaints.

6.3.7. Details of complaints

The details summarised here regarding the nature of complaints are supported by a review of research reported earlier in the report (see 3.4.5). The most common concern by complainants is a disturbance to sleep or rest during the night. Other common concerns are health consequences and the depreciation of real estate. There are also concerns regarding the perception of not being listened to and/or improvements being unlikely (i.e. the attitude of the railway industry to resolving complaints). The significance of stakeholder communication was highlighted in 6.3.6.

The majority (10/15) of the respondents did confirm that they received complaints about vibration, either separately from or in combination with a noise complaint.

The most common railway features causing complaints were ranked as follows:

1. Freight trains
2. New, upgraded or altered infrastructure
3. Maintenance operations (e.g. rail grinding)

Other features, stated as being common causes of complaints, included the frequency of services, points (i.e. turnouts and crossovers), tight curves and train horns, as shown in Figure 4.

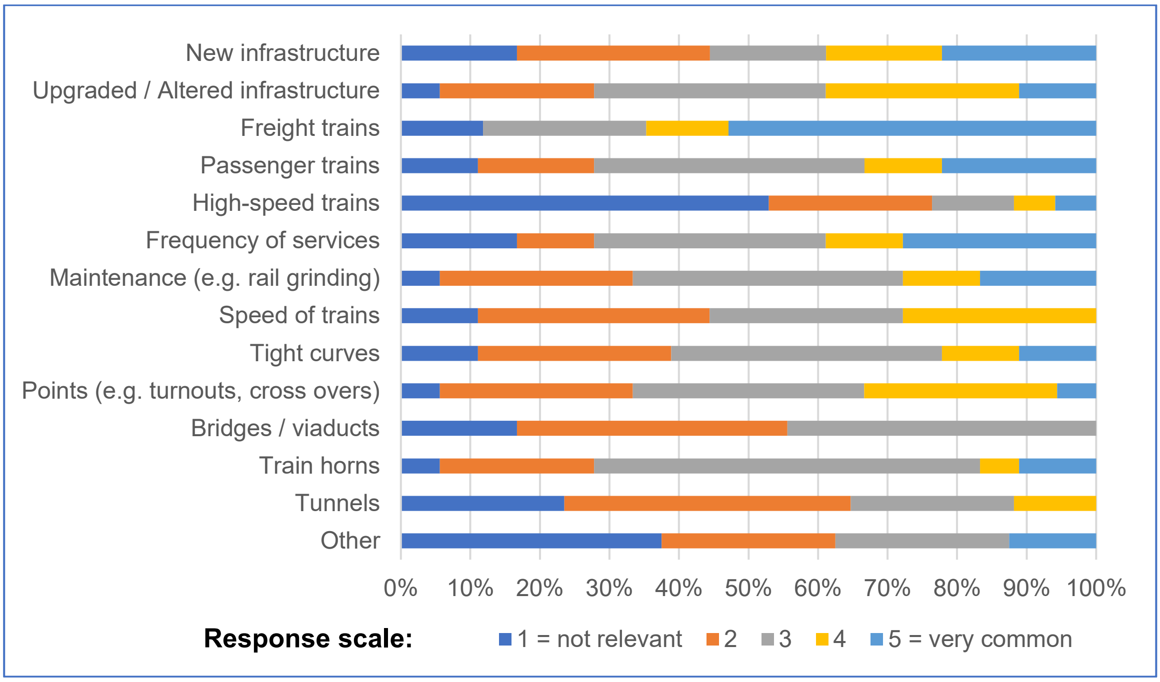


Figure 4: Railway features and how common they are in causing complaints

The case studies in Appendix B support the observations above, in that all reported case studies for complaints are on “atypical noise” (i.e. rail grinding, curve noise), change in noise, areas of extreme sensitivity or where noise limits are exceeded and are difficult to mitigate for various reasons.

The noise indicators used most frequently for investigating complaints are $L_{Aeq,T}$, L_{night}, L_{den} and L_{Amax}. The limitations of indicators such as $L_{Aeq,T}$, L_{night}, L_{den} were highlighted previously in this report, particularly in assessing awakening reactions and arousals from atypical sound sources. There may be an opportunity to consider the wider application of indicators such as L_{Amax} in assessing noise complaints along the railway network.

Half of the respondents (9/18) stated that high-speed trains were not a relevant feature causing complaints for their operation or network. Of the respondents that did consider high-speed trains to be relevant, only one respondent specified high-speed trains as a very common feature causing complaints (SNCF France) and also stated that the national regulations are being revised as a result of extensive complaints adjacent to high-speed railways. Further work would be needed in this area to better understand the public perception of the impact of high-speed railways.

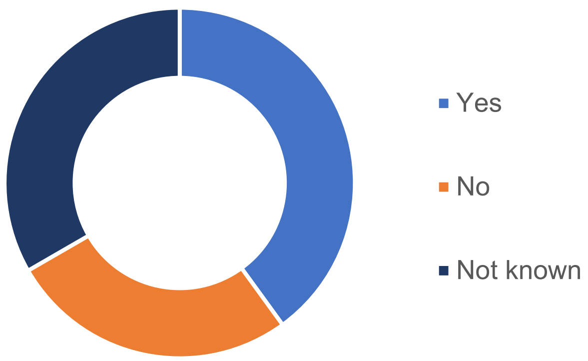
Other contributing factors were deemed to affect the likelihood of complaints within free-form survey responses. They included:

- Socio-economic - higher expectations in high property-value areas and/or higher expectations in areas known for their tranquil or low noise (such as tourist areas or retirement areas).
- Political - organised local initiatives or resident action groups.
- Perception of a lack of action despite the availability of mitigation measures that are effective and easy to implement.

The socio-economic factors mentioned above were generally observed to be the most prevalent non-acoustic factors mentioned by the respondents. This again highlights the significance of effective stakeholder communication.

When asked if there had been a change in the pattern or the number of complaints during the past five years, six respondents indicated that they had experienced a change, whereas four had experienced no change and five did not know whether there had been a change or not, as shown in Figure 5. These answers showed no correlation with the respondent's network size. The mixed responses indicate that there is no consistent pattern of increases in complaints.

Thinking of your network as a whole, have you experienced a change in the pattern or number of complaints during the past five years?



44% experienced a change in the number of complaints (one was a reduction due to mitigation)

39% experienced an increase, but one of these only saw a temporary increase due to COVID which has returned to normal. This leaves **33% who experienced an increase in complaints**.

Figure 5: Questionnaire responses on complaint patterns

Where an increase had been noted in complaints despite no increases in the railway noise levels, the perceived causes for the changes summarised from free-form survey responses are as follows;

- Home confinement due to the COVID-19 pandemic and being exposed to railway noise during extended periods while working from home. This is a major point highlighted by many.
- Residents living near the tracks having a reduced tolerance and acceptance of noise.
- WHO publications and an increase in the number of published articles on this subject.
- Global aspirations for a better quality of life.
- Campaigns by rail operators resulting in the public being more informed about the options available to express concerns.
- More legislation that protects citizens.

This supports the observation that an increased awareness of adverse impacts of noise on health could be a factor in the apparent hardening of attitudes noted in recent annoyance/sleep-disturbance studies.

One respondent noted a perceived reduction in the number of complaints, although the overall number of complaints remained high. The number of complaints was perceived to be reducing due to the successful implementation of various mitigation measures, specifically the retrospective fitting of composite brake blocks to freight trains. Sydney Trains noted that the overall number of complaints has remained consistent, but complaints are now being received from a wider area. This was perceived to be likely due to COVID-19 and the increase in home working.

The survey shows that there is generally no specific seasonal or weather condition causing an increase in complaints. However, one respondent noted that complaints tended to occur more frequently in the summer when people have their windows open for cooling/ventilation.

6.3.8. Mitigation measures

The survey respondents indicated in free-form responses that the most commonly implemented and effective noise control schemes to reduce railway noise levels include:

- Rail grinding.
- Retrofitting freight wagons with Composite Brake Blocks.
- Noise-differentiated track access charges (although this is noted to have ended in 2021).

The findings above coincide with the PHENOMENA study, which concluded that the best railway noise scenario in terms of their reduction in health burden and benefit-to-cost ratio was smoother and quieter vehicles and tracks.

Additional mitigation schemes mentioned by survey respondents include noise barriers and insulation measures at the receptors, gauge face lubrication, top-of-rail friction modifications and rail dampers. In addition to increased rail grinding, Sydney Trains also stated that prioritised wheel-turning maintenance is implemented to reduce ground-borne noise levels in sensitive areas. One respondent noted that there were no noise control schemes applicable to their network or fleet, only that any new rolling stock needs to be compliant with TSI Noise. They also noted that compliance with TSI Noise has not reduced complaints regarding stationary trains.

The most commonly sought-after mitigation measure by complainants was stated to be noise barriers with a close second being noise insulation treatment, such as high-performance acoustic glazing. This also correlates with the ranking of complainant satisfaction with specific noise-mitigation measures. It should be noted that the measures are not necessarily the most acoustically effective, but are the ones which complainants perceive to be the most effective.

It was noted that reductions in speed were also highly sought after by complainants, although this is not considered a practical mitigation measure by operators and infrastructure managers, since it would reduce the efficiency and competitiveness of railways over other modes of transport.

Retrofitting freight wagons is acoustically effective, but it is not typically perceived positively by residents as a significant benefit, because the change is progressive. One respondent did note, however, that the number of complaints has been reduced specifically as their entire fleet has been retrofitted. It is a general opinion among the respondents that, unless the noise emission is removed completely, complaints typically persist from the affected areas despite the overall noise levels or the frequency of the events occurring being reduced. This aligns with research findings summarised in Chapter 3 that people are more likely to respond defensively to an addition of sound rather than to a deletion of sound.

ProRail (Netherlands) observed that noise mitigation is effective at reducing specific types of noise complaints, but the increase in rail traffic may result in a higher number of complaints despite the implementation of noise-mitigation measures. Another respondent (Network Rail, UK) noted that the application of mitigation has a variable impact on reducing complaints depending on the noise source, with mitigation of rolling noise being much more achievable than other sources that are causing complaint. Noise mitigation is most effectively used in combination with strong stakeholder engagement to minimise complaints.

One respondent noted that the legal indoor noise limit is met at all receptors, thanks to mitigation measures. However, the complaints persist and are predominantly due to singular events such as individual pass-by events, squeals and train horns at night. It has also been observed that there has been a steady increase in vibration complaints and possibly ground-borne noise (despite this being difficult to verify) after the reduction of airborne noise which may have been acting as masking noise. These observations support research findings that atypical sounds resulting in arousal reactions are more likely to result in complaints, particularly at night and associated with sleep and rest periods.

It is also a general perception in the railway industry that complaints due to vibration increase as the airborne noise levels are reduced by various mitigation measures.

The majority of the respondents highlighted that the key factors driving the implementation of noise mitigation are value for money (13/18), closely followed by compliance with legal limits (12/18).

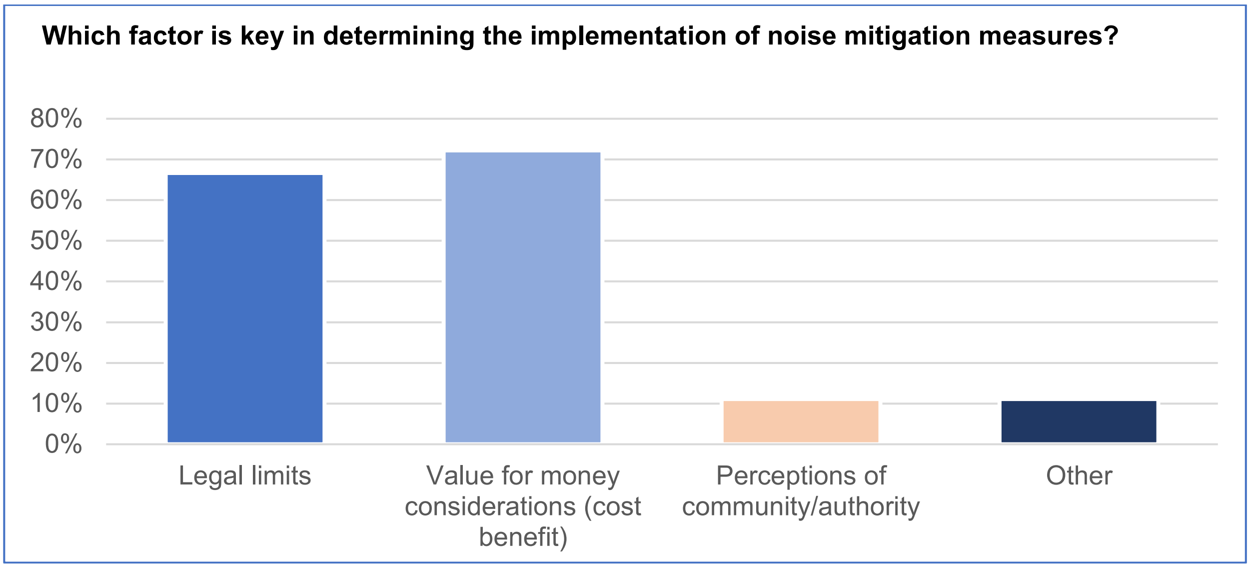


Figure 6: Key factors determining the implementation of noise mitigation measures

Of the thirteen respondents that stated legal limits are a key factor, seven also note value for money as a compounding factor. Trafikverket (Sweden) noted that complaints are not normally a factor for prioritising the implementation of noise abatement measures, which follow an existing noise abatement plan across the network. Where the noise levels exceed the limit values, and with prior agreement of Trafikverket, a complainant can also install their own noise mitigation and claim a repayment of costs from Trafikverket.

Network Rail (UK) stated that train-operating companies are now required to undertake noise planning to reduce the impact of their vehicles on surrounding areas. There are general noise-control options available to the infrastructure manager for new or significantly altered lines, such as noise barriers and acoustic glazing. Otherwise individual locations are targeted based on the type of noise issue with specific mitigation measures such as resilient baseplates, under-sleeper pads, renewals, rerailing, grinding and milling activities.

One respondent noted that they had an increase in noise levels leading to complaints after rail grinding. This may be caused by the noise character after grinding being perceived as unusual (i.e. louder than normal) and therefore triggering an arousal response leading to complaints, as discussed in Chapter 3.3.

6.3.9. Summary of case studies

The survey respondents were given the option to provide a case study, so that they could provide more specific details on a typical situation where complaints were being received. All the case studies are summarised in full in Appendix B.

The reported case studies indicate that the most common situations causing complaints are regarding a change in noise, “atypical noise” (e.g. noise from curves, tunnels or track defects), areas of extreme sensitivity or where noise limits are exceeded, as shown in Table 3.

Table 3: Summary of case studies

Type of Noise Causing Complaint	Situation and Specifics of Complaints	Mitigation and Other Relevant Comments
Change in noise	Introduction of a new maintenance facility. Complaints are due to stationary noise especially during night-time. More complaints were received in summer due to sleeping with open windows.	Reduction in duration of stationary noise from trains. Avoidance of parked trains with running engines on certain tracks (nearest to neighbours), insulation of exhaust of HVAC, frequent monitoring and checks to control stationary noise.
	A situation where the railway in the area previously only had freight train operation, and new train arrangements introduced passenger trains. The passenger traffic is very limited and noise from freight trains will still be dominant. However, there is a concern about increased frequency of disruption.	To reduce complaints, it can be important to build trust with those who live close to the railway and have good communication about what the increased traffic means in terms of noise. Increased communication through, for example, auralisation of noise from different train types can then be a good measure to increase understanding and acceptance of the increased traffic.
	New high-speed lines in rural areas. Complaints are also driven by non-acoustic factors, such as socio-economic ones: fear of reduction in values of houses and/or higher social economic status of residents who are more informed on this topic and political: pressure from local or national politicians.	There are installed mitigation measures, but a financial plan is being established for planned noise mitigation to be installed to address complaints. Some mitigation measures have been installed to address complaints located in specific sectors where L_{Amax} is considered too high, or buildings are considered too close to the track. A large number of people living near the last two high-speed lines launched have complained. An ongoing evolution of French regulation has resulted due to those complaints.
	Complaints regarding noise from a new train station and nearby infrastructure. The complaints are mostly due to noise from the high frequency of services and trains running over turnouts/crossovers. There are, however, also complaints about noise from parked trains.	Implemented mitigation and control measures to address complaints include noise barriers. There are also plans for further noise barriers. There was extensive consultation with neighbours, neighbourhood associations and the city hall to gain feedback on these additional barriers. However, when the construction of the new barriers began, some neighbours complained about them.
	The rail line is located in an urban area with a high density of single- or multi-family buildings. The complaints are mostly in relation to a change in the railway operation, both new additional tracks and an increase in the frequency of services on an existing railway.	Noise barriers were installed by a neighbouring carrier where new tracks had been approved. Monitoring is carried out every 5 years in accordance with the regulations to investigate if still compliant with noise limits.
Area of extreme sensitivity	This situation is a narrow valley with steep mountains on either side and dense population close to the railway lines. There are a high number of freight trains by night (Trans-European Transport Network), with double track on each side of the river causing complaints. Noise complaints have also received high attention by political representatives. The fact that the valley is a touristic hot spot with expectations of low ambient noise levels contributes to complaints.	Implemented mitigation and control measures to address complaints include noise barriers up to 3 m in height, insulated windows and the removal of insulation joints and rail dampers. In addition, in relation to vibration, the masking effect of noise has decreased where noise barriers have been built. Consequently, vibration-induced noise and vibration are more strongly perceived by residents.

Type of Noise Causing Complaint	Situation and Specifics of Complaints	Mitigation and Other Relevant Comments
"Atypical noise"	Rail maintenance causing increased noise after rail grinding. This location is also in the Alps with higher expectations of low ambient noise levels contributing to complaints.	There are noise barriers along the rail line. However, they were not installed due to the complaints. There is no planned mitigation.
	A historic rail corridor with a reversing curved section consisting of 4 adjacent tight curves (down to 200 m radius) on an incline. The complaints are mainly due to curve noise and train horns. The area is also located in a high-level socio-economic area in close proximity to medium-density residential housing. The complaints are also affected by a perceived notion that there is an easy fix for the noise problems that the rail operator does not want to implement.	The implemented mitigation and control measures include improved latest generation gauge-face lubrication systems, top-of-rail friction modification, a customised rail grinding schedule and installation of softer rail pads. These measures and an unsuccessful trial of rail dampers have been undertaken to address complaints.
	Railway tunnel section with complaints about ground-borne noise. The complainants believe that the amount of noise had increased over time. The rail roughness measurement and site survey did find some corrugation in the track, which was subsequently removed, but complaints continued afterwards.	Implemented mitigation and control measures to address complaints. The site has recently been trialled for the use of customised resilient baseplates and the rail has also been re-railed to remove corrugation.
	A ballasted track was upgraded, converting the track from bullhead rail on timber sleepers to new vignole (flat-bottom) rail on concrete sleepers. The change in track form introduced corrugation resulting in a roaring noise as north-bound trains pass through the area.	It was determined that a significant cause of the noise was a coincidence between the P2 rail resonance frequency and the stick-slip frequency at the wheel-rail interface. The track lubrication was increased to move the stick-slip frequency down. This resulted in a reduction in noise level as the corrugation was no longer being excited but also introduced 25 mm corrugation. Further mitigation actions are required to further reduce the level of noise including acoustic rail grinding. Rail grinding was not initially an option because of how quickly the corrugation set in. The increase lubrication has drastically slowed the rate of corrugation growth.
High Noise Levels Exceeding Noise Limits	A 4-track, electrified commuter line offering suburban services with frequencies up to multiple trains per minute. Along a significant part of this line, the tracks are surrounded by multi-storey buildings/dwellings. Up to 50,000 people live in the close vicinity of the rail line. The main problem is the use of a very noisy train type by the rail operator. Complaints are due to high noise levels exceeding the legal limits.	The implemented mitigation and control measures include jointless rails, well-maintained tracks and noise barriers. However, it is difficult to mitigate with barriers due to surrounding high-rise buildings with overlooking higher floors. The rail line is the perfect example of the need for both the infrastructure manager and the rail operator to address noise issues. In this case, the infrastructure manager has done almost everything it can to reduce noise, but the rail operator has not. Many spots remain above the legal limit and the complaints have not stopped.
	Rail line on bridge sections through a residential built-up area with complaints due to high noise levels exceeding the legal noise limits.	The existing bridges do not have a load-bearing capacity to support noise barriers at the location required to mitigate noise. There is a current control measure requiring a lower speed limit for freight trains (with non-composite brake blocks) during night-time. Reconstruction of the bridge is planned in order to install noise barriers to address complaints.

6.4. Summary: situation in European railways

A survey questionnaire was completed by 18 stakeholders from various European and international railways to understand the causes of railway noise complaints linked to the infrastructure management, operation and maintenance of railways across Europe. Respondents included a mix of operators and infrastructure managers, and the countries represented accounted for a total of 64% of the total length of railways in Europe.

The responses illustrate that the emission of noise from the railways is well regulated across the rail sector, either in the form of legal limits or other Regulatory Controls. Where there are legal limits on noise emissions, there are typically different limits for new and existing railways. Additionally, noise limits do not typically differentiate between freight and passenger services, although some separate limits for high-speed railways do exist.

Generally, the number of noise complaints received can be correlated to the size of the rail operator/network. The responses show that noise complaints are generally monitored well and recorded in a way to enable future analysis, with many operators and infrastructure managers utilising dedicated complaint-handling teams and storing complaint data on central databases. Generally, a sufficient level of information is collected to enable meaningful analysis of complaints, although there is some variation across the networks on the nature of data captured, which affects the possible depth of analysis.

Fewer than half of the survey respondents indicated that they have a legal requirement to act on noise complaints. Investigating complaints is therefore partly shaped by external stakeholder pressure and a desire to minimise reputational risk to the railway sector. The majority of respondents stated that noise monitoring is never or rarely used to investigate complaints.

The most frequently used noise indicators to investigate complaints are $L_{Aeq,T}$, L_{night}, L_{den} and L_{Amax}. The limitations of indicators such as $L_{Aeq,T}$, L_{night}, L_{den} were highlighted previously in this report, particularly in assessing awakening reactions and arousals from atypical sound sources.

Freight trains were the most common feature stated as causing complaints, although other features such as changes to the physical rail infrastructure and maintenance operations are also common. In a number of cases, it was noted that socio-economic factors were a contributing factor. High-speed trains were not considered relevant by half of the respondents, with only one operator specifying high-speed trains as a common feature causing noise complaints.

When asked if there was a change in the pattern or number of complaints during the past five years, the answers showed no correlation with respondent network size and the mixed responses indicated that there is no consistent pattern of increases in complaints.

The survey indicated that rail grinding and the retrofitting of freight wagons with composite brake blocks are two of the more commonly implemented and effective measures to reduce noise. However, the most commonly sought-after mitigation measure by complainants was stated to be noise barriers with a close second being noise insulation treatment, such as high-performance acoustic glazing. This also correlates with the ranking of complainant satisfaction with specific noise mitigation measures.

Case studies provided by survey respondents indicated that the most common situations causing complaints involve a change in noise, “atypical noise”, areas of extreme sensitivity or where noise limits are exceeded.

7. Conclusions

The objectives of the UIC "**Noise Technical Advice - Nuisance and health impact of railway noise**" preliminary study were as follows:

1. To acquire a representative picture of the nuisance effect of rail noise and its impact on human health in European railways in 2021 and to prepare a proposal for determining the next steps and for making suggestions for the global railway community.
2. To provide an evidence basis for the impact of noise nuisance on human health for UIC participation in the European Commission meetings with the aim that UIC will inform the EU or national governments' funding and legislation decisions.

The main study outcomes, knowledge gaps and recommendations for future work are summarised below.

7.1. Study outcomes

This scoping study report provides a critical assessment of the existing research into impacts of noise from railways, a summary of methods to address impacts, economic considerations and a survey amongst UIC members to address current information gaps relating to complaints from people living near European railways.

Recent studies have indicated that exposure-response relationships no longer favour railway noise over other transportation sources, and suggest that the numbers of people annoyed by railway noise may have increased. There has been a perception that the rate of complaints from communities living along parts of the railways remain high, despite evidence that noise levels are decreasing as a result of a range of innovations and mitigation measures being employed across Europe. The driving factors that trigger individuals to complain about railway-noise exposure has not been addressed in previous UIC studies. To address current information gaps on complaints, this study gathered information from the railway sector for the first time using an online questionnaire. The survey responses regarding complaints received by UIC members showed that one-third of the respondents perceive an increase in complaints where there has been no change to the railway noise.

The survey responses identified freight trains operating during night-time as the most common cause for complaints. In addition, the case studies provided by survey respondents indicated that the most common situations causing complaints involve a change in noise, "atypical noise", areas of extreme sensitivity or where noise limits are exceeded. This aligns with research findings that noise complaints are a result of the arousal effect of exposure to atypical high-noise events, which may also lead to short-term sleep disturbance.

There are established methods for monetising noise impacts based on long-term exposure, but this approach currently does not recognise any additional short-term impacts from atypical events. This may be a limiting factor in identifying the benefit of mitigation measures in the form of value for money. Therefore, further research in this field may lead to updates to existing monetisation tools.

Future mitigation will likely need to combine the conventional mitigation efforts with innovative ways to more specifically address annoyance/complaints caused by railways. Furthermore, it will be important for infrastructure managers and operators to work together to achieve cost-effective mitigation to further reduce railway noise.

The following sections include a summary of identified knowledge gaps and recommendations for further work.

7.2. Knowledge gaps and limitations

Following the review provided in Chapters 3 to 5 and the stakeholder survey outcomes provided in Chapter 6, this section identifies the key knowledge gaps identified in this study.

- The observed differences in various published exposure-response curves are not fully explained, but may be a function of the size of data and the methodology used in the statistical analysis of the data. Therefore, caution is urged when applying them to the assessment of local noise cases and for designing mitigation measures.
- The exposure-response curves relate to steady-state conditions. This study has not identified robust research on the effects of step-change or gradual change in railway noise on community annoyance or sleep disturbance.
- The treatment of passenger and freight traffic as a combined noise source in the majority of cases could prevent effective actions from being identified.
- There are limitations associated with the use of strategic noise maps to estimate exposure to railway noise, leading to an underestimation of the population experiencing health effects and costs. This is because strategic noise mapping may not cover the full railway network and may omit some areas with populations annoyed by railway noise or making complaints.
- Knowledge gaps linked to the monetisation of some health conditions, productivity losses, noise impacts to ecology and indirect effects were found to result in the exclusion of these factors in monetisation tools, leading to an underestimation of noise-related impacts from railways.
- The complaint statistics gathered as part of the questionnaire survey of UIC members are based on operator/infrastructure-manager interpretations of received complaints rather than a direct or detailed analysis of complaint records.

7.3. Recommendations

When defining a framework for future research and investigations, it is important to consider the sustainability of railways in the long term. This review identified future research needs to address existing and potential risks from noise and adverse health outcomes on communities.

The recommendations for railway operators and infrastructure managers are as follows:

- Most survey respondents have stated that they have a central system for recording all complaints. However, the nature of data collected varied between members. More detailed analysis could provide further evidence for prioritising actions (e.g. number of complaints vs number of complainants). Developing a consistent noise complaint procedure across UIC members would assist with further analysis and the sharing of best practice. Complaint data could be used as an index of non-dose related attitudes toward railways and railway noise. This could help to reduce the uncertainty in predictions of annoyance prevalence rates.
- Further research is needed to better understand the influence of local acoustic and non-acoustic factors on noise exposure-response relationships.
- Identification of appropriate noise exposure-response relationships (self-reported annoyance/sleep disturbance) separately for freight and passenger trains would be useful in identifying local issues.

- There is a need for further research to identify robust and practical noise indicators which can complement the current indicators to better represent the characteristics of railway noise (e.g. LAmax) and also studies to better understand the public perception of the impact of railways (classical passenger lines, freight and HSL).
- Development and use of economic values for the alternative indicators described above ready for incorporation into monetisation tools. This would allow the impacts on short-term health to be considered alongside long-term impacts, as well as providing a specific economic cost of complaints.
- Further polysomnographic investigations into short-term objective effects of noise would be desirable to address concerns about the size of data sets and the age and socioeconomic distribution of respondents, before potential links to long-term effects can be ruled out.
- Research into sources of “atypical noise” (e.g. curve squeal, low-frequency noise, impulsive noise from joints, noise from horns, etc.) and subjective perceptions/ annoyance using psychoacoustic indicators, as identified previously by the UIC (2020).

- There are practical limitations to noise reductions achievable by mitigation methods. There is a need for research to combine the conventional mitigation efforts with innovative ways to more specifically address annoyance/complaints caused by railways. Specific techniques such as examples of auralisation given in the Shift2Rail project could be expanded on.
- A plan of engagement with communities and key stakeholders on an ongoing basis to proactively manage emerging noise issues.
- To improve the DALY calculations for monetisation of noise-related health effects, further research is needed on costs linked to a number of health conditions that are currently excluded, such as breast cancer, respiratory disease and mental health problems. Additionally, the research suggests that the relevance of other impact pathways affecting the monetisation of railway noise needs to be explored further, with pricing models developed as needed for incorporation into existing monetisation tools. This includes productivity losses, noise impacts to ecology and indirect effects.
- The efficiency of improving health through noise (i.e. the cost of noise mitigation leading to a given improvement in health) could be compared with improvements in other areas of health and their cost (e.g. better nutrition). This knowledge could lead to an optimal use of financial means for health in society as a whole. For example, is it more cost effective to promote better nutrition or to undertake noise mitigation in order to get a specific health outcome?
- The survey responses were very limited in number of respondents applicable to high-speed rail and it is recommended that further surveys should be undertaken to better understand the complaints and management of noise from high-speed rail.

8. Acknowledgements

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Atkins and UIC thank the members of the NOVITÀ project within the UIC Noise and Vibration Sector for providing additional peer review feedback for this study:

- ADIF (Spain): Marta Ruiz, Jose Luis Riera Fernandez,
- BaneNor (Norway): Trygve Aasen, Torbjørn Ursin, Celine Chapelier,
- CFL (Luxembourg): Zelito Neves Dos Santos,
- DB (Germany): Rüdiger Garburg, Bernd Asmussen, Lennart Moheit, Ferat Göçmen, Christian Frank
- HS2 (UK): Gennaro Sica
- Infrabel (Belgium): Juliette Florentin, Sander De Bock, Ward Verhelst
- IP (Portugal): Diogo Vasconcelos
- Network Rail (UK): Jamie Wilkes
- ÖBB (Austria): Günther Dinhobl
- ProRail (Netherlands): Nils IJntema, Chiel Roovers, Tryfon Roelofs
- RENFE (Spain): Santos Núñez Del Campo
- SBB (Switzerland): Emilie Freud, Marc Schmid, Roger Mueller
- SNCB (Belgium): Sven Van Driessche
- SNCF (France): Cora Crémézi Charlet, Fabien Letourneaux
- Sydney Trains (Australia): Radek Kochanowski
- SZCZ (Czech Republic): Anna Šiklová
- Trafikverket (Sweden): Matthias Asplund
- Väylä (Finland): Mikael Takala, Taiju Virtanen

9. Glossary

9.1. Acronyms and abbreviations

CEF	Connecting Europe Facility
CI	Confidence Interval
DALY	Disability Adjusted Life Year
DEUFRAKO	German-French cooperation in transport research
EEA	European Environment Agency
END	Environmental Noise Directive
EU	European Union
FAMOS	FActors MOderating people's Subjective reactions to noise
GDP	Gross Domestic Product. Defined as the total value of goods and services produced in a country during one year.
HA	Highly Annoyed
HALY	Health Adjusted Life Year
HSD	Highly Sleep Disturbed
HSL	High-Speed Line
HVAC	Heating Ventilation and Air Conditioning
ICBEN	International Commission on Biological Effects of Noise
IR	Intermittency Ratio
kph	Kilometres Per Hour
NACF	Noise Annoyance Correction Factor
NAP	Noise Action Plans
NDTAC	Noise Differentiated Track Access Charge
NNI	Noise and Number Index
PHENOMENA	Assessment of Potential HEalth Benefits of NOise AbateMENt MeAsures
QALY	Quality-Adjusted Life Year
RIVM	Dutch National Institute for Public Health and the Environment
SAPALDIA	Study on Air Pollution And Lung Disease In Adults
SiRENE	Short- and Long-Term Effects of Transportation Noise Exposure
TAG	Transport Appraisal Guidance (UK)
TEN-T	Trans-European Transport Network
TSI	Technical Specification for Interoperability
UIC	Union Internationale des Chemins de Fer / International Union of Railways
UNEP	United Nations Environment Programme
WHO	World Health Organization

9.2. Acoustic terminology

Arousal effect of noise This arousal effect can be described as an unusual noise stimulus, which results in a conscious recognition as a change from the environment which a person normally expects to hear.

A-weighting The most widely used weighting mechanism that best corresponds to the response of the human ear is the 'A'-weighting scale. This is widely used for environmental noise measurement, and the levels are denoted as dB(A) or L_{Aeq}, L_{A90}, etc., according to the parameter being measured.

C-weighting C-weighting is a type of frequency weighting that is mostly flat, usually used for peak noise measurements.

DALY	Disability Adjusted Life Years. The sum of the potential years of life lost due to premature death and the equivalent of "healthy" life years lost by virtue of being in states of poor health of disability.
Decibel, dB, dB(A)	A logarithmic scale for comparing the ratios of two quantities, including sound pressure and sound power. The decibel can also be used to measure absolute quantities by specifying a reference value that fixes one point on the scale. For sound pressure, the reference value is 20 μPa.
Intermittency ratio	This indicator expresses the contribution in percentage of individual noise events (e.g. aircraft overflights or train crossings) to total noise pollution. IR24h represents the intermittency ratio over a 24-hour period.
$L_{Aeq,T}$, $L_{eq,T}$	A noise level index called the equivalent continuous (A-weighted) noise level over the time period T. This is the level of a notional steady sound that would contain the same amount of sound energy as the actual, possibly fluctuating, sound that was recorded.
$L_{Amax,T}$	A noise level index defined as the maximum A-weighted noise level during the period T. L_{max} is sometimes used for the assessment of occasional loud noises, which may have little effect on the overall L_{eq} noise level but will still affect the noise environment.
L_{PAFmax}	Maximum A-weighted sound pressure level when using fast time-weighting (sampling every 1/8 second).
L_{day}	Equivalent continuous sound pressure level when the reference time interval is the day (07:00 to 19:00 for END strategic noise maps).
L_{den}	Day-evening-night-weighted sound pressure level as defined in Section 3.6.4 of ISO 1996-1:2016. It is based on $L_{Aeq,24h}$ but includes "weightings" of +5 dB and +10 dB for evening and night-time noise levels respectively.
L_{night}	Equivalent continuous sound pressure level when the reference time interval is the night (23:00 to 07:00 for END strategic noise maps).
PNdB	Perceived Noise Level in decibels, used for aviation noise. For conversion from L_{Aeq} to PNdB, 13 dB is added to the maximum value.
SEL	Sound Exposure Level. This is the level which, if maintained constantly for a period of 1 second, would cause the same A-weighted sound energy to be received as is actually received from a given noise event. Used to quantify noise generated by individual trains.
SPL	Sound Pressure Level. A value equal to 20 times the logarithm to the base 10 of the ratio of the root-mean-square pressure of a sound to a reference pressure, which is normally taken to be 20 μPa. Its unit of measurement is the decibel (dB).
TEL	Transient Exposure Level - similar to SEL, but the pass-by duration for TEL is the interval between the passing of the front and rear train buffer before the receptor; for SEL, it is usually the interval between the moments where the level exceeds L_{Amax} - 10 dB.
Tr	Represents the steepest slope of the event curve as rise time of the maximum A-weighted SPL of a noise event in dB/s.

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Appendices

A. Railway noise annoyance studies considered in WHO Systematic Reviews

A.1. Railway noise papers included in the WHO Systematic Review for Annoyance

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[D] T. Sato, Y. Yano and T. Morihara, “Community Response to Noise from Shinkansen in Comparison with Ordinary Railways: A Survey in Kyushu, Japan”, *International Congress on Acoustics ICA 2004*, 2004.

[E] D. Schreckenberg, “Exposure-response relationship for railway noise annoyance in the middle Rhine Valley”, Inter-Noise 2013, Innsbruck (Austria), 2013.

[F] T. Yano, T. Morihara and T. Sato, “Community response to Shinkansen noise and vibration: a survey in areas along the Sanyo Shinkansen Line”, *Forum Acusticum*, Budapest (Hungary), 2005.

[G] S. Yokoshima, T. Morihara, A. Ota, and A. Tamura, “Reanalysis of dose-response curves of Shinkansen railway noise”, *9th International Congress on Noise as a Public Health Problem (ICBEN)*, Foxwoods (USA, CT), 2008.

A.2. Railway noise papers excluded from the WHO Systematic Review for Annoyance

Document	Reason for exclusion
G. M. Aasvang, B. Engdahl and K. Rothschild, "Annoyance and self-reported sleep disturbances due to structurally radiated noise from railway tunnels," *Applied Acoustics*, vol. 68, no. 9, pp. 970-981, 2007.	Acoustics not comparable
O. R. P. Breugelmans, R. K. Stellato and R. van Poll, "Blootstelling-responsrelaties voor geluidhinder en slaapverstoring. Een analyse van nationale gegevens" [Exposure-response relationship for noise annoyance and sleep disturbance. An analysis of national data], *RIVM*, pp. 54, 2007.	Very few persons exposed
X. Chen, F. Tang, Z. Huang, and G. Wang, "High-speed maglev noise impacts on residents: A case study in Shanghai", *Transportation Research: Part D*, vol. 12, no. 6, pp. 437-448, 2007.	Acoustics not comparable
E-M. Elmenhorst, S. Pennig, V. Rolny, J. Quehl, U. Mueller, H. Maaß and M. Basner, "Examining nocturnal railway noise and aircraft noise in the field: Sleep, psychomotor performance, and annoyance", *Science of the Total Environment*, no. 424, pp. 48-56, 2012.	Outcome and acoustics not comparable
M. Heinonen-Guzejev, H. S. Vuorinen, J. Kaprio, K. Heikklikä, H. Mussalo-Rauhamaa and M. Koskenvuo, "Self-report of transportation noise exposure, annoyance and noise sensitivity in relation to noise map information", *Journal of Sound and Vibration*, no. 234, pp. 191-206, 2000.	Outcome not comparable
Z. Koziel, "Exposure-response relationships from railway noise in the presence of vibration", University of Salford, MSc, 2011.	Insufficient data
K-C. Lam and W-H. Au, "Human Response to a Step Change in Noise Exposure Following the Opening of a New Railway Extension in Hong Kong", *Acta Acustica united with Acustica*, no. 94, pp. 553-562, 2008.	Outcome not comparable
C. Lim, J. Kim, J. Hong and S. Lee, "The relationship between railway noise and community annoyance in Korea", *The Journal of the Acoustical Society of America*, vol. 120, no. 4, pp. 2037-2042, 2006.	Insufficient data
H. M. E. Miedema and C. G. Oudshoorn, "Annoyance from transportation noise: Relationships with exposure Metrics DNL and DENL and their confidence intervals", *Environmental Health Perspectives*, no. 109, pp. 409-416, 2001.	Mean age group of rail data: 1981, no data after 1993
T. Morihara, T. Sato and T. Yano, "Comparison of dose-response relationships between railway and road traffic noises: the moderating effect of distance", *Journal of Sound & Vibration*, vol. 277, no. 3, pp. 559-565, 2004.	Insufficient data
S. Oka, Y. Murakami, H. Tetsuya and T. Yano, "Community response to a step change in railway noise and vibration exposures by the opening of a new Shinkansen Line", *Inter-Noise 2013*, Innsbruck (Austria), 2013.	Change study
S. Pennig, J. Quehl, U. Müller, E-M. Elmenhorst, V. Rolny, H. Maaß and M. Basner, "Effects of nocturnal railway noise on annoyance: Dose-response relationships from a field study in comparison to nocturnal aircraft noise annoyance", *10th International Congress on Noise as a Public Health Problem (ICBEN)*, London (UK), 2011.	Exposure-response data only for L_{night}
S. Pennig, J. Quehl, U. Mueller, V. Rolny, H. Maass, M. Basner and E. M. Elmenhorst, "Annoyance and self-reported sleep disturbance due to night-time railway noise examined in the field", *Journal of the Acoustical Society of America*, vol. 132, no. 5, pp. 109-117, 2012.	Exposure-response data only for L_{night}
D. Schreckenberg, U. Moehler, M. Liepert and R. Schuemer, "The impact of railway grinding on noise levels and residents' noise responses - Part 2: The role of information", *Inter-Noise 2013*, Innsbruck (Austria), 2013.	No exposure-response data

B. Case studies of complaints history

B.1. Case study 1 - Stationary noise from trains

Description	The case study is given by a rail operator in Belgium. Former shunting area with a new workshop for the maintenance of trains built and operational since 2017.
Number of complaints	50-100 over the past 5 years. Only complaints about noise; no vibration.
Period of complaints	Night-time. More in summer due to sleeping with open windows.
Reason for complaints	Most complaints are in relation to stationary noise from trains in the parking area and noise of trains as they arrive and depart.
Other factors affecting complaints	There are many factors affecting the complaints. One specific factor is about the green barriers around the nature-based “green” slopes with trees on them. There is also political influence from political parties and influence from environmental inspections and the lawyers of neighbours.
Mitigation or control measures	Reduction of duration of stationary noise from trains. Avoidance of parked trains with running engines on certain tracks (nearest to neighbours), insulation of exhaust of HVAC, frequent monitoring and checks to control and limit stationary noise. These mitigation and control measures were applied as a result of the complaints. They were also obligatory due to the conclusion of an acoustical study and noise mitigation study.

B.2. Case study 2 - Rail grinding

Description	The case study is given by a rail infrastructure manager and operator in Switzerland. A railway in a valley in the Alps with a large lake where maintenance in the form of rail grinding causes complaints.
Number of complaints	<10 over the past 5 years. Complaints about both noise and vibration.
Period of complaints	Not known.
Reason for complaints	Complaints about increased noise after rail grinding.
Other factors affecting complaints	The location has a high grade of steel, which is why noise does not decrease as fast as on other lines after grinding. The line is adjacent to the Lago Maggiore, where many people go to live during retirement or for the nicer weather and Mediterranean flair. They have higher expectations for quiet living conditions than people living in other areas.
Mitigation or control measures	There are noise barriers along the rail line. However, they were not installed due to the complaints. There is no planned mitigation.

B.3. Case study 3 - Increased train frequency

Description	The case study is given by a rail infrastructure manager in Sweden. When we get clusters of complaints, it is often caused by changes in traffic on existing tracks. One example is complaints from residents next to a railway where previously only freight trains have passed, and new train arrangements with passenger trains have now been introduced. Although the passenger traffic is very limited, maybe only two trains an hour during daytime, there is a concern about increased disruption. Noise levels will not increase much as the noise from freight trains is completely dominant, but there is still a concern about increased noise disturbance.
Number of complaints	10-50 over the past 5 years. Only complaints about noise; no vibration.
Period of complaints	Not known.
Reason for complaints	Increased frequency of train operation.
Other factors affecting complaints	Noise levels will not increase much as the noise from freight trains is completely dominant, but there is still a concern about increased noise disturbance. The new traffic with passenger trains is causing more noise events and a change in the noise character.
Mitigation or control measures	There are no existing mitigation measures. We are forced to investigate whether it is relevant to take noise mitigation measures along this railway, but until now we have not prioritized taking any measures here. To reduce complaints, it can be important to build trust with those who live close to the railway and have good communications about what the increased traffic means in terms of noise. Increased communication through, for example, auralisation of noise from different train types can then be a good measure to increase understanding and acceptance of the increased traffic.
Other comments	The case could be regarded as a hotspot concerning complaints, but not as a hotspot concerning noise levels and health risks.

B.4. Case study 4 - New high-speed lines

Description	The case study is given by a rail infrastructure manager in France. The case study is about new high-speed lines created in low-density areas.
Number of complaints	100-500 over the past 5 years. There has been an increase in complaints. However, these are recently installed assets. Complaints about both noise and vibration.
Period of complaints	Daytime.
Reason for complaints	New high-speed train operation in rural areas.
Other factors affecting complaints	Socio-economic: Fear of reduction in values of houses and/or higher socio-economic categories are more informed on this topic. Political: Pressure from local or national politicians.
Mitigation or control measures	Mitigation measures have been installed for the two last high-speed lines; complementary specific measures are being studied, although the noise levels are compliant with the French regulations. In general, no mitigation measures are installed for the technical maintenance centre or parking areas. A financial plan is being established for planned noise mitigation to be installed to address complaints. Some mitigation measures have been installed to address complaints located in specific sectors, where L_{Amax} is considered to be too high, or buildings are considered to be too close to the track. Usually, residents ask to reduce the speed in order to decrease noise. This solution is generally not considered feasible (need a relatively large speed reduction to have significant change that would affect the residents, which is not acceptable for the railway operators).
Other comments	A large number of people living near the last two launched high-speed lines have complained. An ongoing evolution of the French regulations has resulted from these complaints. In addition, a large number of complaints concern trains in the technical maintenance centre or parking areas which are not taken into account properly in the French legislation (e.g. end of an exploited line with houses near the track where trains are parked).

B.5. Case study 5 - Railway noise in tight curves

Description	The case study is given by a rail infrastructure manager and operator in Australia. The case study regards a reversing curved section consisting of 4 adjacent tight curves (down to 200m radius) on an incline, with approximately 460 daily passenger EMU trains, located in a high socio-economic area in close proximity to medium-density residential housing. The corridor which was constructed in the late 19th century with a layout to facilitate steam trains traversing this incline, which required tight curvature in man-made rock cuttings. Over the years, realigning the corridor was not carried out and residential development from 1970s onwards was constructed closer to the corridor exposing the residents to relatively high noise emissions. Now the corridor only carries a high number of daily passenger trains and is one of two main lines serving the northern suburbs of a major city. Given the proximity of this area to the harbour and the city centre, the property values are very high and there is an expectation that the noise from the trains should be much lower given the price of properties. The daily traffic numbers on this line have increased by approximately 20% over the last 5 years.
Number of complaints	100-500 over the past 5 years. The local community has created a local action group which deals with the rail operator directly. They no longer complain via the standard complaint process. Over the last few years, the lobbying for change has increased significantly via various government avenues. Only complaints about noise; no vibration.
Period of complaints	Complaints about both daytime and night-time noise.
Reason for complaints	The complaints are mostly in relation to: ↗ Increased number of passenger trains. ↗ Maintenance (e.g. rail grinding). ↗ Tight curves causing increased noise and potential tonal characteristics. ↗ Train horns.
Other factors affecting complaints	Perceived notion that there is an easy fix for the noise problems that the rail operator does not want to implement. Expectation that the noise levels can be made significantly lower despite the inherent historical nature of the rail corridor in this area of the network. The community group predominately consists of retired residents who have lived in the area for a long period of time. Given their extended period of spending time at home (pre-COVID), they are exposed to the highest noise levels. Anecdotal evidence shows that the younger demographic who moved into the area knowing the extent of the noise emissions accepted this compromise with the other benefits of living in this area.
Mitigation or control measures	The implemented mitigation and control measures include improved latest generation gauge face lubrication systems, top of rail friction modification, customised rail grinding schedule and installation of softer rail pads. These measures and an unsuccessful trial of rail dampers have been undertaken to address complaints. Further mitigation and control measures to address complaints include minor adjustments in track geometry, expansion of top of rail friction modification usage in the area and carrying out of rail milling. Investigations into other applicable noise mitigation measures and trials continue to be carried out.
Other comments	This area of the network requires the most time and resources to manage the noise levels despite not exposing the residents to the highest noise levels on the network.

B.6. Case study 6 - Electrified commuter line

Description	The case study is given by a rail infrastructure manager in Portugal. The case study is about a 4-track, electrified commuter line offering suburban services with frequencies up to multiple trains per minute (considering sections with 4 tracks). Along a significant part of this line, the tracks are surrounded by multi-storey buildings/dwellings. Up to 50,000 people live in the close vicinity of the rail line. The main railway operator uses the worst passenger train (in acoustic terms) used in the whole Portuguese rail network.
Number of complaints	10-50 over the past 5 years. The pattern of complaints did not change over the years. There are complaints from existing dwellings as well as from new developments adjacent to the existing railway. Only complaints about noise; no vibration.
Period of complaints	Complaints about both daytime and night-time noise. There are certain times of year (e.g. seasonal) that cause more complaints.
Reason for complaints	The complaints are mostly in relation to: ↗ Passenger trains. ↗ Frequency of services. ↗ Maintenance (e.g. rail grinding). ↗ Speed of trains. The railway is a well-maintained, modernized, electrified line already fitted with many noise barriers. The main problem is the use of a very noisy train type by the rail operator. Another factor is the height of some buildings, which prevents noise barriers from protecting higher floors.
Other factors affecting complaints	No, only noise.
Mitigation or control measures	The implemented mitigation and control measures include jointless rails, well-maintained tracks and noise barriers. Noise measures are always the result of an environmental impact assessment during line upgrading or the goal of achieving noise limits compliance, not because of complaints directly. There are planned noise mitigation or control measures. However, these are because legal compliance is not fully achieved yet, not directly because of the number of complaints or to address complaints. Of course, indirectly, the number of people affected and the number of complaints makes this line a high-priority spot. Noise Action Plan for the area includes few further measures to be implemented by the infrastructure manager. The main remaining measure to be implemented is to replace/improve the train type used by the rail operator.
Other comments	The rail line is the perfect example that demonstrates the need for noise issues to be addressed by both the infrastructure manager and the rail operator. In this case, the infrastructure manager did almost everything it can to reduce noise, but the rail operator did not. Many spots remain above the legal limit and complaints have not stopped. In Portugal, noise regulations place the burden of compliance on the infrastructure manager, so the rail operator does not feel any pressure to act.

B.7. Case study 7 - Railway line in a narrow valley

Description	The case study is given by a rail infrastructure manager and operator in Germany. The case study is about a narrow valley, with steep mountains on either side and a dense population close to the railway lines. High number of freight trains by night (Trans-European Transport Network), double track on each side of the river. Noise problems have received high attention by political representatives.
Number of complaints	>500 over the past 5 years. Complaints about both noise and vibration. Complaints about vibration increased where noise barriers have been built.
Period of complaints	Complaints about night-time noise.
Reason for complaints	The complaints are mostly in relation to: ↗ Freight trains ↗ Passenger trains ↗ Frequency of services ↗ Speed of trains ↗ Points (e.g. turnouts, cross overs) In addition, in relation to vibration, the masking effect of noise has decreased where noise barriers have been built. Consequently, vibration-induced noise and vibration are perceived as being stronger by residents.
Other factors affecting complaints	Other factors affecting the complaints include: ↗ Socio-economic ↗ Political ↗ Environmental ↗ The residents are organized in local initiatives ↗ The topographic conditions and the demographic structure ↗ And the valley as a touristic hot spot
Mitigation or control measures	Implemented mitigation and control measures to address complaints include noise barriers up to 3 m in height, insulated windows, removal of insulation joints and rail dampers. There are further planned noise-mitigation or control measures to address complaints.

B.8. Case study 8 - Dual-track rail line in built-up area

Description	The case study is given by a rail infrastructure manager in the Czech Republic. The case study is about a dual-track rail line which runs on bridges through a built-up area close to a city centre.
Number of complaints	10-50 over the past 5 years. Only complaints about noise; no vibration.
Period of complaints	Complaints about night-time noise.
Reason for complaints	The complaints are mostly in relation to: ↗ Freight trains ↗ Passenger trains ↗ Frequency of services Noise in the area exceeds legal limits.
Other factors affecting complaints	↗ Not known.
Mitigation or control measures	The existing bridges do not have a load-bearing capacity to support noise barriers at the location required to mitigate noise. There is a current control measure requiring a lower speed limit for freight trains (with non-composite brake blocks) during night-time. Reconstruction of the bridge is planned in order to install noise barriers to address complaints.

B.9. Case study 9 - Ground-borne noise from tunnel

Description	The case study is given by a rail infrastructure manager in the United Kingdom. Moorgate tunnels, between Drayton Park and Highbury and Islington stations. This is the source of a number of ground-borne noise-related complaints.
Number of complaints	100-500 over the past 5 years. Only complaints about ground-borne noise; no vibration. More complaints came in during the COVID pandemic. Whilst no change was made to the infrastructure, the number of trains running had increased slightly which sparked the original complaints.
Period of complaints	Complaints about daytime and night-time noise.
Reason for complaints	The complaints are mostly in relation to: ↗ Maintenance (e.g. rail grinding) ↗ Passenger trains ↗ Tunnels ↗ Combined contribution of wheel and rail in operational infrastructure The complaints stem from operational infrastructure without change, and therefore natural degradation in the wheel/rail interface may have increased. The complainants believe the amount of noise has increased over time. The rail roughness measurement and site survey did find some corrugation in the track, which was subsequently removed, but complaints did continue afterwards.
Other factors affecting complaints	No, only ground-borne noise.
Mitigation or control measures	Implemented mitigation and control measures to address complaints include the fact that the site has recently been trialled for the use of customised resilient baseplates, and the rail has also been re-railed to remove corrugation.

B.10. Case study 10 - Noise from new train station

Description	The case study is given by a rail infrastructure manager in Spain. Complaints regarding noise from a new train station and nearby infrastructure.
Number of complaints	10-50 over the past 5 years. Only complaints about noise; no vibration.
Period of complaints	It is not known if the complaints are mostly due to daytime or night-time noise. However, a pattern with increased complaints during certain times of year (e.g. seasonal) have been observed.
Reason for complaints	The complaints are mostly in relation to: ↗ Frequency of services ↗ Points (e.g. turnouts, cross-overs) There are also complaints about noise from parked trains.
Other factors affecting complaints	No, only noise.
Mitigation or control measures	Implemented mitigation and control measures to address complaints include noise barriers. There are also plans for further noise barriers. There was extensive consultation with neighbours, neighbourhood associations and the city hall to gain feedback on these additional barriers. However, when the construction of the new barriers began, some neighbours complained about them.
Other comments	Also mentioned a separate case of complaints regarding curve squeal noise.

B.11. Case study 11 - Noise from additional train operation

Description	The case study is given by a rail infrastructure manager and operator in Poland. The rail line is located in an urban area with a high density of single- or multi-family buildings. The complaints are concerning additional tracks and train operations. The permissible noise levels were measured in accordance with the applicable regulations. On the basis of the results, the places where the permissible standards were exceeded were determined. New tracks were approved in a given area where permissible standards were not exceeded.
Number of complaints	<10 over the past 5 years. Only complaints about noise; no vibration.
Period of complaints	Complaints about daytime and night-time noise.
Reason for complaints	The complaints are mostly in relation to a change in the railway operation, both new additional tracks and increase in frequency of services. The high frequency of trains travelling together with a large number of inhabitants may result in the emergence of new complaints.
Other factors affecting complaints	No, only noise.
Mitigation or control measures	Noise barriers were installed by a neighbouring carrier where new tracks had been approved. Monitoring is carried out every 5 years in accordance with the regulations. Where monitoring results show exceedance of noise limits, this justifies further mitigation measures being introduced to reduce noise levels.

B.12. Case study 12 - Change to infrastructure causing rail corrugation

Description	The case study is given by a rail infrastructure manager and operator in the United Kingdom. Rail operation between Finchley Central and West Finchley on the Northern line, just north of Finchley Central station. The track form was upgraded from bullhead rail on timber sleepers to vignole (flat-bottom) rail on concrete sleepers with a very tight sleeper spacing (600mm), making the new track form very stiff. The result was that there was 20mm-deep corrugation on the rail head after two to three days, causing a roaring noise as northbound trains pass through the area.
Number of complaints	50-100 over the past 5 years. Only complaints about noise; no vibration.
Period of complaints	Complaints about daytime noise. Also, a pattern with increased complaints during certain times of year (e.g. seasonal) has been observed.
Reason for complaints	The complaints are due to an upgrade in the track form causing rail corrugation. The rail corrugation generates a roaring noise as northbound trains pass through the area.
Other factors affecting complaints	No, only noise.
Mitigation or control measures	It was determined that a significant cause of the noise was a coincidence between the P2 rail resonance frequency and the stick-slip frequency at the wheel-rail interface. The track lubrication was increased to move the stick-slip frequency down. This resulted in a reduction in noise level as the corrugation was no longer being excited but also introduced 25mm corrugation. Further mitigation actions are required to further reduce the level of noise including acoustic rail grinding. Rail grinding was not initially an option because of how quickly the corrugation set in. The increased lubrication has drastically slowed the rate of corrugation growth.

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Published by: UIC Sustainability
Director of publication: Pinar Yilmazer
Cover and layout: Ludovic Wattignies
Photo credit: Adobe Stock, Deutsche Bahn AG, SBB CFF FFS
Printing: UIC

ISBN 978-2-7461-3209-2
Copyright deposit: September 2022

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