UIC SUSTAINABLE DEVELOPMENT UNIT

Railway Noise in Europe
State of the art report

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This report reflects the Noise and Vibration working groups expertise within the UIC Sustainability Unit.

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- International Union of Wagon Keepers (UIP) - Gilles PETERHANS
- European Commission, Directorate - General for Environment (EU DG ENV) - Marco PAVIOTTI
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Executive summary

European railways are well positioned to achieve the United Nations sustainable development goals. The sector remains committed to doing business in a responsible way, providing environmentally friendly passenger and freight transport as well as offering a safe working environment. In this way the railways are a good neighbour and a responsible member of society.

François DAVENNE, UIC Director General

Rail is the most sustainable form of mass transport for both passengers and freight. Due to its intrinsic design, rail generates low CO_2 emissions and air pollutants, and is efficient in use of land and energy. When considering external transportation costs, a recent EC study shows that rail traffic scores better overall for both passenger and freight transport than road and air traffic [27]. In 2019, the European Commission launched its Green Deal[1] to protect the environment and to increase human well-being. This was followed in December 2020 by the new Sustainable and Smart Mobility Strategy[2], setting out how transport transformation will help deliver the Green Deal targets. The aim is for the European Union to be climate-neutral by 2050. For mobility, this requires cleaner, cheaper and healthier forms of transport for both passengers and freight. Rail is set to be the backbone of this transformed mobility system, with the strategy setting targets of doubling high-speed rail by 2030 and doubling rail freight by 2050. Central to the new mobility strategy is the promotion of a modal shift from road and air traffic, which will be needed to deliver important greenhouse gas emission (GHG) savings. The fact that 2021 is the European Year of Rail demonstrates the support for modal shift to rail and presents an opportunity to promote the benefits of rail.

The new mobility strategy will only accelerate the European railways' commitment to helping society, doing business in a responsible way, and continually improving its performance in providing safe working and environmentally-friendly mobility. Environmental noise is of growing importance in this context as an area with significant potential for improvement. There is a growing recognition that environmental noise has negative effects on public health and socio-economic welfare. This has increased even more with the publication of the World Health Organisation (WHO) Environmental Noise Guidelines in 2018 [103]. Transport noise is one of the main sources of environmental noise. Railways are taking responsibility and have already taken actions that will reduce environmental noise.

Over the past few decades, UIC and its members have led many research projects that have helped to better understand the noise-generating mechanisms of wheels and tracks. Examples range from the development of the TWINS interaction model in the 1990s to the current work within the ongoing Shift2Rail programme. These insights have led to the development of effective noise abatement measures that are already having a beneficial effect. New technologies and techniques include retrofitting with composite brake blocks, rail and wheel dampers, low-height noise barriers, and acoustic grinding. Ongoing and new EU research projects are set to further improve performance: we expect a focus on optimisation of the whole system of vehicle, wheel and rail, and their interactions, as well as an increasing focus on ground-borne vibrations.

New European policies, such as the noise-differentiated track access charges (NDTAC) regulation and the introduction of quieter routes in the TSI Noise, will encourage and incentivise improvement. At a national level, large-scale noise mitigation programmes are being executed and various countries have implemented a NDTAC scheme to favour low-noise freight wagons. Railway infrastructure managers are installing soundproof windows and building noise barriers at locations where noise is affecting residents. With all these measures,

[1] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
[2] https://ec.europa.eu/transport/themes/mobilitystrategy_en

noise near the railway tracks has been greatly reduced. This trend will continue for the near future with the ongoing and foreseen measures.

In general, those measures with the best cost-benefit ratio have already or are currently being implemented. There are measures that can further reduce noise, but these come at a relatively high cost, making the case for investment more difficult. High costs for additional noise measures threaten the competitiveness of rail traffic. This burden of cost could hamper the required modal shift towards railways. In this respect, it is important that the recent WHO recommendations are implemented with care, particularly in order not to put environmentally-friendly rail transport at an economic disadvantage in competition with other modes of transport and to support the climate ambitions of the European Green Deal.

> *The railways have accomplished much in terms of noise reduction, they are continuing to research cost-effective measures to ensure the competitiveness of the railways.*
>
> Jakob OERTLI, Chair of UIC Noise and Vibration Sector and Swiss Federal Railways

Contents

1. Introduction

1.1. Purpose of the report

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*.[3] As the world is at a turning point for climate change, this is a more pressing issue than ever. The European Commission launched its Green Deal in December 2019 with the aim of protecting the environment and increasing human well-being. A main goal is that the European Union will be climate-neutral by 2050. This also requires a shift towards greener mobility, requiring freight and passenger transport to shift from road and aircraft to railways.

Parallel to these developments, there is increasing awareness that environmental noise has a growing negative impact on public health and socio-economic welfare. This is highlighted by the publication of the new WHO Environmental Noise Guidelines in October 2018 [103]. Transport noise is the major source of environmental noise and even though the majority of the total noise exposure is caused by road traffic, it is also an important issue for people living close to the railways. The railway sector, including UIC, is fully aware of the noise issues and has been working hard for decades to reduce its noise footprint and will continue to do so in the future. Research and engineering towards low noise rail vehicles and tracks is ongoing and many European countries are spending large budgets to build noise barriers as well as implementing other noise abatement solutions in order to facilitate the increasing traffic while decreasing noise exposure.

Since publication of UIC's previous State of the Art report in 2016 [87] there have been several major developments in Europe regarding railways and noise:

- publication of the WHO Environmental Noise Guidelines - October 2018
- implementation of the European harmonised noise assessment method, Directive 2015/996 (CNOSSOS-EU) in national legislation for every Member State - January 2019
- revision of the TSI Noise, introducing the Quieter Routes approach, through Regulation 2019/774 - May 2019
- publication of the European Green Deal - December 2019
- publication of the new exposure-response functions for noise, replacing Annex III to the Environmental Noise Directive, through Directive 2020/367 - March 2020
- publication of the EEA's Environmental Noise in Europe report - March 2020
- several important national developments, including preparation and execution of noise abatement programmes, the ban on cast iron brake blocks in Switzerland as of January 2020 and the adoption of a law in Germany to ban cast iron brake blocks in Germany from 13 December 2020[4]
- significant Research at European level as e.g. the SHIFT2RAIL project with projects like Roll2Rail and DESTINATE
- the third round of retrofitting funding through the Connecting Europe Facility
- an evaluation of the Noise Differentiated Track Access Charges (underway).

Given all these developments, UIC found it appropriate to publish this updated State of the Art report. The report describes recent railway noise developments and provides an overview of the activities the railway sector is undertaking to improve the railway noise situation and to prepare for future increases in traffic.

[3] https://uic.org/about/about-uic/ [retrieved 15 July 2020]
[4] Schienenlärmschutzgesetz, see https://www.gesetze-im-internet.de/schl_rmschg/Schl%C3%A4rmschG.pdf

As a complement to this present State of the Art report, the White Paper on Acoustics was published in February 2020 by the UIC Train Track Interaction Sector's subgroup for Aerodynamics and Acoustics [93]. The objective of this White Paper was to address the technical issues pertaining to railway acoustics according to the three following topics:

- noise source generation;
- acoustic comfort, subjective perception and psychoacoustic indicators;
- ground-borne vibration.

Intended for technical experts in the field of railway noise and vibration, the UIC-TTI White paper provides a brief summary of current knowledge and recent developments according to each of the above topics. It should be referred back to as a technical support to this State-of-the-Art report for Railway Noise in Europe.

1.2. Scope

This report covers freight transport as well as passenger transport. The focus is on heavy rail vehicles, as opposed to light rail (trams, metro and similar light rail), although many sections could apply to such rail transport modes as well.

1.3. Target audience

This report covers the broad subject of railway noise and covers technical issues, noise abatement measures, costs and health impacts as well as European and national policy. As such, it is useful as an in-depth introduction for readers that are relatively new to the subject, for policy makers that want to learn more about technical issues and for engineers that want to read up on policy and legislation. More experienced readers will find it useful as an overview of what is new and what has happened in the past few years. And overall, it may serve as a reference for other publications regarding environmental noise, or environmental aspects of railways in general.

1.4. Writing process

This report was written by M+P and commissioned by the UIC. For this report, an extensive literature review was undertaken. Where information from existing literature was lacking, the UIC Noise and Vibration Sector has supplied further knowledge, expertise and data. The core group of the UIC Noise and Vibration Sector has served as a steering group, has reviewed several draft versions and collected input from the European Commission, CER and other stakeholders as listed in the references.

1.5. Document structure

Chapter 2 explains the big picture in which we will compare railway traffic with other means of (freight) transport. We will summarize what favours railway traffic over other modes of transport and how this affects noise emission, exposure and health impact. Chapter 3 discusses the different noise sources and presents various models to describe these. Chapter 4 provides a systematic overview of noise control methods at the source (both track and vehicle) in the propagation path and at the receptor, and chapter 5 discusses the costs of these railway noise abatement methods. In chapter 6 we consider noise assessment methods. We begin with a discussion on noise indicators. Next, we introduce models for noise assessment. The chapter ends with an overview of noise monitoring systems in use. The impact of noise on people is addressed in chapter 7. Chapter 8 explains the costs of environmental noise: internal, external and infrastructural costs and how these costs are quantified. The EU policy and legal requirements are described in chapter 9, which include among others the Environmental Noise Directive and the Noise Differentiated Track Access Charge. In chapter 10 we look at implementation of legislation in the different European countries. At the end, chapter 11 summarizes the main conclusions and gives a short outlook into the future.

2. The big picture

UIC vision on railways and noise

Railways are a sustainable means of transport. They are an important element of climate friendly transport, both for passengers and for goods.

Therefore, it is expected that railway traffic will increase in the future, which brings the risk of an increase of noise emissions and the associated effects on people and ecology. Reducing the environmental externalities of the railways through noise mitigation is a specific target under the United Nation's Sustainable Development Goals (SDG) 3,[5] 9,[6] 11[7] and 12.[8] The railways acknowledge the negative effect of noise and therefore the sector has undertaken considerable effort to minimise noise emissions and will continue to do so in the future - all in accordance with the legislation of the European Union as well as that of individual countries.

There has been extensive construction of noise barriers and the retrofitting of block or tread brakes on freight wagons with composite brake blocks, making these vehicles considerably less noisy. In addition, much effort is being put into understanding the properties of the track in relation to noise emission. This will enable developing optimal combinations of track components, which not only reduce noise but are also beneficial for track maintenance. A good example of this are rail pads - elastic materials that are placed between the rail and the sleeper. Soft rail pads are beneficial for maintenance while stiff rail pads are less noisy. The challenge therefore is to develop a rail pad that supports both noise reduction and maintenance. In addition to improving the track, railways are developing improved rolling stock. This does not only concern reducing noise at high speeds but also at lower speeds in urban areas as well as for parked trains. Since rolling stock will develop in the future, noise is being considered in new vehicle designs as well.

Noise mitigation measures, however, must have a good cost-benefit ratio. There are two reasons for this: First, noise mitigation is expensive and therefore as much noise reduction as possible must be achieved with the funds being invested. Second, the high costs for noise control must not endanger the competitiveness of the railways, otherwise the benefits of the railways in terms of sustainability are endangered. It is therefore important to find a balance between noise mitigation and costs. This will enable the railways' aim for the future to be achieved: To remain a competitive, sustainable, and quiet means of transport.

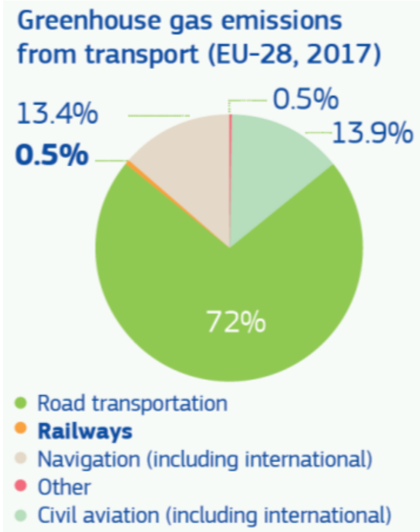
UIC Noise Core Group - 2020

2.1. The European Green Deal

The European Green Deal [25] is the European Commission's *roadmap for making the EU's economy sustainable. This will happen by turning climate and environmental challenges into opportunities across all policy areas and making the transition just and inclusive for all*.[9] Europe strives to be climate-neutral by 2050 and expects to be the first continent to achieve this. This requires action by all sectors of economy, including transport. The Green Deal aims to reduce transport GHG emissions by 90% in 2050 while also making private and public transport cleaner and healthier.

[5] Sustainable Development Goal 3 - Ensure healthy lives and promote well-being for all at all ages: https://sustainabledevelopment.un.org/sdg3
[6] Sustainable Development Goal 9 - Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation: https://sustainabledevelopment.un.org/sdg9
[7] Sustainable Development Goal 11 - Make cities and human settlements inclusive, safe, resilient and sustainable: https://sustainabledevelopment.un.org/sdg11
[8] Sustainable Development Goal 12 - Ensure sustainable consumption and production patterns: https://sustainabledevelopment.un.org/sdg12
[9] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (retrieved 16-03-2020)

In order to support this, the European Parliament has accepted the Commissions proposal to make 2021 the European Year of Rail.[10,11] Railways are a key factor to achieving the climate goals expressed in the European Green Deal. Rail traffic is one of the most environmentally friendly and energy-efficient transport modes. More than half of European railways are electrified[12] and emit far less CO_2 than equivalent travel by road or air. In the total GHG emissions for the EU, the contribution from railways is negligible (0.5%), see [20]. UIC is committed to achieving the desired carbon neutrality by 2050, and more than 60 UIC members have signed the Climate Responsibility Pledge to underline this.[13]



GHG emissions from transport in 2017, from [20]

The subject of environmental noise, from transport or other sources, is not explicitly mentioned in the Green Deal. However, the Green Deal and the accompanying roadmap [25] do announce the Zero pollution action plan for water, air and soil [32] to reduce emissions from air, water and ground. These emissions can also include noise. The reduction of noise is also mentioned as a responsibility in the Mission letters from Ursula von der Leyen, President of the European Commission, to the European Commissioner for Transport Adina Vălean [29] and to the Executive Vice-President for the European Green Deal, Frans Timmermans [28].

> *The climate neutrality objective of the EU Green Deal requires a modal shift to rail being the greenest transport mode. This requires rail to be more competitive and attractive for the customers and for society. To meet this challenge European railways must become more silent - and they are working hard on it.*
>
> Ethem Pekin - CER

2.2. Comparison between rail and other means of transport

In figure 1, the different transport modes are compared in terms of their external costs for climate, accidents, air pollution, noise and other environmental impacts. External costs provide a common scale to compare different environmental aspects. This common scale is the monetary effect on society expressed in Euro (€) per kilometre travelled. These figures originate from a recent study for the Commission [34]; details on the background to these values can be found in [27] and in Chapter 8 below. From these figures, it is clear that:

- for passenger transport, the total external costs per km are lower for railways than for any other transport mode. For freight transport, rail is second-to-lowest and is much lower than road transport (by heavy goods vehicles);
- *climate* costs as well as *air pollution* costs are lower for rail than for all other modes, for passenger and freight traffic.

[10] https://ec.europa.eu/commission/presscorner/detail/en/ip_20_364 (retrieved 17-03-2020)
[11] https://www.railjournal.com/regions/europe/european-parliament-approves-2021-year-of-rail-proposal/ (retrieved 11-11-2020)
[12] Situation in 2018 according to https://ec.europa.eu/transport/facts-fundings/statistics/pocketbook-2020_en (retrieved 11-11-2020)
[13] https://uic.org/sustainable-development/energy-and-co2-emissions/railway-climate-responsibility-pledge#Railway-climate-responsibility-pledge (retrieved 11-10-2020)

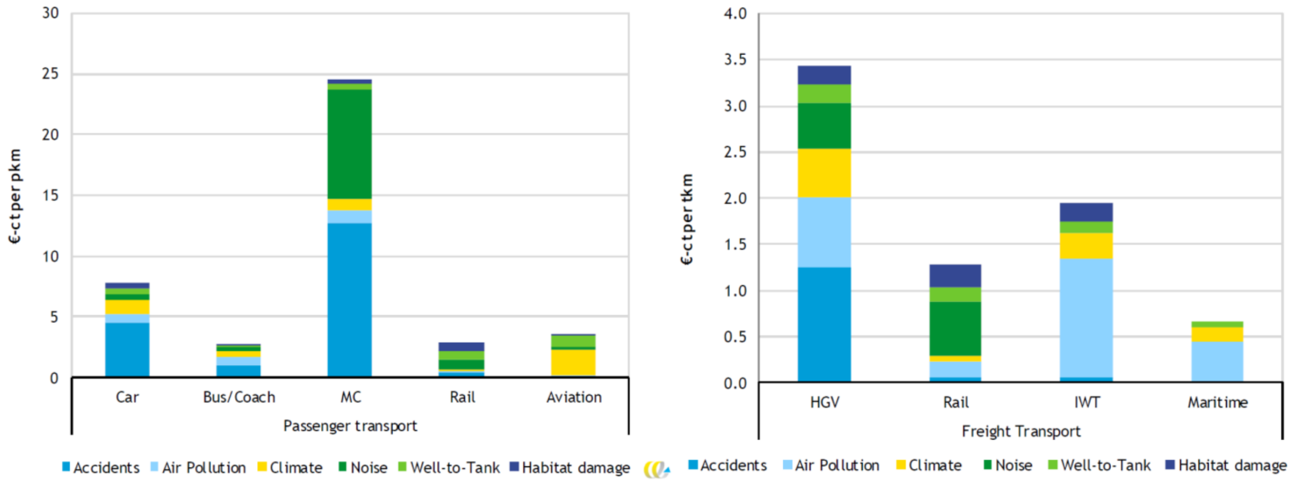


Figure 1: Average external costs 2016 for EU28 (excluding congestion); left: passenger transport costs in €-ct per person-km, right: freight transport costs in €-ct per ton-km[14,15] (from [34])

Clearly, rail transport is the most climate- and eco-friendly transport mode and at the same time leads to fewer accidents than other modes. Nonetheless, the majority of passenger as well as freight transport is currently undertaken by other modes, mainly road traffic. Table I shows EU transport statistics for 2017 [33].

- For passenger transport, 80% of all person-kilometres are covered by car, bus or motorcycle, 11% by airplane and 8% by train or urban rail.
- For freight transport, 52% of all ton-kilometres are covered by lorries, 37% by ships, and 12% by freight trains.

This leads to the total share of external costs for each transport mode as shown in figure 2. The contribution of railways is smaller than 2%, almost negligible in the total. It is evident that a shift from road to rail for freight and passenger transport would benefit the environment and citizens in Europe. A shift from air to rail traffic for European land routes will also contribute to this.

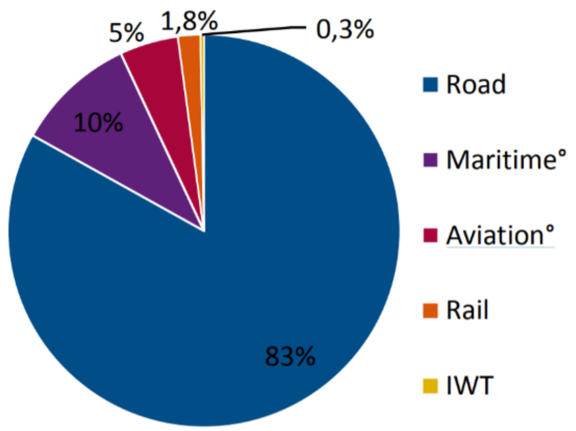


Figure 2: Share of the different transport modes on total external costs 2016 for EU28[9,10] [27]

[14] MC = motorcycle, HGV = heavy goods vehicle (i.e. lorry), IWT = inland water transport
[15] Note: figures for aviation are averages for selected EU28 airports, figures for maritime transport are averages for selected EU28 ports

Table 1: EU-28 transport performance by mode (2017, from [33])

	passengers [billion pkm]			freight [billion tkm]		
road	5,534	80%	cars: 4 901 motorcycles: 123 bus / coach: 510	1,870	52%	
rail	577	8%	train: 470 tram / metro: 107	421	12%	
air	777	11%		3	0.1%	
water	24	0.3%	sea: 24	1,323	37%	IWT: 147 sea: 1,176
total	*6,913*			*3,617*[16]		

Table 1, obtained from the statistical evaluation of EU transport, shows that road traffic is the dominant source of transport noise in both freight and passenger transport [33]. In addition, rail has the lowest external costs compared to road traffic and aviation, as indicated in the EC study on external costs. Of the external environmental costs associated with rail transport, noise represents the largest share: around one third in passenger transport and almost half in freight transport (see Figure 3) [27]. The railways have already taken action to be a good neighbour and a responsible member of society.

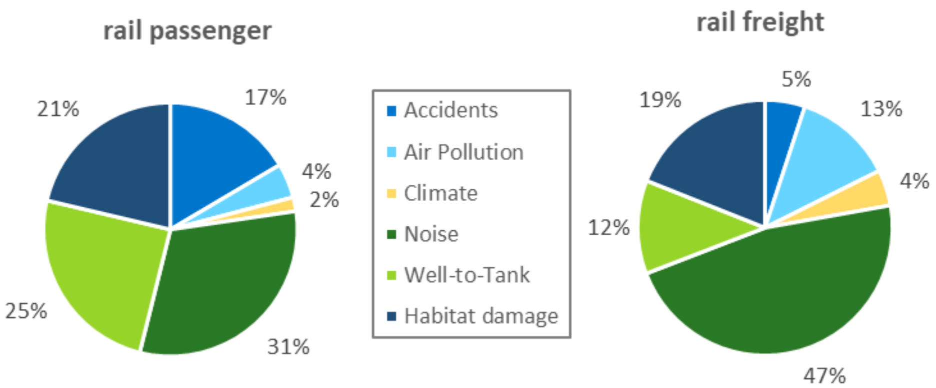


Figure 3: Average external costs 2016 for EU28 divided over environmental impacts, for rail passenger and freight transport; with data from annexes to [27]

2.3. Concerns

The railways acknowledge the need for noise mitigation measures, but there are some risks which must be considered [63]. The mitigation measures are described in more detail in chapter 5.

Competitiveness

The railway sector is in competition with other modes of transport and keeping the railways competitive is crucial for the green deal. The sector promotes retrofitting of freight wagons with composite brake blocks and the construction of noise barriers as well as further measures on the infrastructure, but these ought not to reduce the competitiveness of the railways. European policy makers should not only consider the costs of noise mitigation measures, but also their influence on the traffic capacity of the network and the impact on intermodal competition. Costs not only originate in the investment and maintenance costs of the measure itself, but also in effects on other parts of the system such as the increased necessity to reprofile the wheels after retrofitting freight wagons [8][14].

Trade-offs

Measures or goals for noise, vibrations and asset management cannot be always combined or may even contradict each other. An example of this is the rail damper. Rail dampers can be beneficial for noise but can complicate certain aspects of maintenance such as track inspection [54][62] and in some cases also safety issues [43].

[16] Pipeline transport (114 billion tkm) not included

Network capacity

While creating a level playing field between transport options, the network capacity of railway shall be improved, and noise policy should not reduce the traffic capacity.

Damage and vandalism control

Noise mitigation measures are often subject to damage and vandalism, e.g. graffiti on noise barriers. It is therefore needed that research efforts focus on measures considering the potential for damage and vandalism as well. Solutions that are in use are the incorporation of noise barriers in landscaping projects and planting shrubs on the outside of noise barriers.

Product requirements

Noise control measures used in the track or on the railways must follow specific requirements. Among others, the specifications include the resistance to dynamic loads, a minimum life span, the resistance to the effects of moisture, ozone and ultra-violet light.

Minimal maintenance and replacement costs

Costs for maintenance and replacement must be included when choosing between different noise mitigation options. It is best to work with high quality products with long life spans. This will also minimise the effect on availability of the track.

2.4. Policy makers and stakeholders

The table below lists the (international) stakeholders in the field of railways and railway noise. The table covers most European organisations. Stakeholders not in the list include the railways themselves and national and local governments, as well as local communities.

Table II: Overview of European and international railway stakeholders

Railway sector associations		
UIC	International union of railways *Union Internationale des Chemins de fer*	Worldwide organisation for international cooperation among railways, founded in 1922, counts more than 200 members on all 5 continents, among them rail operators, infrastructure managers or vehicle keepers. Main tasks: promotion of rail transport at a global level, understanding the business needs of the rail community, developing innovation programmes to identify solutions for those needs, publishing International Railway Standards (IRS) that facilitate the implementation of the innovative solutions UIC noise activities are described further in Annex A
CER	Community of European Railway and Infrastructure Companies	Organisation of European (EU-27 and other countries) rail sector members, including integrated companies, infrastructure managers, passenger and freight operators, national associations Main tasks: represent rail sector members in EU-policy making; evaluate regulations; position papers and lobbying
UIP	International union of wagon keepers	European organisation of fourteen national associations, representing freight wagon keepers and entities in charge of maintenance (ECMs), together responsible for 50% of European rail freight transport and managing more than 220'000 freight wagons. Main tasks: representing the wagon keepers and ECMs towards the EU institutions and sector stakeholders, evaluate European Policies and lobbying.
EIM	European Rail Infrastructure Managers	Non-profit association forming a representative body for infrastructure managers (IMs). Main tasks: represent IMs to the relevant EU institutions and sector stakeholders, assist members through sharing experiences and contribute to technical and safety activities of the ERA

UNIFE	European Rail Supply Industry Association	Organisation representing companies and national associations involved in engineering, manufacturing and maintenance of rail transport (sub)systems and equipment. This includes infrastructure, energy and signalling suppliers, as well as rolling stock manufacturers. Main tasks: public affairs, standardisation & harmonisation, research and innovation, certification and quality management
ERFA	European Rail Freight Association	ERFA represents private and independent railway companies from across Europe. EFRA today represents 30 members. Main task: represent the voice of private and independent rail freight companies in Europe. We support the EU decision-making process with a focus on policy and technical affairs.
European Commission - relevant Directorates (DGs)		
MOVE	Mobility and Transport	Responsibilities: transport investments, innovative & sustainable transport, competitiveness of passenger and freight services, internal transport market, safety and interoperability legislation and standards, technical specifications, regulations on Connecting Europe Facility (CEF), noise-differentiated track access charges (NDTAC)
ENV	Environment	Responsibilities: environmental policy, to protect, preserve and improve the environment for present and future generations, Environment Action Programme (EAP), Environmental Noise Directive, Noise Expert Group
GROW	Internal Market, Industry, Entrepreneurship and SMEs	Responsibilities: internal market for goods and services, sustainable and inclusive economy, jobs and investments, fostering entrepreneurship and growth, industrial property rights
ENER	Energy	Responsibilities: energy security, internal energy market, innovation and competitiveness, energy efficiency and decarbonisation of the economy
EU agencies		
ERA	EU Agency for Railways	Main tasks: creation of a Single European Railway Area, ensure cross-border compatibility of national systems, technical and legal frameworks to harmonise safety and remove technical barriers, technical specifications for interoperability (TSIs), EU authority to issue vehicle (type) authorisations and safety certificates
EEA	European Environment Agency	Main tasks: provide independent information on the environment, to support developing, implementing and evaluating EU environmental policy, collecting strategic noise maps and action plans required under the Environmental Noise Directive; EEA works closely with the European Environmental Information and Observation Network (EIONET) consisting of its 32 member countries, with collaborating experts from the national Environmental Protection Agencies.
Other institutions		
WHO	World Health Organization	Worldwide organisation with 194 Member States across six regions, focused on combatting diseases and improving public health. Regarding environmental health, this includes climate change, chemical safety, water and air pollution and noise. The WHO provides research, guidelines and methods for health impact assessment.
EPA Network	European Network of the Heads of Environmental Protection Agencies	Informal network organisation of European Environmental Protection Agencies (EPAs) and similar bodies. The EPA Network has various interest groups, including an Interest Group on Noise Abatement (IGNA). Main tasks: exchange views, experience and knowledge on practical implementation of environmental policy, communicate through public reports and letters to EU institutions.

3. Noise sources

3.1. Noise sources

The main sources for railway noise are

- Rolling noise
- Power equipment or traction noise
- Aerodynamic noise

The severity of these noise sources depends on the speed of the train. At low speeds, power equipment noise is the dominant source and at medium speed rolling noise is the most important noise source. Only at (very) high speeds does aerodynamic noise come into play. This is illustrated in figure 4. Other noise sources include impact noise, curve squealing noise and noise from bridges for rolling trains but also shunting yards, noise from parked trains as well as braking noise.

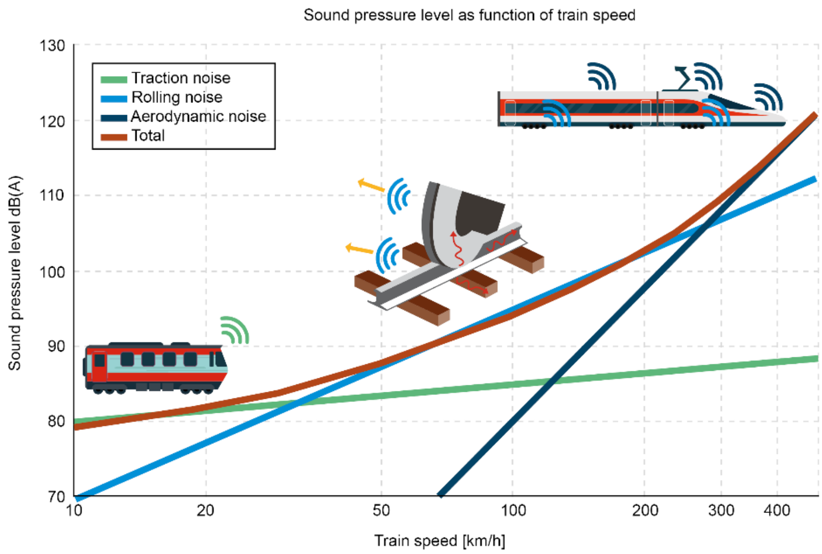


Figure 4: Sources for railway noise as function of the driving speed [31]

3.1.1. Rolling noise

Rolling noise is caused by rail and wheel vibrations at the wheel/rail contact. Roughness on the wheel and on the rail running surface produces vibrations of the wheel and rail system. The vibrations transmitted into the wheel and rail structures lead to sound radiation. Both the rail and the wheel are of importance for the overall sound pressure level and both should be considered. Rolling noise is of a fairly broadband nature (typically, in the range from 250 to 2500 Hz). In addition to the rail and the wheel, sleepers also contribute to the total rolling noise. Ballast-less tracks or ‘slab track’ is growing in popularity several countries for high speed lines. Slab track is considered to be noisier than ballasted track as slab track incorporates softer rail fasteners which leads to higher rail noise.

A typical result from a theoretical prediction of the rolling noise is shown in figure 5. It distinguishes between the contribution of the sleepers, the wheel and the rail. The sleeper is modelled as the main source for the lower frequency range. The wheel is predominant in the higher frequency range. In the mid frequencies around 1000 Hz, the rail is the dominant noise source.

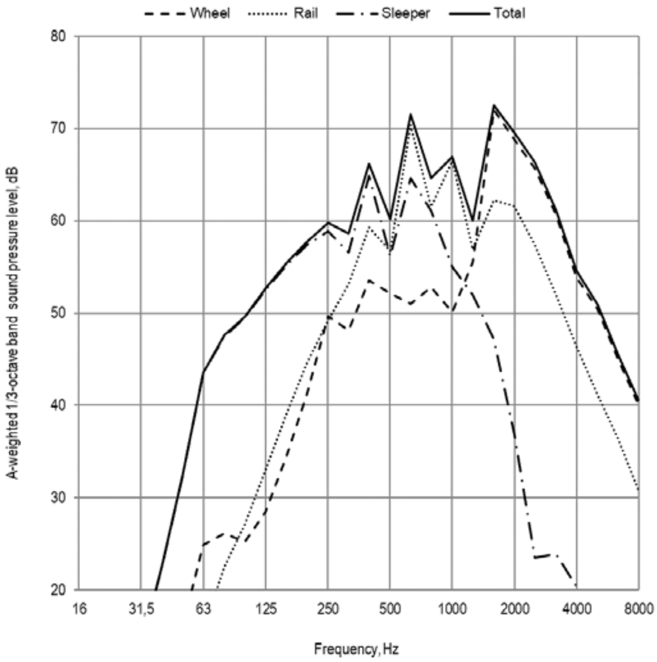


Figure 5: Results from a typical prediction calculation of the contribution of the sleeper, rail and wheel components to the overall sound pressure level using the RIM[17] model [61]

3.1.2. Locomotive and traction unit noise

Traction noise is important in certain operating conditions: The equipment is the only source of noise when a train is standing in stations when stopping on open tracks or when idling. When starting, driving at low speed and during electric braking, the noise emission of the traction units is the most important factor. This applies equally to both noise heard inside and outside the train. Traction noise originates from several sources on the train including diesel engines, engine cooling fans, exhaust and intake, traction components such as the inverter, compressors, gearboxes. These are displayed in figure 6. Also shown in there are the heating, ventilation and air conditioning (HVAC). These are more important for idling trains (see section 3.1.8)

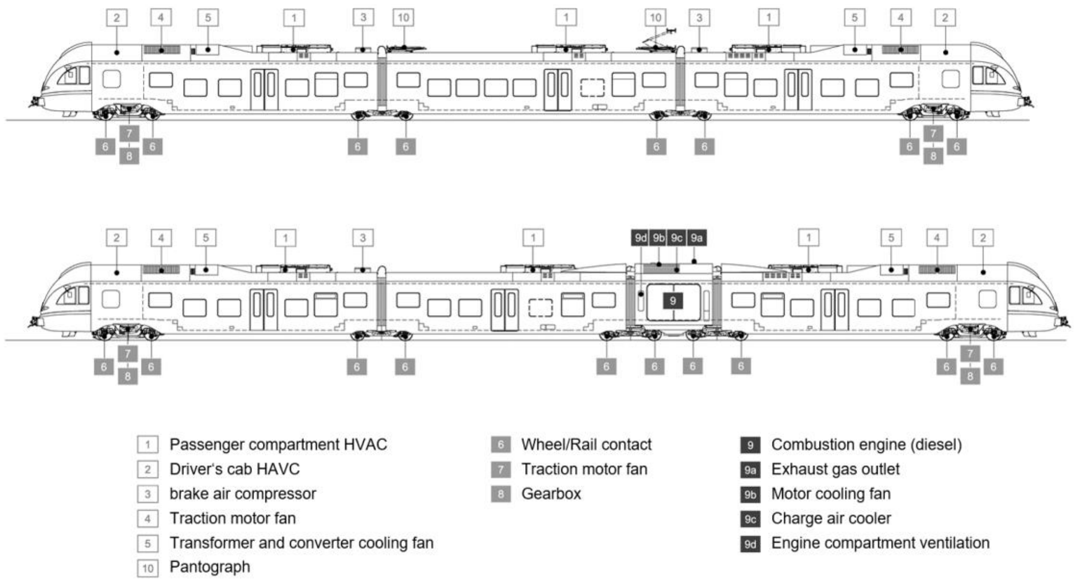


Figure 6: Traction noise sources of an electrical and a diesel multiple unit [77]

[17] The RIM-model is a wheel/rail impedance model. It is described in section 3.2.5

3.1.3. Aerodynamic noise

When the train is running, air flows around the outer contour of the train. This creates a turbulent boundary layer around the vehicles, which in turn generates aerodynamic noise. This type of noise starts becoming relevant at speeds around 200 km/h and at speeds above 300 km/h it is the dominant noise source [81]. Aerodynamic noise affects the external as well as internal noise. Aerodynamic noise sources may differ between various trains but usually they include

- the bogies of the train
- the pantographs, the recesses in the roof and other roof-mounted equipment,
- the nose of the train
- the gap between coaches
- ventilation grilles
- door handles, steps.

The contribution of aerodynamic noise from the bogie region to the overall sound power of the whole train has been estimated to be around 15 dB greater than that from the pantograph [80].

3.1.4. Impact noise

Impact noise is an impulsive noise caused by discontinuities of the rail or the wheel surface such as wheel flats, rail joints, switches and crossings. Impact noise has a higher disturbing effect because it is characterized by individual impulses.

3.1.5. Squealing noise in curves

The interaction between rail and wheel in narrow curves may cause a high frequency squealing noise, typically in the range from 1 kHz to 5 kHz. There is a distinction between squeal and flange noise.

- Squeal noise: a multi discrete frequency noise caused by lateral creep movement of the wheel while rolling along the surface of a rail on a curve. It is strongly tonal due to the wheel vibrating in one of its resonances. Squeal noise typically occurs in the frequency range from 1 kHz to 5 kHz with sound pressure levels of up to 110 dB(A) in 10 m distance from the track.
- Flange noise is caused by the lateral contact of the wheel flange to the rail face: it is a more broadband high-frequency noise without specific tonal components. It is usually more intermittent than squeal noise.

Squealing noise may not occur along the whole length of a curve and depends on numerous factors like vehicle and track construction, the condition of the curve itself and weather conditions [56].

3.1.6. Brake squeal noise

A similar squealing noise can also occur during braking as a high frequency tonal or multi-tonal noise can be emitted during braking. This may occur on vehicles, but another source is the braking of freight wagons by beam retarders in railway yards [55].

3.1.7. Noise from bridges

When the train runs over a bridge, the bridge is excited by dynamic forces from the wheels. The dynamic forces cause vibrations of the bridge structure that are radiated as low-frequency noise, which can increase total noise significantly. Bridge noise strongly depends on the type of bridge, steel bridges with a direct fastening in particular are very noisy:

- The forces are directly transmitted to the bridge structure (gravel structures would have a better damping effect). The rail fastening system may cause a decrease in the track decay rates and then a strong increase in noise radiated by the rail.
- These bridges usually consist of large steel surfaces which act as noise radiators, e.g. the steel deck, or the supporting structure.

The increase in the noise level can be up to 20 dB. As the A-weighted sound pressure level may not fully take this effect into account, the so-called Z-weighting is often used [55], [80]. A recent measurement campaign in the Netherlands confirmed the low frequency increase [97] where increases up to 20 dB were observed for steel bridges.

3.1.8. Noise from parked trains

Noise from parked or idling trains is an increasing problem [90] as older trains are being exchanged more and more for modern multiple units that are generally fitted with a far larger number of technical aggregates to make the train more comfortable for passengers (e.g. air conditioning, electrical outlets). In addition, more and more yards and sidings at final destinations of railway lines are in urban areas, which inevitably raises the number of people affected by noise from parked rolling stock.

Nowadays, parked railway units must be ready for operation at short notice and essential preparation work (e.g. cleaning) and maintenance of rolling stock must be carried out at night. Thus, different aggregates such as HVAC or compressors are often in operation during the parking of the vehicle and cause noise.

For parked trains in depots, the following stationary noise sources have been identified: HVAC, cooling fans and pumps for technical aggregates, air compressors (especially fluctuations due to multiple compressors running at slightly different rotational speeds), the blow-off via the exhaust valve of the air dryer within the air supplying device, power supply engines (both diesel and electric train units) and supply aggregates. In addition, starting noise, impulse noise in joints and switches and horn tests are common noise sources.

The location of some of the aggregates on the roof of the vehicle (low-floor vehicle to provide better accessibility) makes countermeasures such as sound barriers far less effective.

At shunting yards, the main noise sources are locomotive noise, rail brakes and buffer noise but also rolling noise and impact noise. Within EUROSPEC, a voluntary specification is being developed for product specification as an add-on to the TSI Noise. CEN TC WG256 WG 03 started to implement this topic into a future version of ISO EN 3095.

Some railways park stable trains in a strategic way, so that less noisy trains act as a barrier for noisier trains.

3.1.9. Tunnel noise

When trains travel through a tunnel, increased noise emission can occur at the portal, a so-called “sonic boom”. At both low and high speeds, some of the driving noise generated when trains travel through the tunnel can be emitted at the tunnel portals. At high speeds, micro pressure wave emissions can also occur at the tunnel portals. When a train enters a tunnel, the air in the tunnel is compressed. A compression wave is generated that depends on the speed of the train and the geometry of the train and tunnel portal. The compression wave travels ahead of the train at the speed of sound through the tunnel and can become steeper in tunnels with especially low absorption (no ballast, no absorbers). At the opposite exit portal, the incoming compression wave is partially reflected into the tunnel and part of its energy is radiated outwards as a so-called "micro pressure wave" (MPW) [55].

3.1.10. Construction noise

The construction of railway tracks or noise measures generates noise. This construction noise is a temporary local issue and in general it is not the responsibility of the railway infrastructure managers. We will therefore not consider construction noise in this report.

3.2. Noise source modelling

Different models exist to predict railway noise (and vibrations). This section describes the software tools TWINS and RIM. Additionally, we will introduce recently developed tools in European research projects, e.g. STARDAMP.

3.2.1. TWINS

TWINS (Track Wheel Interaction Noise Software) is a computer-based software tool to calculate the acoustic effects of wheel and track design on railway rolling noise. In the TWINS software, the user can specify the design of wheels and track, using numerical inputs including finite element data. TWINS calculates vibration levels and sound emission of wheels, rails and sleepers during a train pass-by. Wheel and track surface roughness spectra are also inputs. The resulting sound power and sound pressure levels can be presented in one-third octave plots.

TWINS can assess the effects of many design parameters including wheel and rail geometry, choice of materials, wheel/rail surface conditions and damping of wheels and rails.

3.2.2. STARDAMP

STARDAMP (Standardization of damping technologies for the reduction of railway noise) is a Franco-German research project within the DEUFRAKO framework. The target of STARDAMP was to support the transfer of wheel and rail dampers from R&D to their regular application. A software tool has been developed within STARDAMP and based on TWINS that is dedicated to the prediction of the efficiency of wheel and rail dampers. The necessary input can be produced using relatively simple laboratory measurements.

3.2.3. ACOUTRAIN

The project aimed to speed up product authorisation by introducing virtual testing features while retaining the same degree of reliability and accuracy of real-life testing. ACOUTRAIN also worked on harmonising the assessment of noise conformity across Europe by providing standard procedures. ACOUTRAIN developed a virtual testing simulation tool for stationary and pass-by noise levels. It also worked on validating and verifying both the tools and methods to assign them acoustic source strengths. It pointed out that more work needs to be done in this area, highlighting the need to produce a cost-benefit analysis of different virtual testing scenarios in the future.

The new European research project TRANSIT will build upon tools developed within ACOUTRAIN [83].

3.2.4. Train Noise Expert

Train Noise Expert (TNE) is a software package developed by the Institute of Sound of Vibration Research (ISVR) which combines the functionality of the ACOUTRAIN tool with new software based on the TWINS rolling noise calculation method. The rolling noise sources can be manually input into external noise predictions as sound power spectra, but a TWINS-based calculation is also available as an optional add-on. This allows rolling noise sound powers and pressures to be calculated for arbitrary wheel and track designs.

3.2.5. RIM

The wheel/rail impedance model RIM is a validated numerical programme for the prediction of rolling noise and vibration [17]. It considers the wheel and rail roughness and irregularities, the unbalanced wheel masses and the parametric excitation due to the sleeper distance and variations in the stiffness of the rail pads as excitation mechanisms. RIM calculates the wheel rail interaction and determines the mechanical impedances of the vehicle and track and all components involved, such as car body-, bogie- or wheel-set mass and dynamics such as wheel, sleeper, pad, or ballast properties. The impedance model of the track is implemented using a serial connection of complex stiffnesses, including loss factors, the rail as a continuously supported beam, the rail pad and the ballast, the sleeper and the soil.

RIM can determine the

- total sound pressure level during a train pass-by and the contributions of the wheel, the rail, the sleeper,
- structure-borne noise of the track and vehicle components and the wave propagation in the soil,
- impedances of the different system components,
- bridge noise.

RIM makes it possible to investigate the contributions of the individual components (parameter studies), which is hardly possible in the context of measurements.

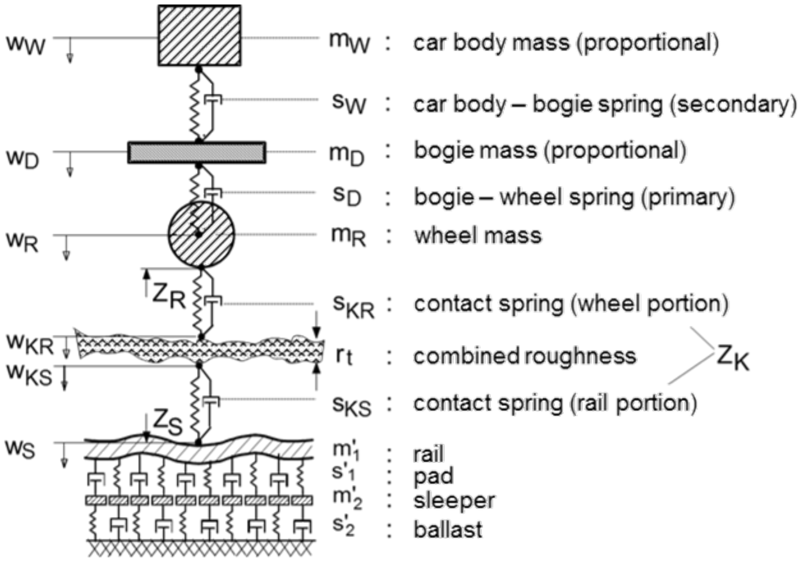


Figure 7: Structure of a RIM-model [61]

4. Noise control methods

4.1. Introduction

The classical approach for noise mitigation measures has three options:

- Noise mitigation at the source (preventing noise emission: track design & maintenance, acoustic rail grinding, track damping, low-noise brakes for freight wagons, silent rolling stock)
- Noise mitigation in the propagation path (e.g. installation of noise barriers)
- Noise mitigation at the receptor (e.g. installation of soundproof windows)

The various options for noise mitigation measures are discussed below. Noise mitigation at the source can be divided into measures for rolling noise and for equipment and traction noise.

For the planning of new lines, keeping the noise source (such as switches and crossings or sidings where trains may be kept idling at signals) away from sensitive areas can be considered.

4.2. Noise mitigation at the source

4.2.1. Mitigation and measures for locomotive and traction unit noise

Locomotive and traction noise can be reduced by acoustic measures at the vehicle, such as [55]

- demand-based control of the fan speed,
- acoustically optimised airfoils,
- optimisation of the cooling concept,
- silencers,
- water and natural convection air cooling
- encapsulation of the aggregates,
- optimisation of pulse patterns of electrical converters,
- reduction of the sound radiation of the housing of gearbox and engine.

It is important that the noise management [76] measures for the acoustically relevant sources are already taken into account at an early stage of vehicle design and coordinated with the other tasks involved.

4.2.2. Mitigation measures for rolling noise

Rolling noise mitigation at the source can be divided into measures that affect the excitation, measures that are able to damp the vibrations of the wheel and the rail and measures that reduce the noise emission. This is illustrated in figure 8.

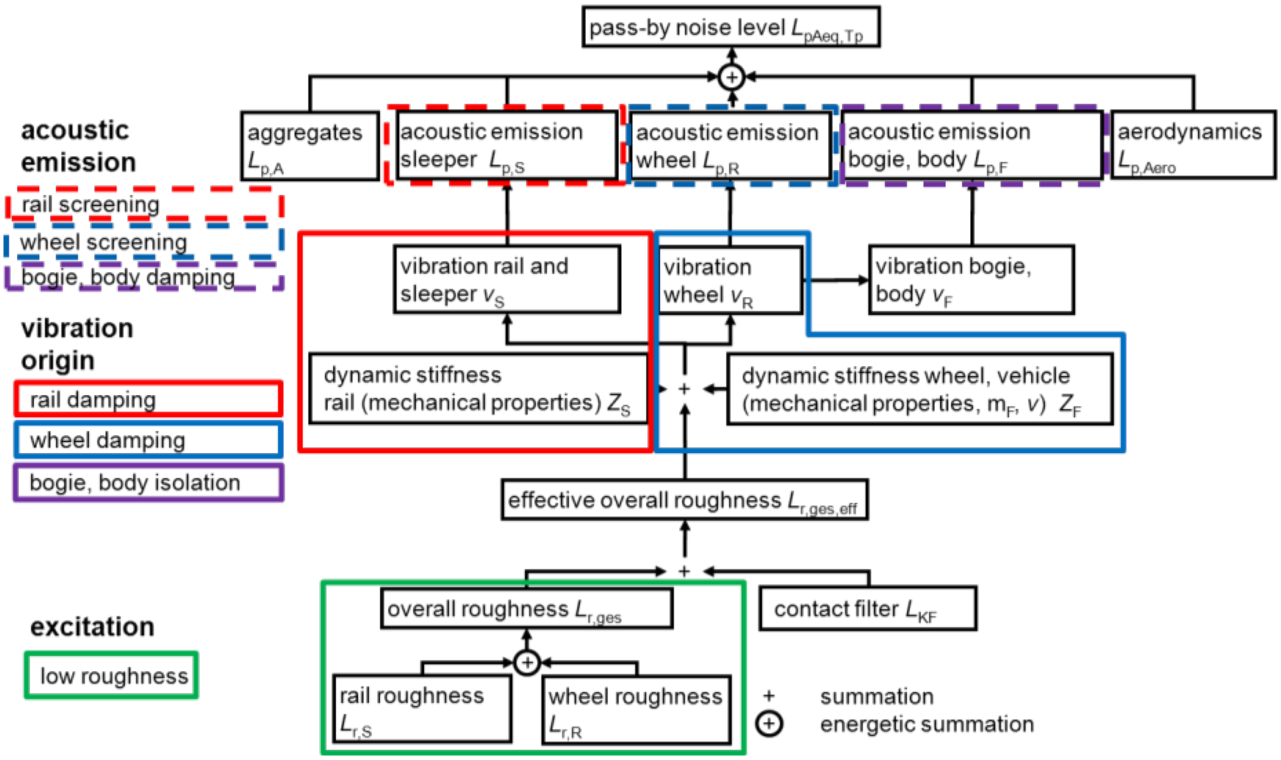


Figure 8: Schematic representation of railway noise mechanism and noise sources. The coloured blocks indicate what type of measures can be taken and which mechanism they influence [84]

Low roughness (smooth wheels and smooth rails)

Investigations have shown that the condition of the surfaces of wheel and rail has the greatest influence on noise emission. This is because rolling noise is mainly excited by the roughness of the wheel and the rail. Smooth wheels and rail surfaces are major factors for silent railway traffic. As the sum roughness of the wheels and the rails excite the rolling noise, a noise reduction is only achieved if both, the wheel and the rail have low roughness.

Wheels can become rough or form polygons. The rails can also become rough or form waves and ripples. Both causes an increase in noise emission.

The first step should thus always be to identify the dominant roughness (wheels, rails, or both) and then to reduce the roughness. This is usually done in terms of overturning of the wheels or (acoustic) grinding of the rails.

Freight wagons that are established with cast iron brake blocks or tread blocks (see EN14478:2017 [12]) are currently the most significant issue in railway noise. This is due to the very high wheel roughness caused by braking with cast iron brake blocks. The retrofitting with K-blocks, LL-blocks or disc brakes is the most important measure. This will reduce the wheel roughness and thus lead to significantly lower rolling noise levels.

The noise reduction effect depends on the rail condition and can have values between approximately 12 dB (smooth track) and 2 dB (corrugated track). This is illustrated in figure 9.

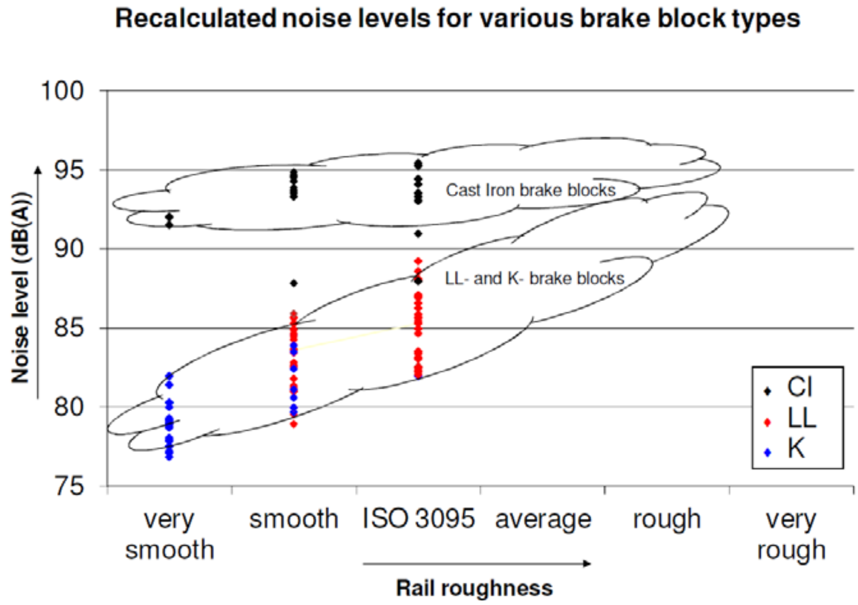


Figure 9: Noise reduction for retrofitting as a function of the rail roughness [91].

It should also be noted that the noise reduction effect is strongly dependent on the number of vehicles with cast iron brake blocks in the train composition. Retrofitting only individual vehicles in a train set does not significantly reduce noise emissions. A significant number of vehicles must be retrofitted so that the noise emission of the whole train is reduced. As figure 10 shows, it is important to equip a high percentage of wagons with composite brake blocks before such reductions (on smooth rails) are achieved for the freight fleet as a whole: at 50% share of retrofitted wagons, the reduction is only 2.5 dB.

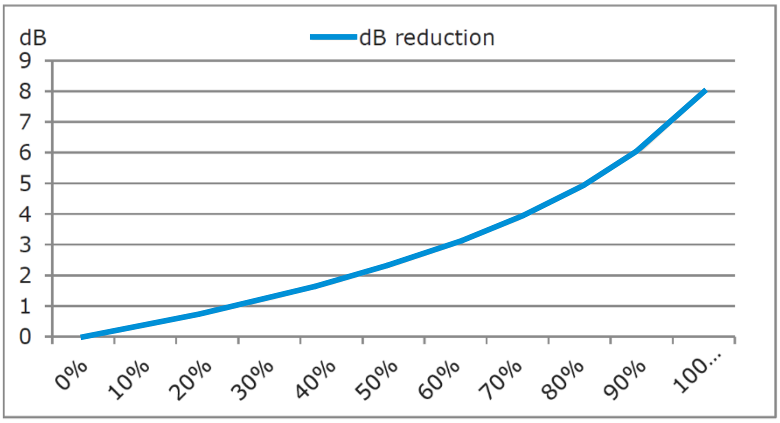


Figure 10: Noise reduction of composite brake blocks as a % of retrofitted wagons within the fleet, from [14]

Track and wheel maintenance are of particular importance in combating rail noise [78]. Both can be achieved based on a regular monitoring. Rough wheels and rough tracks can be identified.

Rails must be ground regularly in order to remove cracks in the surface of the railhead at an early stage before they start growing further into the railhead, thereby endangering the mechanical stability of the rail. Grinding for maintenance reasons also affects the noise emission of the rail. Traditionally grinding was carried out condition-based as a corrective measure. Infrastructure managers nowadays are changing more and more to a preventive grinding strategy where grinding is carried out at shorter time-intervals (for instance twice per year) and with less material removed. This generally also reduces noise emission as a side effect in case the grinding results a lower roughness. Not all grinding procedures reduce the roughness, however, and thus may even increase the noise emission until the grinding pattern has been smoothened out again.

All networks monitor the geometric track quality (examples are presented in chapter 6.3.2) and have implemented a regime of corrective and/or preventive grinding. In a few networks, the acoustic quality of the track is regularly monitored, and acoustic grinding is applied. Examples of these are the “Besonders überwachtes Gleis” (BüG) in Germany and the highspeed line HSL-Zuid in the Netherlands. In both situations, the roughness is monitored by a measurement vehicle that determines rolling noise. When the roughness exceeds a certain threshold level, the rail is ground to a lower roughness level ([51], [75]).

Reduced vibration of the wheel and the rail

Measures to reduce vibration generation are a higher stiffness of the wheel (shifting of relevant vibration modes into a higher frequency range of lower acoustic relevance), decoupling of the axial modes of the wheel from the radial modes or damping measures (wheel dampers, damping rings, constrained layer or rail web dampers).

Wheel dampers are occasionally used on light rail and high-speed trains to reduce the noise emission, e.g. wheel dampers are a standard for ICE-wheels in Germany and ICE trains running in Spain. Wheel dampers are an efficient measure against curve squeal, reducing the noise with 10 to 15 dB(A).

Recent studies have been testing wheel dampers to further reduce the noise levels of freight wagons to values well below the TSI-limit value. Within the framework of the 5L-project by SBB Cargo [45], wheel dampers were tested on freight trains, showing that noise values between 73 and 75 dB (LpAeq,Tp at a speed of 80 km/h) are feasible. In Germany, innovative freight wagons are developed and tested within the research project “Development and testing of innovative freight wagons” [98]. Both projects not only research the noise aspects but also consider energy-efficiency and cost-effectiveness.

The rail pad is a key component to track dynamics. It has a certain characteristic behaviour mainly depending on its dynamic stiffness and damping. The rolling noise emission depends on the dynamic stiffness. The noise emission will decrease with higher stiffness. However, raising the stiffness leads to higher stress on the sleepers and is known to increase ground vibrations. A higher damping leads to a higher track decay rate and thus to lower noise levels but it is difficult to adjust only the damping of the rail pad. Therefore, the ideal rail pad would to be frequency dependent and (inversely) load dependent. A low stiffness at low frequencies would be desirable for reasons of track dynamics and a high stiffness at high frequencies for a high rail resonance and a high structural damping of the rail should be aimed for together with low stiffening under load. Recent studies in Switzerland and in Belgium have been aiming at improving the rail pad by making it soft to distribute axle forces at low frequencies and having high damping at high frequencies to damp the rail vibrations and lower the noise emissions.

Another way to reduce the rail vibration is using tuned mass rail dampers. The rail damper mitigates vibrations of the rail by an added mass-damper-spring system or an added damper in form of a rubber, which is designed as a broadband tuned vibration absorber. As the vibration is reduced, less noise is emitted from the rail.

The effect of rail dampers varies between tracks, strongly depending on the stiffness of the rail pad. If the track is stiff as a starting point, then the noise reduction of the rail damper is limited. If the rail pad is softer, the rail damper will be more effective. The noise reduction of the rail damper is also different for various vehicle types. If the contribution of the wheel to the rolling noise is larger, and thus the contribution of the rail is smaller, the effect of the rail damper will be less. Therefore, depending on circumstances, the effect of a rail damper is between 0 and 3 dB.

Reduced noise radiation

Rail shielding is a technique for shielding the sound radiation from rail webs. The airborne sound radiated by the rail is reduced by partially enclosing the rail foot and rail web. Rail shielding consists of steel panels that fit around the rail foot and web. The panels are fixed with brackets clipped around the rail foot. The side walls of the shielding are covered on the inside with structural damping material and absorption foam. The effect of rail shielding depends on the proportion of the lateral sound radiation of the rail in the total sound radiation. The more noise is radiated by the rail, the higher is the noise reduction by rail shielding and vice versa [18].

4.2.3. Mitigation measures for aerodynamic noise

The mitigation of aerodynamic noise from the train's body is generally achieved through a streamlined design of the train's nose [53]. This is generally driven by the reduction of aerodynamic drag and energy consumption, and the reduction of any discontinuity of the train's body, i.e. inter-coach gaps, in order to reduce turbulence areas which can generate additional noise sources.

Bogie skirts

Reduction of aerodynamic noise is generally achieved with the introduction of bogie skirts.

Performances of bogie skirts are only reported in literature for European and Japanese high-speed trains. The effect is reported to be around 1 dB reduction [81]. Bogie skirts are commonly used in Japan where a larger loading gauge allows this mitigation to be easily adopted sometimes in combination with absorptive treatment applied to the lower part of the car body, which can reduce the noise at 25 m by almost 1 dB [52].

Pantograph noise

Mitigation of pantograph noise is generally achieved through its design minimising the turbulence flow around the cylinder, the knees joint and the panhead. Japanese high-speed trains have also used pantograph 'covers' which act as noise barriers reducing the noise by 3 dB [81]. Noise reduction from pantograph designs adopted in the far east can achieve reductions of around 5 to 10 dB but the mitigation adopted on Japanese high speed trains cannot be directly implemented on European trains mainly due to differences in loading gauge and position of the contact wire in relation to the train roof. Recently, application of flow control methods has been investigated in order to reduce pantograph noise [60].

4.2.4. Traffic planning

In those areas where noise is an issue, there is an intense use of the line. This means that traffic planning issues such as rerouting or speed changes cannot be used as a noise control possibility because this would result in a reduction of the capacity of the network. Traffic planning as a noise reduction option is therefore not included in this report.

4.2.5. Effect of reduction measures

Table III gives an overview of the effect for the different noise reduction measures. The effect is given as a range as the actual effect depends on the properties and conditions of the track. For most measures, the lower value for the noise reduction is set to 0 dB as there are situations in which a measure has hardly any effect on the noise emission.

Table III: Effect of different noise reduction measures in dB (--: no valid results available) ([55],[68], [84], [81])

Measure	High speed traffic	Conventional traffic
Optimisation of the Wheel geometry	*1-2*	*0-1*
Wheel dampers	*1-5*	*1-3*
Bogie skirts	*0-2*	*0-3*
Pantograph design	*0-4*	*No issue*
Optimised rail pad	*-*	*0-4*
Rail dampers	*0-2*	*0-3*
Rail shielding	*---*	*0-1*
Rail grinding	*0-3*	*0-5*

4.3. Noise mitigation in the propagation path

Noise barriers are the most commonly used noise mitigation measure. In the last few years, many new noise barriers have been built and more noise barriers are foreseen in the near future. Noise barriers are applied along new railway lines, along significantly changed infrastructure and as noise abatement measure in existing situations. Key factor for the effectiveness of the barrier is the distance to the rail, the height of the noise barrier and the position of the noise reception point considered.

Important characteristics of the noise barrier itself are the sound insulation and the sound absorption. The sound insulation prevents the noise being transmitted through the barrier. Reflections between the train and the noise barrier can affect the noise reduction. This is called the canyoning effect. The canyoning effect can be avoided by assuring that the track side of the noise barrier is highly absorptive, which is a requirement e.g. for noise barriers at Deutsche Bahn. An alternative way to achieve this is to put the noise barrier in an inclined position. This is often used with transparent noise barriers.

There is a large variety in noise barriers. A recent survey shows that the materials most used for noise barriers are concrete and aluminium. Wooden noise barriers are used in Sweden but no longer in most other European countries. The use of transparent plastic, glass, stone gabion or low height noise barriers is rare, for various reasons. Transparent barriers will get dirty over time and need cleaning. This is problematic near electrical currents. Stone gabions are thicker than a conventional concrete or aluminium noise barrier. This is a problem in urban areas with limited space.

Noise barrier attachments like interference absorbers or porous absorbers, which are placed on top of the noise barrier, have not yet shown any significant effects beyond their pure geometric effect where the best results are obtained with a Y shaped top [6].

Low height noise barriers are not installed that often. Due to their low height, they are positioned in close proximity to the track. They are effective for the rail adjacent to the low height noise barrier because of the close position to the track. Disadvantages of these barriers are the low noise reduction effect for tracks that are further apart, safety issues and the negative effect they have on maintenance [92].

Residents can experience noise barriers as an intrusion to the visual quality. It is therefore common that the community is involved for the impact on the environment. This involvement varies between countries but ranks from informing the public to consulting the community about the design of the barrier.

In some locations, earth berms or bunds (raised earth along the tracks) are installed. Their sound insulation will always be sufficient. The canyoning effect is not an issue as earth berms have a limited inclination angle and absorbent properties. They use a larger area which can limit their application in dense area. Earth bunds can be combined with a small noise barrier on top so the diffraction of noise over the earth berm is limited. When combined with sympathetic planting, these bunds or berms can provide visual screening benefits as well as flood prevention and biodiversity benefits including the reduction of potential for trains striking flying wildlife (bats and birds).

4.4. Noise mitigation at the receptor

At the receptor end, measures are taken to reduce the noise levels inside the building. This includes the use of noise insulating windows, possibly also to improve thermal performance, and doors. It also includes ventilation solutions with noise reducing provisions and the strengthening of dwelling façades.

The chosen measure(s) depend on the required noise reduction. The most common measure is double glazing of windows. This is usually sufficient when a low noise reduction is needed. For higher noise reduction, double laminated glass is an option. Additional measures like the sealing of cracks around windows and in façades may be needed. When a high noise reduction is required, also the insulation of walls/panels in the façade or inclined roofs may be needed. The part of the windows that can be opened needs special sealing (double window rubbers). Additionally, air ventilation systems with passive or active noise damping may be applied. Many types are available to use, depending on the required noise reduction. Finally, when a high noise reduction is necessary, the insulation of walls/panels in the façade or inclined roofs might also be needed. The architectural design of the building influences the noise inside the dwelling. Buildings along the track may be designed with a ‘blind’ façade, where the side of the building towards the track contains no openable parts.

4.5. Future developments

The research of cost-effective mitigation measures to reduce the noise of the railway system is an exciting challenge. Innovative design, new materials and adapted rules of operation will ensure silent freight and passenger rail transport tomorrow, during pass-by but also when at a standstill and parking for the well-being of residents.

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Combined actions should continue to be carried out to reduce noise reception and transmission. A next step is to increase the knowledge of the vibrations caused by the train track interaction. Ideally measures would be based on this knowledge. Since this work is very complex, the primary focus in the immediate future will be on the improvement of existing technology.

A relatively new development is the use of a diffracting element on top of a noise barrier, pilot tests have been performed in the Netherlands and more recently in Germany and the United Kingdom. The element on top diffracts the sound waves in an upward direction creating an additional noise reduction compared to the conventional barrier [74], [105].

Figure 11: Diffracting element on top of a low height barrier

There is a development towards more sustainable solutions. For example, the application of so-called green noise barriers. Green noise barriers are made from sustainable or recycled materials.

We also see the design of new vehicles such as hybrid trains, battery-powered electric trains (BEMU) and Hydrogen- powered trains. Hydrogen trains aim to eliminate emissions at the point of use (railway yards, terminals, etc.) aside from pure water. Tests show that a reduction of 15% in fuel consumption van be achieved compared to a conventional diesel multiple-unit (DMU) when using a hybrid version of its powerpack. The test trails also show that the hybrid DMU has a lower noise emission, up to 5 decibels, than the conventional version, when running. At standstill the noise reduction is even more[18]. Recent tests in the Netherlands show that a hydrogen train achieves a noise reduction of 2 to 3 decibels for the speed range from 80 to 110 km/h [70].

[18] https://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/hybrid-drive-demonstrates-15-fuel-saving.html

In the Netherlands the project NEWRAIL (Noise Energy Wall Rail America in Limburg) has started, The goals of the project are to gain experience with, and insight into, the technical possibilities and related risks of installing solar panels - on both the railway side of the barriers and the non-railway side.

The UIC TTI White paper [93] lists several ideas for future research. On the topic of noise source generation, it mentions e.g. rolling noise for non-ballasted track and the monitoring of curve squeal noise. On the topic of acoustic comfort, subjective perception and psychoacoustic indicators, the annoyance of low frequency noise is mentioned as a potential research subject.

Annex A presents some of the ongoing research on railway noise initiated by the UIC itself.

5. Costs of railway noise abatement measures

5.1. Life Cycle Costs

A life cycle cost (LCC) analysis is a method for calculating the total costs of a system or a product over its total lifespan. It is a systematic process to quantify and evaluate cost impacts. It allows decision making through economic assessment and comparison of alternative strategies and designs. Essential elements of the life cycle cost in general are:

- the **lifetime** itself: a distinction can be made between the technical lifetime and the economic lifespan. The technical lifetime is the time span in which the asset is capable to deliver a given function. This span is generally longer than the economic lifespan, i.e. the period after which a replacing asset has lower operating and maintenance costs, so that it is economically better to replace the asset;
- **acquisition** cost: in the case where the asset is supposed to deliver certain revenues, the acquisition cost is often referred to as investment. Usually, life cycle cost assessment uses the net present value of the capital required to be able to renew an existing asset at the end of its lifetime. In assets that have to be constructed on site, the acquisition cost generally includes planning, design, engineering, material acquisition, construction site preparation, construction, delivery and cleaning of the construction site. A significant cost category to be included are also the particular costs for safety measures for construction work during train traffic, or increased labour costs due to the fact that the work can only be carried out during traffic stops;
- **operating** cost: any alteration in the cost of operating a system (e.g. a railway system) directly or indirectly caused by the asset;
- the **maintenance** cost: the capital required to be able to pay for the maintenance during the full lifespan of the asset. Maintenance can be divided into corrective and preventive maintenance. Also, the costs for inspection, if any, should be included in the maintenance costs;
- **disposal** cost: i.e. site preparation, demolishing, recycling of materials, disposal of nonrecyclable materials.

The money sources for the various costs can differ. Often, the money for the acquisition costs comes from one source, e.g. within a project where changes are made to the layout of the track. The costs once a measure is taken, like the maintenance cost, will have another source.

RAMS-elements

In railway management, the concept of RAMS is considered highly relevant. RAMS stands for the topics Reliability, Availability, Maintainability and Safety. These four topics are the key elements of a good quality railway. When assessing the cost of noise mitigation measures, one should bear in mind that any alteration to the system can affect one or more of these essential topics. It is highly recommended, when assessing the cost of an intervention such as a noise mitigation measure, to check whether this has an influence on the RAMS topics. If so, then this influence should be quantified, and the corresponding (additional) cost shall be assessed. They may be part of the operational cost or maintenance cost; in exceptional cases the cost of RAMS should be assessed separately and added to the overall cost.

5.2. Costs of vehicle measures

One of the major cost components for vehicle measures are the acquisition costs. For vehicle measures, there can be a difference between

- the extra costs when purchasing new vehicles and
- the costs for exchanging components for existing vehicles.

Unless stated otherwise it is assumed that exchanging components is performed during regular servicing of the wagons, as this is the most cost-efficient way of exchanging components.

5.2.1. Retrofitting with composite brake blocks

An important factor for the costs of retrofitting is the choice of composite blocks. Retrofitting with K type brake blocks require extensive modifications to the brake system. On the other hand, retrofitting of existing stock with LL-blocks can in most cases be done without modifying the brake system. Therefore, retrofitting with LL-blocks is less expensive than retrofitting with K-blocks.

In addition to the upgrading costs, both K- and LL-type composite brake blocks have higher costs during operation because the wheel wear is considered greater than for cast iron blocks.

Several studies (summarised in references [8] and [14]) have been conducted to determine the costs for retrofitting. Reference [8] reports retrofitting costs for K-blocks in the range from €3,000.- to €11,000.- per wagon. For LL-blocks the retrofitting costs are estimated at between €250,- and €6,600.- per wagon. The studies estimate the costs for maintenance for K-blocks at between €0.0002 and €0.026 per wagon kilometre and for LL-blocks at between €0,0003 and €0,03 per wagon kilometre.

COWI [14] uses three estimates for costs of retrofitting with LL-blocks: a low estimate of €1,360.-, a middle estimate of €1,688.- and a high estimate of €2,100.-. For the operational costs they also propose a low (€0.004 per wagon km) a middle (€0.006 per wagon km) and a high estimate (€0.008 per wagon km). A more recent study uses €1,700.- as average costs for retrofitting for a four axle wagon. The estimated additional operational costs following the retrofitting is €0.005 per axle/km [69]. ERA conducted an impact assessment of the TSI Noise and investigated costs for retrofitting. ERA distinguishes between three types of wagons. The cost vary between €1,756.- and €13,776. The latter is for tyred-wheels wagons on which the brake blocks cannot be retrofitted directly. The estimated additional life-cycle costs are €0.0215 per wagon per km [41].

5.2.2. Wheel dampers

The costs for wheel dampers depend on the type and are estimated at between €500 and €25,000 acquisition costs per wagon with 4 axles given a life cycle of the damper of 15 to 20 years [85]; the annual operational costs are estimated at €100 to €900 per wagon. However, for a more expensive damper, which can only be retrofitted, which needs replacement of the entire wheel set and requires recertification of the wagon, the costs can still be high. The lowest costs are incurred for dampers that can be built in directly, do not require any modifications to the wheel and can be ordered in large numbers. For large scale use, a value of €8,000 to €10,000 per wagon is used as a reference [85].

5.3. Costs of track measures

The costs for acoustic rail grinding depend on whether the acoustic grinding is integrated within the regular grinding or not. The costs vary between €4,000 and €14,000 per kilometre of track [48], based upon the assumption that roughness control is applied for a period of ten years over 60 km track. The life span was expected to be 1 to 3 years. The costs for the BüG in Germany are estimated at €15,000 per kilometre of track for a life span of 7 years. The costs for high speed grinding (HSG) are estimated at €1,600 per track kilometre but grinding is to be performed 3 times a year [16], [85]. These costs are in general not extra costs because HSG is done as preventive grinding and usually not for acoustic purposes only.

The costs for rail dampers are estimated between €260 and €400 per meter of track[19] ([54], [85]).

Main factors influencing the costs is the number of train-free periods available to install the rail dampers in the track, as they can only be installed when there is no traffic and they have to be removed and reinstalled when exchanging the rails. For rail dampers no long-term experience is available yet so the information about average life span is not clear.

[19] The cost figures for rail dampers are based on values found in literature and data provided from members of the UIC NNV

5.4. Costs of propagation measures

The costs for noise barriers depend on many variables including the type of barrier, e.g. a gabion wall is in general relatively cheap compared to other noise barrier types and the height of the barrier. Also, the location of the noise barrier influences the costs: the costs will differ whether the noise barrier is built along a new railway track or an existing one. In the latter there will be additional costs for safety measures and track access costs. It might also be necessary to acquire new land to install the noise barrier. But what is included in the costs and the year that the cost figures are determined is also important.

Due to all these variables, the costs for noise barriers vary significantly, which is also clear from figure 12. This figure shows the range of costs over various European countries for noise barriers as a function of their height. It can thus happen that a noise barrier of 1 or 2-metre height in one location in a specific country can be just as expensive as a 5-metre-high noise barrier on another location in another country. At specific locations, the cost can be higher than indicated in the figure. More and extensive research is needed to completely explain the differences in costs for noise barriers between the different countries.

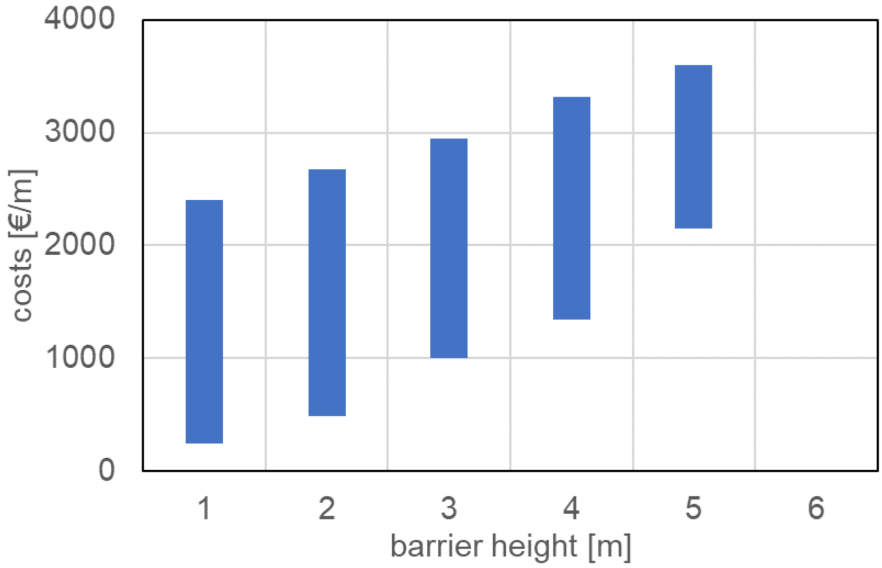

Figure 12: Average costs for noise barrier as a function of its height[20]

[20] These cost figures are based upon data from various European countries and have been provided by members of the UIC NNV

6. Noise assessment methods

6.1. Noise indicators

To quantify noise, different indicators exist that express the noise level in A-weighted decibels (dB(A)). For every noise level in dB, it is important to know which indicator it concerns. Table IV shows different indicators that concern different time periods. When a train passes by, the maximum noise level L_{Amax} will only be achieved for less than a second while the level during the rest of the pass-by will be lower. It is common to "average"[21] the noise level over a longer period, e.g. over the entire pass-by of a single train, over all trains during a day or night period, or over a whole year. When averaging over the day or night the average sound level is computed over the whole period: so, both the time that trains are passing and the time between trains passing. Due to the logarithmic nature of the dB-scale, averaging over a time period is done by averaging the sound energy within that time period rather than the noise level itself. Such an average level is referred to as an "equivalent level": the SEL, L_{eq}, L_{day}, L_{night} and L_{den} are all equivalent noise level indicators. Different noise indicators exist: long-term, short-term and very short-term indicators.

Table IV: Different noise indicators, with their description and time-constant (from [39])

Indicator *	Description	Time-constant
L_{max}	Maximum sound pressure level occurring in an interval, usually the passage of a vehicle	125 ms **
SEL	Sound exposure level = Sound pressure level over an interval normalised to 1 second.	1 s
L_{day}	Average sound pressure level over 1 day. This day can be chosen so that it is representative of a longer period — for example, L_{day} occurs in the END; if used in that context, a yearly average daytime level is intended.	12 or 16 hrs
L_{night}	Average sound pressure level over 1 night. This night can be chosen so that it is representative of a longer period — L_{night} also occurs in the END; if used in that context, a yearly average night time level is intended. This is the night time indicator defined in EU-directive 2002/49 and used by WHO.	8 hrs
L_{24h}	Average sound pressure level over a whole day. This whole day can be chosen so that it is representative of a longer period.	24 hrs
L_{dn}	Average sound pressure level over a whole day. This whole day can be chosen so that it is representative of a longer period. In this compound indicator the night value gets a penalty of 10 dB.	24 hrs
L_{den}	Average sound pressure level over all days, evenings and nights in a year. In this compound indicator the evening value gets a penalty of 5 dB and the night value of 10 dB. This is the 'general purpose' indicator defined in EU-directive 2002/49.	Year

Note: * Noise levels refer to the outside façade of buildings if not otherwise specified.
** If sound level meter setting 'fast' is used, which is common.

Most noise assessment methods and limit values in national railway noise legislation as well as in the Environmental Noise Directive are based on long-term equivalent levels: the L_{day}, $L_{evening}$, L_{night}, L_{24h} and/or the L_{den}, see [64]. In Sweden, Norway and Denmark both L_{Aeq24h} and L_{Amax} are used as noise indicators and limit values in national noise legislation. Finland has recommended levels for L_{Amax} indoors. Also, the WHO Environmental Noise Guidelines and most of the research on noise and health are based on these long-term indicators. In general, the different long-term indicators correlate well and conversions between values of one and the other are reasonably possible, see [9]. French studies by SNCF [67] show that very short-term indicators such as the L_{Amax} show wide ranges, indicating a certain degree of randomness, and do not correlate well with short- and long-term indicators. Their conclusion is that a short-term indicator representing the total single pass-by, such as an SEL or TEL[22], is more relevant than a very short-term indicator (L_{Amax} or similar).

[21] Averaging for noise is done according to the 'equal energy principle', also known as 'energetic averaging', which is not the same as a regular arithmetic average.
[22] TEL (transient exposure level) is 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 LAmax - 10 dB

It has been argued by residents as well as researchers (e.g. [94]) that for noise sources characterised by single events, such as aircraft noise or night-time railway noise, equivalent noise levels over longer periods may not represent their annoyance well. The WHO also states in their guidelines that *average noise levels like the* L_{den} *or* L_{night} *indicators may not be the best to explain a particular noise effect*, as awakenings and other physiological reactions to night-time aircraft and railway noise are mostly determined by the maximum level (LA,max). Such single-event sources exhibit longer periods of relative silence between individual vehicle events. These quiet periods are also included in the long-term equivalent level, which is consequently considerably lower than the noise level during a vehicle pass-by.

Currently, a long-term equivalent indicator (such as L_{den} or L_{night}) is the most correlated indicator for railway noise with long-term resident's annoyance. Before a L_{Amax} is introduced, further studies would have to be undertaken - not only to define the methodology of defining the L_{Amax} but also to determine what limit values would be necessary. More research is needed on this topic, as also suggested by SNCF [67].

6.2. Noise assessment modelling

Paragraph 3.2 describes noise source models that simulate the wheel/rail interaction to study and reduce noise emissions. Noise assessment methods have a different goal: to calculate the noise levels at locations in the proximity of a railway line. From this result, one can calculate the number of people exposed to particular noise levels and from there estimate the effects of the noise source on the environment. Noise assessment models are applied on large scales. Typical uses are:

- noise impact assessment, as part of health or annoyance impact assessment, as often required in the planning stage of (re)construction projects, e.g. when constructing a new railway. The calculated noise levels at all nearby dwellings are checked against the noise limits. Multiple scenarios and multiple sets of noise measures may be compared.
- noise mapping: the existing noise situation in a large area (e.g. a city, state, or country) is calculated to assess the current state of the environment. This is done at regular intervals to monitor the evolution of environmental noise and plan countermeasures. Examples are the END noise mapping, every 5 years, or the yearly noise monitoring system in the Netherlands. Noise mapping may also be applied to predict future scenarios, e.g. expected effects of silent stock.

6.2.1. EU Directive 2015/996 “CNOSSOS-EU”

The Environmental Noise Directive 2002/49/EC (END), [26]) demands the calculation and publication of noise maps for each EU Member State (MS) every five years, see paragraph 9.1. For the first noise maps, MS were allowed to use different national interim methods, as described in Annex II of the END. Annex II has now been replaced by EU Directive 2015/996 [21], which describes the European harmonised noise assessment methods for road, rail, aircraft and industry noise that MS must use for future noise maps, starting from the 2022 mapping round. The method described in the 2015/996 is the result of the “CNOSSOS-EU” project and is still referred to by that name.

The CNOSSOS-EU methods consist of separate modelling parts, see figure 13:

- the emission model for rail largely follows the TWINS approach: the effective wheel and rail roughness, vehicle speed and a contact filter are input to a set of transfer functions to calculate wheel, superstructure and slab contributions (see figure 14). Separate contributions are added for impact noise (crossings, switches, and junctions), curve squeal, traction noise (including fans, compressors, etc.) and aerodynamic noise. A correction to the emission is applied for structural radiation from bridges. The emission is calculated in 1/3-octave bands from 50 Hz to 10 kHz.
    - The noise emission is appointed to two source heights: 0.5 m and 4 m. Aerodynamic and traction noise are partially attributed to the high source, all other noise to the low source.
    - A database is provided in Appendix G. This contains default rail and wheel roughness values for a few brake types and track conditions. Contact filter coefficients are given for different wheel diameters and

axle loads. Transfer functions are provided for different sleeper / pad combinations and for different wheel diameters. Traction noise coefficients are given for different Diesel and electric locomotives. The database is not mandatory: Member States are allowed to use their own data.

- the propagation model is derived from the French NMPB model. It specifies the noise attenuation due to the distance and air absorption, terrain heights, reflections and diffraction from barriers and buildings, the influence of the ground depending on its composition. Typical for the CNOSSOS propagation model is the calculation of two meteorological scenarios, for homogeneous conditions (straight noise paths) and favourable conditions (downward curved paths), the results of which are combined with a location-specific fraction.
- for the receptors, it is specified how receptor points should be placed on the dwelling façades, and how the number of people in buildings and dwellings should be attributed to the calculated noise levels.

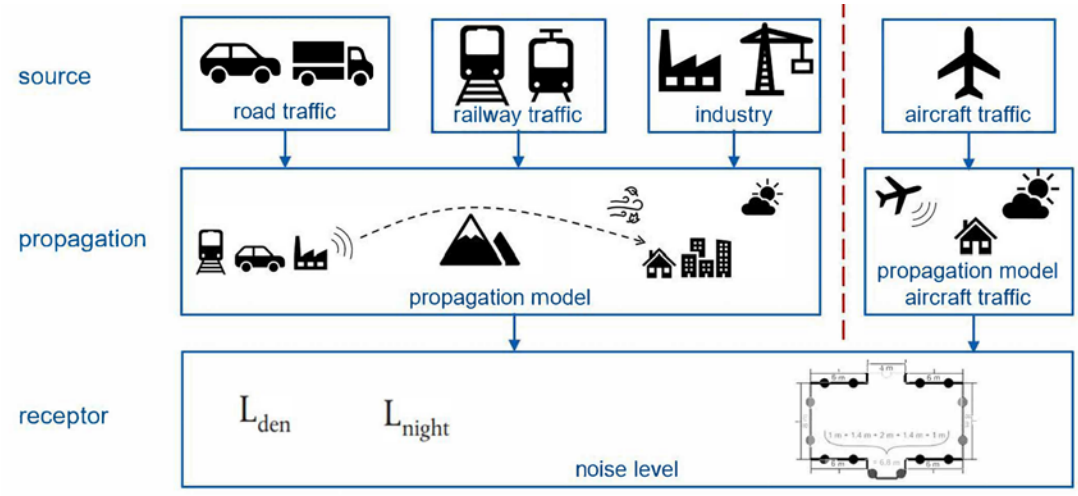

Figure 13: CNOSSOS-EU: emission, propagation and receptor modelling parts for different sources

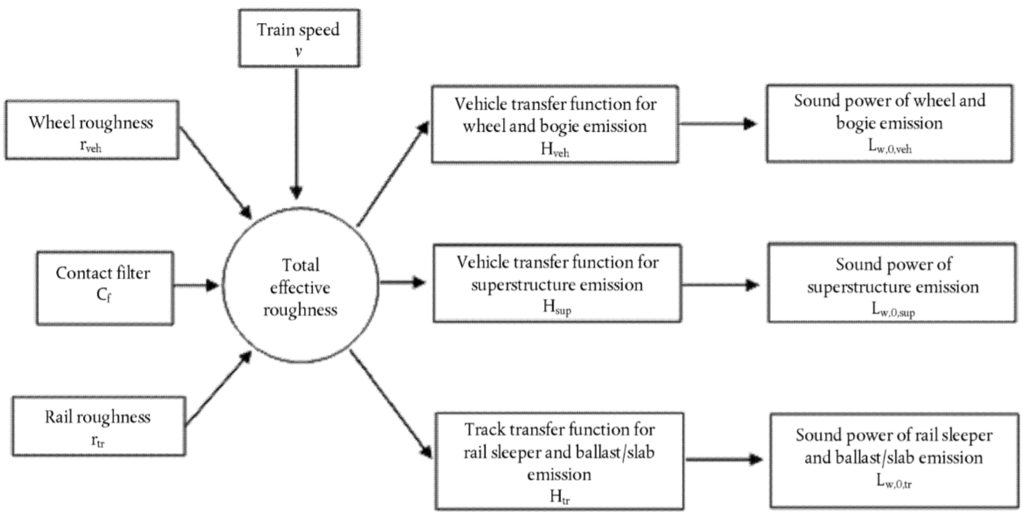

Figure 14: CNOSSOS-EU: Scheme of the use of the different roughness and transfer function definitions

In 2019, a European working group led by the National Institute for Public Health and the Environment (RIVM) of the Netherlands published a report containing a number of amendments and suggested improvements to the CNOSSOS-EU method as described in the 2015/996 Directive [50]. DG ENV is currently in the process of adopting the suggested corrections and publishing a new version of the model. It is advisable, therefore, not to use the current Directive 2015/996 model.

6.2.2. Examples of national methods

Currently, many EU countries have a national noise assessment method in place for road and rail noise, as well as for other sources. Now that CNOSSOS-EU is available and mandatory for the END, countries may consider whether or not to replace their national methods. Some examples of national rail noise assessment models, and their main differences and characteristics, are the following:

- SRM2 (The Netherlands): five source heights, braking noise included, traction noise separated into cooling and engine noise, no squeal noise correction. Different noise contributions are calculated in dB as a function of speed, rather than starting from a total roughness. Separate class for low-noise passenger stock.

- Noise mapping in Germany was conducted so far based on a provisional calculation method for environmental noise on Railways (VBUSch) [96]. VBUSch defines the noise sources rolling noise and aerodynamic noise at different heights. It is based on the German calculation procedure for assessing railway noise Schall 03 (1990) [73]: In Annex 2 of the 16th BImSchV, the regulations for the calculation of assessment levels for railways are laid down in a detailed calculation specification (Schall 03). In the current version of 2014, the noise immission calculations have been made considerably more precise and adapted to current findings. Schall 03 distinguishes between the noise sources rolling noise, aerodynamic noise, aggregate noise and traction noise whereas every noise source has components at different heights. Furthermore, future developments of the technologies such as rail dampers or rail shielding are taken into account.

- sonRail (Switzerland): quite similar to CNOSSOS-EU, but with five source heights. Calculations start from total wheel/rail roughness and contact filter. Three roughness types (smooth, average and bad) are provided. No curve squeal included, but track curvature is an optional parameter influencing the emission. Includes different types of bridges (concrete and steel bridges with different construction options). Calculations in 1/3-octave bands from 100 to 8,000 Hz. Available through a web calculation tool (https://sonrail.empa.ch/).

- HS2 method (United Kingdom, High Speed trains): The HS2 method considers the following noise sources: rolling sound, which includes sound emitted by the wheels and the track, at 0.0 m top of the rail (TOR); body aerodynamic sound which includes sound generated by flow in the lower regions of the train, at 0.5 m TOR; starting sound, at 2.0 m TOR , which includes sound generated by power, traction and auxiliary systems; pantograph recess aerodynamic sound, at 4.0 m TOR; and raised pantograph aerodynamic sound, at 5.0 m TOR. The different contributions are calculated for broadband SEL, LAeq,tp and LpAFMAX as a function of speed up to 360 km/h which are then combined at receptor location. Noise is increased by 1 dB at receptor location for bridges and the method includes corrections for conventional and swing nose S&C. The source terms are specific to a particular train running on a specific type of track [57].

- Nord2000 (Sweden, high speed trains): four source contributions: rail/track at 0.01 m, wheel at 0.5 m, aerodynamic noise around bogie at 0.5 m, pantograph noise at 4.5 m. Braking noise is not included, traction noise is an implicit part of the other contributions. Noise is increased by 3 dB for bridges. Different contributions are calculated in dB as a function of speed ranging from 30 to 320 km/h. The Nord2000 propagation model is different from CNOSSOS-EU and more similar to the Harmonoise model. Calculations in 1/3-octave bands from 25 Hz to 10 kHz. Source data are available for future high-speed electric trains (2015 - 2035 forecast) for ballast bed and slab tracks.

- Nord96/NMT96 (Norway): less complex than Nord2000, with calculations done in single-octave bands and no aerodynamic contribution calculation. Acceptable for speeds 30-200 km/h.

- NMPB (France): is used for noise mapping and study impact. From acoustic emission power (Lw) of rolling stock- obtained by measurements, track characteristics for the area concerned (type of track, specific points, …) and traffic data (type of train, number, speed); the noise level is calculated at 2 m in front of the façade of buildings. The propagation model issued from NF S 31-133 French standard is quite equivalent to CNOSSOS-EU. The calculations are done in 1/3-octave bands from 100 to 5,000 Hz with two source heights activated: 0 m and 0.5 m (one height by frequency). The model is validated using measurements at the building façades nearby.

6.3. Noise measurements

Many EU countries perform noise measurements for various purposes: to assess the (acoustic) quality of the track or to monitor the sound emission. Noise measurements can be divided into vehicle bound measurements or stationary measurements.

6.3.1. Noise monitoring stations

Stationary noise monitoring systems are in use in different countries.

In the Netherlands the system of noise ceilings is in place, see section 10.4. Each year, the amount of noise produced by railway traffic is calculated. RIVM measures the sound emission to check these results in a document called the noise monitor [99]. In recent years, the noise monitor revealed that the modern passenger trains, such as the sprinter, produces 3 to 4 decibels less noise than the values assigned to this category by the model. Therefore, a research programme has started to set up a separate category for the sprinters so that the calculation method better matches the measurements.

In Germany, 19 monitoring systems are placed at different locations, see figure 15. With the network-wide noise monitoring, the Federal Government documents the long-term trend in rail traffic noise in a transparent and comprehensible manner. To this end, measuring stations have been set up along the rail network to measure the sound pressure of passing trains using a uniform method. The 19 measuring stations in the network record more than two thirds of all rail freight traffic. The goal of the monitoring system is to determine the effect of retrofitting freight wagons.

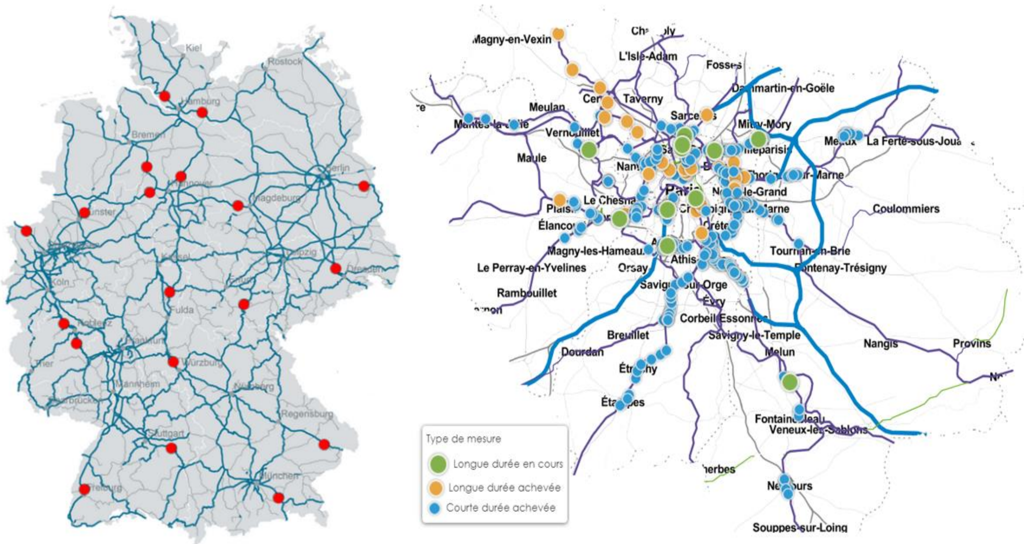

Figure 15: Noise monitoring network in Germany[23] and in the French île-de-France region[24]

In Switzerland, noise monitoring stations have been in use for several years. The continuous measurements serve as ongoing review of the current state and they can prevent extreme situations going over the noise limits.

[23] https://www.laerm-monitoring.de/
[24] https://reseau.sncf.bruitparif.fr/

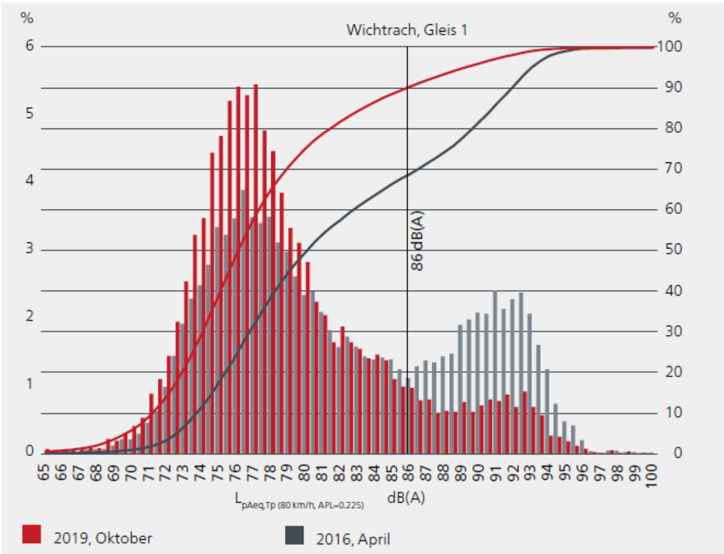

Figure 16: Noise monitoring in Switzerland: bar graphs show the percentage of pass-bys at a certain noise level; the solid lines show the cumulative percentages. The graph shows a clear noise reduction between 2016 and 2019 (from [10])

In Belgium, 13 permanent noise monitoring stations are in use, see figure 17. These noise monitoring stations cover 91% of the freight traffic in Belgium. The monitoring focusses on the port traffic and the connections with other countries.

In France the development of noise monitoring stations is ongoing. By the end of 2020, 15 permanent noise monitoring stations should be in use.

In Austria there exist two noise monitoring stations for research issues since 2006. One is situated in the straight line and the other in a narrow curve of 180 m mainline track. At the end of 2020, one additional noise measurement site is being built for freight wagon monitoring issues.

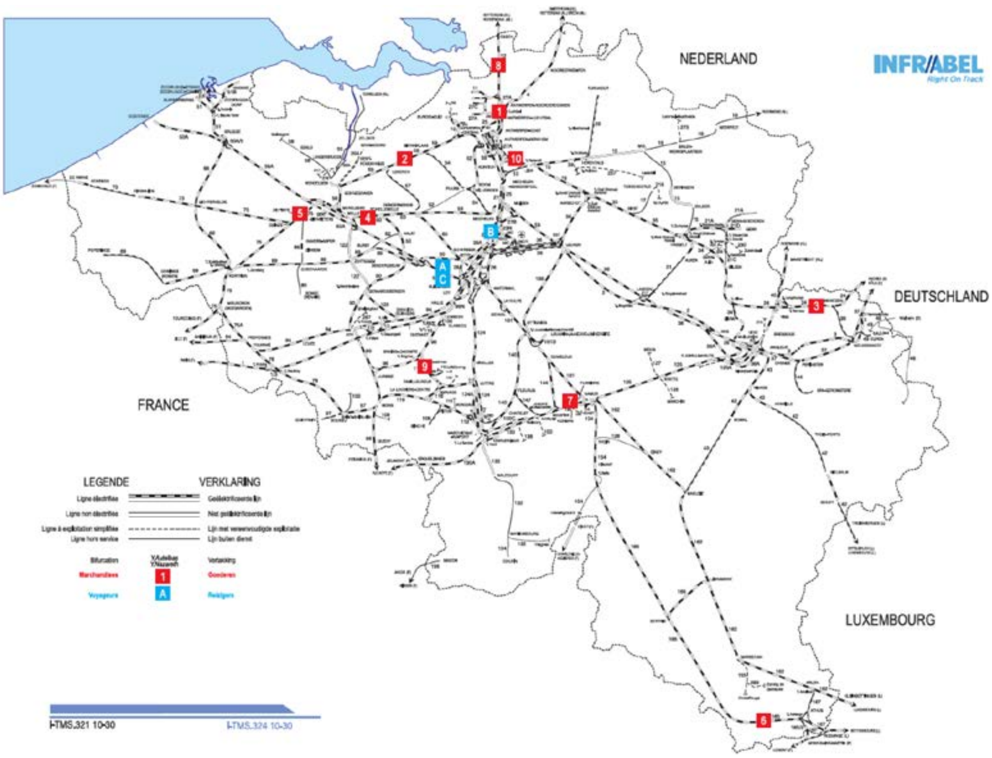

Figure 17: Noise monitoring stations in Belgium for freight traffic (red) and passenger traffic (blue)

6.3.2. Vehicle-bound measurements

There are many vehicle-bound measurement systems to assess the track quality. This section only addresses systems that use noise levels as an indicator or that assess the acoustical quality of the track.

In Denmark, a system has been developed, which monitors the roughness levels of the track expressed in $L_{\lambda ca}$ (a single value indicator for roughness levels). The results were used to schedule a nationwide grinding campaign including prioritising the sections with the most degraded rail surface. In addition, the results are used for communication with lineside inhabitants. The system enables a better service to persons complaining because the results reveal whether there is a higher local roughness level. Infrabel in Belgium uses a track dynamics logger, equipped with microphones and accelerometers. The goal is to measure the entire rail network 8 to 10 times each year. Results will be used as input for asset management for wheel rail noise calculations, for noise mapping and for use in action plans. In the future, Infrabel will know the acoustical status of the Belgian railway network almost in real time. In the Netherlands, sensors including microphones have been placed on regular passenger trains to assess the track quality. The results show the acoustical quality of the network allowing easy location of noise hotspots, for instance, the curves with the highest amount of noise levels due to curve squeal.

A special train with noise measurement equipment (Schallmesswagen) in Germany regularly monitors the acoustic quality of the German railway network. The average acoustic quality of the track has increased over the last few years due to the increased amount of rail grinding and is significantly better than the “average acoustic quality” defined in the calculation method Schall 03.

In France, the research development is ongoing to define sensors including microphones to be placed on regular passenger trains to assess the track quality.

7. Impact of noise on people

7.1. Adverse effects of noise

Noise, being unwanted sound, negatively affects people exposed to it. This may be limited to temporary irritation or disturbance, or loss of sleep quality. Longer, more regular exposure may lead to a systematic increase of stress. Stress reactions and sleep effects also occur unconsciously, by direct activation of the brain and body upon auditory stimulation. In time, higher stress levels and disturbed sleep can affect the biological system, such as increased blood pressure, leading to mental or physical illness. And eventually, such diseases may lead to increased mortality.

The WHO defines *health as a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity* [101]. Annoyance and sleep disturbance are included in this definition even if these effects do not lead to mental or physical disease. For other applications, such as cost/benefit analysis, there is often a separation between annoyance, that affects people's opinions and behaviour, and *health* in terms of disease, leading to disability and medical costs.

In its Environmental Noise Guidelines (see text box below), the WHO identifies several critical health outcomes related to noise. For railway noise, the systematic reviews published by the WHO have found quantifiable relations only for annoyance (L_{den}) and sleep disturbance (L_{night}), which are discussed further below. For cardiovascular diseases, some studies have been found, but the WHO guideline development group rated the evidence quality as low or very low. For other health impacts, evidence was lacking.

Besides decreased health and well-being, there are other negative effects of environmental noise:

- reduced housing and land prices: noisy areas are less attractive to live and work in. Lower demand will lead to lower house and building prices, lower rents and lower land value [2][5];
- social inequality: groups in society with lower socio-economic status tend to be affected more by noise pollution than others, as a result of both greater exposure and higher vulnerability [40];
- loss of quiet: quiet areas, in- and outside the city, provide restorative environments that reduce stress and, more generally, quietness increases attractiveness of healthy green spaces [7];
- effects on nature: transport noise has adverse effects also on non-human species, influencing their population density and reproductive success [19].

7.2. Annoyance

There is clear evidence that a relevant number of people is annoyed by environmental noise, including railway noise, and that this number increases with higher noise levels. Annoyance, in this case, means regular, systematic disturbance over long periods of time. Even if this would not lead to physical or mental disease, annoyance in itself is worth studying and reducing. Annoyance leads to loss of welfare, in a social sense (decreased happiness, less positive attitude of people towards their surroundings) and in an economic sense (loss of property and land value).

The systematic review by Guski et al. [43] presents an exposure-response function (ERF) indicating the average percentage of people highly annoyed by railway noise at a certain L_{den} level. Figure 18 shows the ERFs for railway noise as well as road traffic noise. These ERFs are based on surveys asking participants to indicate their annoyance on a standardised scale and relating their answers to the L_{den} calculated or measured outside their home, at or close to the dwelling façade. The evidence was graded as *moderate quality*, indicating that additional research is likely to impact the certainty of the ERF curve and may also change the curve itself. Due to the statistical methods used, the WHO could not provide accuracy intervals for these ERF curves. Some bandwidth must certainly be presumed.

WHO Environmental Noise Guidelines

The WHO Regional Office for Europe published their new Environmental Noise Guidelines in October 2018 [88], following earlier WHO community noise guidelines from 1999 [54] and night noise guidelines from 2009 [58]. While the guidelines focus on the European Region, the evidence was based not only on European studies, but also on research from Asia, Australia and the USA.

Separate recommendations are provided for road traffic noise, railway noise and aircraft noise. New are recommendations for noise from wind turbines and for 'leisure noise', which is primarily the risk of hearing loss due to personal listening devices and other leisure activities.

Methodology

The guidelines have been based on systematic reviews of existing evidence from the noise and health community [102]. Each review provides, if possible, a relation between the noise levels and the risk increase of a particular health outcome (an exposure-response function, ERF). The quality of the evidence is graded from high to very low, following a predefined process (GRADE). The evidence for a specific health outcome is graded as a whole: if different high-quality studies show contradictory results, the quality is downgraded. Although the guidelines are published in 2018, the research base for rail noise is from 1997 to 2010, thus reflecting the situation some years ago.

A separate team of experts, the Guideline Development Group (GDG), has formulated recommendations based on the systematic reviews and the quality assessment. The GDG has pre-set absolute or relative risk levels for each health outcome which, combined with the ERFs, result in recommended maximum L_{den} and L_{night} noise levels. Recommendations are rated either:

- strong: the recommendation can be adopted in most situations, as there is confidence that the benefits outweigh the undesirable consequences, or
- **conditional**: the recommendation should be considered in a policy-making process with various stakeholders, as it may not be applicable in all circumstances.

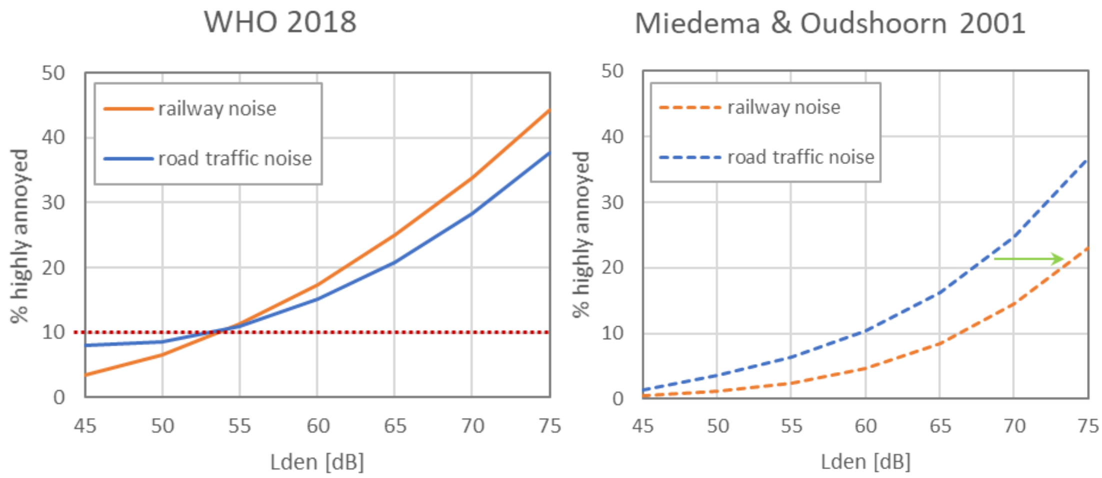

Figure 18: Exposure-response functions for annoyance: %highly annoyed (HA) vs. L_{den}; left: WHO2018 guidelines [103], with red dotted line indicating 10% HA benchmark level, right: previous standard curves by Miedema & Oudshoorn [59] with green arrow indicating the 'rail bonus' (see 10.3)

The right graph of figure 18 shows the ERFs for rail and road traffic noise from Miedema and Oudshoorn [59], which have been the de facto standard since 2001. If the old and new curves are compared directly, it could be concluded that railway annoyance has increased over the years, as the %HA at the same L_{den} level is higher in the WHO2018 curve than in the Miedema curve. This conclusion is, however, questionable, as discussed below and in 7.4. Compared to road noise, railway noise annoyance now appears to be similar at the same L_{den} level. Previously, based on the Miedema curves, people were considered to be less annoyed by railway noise than by road traffic noise; this difference was expressed in a noise annoyance correction factor, or 'rail bonus', see section 10.3.

Some remarks are relevant with regards to these conclusions. No clear explanation is given for the increased annoyance from railway noise. The evidence seems convincing, as all of the ten studies used in the WHO review show equal or higher annoyance than the Miedema curve. Yet, with regards to this comparison, the reviewers mention that:

- the number of studies in both the WHO 2018 and the Miedema 2001 datasets is rather small. The Miedema dataset also included two tramway studies;
- different studies use different definitions of 'highly annoyed', e.g. ≥ 60% on a 5-point scale or ≥ 73% on an 11-point scale;
- four studies used by WHO are performed in Alpine valley regions, where noise propagation is different and possibly underestimated in calculation models, and where high-volume road and rail transport corridors lead to combined exposure and are subject to negative public debates. Also included is a Japanese study, for which the WHO authors mention [43] that annoyance may have been influenced by railway vibrations due to houses being relatively close to the track.

The first two points would explain why there is a variation between the two studies. As confidence intervals around the ERF are not given for the WHO 2018 curve, it is not possible to assess whether a conclusion that annoyance has increased can be confidently drawn. The third point suggests a bias towards noise-sensitive locations. With regards to the older Miedema studies, the WHO review itself concludes that there is a "necessity to re-evaluate the old railway exposure-response relation" and that the results of the old and new studies should not be directly compared. A conclusion that railway annoyance has increased over time, therefore, cannot be drawn based on these studies.

7.3. Effects on sleep

Sleep disturbance indicates trouble with sleeping in a broad sense: awakenings, difficulty falling asleep, less deep sleep and decreased restoration or waking up tired. Although there are plausible biological mechanisms [42], no solid statistical evidence was found that sleep disturbance leads to long-term health consequences. There are, however, next-day consequences (e.g. increased sleepiness, impaired cognitive performance) that may increase the risk for errors and accidents. Also, as for annoyance, sleep disturbance may lead to loss of social and economic welfare.

For sleep disturbance, the ERFs are based on night-time noise levels (L_{night}) and self-reported sleep outcomes. Polysomnography or laboratory sleep tests were not used. The systematic review on sleep disturbance [4] presents the ERFs for the % of highly sleep-disturbed (%HSD) people as a result of rail and road traffic noise shown in figure 19. The evidence was graded to be of moderate quality.

Similar to annoyance, the impact of railway noise has increased with respect to the earlier Miedema relations from 2003 [39][58]. Railway noise now shows to have a larger negative effect on sleep than road noise, whereas this was previously assumed to be the other way around. The authors mention several factors with regard to this comparison of the sleep disturbance relations:

- Several studies in the Miedema analysis asked about annoyance occurring due to sleep disturbance, whereas the new analysis focuses on the severity or frequency of the disturbance.
- More night-time events were reported in the new studies than in previous studies. More night trains would lead to higher exposure levels as well as higher disturbance, yet the effect on the response could be higher than on the exposure.

It is important to note that the L_{night} exposure levels used to assess the effects on sleep are noise levels measured or calculated outside at the most exposed façade, as these data are more commonly available. The actual noise levels in the bedroom will be much lower. An ERF based on indoor night-time levels would be shifted more to the left than the curves in figure 19.

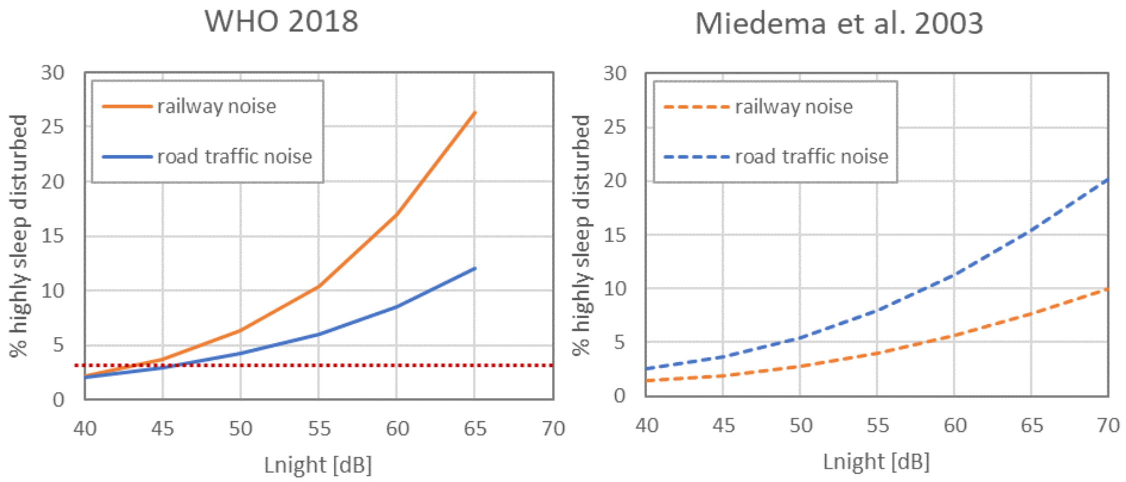

Figure 19: Exposure-response functions for sleep disturbance: percentage highly sleep-disturbed (HSD) vs. L_{night}; left: new WHO2018 guidelines [103] with the red dotted line indicating the 3% HSD benchmark level, right: previous standard curves by Miedema et al. [58]

7.4. Recommended levels

Based on the evidence for each of the priority health outcomes, the WHO Guideline Development Group formulated recommendations for railway noise, most importantly the recommendation to reduce noise levels below a certain maximum level. These maximum levels are given in table V along with their rationale. There are separate recommendations for Lden and Lnight. The WHO considers the impact of more than 10% highly annoyed or 3% highly sleep disturbed people to be sufficiently important to society to take noise reducing measures.

Table V: WHO recommended average and night-time levels for railway noise [103]

	average level (Lden)	night-time level (Lnight)
recommended maximum level	***54 dB***	***44 dB***
recommendation strength	*strong*	*strong*
related health outcome	*annoyance (highly annoyed)*	*sleep disturbance (highly sleep disturbed)*
benchmark level	*10% absolute risk*	*3% absolute risk*
evidence quality	*moderate quality*	*moderate quality*

Some critical remarks should be made with respect to these recommended levels, some of which have also been put forward for aircraft noise by the ACI [1]:

- The recommended L_{den} and L_{night} levels are strong recommendations but both are based on moderate quality evidence, meaning that additional research may change the exposure-response functions. Judging from figure 18 and figure 19, a small change in the ERFs could lead to a benchmark level that is several dBs higher or lower.
- With regards to annoyance, more research is needed into why the new WHO exposure-response function is higher than the previous curves, and why the preferable attitude towards rail noise with respect to road noise has disappeared. As stated in the WHO systematic review for annoyance [43], regarding railway noise: “The reasons for the differences between ‘old’ and ‘new’ results could not be analysed systematically within the scope of this review, and we suggest doing so by means of original

data before deciding upon a revision of the earlier curve." Also, such a study based on original data may provide the confidence intervals around the railway noise annoyance ERF, which are currently missing. More research is needed before drawing a conclusion with regards to railway annoyance.

- The WHO report states that "the benefit of implementation of the recommendation […] for a majority of the population exceeds the (monetary) resources needed". This is not quantitatively substantiated: "no comprehensive cost-benefit analysis for the WHO European Region has yet been conducted, so this assessment is based on informed qualitative expert judgement". Regarding costs for noise abatement measures, it is stated that some solutions could be planned as part of regular maintenance or speeding up track and vehicle modernisation. It is mentioned that some EU countries already have programmes to replace cast-iron (CI) brake blocks on freight trains, which "illustrates that solutions to achieve recommended noise levels can be implemented at reasonable cost".
- The fact that the use of rail transport is beneficial for the environment and greener economy, as it is more eco-friendly than other transport modes, is recognized by the WHO and "there is a need to balance the expected health benefits from reduced continuous railway noise exposure and the overall positive effects on the health of the population from increased reliance on the comparatively environmentally friendly mode of railway transport". Yet, this balancing has not been done, or does not seem to have influenced their qualitative assessment of benefits and harms. The cost-benefit aspect of railway noise reduction and the possible effects on the modal shift also require more research before implementing the WHO recommendations.

8. Costs of environmental noise

8.1. Internal, external and infrastructure costs

Transport involves various costs for building, maintaining and operating infrastructure. Transport costs also arise from the external effects on society, such as the impact on environment and health. Only part of these costs are paid by the transport users, i.e. the people travelling or the freight companies bringing their goods from A to B. Transport costs can thus be divided into three categories:

- internal costs: the costs borne by the transport users, e.g. fuel costs, vehicle sales or rent, tickets, taxes and tolls;
- infrastructure costs[25]: investments in new infrastructure or renewal of existing infrastructure, expenditures on maintenance and operational expenditures to enable the use of the infrastructure;
- external costs or 'externalities': costs imposed on society by social or environmental effects, such as air pollution, noise, accidents and congestion. These may lead to actual monetary expenditure, such as health costs for treatments and medication, but mostly they are indirect effects on the economy, such as loss of time and productivity, decreased land and real estate values.

An important aspect in environmental policy, including noise, is the *internalisation* of the external costs: How should the external costs be transferred to the user, thereby making them part of his or her decision? If external costs can be internalised ('user pays'/'polluter pays') this has a positive effect on the behaviour of users, to avoid congestion, drive safely and use environment-friendly modes and vehicles. Internalisation also generates revenues to build or improve infrastructure and finance environmental mitigation measures, including noise measures.

There are also potential downsides to internalisation. Transport could be seen as a public good that should be available to all income levels equally. Internalisation would make transport more expensive and thereby less accessible to poorer people. And, in principle, internalisation would lead to a fairer competitiveness of transport modes as each mode would cover its own externalities. However, if internalisation is not done for all transport modes, this provides an undesired imbalance in competitiveness, which would lead to the opposite of the desired effect.

Noise-differentiated track access charges could be seen as an example of noise costs: railway operators pay higher fees if they use noisy trains. Similar methods exist for aircraft, using noise-differentiated landing and take-off fees. Such noisedifferentiated charges are not usually applied to road traffic.

The Commission has recently contracted and published a study on external transport costs and the current state of internalisation [34]. CER has focused on the conclusions for railways in their position paper [12].

Infrastructure costs can be regarded in different ways:

- *total* costs: all financing and annual depreciation costs for new and existing infrastructure, including investments, maintenance and operations, per transport mode and vehicle category;
- *average* costs: the total costs divided by the total amount of passenger- or ton-km travelled;
- *marginal* costs: the additional costs of one extra passenger- or ton-km;
- *variable* vs. *fixed* costs: variable costs, such as maintenance, increase with the amount of traffic, whereas fixed costs, such as construction costs, are constant expenses no matter how many vehicles travel over it.

Ideally, according to economic principles, the internal costs (taxes and charges) should cover all marginal / variable costs for infrastructure as well as the external costs. Marginal costs will be lower than average

[25] Note: costs and expenditures are not the same: costs include financing and depreciation costs, whereas expenditures do not; they are one-time expenses [28]

costs, as the fixed costs for constructing or replacing infrastructure are not included. Marginal costs are often approximated by average variable costs, which give the additional costs of an extra vehicle-km regardless of whether it is the first or the 1,000th vehicle. The fixed costs are generally part of larger economic cost-benefit decisions. As these costs are non-recoverable ('sunk' costs), they are considered irrelevant for internalisation schemes.

The recent EC study on the state of internalisation of external transport costs has also investigated the taxes and charges in all EU Member States. The main findings report [34] summarises the methods and findings, and provides EU-average taxes and charges per km. For railway passenger transport, as shown in figure 20, the sum of the average variable and external costs is fairly well covered by the taxes and charges. For electric passenger trains, there is still a gap between costs and revenues: taxes and charges amount to circa 50% of the costs. For Diesel passenger trains, the cost coverage is higher, close to 100%, whereas for high speed rail there is a surplus: the revenues are higher than the costs. For freight traffic, as shown by figure 21, the variable external and infrastructure costs for railways are covered for circa 60% by the taxes and charges.

It should be noted that these graphs indicate average costs, per km. The share of railways in the total external costs at present is much lower than these graphs indicate, as the total volume of railway transport in km is lower compared to road traffic, see table I earlier in this report.

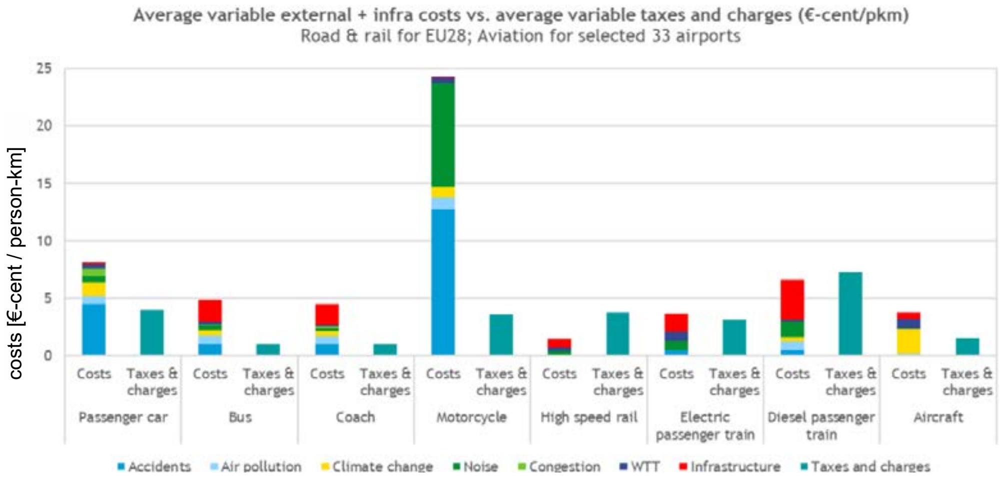

Figure 20: Average external + average variable infrastructure costs vs. average taxes and charges, for passenger transport, per person-km [34][26]

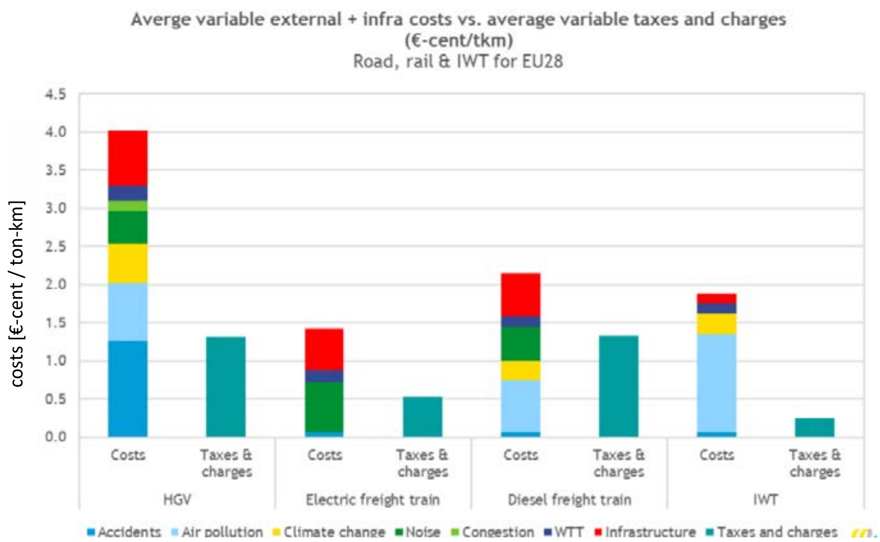

Figure 21: Average external + average variable infrastructure costs vs. average taxes and charges, for freight transport, per ton-km [34][27]

[26] WTT = Well-to-Tank
[27] HGV = Heavy Goods Vehicle, IWT = Inland Water Transport, WTT = Well-to-Tank

All in all, it can be concluded from the EC study that the current state of internalisation is more advanced for railways than for other transport modes: the railway sector is able to let their users pay for a relatively large part of the marginal costs, or average variable costs. As pointed out in the CER position paper [12], railways lead transport on cost coverage of variable infrastructure and external costs, both for passengers and freight, as shown above.

With regards to competitiveness, there seems to be a degree of unfairness here, and there is not a level playing field between the individual transport modes. That is why CER recommends that:

- external-cost charging ('polluter pays') is implemented for *all* transport modes;
- distance-based charging ('user pays') infrastructure charging is implemented on all major roads;
- robust investments are made, both at an EU and national level, in new and enhanced rail infrastructure, to promote a shift to rail, which would benefit the environment and public health in Europe.

As the economic and environmental impacts of introducing charging on polluters are very important, sustainable transport policies should enhance the role and scale of rail freight transport.

8.2. Quantifying external noise costs

In order to enable adequate internalisation of external costs, but also for more general cost/benefit decisions, the impact of transport noise on society needs to be quantified. Different methods for cost/benefit decision-making have recently been described by M+P for the EPA Network [66] and specifically for road traffic noise by CEDR [11]. They may be summarised as follows [65]:

- cost minimisation: the most inexpensive set of noise measures that fulfils the noise limits;
- cost effectiveness: the optimal ratio between noise reduction and costs;
- cost utility: the optimal ratio between the public health impact and costs;
- cost benefit: the optimal ratio between multiple monetised criteria, summed to a single monetary value, and costs;
- multi-design criteria analysis: the highest score as a weighted sum over multiple criteria, including costs, each on a different arbitrary scale.

These methods differ in complexity and in the way the benefits are quantified. The simplest approach is to look for a *minimal costs* solution, for example: what is the cheapest solution that reduces the noise to the required limit for every dwelling? In practice, this approach may actually lead to high costs in order to reduce the very last dB at every single dwelling. When designing an optimal set of noise measures, there is often some evaluation of *cost effectiveness*: if we spend a certain extra amount of money, does the extra reduction outweigh the extra costs? In this approach, a value to calculate the benefits is needed. A simple example would be the reduction in dB times the number of dwellings that profit from it. Cost effectiveness schemes have been formalised in legislation, for instance in the Netherlands and in Switzerland.

In terms of cost effectiveness, it has often been shown, for instance in the STAIRRS project [15], that source measures, such as rail dampers and track grinding, are more cost-effective than noise barriers: the "value for money" of track measures is relatively high. The same is true for retrofitting: once a wagon has been equipped with composite brake blocks, its noise is reduced for every single kilometre travelled.

In a *cost utility* analysis (CUA) the benefits are expressed as the reduction in the public health impact as a result of a certain set of noise measures. To quantify this impact, it is common to estimate the total 'burden of disease' in a certain area using Disability Adjusted Lifetime Years (DALYs), as described in the WHO 2011 Burden of Disease report [102]. DALYs are the sum of the potential years of life lost due to premature death and the equivalent years of "healthy" life lost by being in states of poor health or disability. The Institute for Health Metrics and Evaluation (IHME)[28] also uses DALYs, to calculate the Global Burden of Disease as a result of many worldwide diseases, injuries and risk factors. A comparison with DALYs for noise would be hampered

[28] http://www.healthdata.org/gbd

by the fact that annoyance and sleep disturbance, being the most important noise impacts, are generally not included in the other GBD calculations. Other quantitative indicators for health impact assessments exist and are compared and described using an application guide by RIVM [95]. These include the number of people affected by noise (NafP) or the cumulative health-based environmental risk indicator (CHERIO).

For a *cost benefit analysis*, the costs are directly compared to the benefits, which requires that the effects of noise reduction be monetised, i.e. expressed in monetary units, typically €/person/year. This 'price of noise' includes costs for annoyance and costs for health.

The annoyance costs are represented by the concept of Willingness-To-Pay (WTP): how much money would a particular person be willing to pay for a reduction of one dB? Such values are derived by actually asking people such questions, the 'stated preferences' method, or by correlating the noise level to the differences in real estate and land prices, the 'revealed preferences' or 'hedonic pricing' method. Health costs can be derived in different ways, but commonly this is done by calculating the burden of disease in DALYs, not including annoyance and sleep disturbance, and then multiplying the DALYs by a monetary value of a healthy life year (VOLY).

The recent EC handbook on external costs [27] combines annoyance and health costs from noise into environmental prices in €/dB/person/year that increase with the noise level, from 50 dB upwards. For different noise levels, the costs in €/person/year are shown in figure 22. These values are for road and rail noise. Whereas previous versions of the EC handbook applied a 5 dB rail bonus resulting in lower noise prices for rail, the 2019 handbook no longer applies this, based on the insights from the recent WHO Guidelines.

It should be noted that several countries use national cost factors for noise that vary widely. The aforementioned studies by M+P and CEDR report differences up to a factor of 10 between countries with similar levels of welfare. It is important to consider these bandwidths when applying such cost factors in any cost-benefit decision.

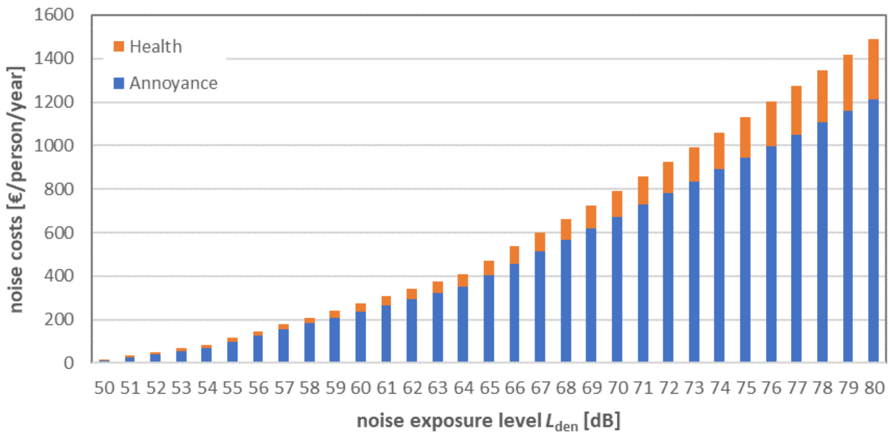

Figure 22: Environmental noise prices for rail traffic, for EU-28 in €/person/year, price level 2016, as a function of L_{den} (data from [27])

Finally, multi design criteria analysis (MDCA) is a decision method that allows the inclusion, in principle, of any criteria relating to noise abatement measures, even if these cannot be monetised, such as aesthetic and socio-cultural aspects. It involves an approach where each criterion is scored on an arbitrary or dimensionless scale, with the help of experts or a public panel, and summed with weighting factors to find the optimal solution. Good examples of MDCA for noise are described in the M+P report [66], in the Go-Leise project [15] and also in the DESTINATE project [45].

9. EU policy and legal requirements

> *Railways are an efficient and sustainable form of mass transport. But some have a negative side: they can be noisy, and citizens suffer as a result. Working for Europeans and their environment, that's what I want to change!*
>
> Marco Paviotti - EU Commission, DG Environment

9.1. Environmental Noise Directive

The Environmental Noise Directive (END) [26] 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 action plan should include a view to preventing and reducing environmental noise where necessary and particularly where exposure levels induce harmful effects on human health. It should also view to preserving environmental noise quality where this rated as good, including the protection of quiet areas. Noise mapping and action planning is required for major roads, railways and airports as well as for all agglomerations of 100,000 inhabitants or more. Major railways are defined as those with more than 30,000 train passages per year. Low intensity railways and urban rail should be included in the noise maps for the agglomerations.

Annex II of the END provides harmonised noise assessment methods for road, rail and industry noise. Since July 2015, its contents are given by Directive 2015/996 [21], see section 6.2.1. Member States are required to use it for the upcoming round of noise mapping in 2022. For the previous noise mapping rounds (2007, 2012 and 2017), different national methods have been allowed. Annex III provides the exposure-response functions to assess the effect of noise on the population. As of March 2020, Annex III is replaced by Directive 2020/367 [22] which for rail noise contains the new ERFs for annoyance and sleep disturbance found by the WHO (see Chapter 7).

Environmental Noise in Europe 2020

The European Environment Agency (EEA) collects and analyses the noise map data. Based on these analyses, they regularly report on the state of environmental noise in Europe and observed trends. The most recent report was published in March 2020 [38]. EEA concludes that:

- noise is a major environmental problem in Europe, with at least 20% of the EU population living in areas where traffic noise levels are harmful to health;
- road noise is the prevalent source of noise exposure, with 113 million people exposed to L_{den} levels higher than 55 dB; rail noise is the second most important source, but with 20 million people above 55 dB L_{den}, the exposure is considerably smaller than for road noise;
- noise mapping data reported to the EEA are incomplete for 2012 (92% complete) and 2017 (66% complete) and gap-filling is needed to estimate the complete picture.

For railway noise, EEA states that the exposure has broadly remained stable between 2012 and 2017, with a slight increase outside agglomerations. However, there are large differences between countries. The total noise exposure from major railways in Europe has slightly increased (+3%), but the total is actually dominated by a small number of countries. For some Member States, the conclusion that rail noise exposure remains stable or increases contradicts their expectations and also their large efforts taken in recent years to reduce rail noise, for instance by reducing the number of wagons with cast-iron brake blocks and by building new noise barriers. As an example: in Austria, the number of people exposed to noise from major railways decreased from 1.5 million to 0.75 million.

For several other countries, the reported changes in exposure from 2012 to 2017 are unrealistic and could be caused by changes in the methodology and input data, for example:

- In France, the number of people above 55 dB L_{den} outside agglomerations has increased by +153% and for the agglomeration of Paris, the number of people exposed to noise from all railways has increased from 260,000 to 840,000. Upon inquiry, SNCF explains that 2012 numbers outside agglomerations may be an underestimation due to a simplified approach being applied in sparsely populated areas. The outline of some agglomerations has also changed. The apparent increase is caused by a method change and do not reflect reality.
- For Poland, PKP indicates that major changes have been made between 2012 and 2017 to the level of detail of the input data, e.g. the number of train categories, speed and track parameters as well as the 3D terrain model. The 2012 numbers are considered less accurate and the change in data may very well have caused a systematic difference between 2012 and 2017.
- For the Czech Republic, SZDC has also indicated that their assessment method has changed between noise mapping rounds.

Finally, there are differences in noise assessment methods between countries. One of the major aspects is to what extent the new, more silent rolling stock is actually included in the calculations. Some countries have no provisions for the silent stock in their assessment methods, thereby overestimating the noise exposure.

All in all, general conclusions about the development of railway noise exposure in Europe based on the noise mapping results are not possible, due to significant differences in the assessment methods between years and between countries. The introduction of the harmonised noise assessment method (CNOSSOS-EU) in the END Annex II will partly solve this issue, but differences in national input values and data collection methods will remain. Also, a new trend based on multiple rounds of noise mapping with CNOSSOS will only be visible starting from 2027. Finally, the actual developments of railway noise in different Member States differ widely and are not well represented by a European total or average.

9.2. TSI Noise

The Technical Specification for Interoperability relating to the subsystem 'rolling stock - noise' (TSI Noise) sets out the optimal level of harmonisation for specification on the rolling stock subsystem with the aim of limiting the noise emission of the railway systems of the European Union.

A main effort to trigger the retrofitting of freight wagons with composite brake blocks is the revision of the TSI Noise by introducing so called Quieter Routes [36], [37]. From December 8, 2024 wagons with cast-iron brake blocks will be banned on Quieter Routes. A Quieter Route is defined as part 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. The European Union Agency for Railways publishes the lists of Quieter Routes provided by the Member States in accordance with Appendix D.1 of the Noise TSI. It also publishes the maps illustrating the Quieter Routes if provided by the Member States[29]. As an example, figure 23 shows the Dutch map of Quieter Routes.

[29] https://www.era.europa.eu/activities/technical-specifications-interoperability_en#meeting4

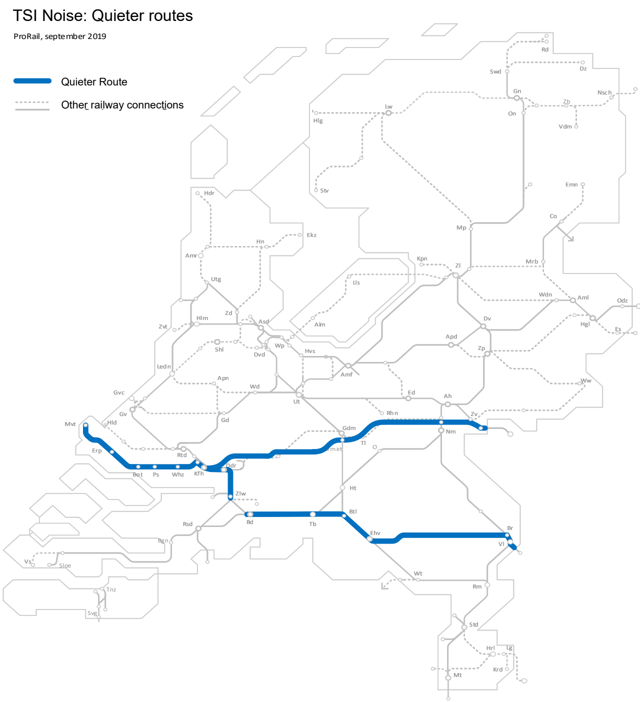

Figure 23: Example of a map with the Quieter Routes for the Netherlands

Special cases or exclusions are possible. Examples include several countries such as Finland, track gauges that are different from the main rail network or the Channel Tunnel.

There is an unresolved, reported problem with the braking performance of composite brake blocks during Nordic winter conditions. Therefore, the TSI Noise has a backstop clause: If ongoing tests prove safety issues, the TSI Noise can be further amended to give dispensation for a limited number of wagons in Europe.

The Quieter Routes approach will have an additional effect, referred to as the spillover effect. This means that the Quieter Routes will de-facto also limit the number of "noisy" freight trains on non-quieter routes as the retrofitted wagons will also run partly on the non-quieter routes. The European Commission expects that this will have a positive effect on 90% of the people living close to the railway track.

> *The "Quieter Routes" that were published in 2019 provide a beckoning perspective for people living along railway lines: lasting quieter freight traffic.*
>
> Chiel Roovers - Chairman of the EIM working group of noise and vibrations

9.3. Noise Differentiated Track Access Charge

In 2015, the European Commission adopted the Commission Implementing Regulation 2015/429 on the Noise Differentiated Track Access Charge (NDTAC), setting out the modalities to be followed for the application of the charging for the cost of noise effect [23]. This provides the legal framework to EU Member States as well as infrastructure managers for NDTAC schemes within the European Union. The application of this scheme shall however not result in the undue distortion of competition between railway undertakings or negatively affect the overall competitiveness of the rail freight sector.

The regulation differentiates between bonus and malus when applying an NDTAC scheme:

- The infrastructure manager shall introduce a bonus for Railway Undertakings (RU) using retrofitted wagons. The minimum level of a bonus shall be set at EUR 0.0035 per axle-km.
- Infrastructure managers may introduce a bonus for railway undertakings running silent trains.
- Infrastructure managers may introduce an additional bonus for railway undertakings running very quiet wagons and locomotives.
- The infrastructure manager may also introduce a malus for railway undertakings running noisy trains, i.e. trains containing more than 10% of noisy wagons. Throughout the duration of the scheme, the total malus received may not exceed the total bonus paid out.

The scheme shall apply until 31 December 2021. For national implementations of NDTAC see chapter 10.

In 2019, the European Commission carried out an evaluation of the implementation of the NDTAC schemes. At the time of writing this report, the results of this evaluation are not yet publicly available.

9.4. Connecting Europe Facility

The Connecting Europe Facility (CEF) for Transport is the funding instrument to realise European transport infrastructure policy. It aims at supporting investments in building new transport infrastructure in Europe or rehabilitating and upgrading the existing one. The CEF provides funding of 20% of the eligible costs for retrofitting and is formalised in Regulation (EU) No 1316/2013. Three calls were undertaken. The first call took place in 2014, for this call there was only limited interest. The second call was in 2016. The most recent call was launched in 2019. It is estimated that around 200,000 freight wagons have been retrofitted through CEF.

9.5. Steps toward future noise policy

The Commission contracted a Phenomena Project (Assessment of Potential HEalth Benefits of NOise AbateMENt MeAsures in the EU) at the end of 2019 with the objective of[30]:

- defining the potential of measures capable of delivering a significant reduction (20-50%) in the health burden due to environmental noise from roads, railways and aircraft by 2030, with respect to a baseline scenario;
- analysing what are the main drivers for implementation of the different measures;
- assessing how relevant noise related Union legislation could enhance the implementation of measures, while considering the constraints and specificities of each transport mode.

For railways, the scope includes major railway lines with more than 30,000 trains per year where noise levels are above 54 dB L_{den} and railways inside agglomerations of more than 100,000 inhabitants. As noise abatement measures, the study will look at infrastructure improvements (rail grinding, rail pads, rail dampers, rail shielding), new generation rolling stock with quieter powertrains and smoother or damped wheels, noise barriers, façade insulation and noise cancelling solutions. Also included in their assessment are traffic and urban planning measures. From all of these individual measures, effective combined scenarios are compiled, aiming to achieve the desired 20 to 50% reduction of health impacts.

The study is planned to finish in early 2021. The work plan includes a literature legislation review, analysis of noise action plans, workshops and interviews with experts. Also, the effects of noise measures will be quantified by noise mapping of test sites, extrapolated to EU level and followed by a cost/benefit analysis. UIC is in contact with the researchers directly and UIC and CER will also be involved through their participation in the workshops. The first workshop has taken place in June 2020 and intermediately, UIC has provided information regarding rail noise measures and their expected reductions, as input to the Phenomena scenario and cost/benefit studies.

[30] Source: presentation TNO (M. Dittrich) and VVA (I. Taranic) in DG ENV Noise Expert Group meeting, 12 February 2020

10. Implementation

10.1. NDTAC implementation examples

Noise differentiated track access charges are voluntary, so European member states are free to choose to implement them. Germany, Austria, the Netherlands and Czech Republic have implemented a system.

Germany started the implementation of the NTDAC in 2012. It will be collected for the last time in timetable period 2019/20 in December 2020. Starting 13th of December 2020, a ban on cast iron brake blocks is in place. The German system consists of a bonus rate for wagons but also has a malus for noisy trains. Austria has introduced a NDTAC scheme in December 2017 where the noise bonus is paid to the railway undertaking. A mechanism to pass on the bonuses from the undertaking to the wagon keeper was not embedded but there is agreement on a system passing on the bonus. The effect of the NDTAC is that within one year the number of retrofitted wagon-km was increased by 47%.

The Netherlands have an NDTAC system in place since 2008. It has a bonus rate for the use of low noise wagons but also a bonus for silent trains. The costs cover both the retrofitting costs and the operational costs.

Austria implemented the EC regulation 2015/429 in 2017. The bonus model of this regulation is implemented and is paid to the Railway Undertaking. An automated forwarding to the multinational database ("Single Entry Point", the Contact point for bonus applications, by the BAV Bundesamt für Verkehr, DB Netz AG, ProRail and ÖBB-Infrastruktur AG) is also realised.

The Czech Republic started the NDTAC scheme on January 1st 2020. It gives a bonus for the use of modernised freight cars. The bonus is paid to the railway undertakings.

10.2.Limit values

Many European countries have defined limit values in their national legislation for environmental noise from roads, railways, aircraft and industrial sources. Recently, the EPA Network Interest Group on Noise Abatement (IGNA) has published a report [64] on the use of noise limit and target values in the European Region, based on a survey around 29 countries. The study was performed in January 2019; any legislation updates as a result of the new WHO guidelines have not yet taken place, although several countries indicate that they are considering such an update.

A 'limit value' is defined here as a noise level that should not be exceeded, with a legal obligation to check this, e.g. as part of a mandatory environmental or health impact assessment for infrastructure (re)construction projects or building permits. Noise limits are expressed as an average value like L_{den} or L_{night}, although a few countries have additional restrictions on peak levels (L_{Amax}) and the number of exceedances. The actual consequences of exceeding the limit may vary widely, as reported by IGNA, including a full prohibition of activities or the obligation to consider active noise measures (e.g. source measures, noise barriers) or passive measures (e.g. façade insulation, financial compensation). A few countries report having not only a limit value that is not or rarely to be exceeded, but also a target value above which authorities should consider taking action but may decide not to, given cost/benefit considerations.

About 80% of the countries responding to the survey report have a legal railway noise limit for the daytime or L_{den}, and about 70% have separate night-time limits. Figure 24 shows the actual dB values used as limits in the different countries. Different noise limits may apply within one country for different situations: limits in urban areas may be higher than in suburban areas, and higher in industrial or commercial zones than in residential areas. In countries with rail noise limits, these usually apply to both new situations, i.e. new railway lines or new housing, and existing situations: 75% of countries with rail noise limits report having limits for both new and existing situations. In some countries, the limits for existing situations may be higher than for new situations, usually with a 5 dB difference.

All in all, the conclusion is that, in comparable situations, the limit values used around Europe show a variation of 20 dB, and that the majority of limit values are higher than the values recommended by the WHO. This is the case for all noise sources, not just for railways. National limits are set taking into account other factors, such as the costs of the measures to attain the values, whereas the WHO recommended levels are based on a health perspective only. This is acknowledged by the WHO: *In the policy decisions on reference values, such as noise limits for a possible standard or legislation, additional considerations - such as feasibility, costs, preferences and so on - feature in and can influence the ultimate value chosen as a noise limit* ([103], section 5.1).

It should be noted that many different methods are used throughout Europe to assess noise levels and limits, and results of different calculation or measurement methods may be different even in the same situation. This makes a direct comparison of noise levels between countries difficult and may also cause discrepancies between national noise limits and WHO recommended levels. The question which methods are used in each of the countries and to what extent the results are comparable was not answered in this particular IGNA study.

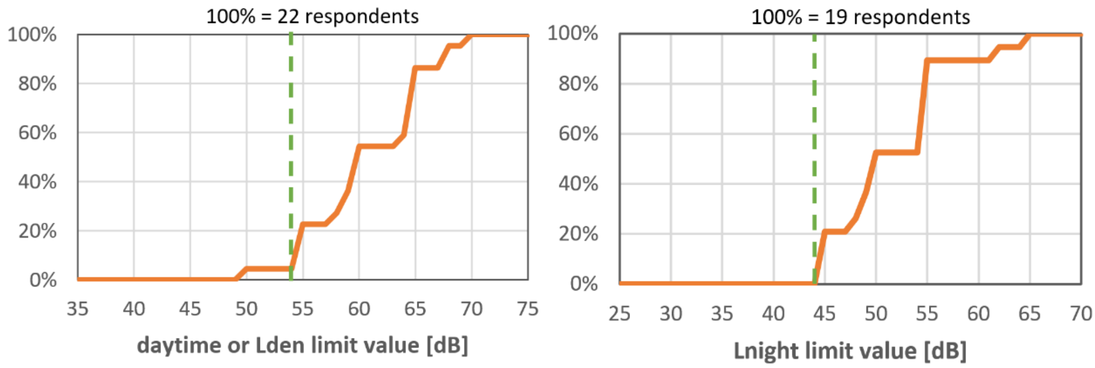

Figure 24: Cumulative distribution of railway noise limit values: vertical axis indicates the percentage of European countries with a limit lower than or equal to the value indicated on the horizontal axis. Countries without rail noise limits have not been taken into account. Dashed vertical line shows the L_{den} value recommended by WHO. **Left graph**: *daytime noise limits (L_{day}, L_{den} or other daytime indicator),* **right graph**: *night-time noise limits (L_{night}) (from [64])*

10.3.Noise Annoyance Correction Factor

The research base on transport noise built over the last 40 years has shown on a regular basis that people are less annoyed by noise from railways than by noise from roads and aircraft, at the same dB level, using usual long-term equivalent indicators (L_{day}, L_{den}). A UIC discussion paper from 2010 [89] summarises the research base and provides possible explanations for differences in people's degree of annoyance. Although a few studies are mentioned, e.g. from Japan, that do not show this difference, the majority of the studies confirms a less negative attitude towards railway noise. The Miedema curves that were previously commonly used as the de facto standard exposure-response functions (ERFs, see Chapter 7), also show higher annoyance for road than for rail noise at the same L_{den}, and it is also stated in the ISO1996-1 standard [47] on environmental noise assessment procedures. Similar conclusions were drawn for night-time noise, albeit on a thinner evidence base. Given these conclusions, it has been common in several countries to allow higher noise levels for railway noise than for road noise. The purpose of noise limits is not, after all, to limit the noise level, but rather to limit the effects on annoyance, sleep and other health effects that arise from the noise.

The difference in the allowed noise levels is expressed by a noise annoyance correction factor (NACF). In approximately 20% of countries in Europe (e.g. NL, DK, AT and CH) a positive NACF is applied, i.e. higher (less stringent) limits for rail noise than for road noise [64]; the difference is usually 5 dB. This difference may either be implemented as a difference in limit values for road and rail, or as a correction subtracted from the calculated or measured rail noise levels prior to comparing with the generic limit value for transport noise.

The NACF is also often referred to as a 'railway bonus'. As argued by UIC and others, this is a misleading term, as it suggests that it is based on a political preference, goodwill or 'X-factor' to favour railway transport over road transport. This is not the case: the NACF has always been based on objective and solid evidence from many health studies.

The recent WHO Environmental Noise Guidelines present new exposure-response functions as well as recommended maximum noise levels that are approximately equal for road and rail traffic noise. Also, the WHO ERFs are now published in the END Annex III [22], which means that the future noise maps will show an increase in the annoyance and sleep disturbance from rail with respect to road noise due to the new ERFs, counteracting decreasing rail annoyance expected from the rail sector's recent efforts towards noise mitigation.

The consequences of eliminating the NACF to European rail transport could be severe. If it would be simply eliminated, the number of people suddenly exposed to noise levels above the limit could drastically increase, as shown by the example of Switzerland in figure 25 [68] where there have been large efforts to reduce this number in recent years and additional efforts would be therefore be costly. For Switzerland as well as for other countries, and for Europe as a whole, the elimination of the NACF would hamper the competitiveness of the rail sector and endanger the shift from road to rail that is needed and desired to fulfil the ambitions of the European Green Deal.

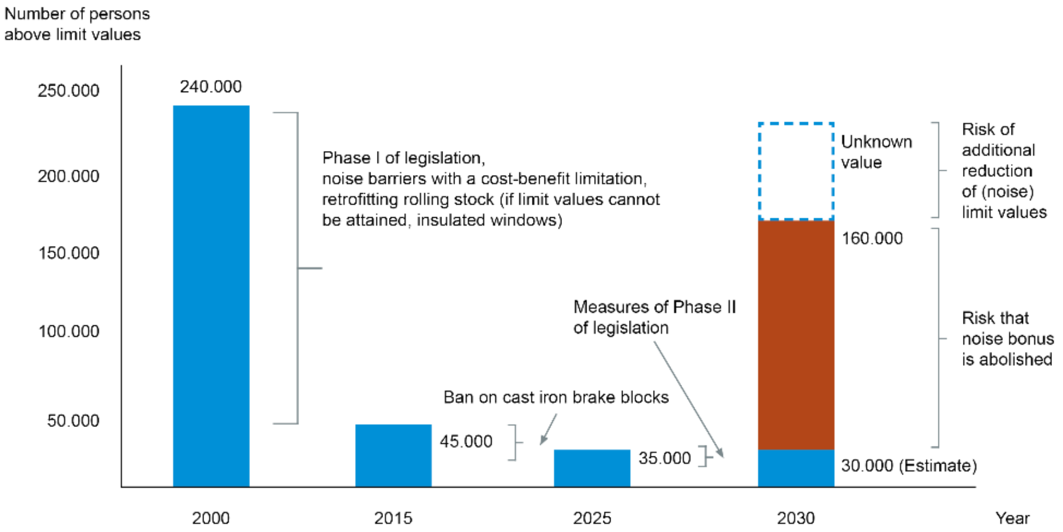

Figure 25: Development of the number of people exposed to railway noise levels above the limit value since 2000 in Switzerland; the red bar shows the increase in this number when the NACF (K1 factor in the Swiss noise assessment method) is abolished (from [71])

10.4. Examples of noise legislation in Europe

Noise legislation serves different goals:

- to improve the current situation;
- to reduce possible effects of infra projects, e.g. building of new lines or improving an existing line;
- to reduce or prevent possible negative effects of traffic growth.

Countries in Europe have different strategies for these purposes. This paragraph highlights various strategies.

Improving the current situation

There are several ways to improve the current situation. One way to do so is by noise abatement programmes. Several countries, like Denmark, Germany, the Netherlands and Switzerland, have started or finished such a programme. For instance, the Swiss noise abatement programme was implemented between 2000 and 2015. The programme included rolling stock improvement, noise barriers and insulated windows. Aimed at the rolling stock and at measures on the track. A total of 290 km noise barriers was planned, of which more than 99% has been completed. It is expected that the last noise barriers will be finished in 2021. Soundproof windows were installed in all cases where the first two measures were insufficient to attain the legislated limit values. This resulted in more than 70,000 windows in more than 18,000 buildings [10].

Another way to lower the noise levels in existing situations is by applying innovative measures. In Belgium, rail pads are being replaced with a new model displaying improved acoustical performance.

In Denmark, a noise strategy is implemented that has set a limit on the rail roughness level. In the United Kingdom, research and development is on-going on rail roughness with respect to noise and investigating maintenance strategies for noise based on traffic rather than time. This will feed into national legislation when complete.

Sweden has explicitly set a noise limit value in the existing situation. If the maximum noise level, $L_{A,max}$, indoors in dwellings exceeds 55 dB(A) at night time, the situation must be improved. Sweden also takes measures when the noise levels exceeds 65 dB(A) L_{eq24h} outdoors [82].

Reducing possible negative effects of infrastructure projects

When building new railway lines, or when improving or expanding existing lines, noise measures are very often part of the project. The driving force to take these measures is mostly the legal requirement to fulfil the regulatory limits, or the obligation to prevent any increase in noise as a result of the infrastructure changes. Almost all countries have noise limits imposed for new tracks or when improving existing lines.

The French noise law defines noise limit values at points located 2 metres in front of the façade, windows closed for new line and for modification of existing lines. The actual value depends on the building (e.g. dwelling, school, hospital), the type of area (quiet area, or not), the type of line (conventional or highspeed) and other factors. Limit values are defined for the day and for the night. The French law is evolving. Complaints about pass-by noise in general and the opinion that long-term indicators are not representative have led to research to the added value of short-term indicators into the French law, which is on-going.

In Germany, there is the so called “Lärmvorsorge”: preventive mitigation measures for new lines and essential improvements of existing lines. There are limit values for day and night time. The value depends on the function of the building.

In the Czech Republic, noise measurements and noise prediction models are used in the process of modernisation or optimisation of rail track. When the noise is expected to exceed the limits, noise control measures are proposed, which include noise barriers, rail dampers or individual noise control measures.

In Norway, recommended noise limit values for new lines are L_{den} 58 dB and L5AF 75 dB. L5AF, a statistical maximum level for L_{AFmax}, excluding the top 5% fringe incidents, is applied when there are, on average, more than 10 noisy incidents during the night time - from 23.00hrs-0700hrs. The measurement or calculation point for L5AF is only outside of bedrooms. For improvements or expansions of existing lines, the same values apply if noise levels are deemed to change noticeably (> 3 dB), and if dwellings either have or will gain noise levels that exceed the limit values as a consequence of the project.

Reducing or preventing the possible negative effects of traffic growth

A few countries have implemented a strategy to monitor the effect of traffic growth and to take measures to reduce or prevent a noise increase. A good example for this is the situation in the Netherlands. The Dutch have a system with noise emission ceilings. The idea of the noise emission ceilings is to have a network of virtual evaluation points next to the roads and railways. On each of these points, a noise level is determined by calculation and the infrastructure provider must ensure that these maximum noise levels will never be exceeded. The noise emission ceilings prevent the unlimited growth of traffic in noise-sensitive areas. Traffic can grow if the noise emission does not exceed the maximum allowed value. Noise abatement is needed when this happens.

Switzerland has the obligation to see if limit values are attained and to undertake noise measures if the noise levels increase by more than 1 dB due to a traffic increase.

Miscellaneous national legislation

Starting in 2020, both Switzerland and Germany introduced a ban on noisy freight wagons on their railway network. This means that the freight wagons with cast-iron blocks cannot be used anymore on their railway networks. In Switzerland, the ban started on January 1st, 2020. In 2020 no penalties are given, but wagon keepers/operators will receive a warning if there is an infringement. Starting from 2021 the operators will lose the NDTAC if there is a noisy wagon in a train, also regular inspections will be undertaken and non-compliant wagons will be taken out of service

The European Commission is not in favour of unilateral restrictions, see reference [35]. They fear that this could take the form of restrictions for rail freight traffic like speed restrictions or restrictions on operating at certain times. Such measures would result in bottlenecks which might have an adverse effect on European economies and the railway sector. It might lead to a reverse shift with freight being moved from rail to road to avoid the ban.

11. Conclusions and next steps

11.1. Conclusions

We have shown that the railway traffic is a transport sector leader on safety, air quality and CO_2 emissions, as well as a low impact on health and the environment in general. Expressed as external transport costs in €/km, rail scores better than most other transport modes for passenger as well as freight transport. With the ambitious European Green Deal ahead of us, railways are an essential transport mode to ensure that the goals of the Green Deal can be achieved. Therefore, promoting rail transport as the environmentally-friendly transport mode is needed: For those reasons, the European Commission has decided to make 2021 the European Year of Rail. In June 2020, the Dutch State Secretary for Infrastructure and Water Management presented a statement on international railway passenger transport to the European Commission to promote railway's modal share for distances from 300 - 800 km. This statement was supported by a list of EU member states and by Norway and Switzerland[31].

The railway sector is well aware that noise can be a health problem. Therefore, a large set of noise mitigation measures has been implemented in the past, are being implemented now and further measures are foreseen. These measures are implemented on three different levels: the EU-level, the national level, and the local level. Examples on the EU level are the NDTAC regulation that has been set in place, the CEF funding for retrofitting and the introduction of the quieter routes in 2024. On a national level, NDTAC schemes have been implemented and national mitigation programmes are in progress. On locations where noise is a (potential) issue infrastructure managers plan and build noise barriers and apply rail dampers in the track.

With all these measures, railways have become quieter and with the ongoing and future measures this trend is expected to continue for the near future. At the same time, there is an increasing demand, from the transport sector as a whole, but also from the desired shift from road and air to rail transport, and traffic intensities will grow as a consequence. And in many countries and regions, the population is growing and the demand for new housing is increasing, putting pressure on scarce space. Shrinking rail noise contours may be filled with new residential areas if the noise problem is not raised on the agenda of local authorities and urban planners as well.

The cost-benefit ratio is an important factor when implementing noise measures. For the largest part, those measures with the best cost-benefit ratio have been or are in the process of being implemented. Achieving more decibels of noise reduction is possible but will come with a higher price and a lower cost benefit ratio. Applying these measures can endanger the competitiveness of the railways and might lead to a reverse modal shift, from rail to road and aircraft. One should thus avoid very costly measures that have little effect. In this respect, if the recent recommendations by the WHO are implemented by policy makers and legislative authorities, this should be done with care so as not to support this reverse modal shift. The recommendations, based on the health effects of noise, must be regarded in a broader perspective, balancing the noise problem with the other environmental aspects and climate change.

11.2. Outlook

The report was written during the COVID-19 pandemic when mobility was drastically reduced. Nevertheless, railways have continued to serve the public and to move goods across Europe. Because the railways are a sustainable means of transport and are therefore an important element of attaining climate goals, it is expected that railway traffic will increase in the future.

This will mean that railway noise emissions can increase if no countermeasures are taken. Various strategies have been implemented by the sector that aim at coping with noise problems and it will continue to be active in finding solutions for reducing noise in a cost-effective way, preferably at the source. We do not expect future measures to be as cost-effective as the current measures, e.g. retrofitting.

[31] https://www.tweedekamer.nl/kamerstukken/brieven_regering/detail?id=2020Z10167&did=2020D22072

After completion of the current retrofitting efforts resulting in a significant reduction of rolling noise, other vehicle measures will also be investigated. Successful implementation of such rolling stock measures will require a European solution. However, we expect that the main research will focus on the track. One way to achieve further reduction is to focus on the whole system optimisation, by looking at all the different components of the track and their interaction aiming to find novel ideas to lower the noise emissions. These novel ideas are needed because the sector has already undertaken the big and most cost-effective steps in noise reduction such as constructing noise barriers or retrofitting the freight rolling stock.

Another focus for future research is on developing new technologies to reduce noise from auxiliary equipment that is mainly perceived at slow speeds, e.g. in the urban environment that is becoming increasingly densely populated.

The rail sector is always innovative, rolling out new technologies. Such new technologies may also be beneficial for noise: digital automatic coupling and interconnected driver assistance systems, for instance, may reduce braking and accelerating that generate noise or cause deterioration of the wheel surface condition. Further electrification as well as the introduction of hydrogen engines and battery trains will show positive effects on noise.

On a policy level, external costs should be internalised for all transport modes in order to ensure fair competitiveness. This may require efforts from policy makers to ensure a tax and charging system that guarantees a level playing field and stimulates the desired modal shift.

As residents' sensitivity on ground vibrations increases, railways have to take them better into account. This is a trend that can already be seen in different European countries. The railways and UIC are aware of this and are working hard to deal with it.

All in all, the railways endeavour to provide sustainable transport. The railways are aware of the noise issues, have undertaken considerable efforts and will continue to do so in the future. The target is and will be to enable more rail traffic while reducing the noise.

> *For the successful implementation of rail noise reduction measures, innovative solutions have to be at the heart of any future noise abatement programme. All together, we need to address noise as the last remaining environmental challenge for the European rail sector while fostering the competitiveness of rail freight transport, thereby ensuring a real modal shift to rail and fulfilling the EU's Green Deal objectives.*
>
> Gilles Peterhans - Director UIP

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Annex A - UIC noise activities

The UIC Noise and Vibration Sector promotes effective management of railway noise and vibration in the context of sustainable development. The group forms a centre of excellence; it supports transfer of knowledge, coordinates events/activities, leads research projects and facilitates communication with key stakeholders. It works in close cooperation with other railway organisations, the EU commission and national authorities.

The sector provides a technical lead on transport noise and vibration policy, in particular:

- The rail sector response to growing pressure from the EU, national governments, lineside inhabitants, health organisations and NGOs.
- Evaluation, review and guidance on upcoming new noise and vibration legislative initiatives and mitigation policy ideas and incentives (e.g. noise-differentiated track access charges, prohibition of cast iron brake blocks, rail dampers etc.). In addition, it will consider the effects of noise mitigation methods on vibration and vice versa.

The sector covers activities of two following working groups:

- UIC Noise working group is concerned with all aspects of railway noise, e.g. rolling noise, stationary noise, and noise from shunting yards.
- UIC Vibration working group is dedicated to study vibrations and ground-borne noise issues.

The working group meetings of the sector are held twice in a year.

Ongoing UIC research projects:

LOWNOISEPAD lownoisepad	UIC will start the new project, called Low cost noise control by optimised rail pad (LOWNOISEPAD) in 2021. With this project, the project participants will individually measure and analyse their existing rail pads on their respective network and will aim to optimise rail pad stiffness confirming its dependence on acoustics-relevant parameters: ▪ track decay rates (TDR), ▪ rail fastening system, ▪ static/dynamic stiffness data including the damping parameters. Having experiences on rail pad research will help the project's participants to trigger their internal research for future rail pads on their network.
AeroNoise project - Rail system department	One of the few oppositions to the development of existing and/or new schemes are the social criticisms related to the fears of ambient noise impact. This opposition is even greater around the development of High-Speed Railway Schemes due to the increase in the number of noise sources related to the rolling stock's aerodynamic behaviour. The understanding and characterisation of aeroacoustics sources is a new challenge for the European railway industry in order to design, implement and validate appropriate mitigation measures to be applied on high speed rolling stock. The UIC Aero Noise project is intended to: ▪ Drive and influence the development of a common approach for characterising aerodynamic noise of trains at High-speed; ▪ Drive and influence the development of a common requirement for the evaluation and verification of aerodynamic noise sources; ▪ Influence the improvement of the current TSI limits for high speed rolling stock; and ▪ Identify and resolve the current gaps in ISO 3095, and enhance the "simplified evaluation" set out in 6.2.3 TSI NOISE

Annex B - Members of UIC Noise and Vibration sector

The list of members below was taken from the UIC Extranet on January 20th, 2021.

Name	Surname	Organisation
Pedro	PEREZ	ADIF
Marta	RUIZ	ADIF
David-Iban	VILLLALMANZO RESUSTA	ADIF
Lisette	MORTENSEN	Banedanmark
Trygve	AASEN	BaneNor
Ethem	PEKIN	CER
Florian	CZECH	CFL
Jean	NICOLAOS	CFR-SA
Stefan	DORSCH	DB
Bernd	ASMUSSEN	DB Netz AG
Christian	FRANK	DB Netz AG
Martina	FLECKENSTEIN	Deutsche Bahn AG
Ruediger	GARBURG	Deutsche Bahn AG
Ferat	GOECMEN	Deutsche Bahn AG
Lennart	MOHEIT	Deutsche Bahn AG
Gualtiero	POSO	FS
Oliver	BEWES	HS2 - High Speed Two Limited
Gennaro	SICA	HS2 - High Speed Two Limited
Sander	DE BOCK	INFRABEL
Juliette	FLORENTIN	INFRABEL
Eduard	VERHELST	INFRABEL
Diogo	VASCONCELOS	Infraestruturas de Portugal
Jude	CAREY	Irish Rail
Jamie	WILKES	Network Rail
Martijn	WOLF	NS Reizigers BV
Christian	MALEK	NS Reizigers BV
Peter	KUMPERA	ÖBB-Infrastruktur
Gunter	DINHOBL	ÖBB-Infrastruktur
Adam	OSIAK	PKP Cargo
Joanna	SALAWA	PKP Cargo
Sylwia	KUZMICZ	PKP S.A.

Name	Surname	Organisation
Nils	IJNTEMA	ProRail
Tryfon	ROELOFS	ProRail
Chiel	ROOVERS	ProRail
Cynthia	LULHAM	Railway Association of Canada
Simone	RELANDINI	RFI
Luca	RICCIARDI	RFI
Marius-Ovidiu	ENE	Romanian Railway Authority - AFER
Jakob	OERTLI	SBB AG
Marc	SCHMID	SBB AG
Estelle	BONGINI	SNCF
Cora	CREMEZI-CHARLET	SNCF
Baldrik	FAURE	SNCF
Fabien	LETOURNEAUX	SNCF
Florence	MARGIOCCHI	SNCF
Franck	POISSON	SNCF
Rodolphe	POTVIN	SNCF
Jean-Philippe	REGAIRAZ	SNCF Reseau
Pascal	FODIMAN	SNCF SA
Radek	KOCHANOWSKI	Sydney Trains
Lukas	HEJZLAR	SZCD
Anna	SIKLOVA	SZCZ
Bohumir	TRAVNICEK	SZCZ
Lenka	VANKOVA	SZCZ
Karin	BLIDBERG	TRAFIKVERKET
Alf	EKBLAD	TRAFIKVERKET
Umut	BICER	Turkish State Railways
Mercedes	GUTIERREZ	UIC Rail System
David	MIRAYO	UIC Rail System
Lucie	ANDERTON	UIC Sustainability
Pinar	YILMAZER	UIC Sustainability
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