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INTRODUCTION

Plans for new and upgraded railway lines, as well as growth in traffic on existing lines, sometimes prompt strong adverse reactions from local residents due to concerns about increased noise and ground-borne vibration from railway lines. Although rail is widely acknowledged to be the transport mode with the lowest environmental impact, noise and vibration caused by the interaction between the train and the track remains an important issue for the railway sector as a whole.

The Train Track Interaction (TTI) Sector within the UIC Rail System Department (RSD) has set out to address these concerns and provide roadmaps on this topic with a view to offering new solutions.

This White Paper on Acoustics, prepared at the beginning of this process, reflects on the current situation and main issues and provides information on proposals for technical projects to conduct research and devise solutions for infrastructure managers (IM) and railway undertakings (RU).

A number of UIC reports on topics relating to noise and vibration issues have been prepared by the UIC Sustainable Development unit’s Network Noise and Vibration (NNV). The UIC NNV periodically produces status reports on general and specific issues. Such reports include *Railway noise in Europe – State of the art report (2016)* [5] and *Railway Induced Vibration – State of the art report (2017)* [80]. These reports can be found on the UIC NNV website [81].

Railway noise and vibration are systemic issues and are largely related to train/track interaction. Thus, the TTI Sector is well placed to propose, manage and carry out research projects addressing technical aspects of railway noise and vibration, providing useful technical inputs to NNV projects, and vice versa.

A further objective underpinning this White Paper on Acoustics is to create synergies between the activities developed by the Rail System department within its Train Track Interaction (TTI) Sector and the Sustainable Development unit within its Network Noise and Vibration (NNV) in order to identify and fill any gaps in current standards.
FOREWORD AND OBJECTIVES

The railway sector needs to focus on a number of specific areas in order to reduce travel times and facilitate modal exchange, faster and more straightforward shipments, efficient energy use and reduced omissions if the objectives set out for the railway sector by the UN Sustainable Development Goals and in Agenda 2030 are to be achieved and to ensure that consumers’ needs with regard to intermodality are met.

The last number of years have seen significant development with regard to legislation, approvals, procedures, technical solutions and distribution of responsibilities amongst the various parties involved in order to reduce acoustic emissions. Furthermore, there is now greater insight into the effects of noise and vibration emissions on local residents and a growing pressure on railway undertakings and infrastructure managers to keep reducing emission levels wherever feasible.

The rail sector must work within the framework of regulations and requirements set out by the European Commission, as well as national authorities, regional and city authorities, citizens’ groups and individuals, and must align these requirements with its own strategies.

Efforts need to be made to support the proposals put forward in this White Paper in order to prepare operational and technical subsystems (comprising both infrastructure and rolling stock) for the new acoustics requirements in line with the European Commission’s existing vision for the future of the railways. These efforts shall complement the actions that have already been implemented, as well as those currently underway within the context of international frameworks for research and development, such as Shift2Rail (S2R) and the Innovation Projects (IP), lighthouse activities, and other research and framework programmes.

This White Paper on Acoustics has been drafted and finalised by the TTI Subgroup (SG) for Aerodynamics and Acoustics in order to address technical issues pertaining to railway acoustics. The document was completed in September 2019. This Subgroup is composed of highly qualified experts.

Following an initial consultation between the expert members participating in the TTI Sector in May 2017, the participants worked together to share their knowledge and information on relevant ongoing projects. It became evident during this process that the field of acoustics presents significant challenges to global railway development.

Once the group’s objectives and aims had become clear, the various topics were organised into the following three main categories:

- Noise source generation
- Acoustic comfort, subjective perception and psychoacoustic indicators
- Ground-borne vibration

A brief summary of current knowledge and recent developments is provided in this document in respect of each of the above topics, and outstanding issues or “gaps” in the applicable standards identified by members are outlined.
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In addition to those mentioned above, the following people also contributed to the draft of this White Paper, kindly offering suggestions for improvement: Pinar Yilmazer (UIC), Álvaro Andrés (ADIF), Björn Paulsson (Chalmers University of Technology), Rüdiger Garburg (DB), Terence Johnson (RSSB), Gennaro Sica (HS2), Martijn Wolf and Christian Malek (NS), Pascal Fodiman, Fabien Letourneaux and Jean-Philippe Regairaz (SNCF), and Alf Ekblad (Trafikverket).
Technical specifications for acoustics are harmonised only to a limited extent internationally, with some efforts being made within the European Union by the European institutions (TSIs) on the one hand, and by railway undertakings on the other.

The Technical Specifications for Interoperability (TSIs) developed by the European Union Agency for Railways (ERA) set out the optimal level of harmonised specifications required for each rail subsystem or component thereof in order to ensure rail interoperability within the European Union. The TSIs form part of the EU body of legal frameworks and regulations.

The main TSI in relation to acoustics is the TSI Noise, which aims to limit noise emissions in the railway system. The TSI Noise addresses the following “basic parameters” of railway noise identified as critical for interoperability:

- Stationary noise
- Starting noise
- Pass-by noise
- Driver’s cab interior noise

In particular, the TSI Noise assigns limit values for the above parameters for the various types of rolling stock. The indicators contained in the TSI must be calculated in accordance with European or international standards. The TSI application guide [1] provides additional guidance on the application of simplified evaluation methods based on Deliverable 1.1 of the EU project ACOOUTRAIN - Clarification of the simplified method in the partial revision of the TSI [2]. This document covers the following:

- Certified tools/calculation of uncertainties
- Validation strategy
- Definition of representative operating conditions (ROC)
  - Additional guidance on applying modifications relating to:
    - Number of axles
    - Unit maximum speed
    - Wheel type
- Braking system (influencing only the acoustic roughness of the wheel)
- Composition of the unit in terms of stationary and pass-by noise
- Selection of the noisiest configurations of different single vehicles
- Equipment configuration on board the vehicle (stationary/pass-by/starting noise)

In addition to the TSI, EuroSpec [3], a group of European train operating companies, also provides harmonised product specifications for use in train procurement and refurbishment. The main objective is to improve train reliability and quality by using common, standardised functional and non-functional specification and verification methods for new train procurement. The EuroSpec specifications comprise functional and basic product requirements and focus exclusively on technical considerations on the basis of existing national requirements. Application of the EuroSpec specifications is voluntary.

The EuroSpec specifications are designed to be used within the European region. The primary field of application is the European rolling stock domain and all associated interfaces.
FOCUS AREAS

A number of key focus areas were selected for the purposes of this White Paper. For each focus area, the relevant information was gathered from amongst the participating members in order to respond to the following questions:

- What is the state of the art, i.e. the current level of knowledge of the topic in the sector?
- Is this particular topic taken into consideration by standardisation bodies?
- What are the outstanding issues in terms of regulation and standardisation (TSIs, CEN, ISO, other standards)?
- Is the topic included in any current research programmes at European, national or company level?
- What elements need to be considered in future research programmes?

The responses to these questions are summarised in the sections below.

Based both on these answers and on the discussions between the partners, ideas for technical projects are then proposed.
INTRODUCTION

This section examines the fundamental physics of railway noise. Railway noise has been the focus of a number of academic research projects since the 1970s, when it first became a major concern in terms of public health.

A detailed report on railway noise modelling was published in 2009 by D.J. Thompson [4]. The UIC NNV published a state of the art report in 2016 [5], focusing on railway noise at European level and containing information on legislation, noise control strategy, the effects of noise on health, etc.

This section contains a general overview of the main phenomena associated with railway noise, focusing on areas currently being investigated in the railway noise community or which have been identified as outstanding issues.

The main sources of railway noise are as follows:

- Rolling noise
- Aerodynamic noise
- Traction noise (including engines, fans, converters, etc.)
- Local phenomena: squeal and bridge noise

Each of these sources dominates railway noise in certain train speed ranges, as illustrated in Figure 1.

Railway noise is largely associated with freight trains and trains containing older wagons or engines, and is particularly problematic at night. Poorly maintained rail vehicles and trains running on poorly maintained infrastructure generally generate higher levels of rolling noise. Aerodynamic noise is particularly relevant on high-speed lines where, in most cases, noise limiting measures such as noise barriers are implemented; noise barriers reduce the impact of rolling noise, but are usually too low to have any effect on noise originating at the upper part of trains such as train roof, pantograph recess or pantograph itself. Engine noise usually occurs at lower speeds of up to about 30 km/h, rolling noise occurs above 30 km/h, and aerodynamic noise dominates above 300 km/h [7].

The level of aerodynamic noise increases more rapidly with the train speed $V$ than rolling noise. Rolling noise is typically assumed to have a train speed dependence of $30 \log_{10} V$ for $L_{Aeq,Tp}$ and $L_{PAF,max}$ ($20 \log_{10} V$ for SEL). Aerodynamic noise is typically assumed to follow a different speed dependence of $60 \log_{10} V$ [94].
Traction noise is not considered in the scope of this document because it is not caused by interaction between elements. This type of noise comes mainly from diesel engines and power packs, exhausts, cooling fans, compressors and electrical converters.

Parked trains emit noise from equipment, which includes not only engines but also other elements such as exhausts, cooling fans for HVAC systems or other technical equipment, and electrical converters. Some of those operate continuously while others, such as compressors, are intermittent.

The UIC NNV has published a report, *Managing Noise from Parked Trains*, on the basis of work undertaken by Müller-BBM in 2014 [8]. This report provides a comprehensive overview of current parking noise management practices, legislation, ways to mitigate noise and guidelines for managing noise from parked trains.

Localised railway noise issues, such as curve squeal or noise while passing bridges, do not affect as many people as freight and high-speed trains, but can nevertheless result in significant localised disturbance.

**Rolling noise**

Rolling noise is mainly generated by the wheel-rail interaction resulting from vertical relative displacement caused by wheel and rail irregularities, including roughness. Vibration propagates through wheels, rails and sleepers, which radiate acoustic energy as illustrated in Figure 2.

Rolling noise is a well-known phenomenon that is widely addressed by means of numerical models, experimental approaches and normative context. Many train-track interaction models, together with acoustic radiation models, are able to predict acoustic levels at pass-by quite accurately. The TWINS model [9] is one such example.

These models have been used for decades. They are validated using numerous measurements and are continuously improved but are less suitable for slab tracks.

One current limitation of these models relates to acoustic waves on the ground surface (ballast, slab, grass, etc.). Some studies have been carried out in this area [95]. Differences of up to 5 dB may be observed, depending on the ground surface, but this phenomenon is not fully understood due to a lack of data.

There is an increasing interest in the different behaviour of slab track model, as this type of track design is now more widely used, for example in high-speed lines.

Updated track models have been proposed in [102] to account for the differences between slab and ballasted track, not only including the slab noise contribution to the side of slab...
track, ballast absorption and vibration effects for ballasted track, but also other effects in both types of systems caused by the different earthworks layers, and in ground transmission.

Other newer models perform audio synthesis of rolling noise at pass-by. There is currently insufficient data available to validate such models.

Another source of wheel-rail interaction noise concerns rail joints and wheel flats [11]. Although a number of studies have been carried out in this area, there is a need for greater insight into noise generated by switches and crossings [12].

Roughness generation and growth is therefore an important consideration for noise prediction, as well as for rail maintenance driven by noise emissions [13]. This remains a difficult phenomenon to predict, though a university project to investigate the development of rail-head acoustic roughness was initiated in 2009 [15]. The numerical results from this project are not consistent and have yet to be compared with field measurements.

Another important consideration is corrugation. Various types of corrugation have been identified and classified, but there is a need for numerical models to be developed in order to evaluate them [15]. Apart from on light rail and sharp curves, corrugation is not a common problem in Europe, most likely due to the rather soft fastening system used. However, it seems to be a recurrent issue for the Chinese high-speed network, which consists of slab track with stiffer rail pads than those used for ballasted track.

The influence of the grinding techniques on rail roughness is also very important. One of the main issues that might be harmful for rolling noise resulting from rail grinding is the presence of periodically spaced grinding marks emerging in the rail roughness spectrum. The amplitude and the wavelength of these marks depend, among other factors, on the pressure applied to the grinding stones and on the operating speed of the grinding machine.

Qualitative knowledge of roughness generation on wheels due to the use of brake blocks has improved. Composite materials have proven to be effective in reducing wheel roughness in comparison to cast-iron blocks [16]. One question that remains to be resolved relates to the acoustic performance of various composite brake blocks, setting aside the known phenomenon of fragility when this braking system is exposed to extremely low temperatures.

**Aerodynamic noise**

Plans are currently underway in Europe to run high-speed trains at speeds of up to 350 km/h to form a trans-European high-speed railway network. Noise from high-speed lines, mostly operating during the daytime, will be a key issue. At such speeds, aerodynamic noise is generated predominantly from the leading train car (bogie) and the upper parts of the train. The pantograph and recess, as well as the contact between the pantograph and the catenary, pose a significant problem as most noise barriers are too low to shield from noise originating from these sources. This issue often arises at the planning stage for new high-speed lines [94] or services when noise mitigation becomes a key requirement [6].

Specific source models have been developed for the leading car [96], the bogie [17] and pantographs [18]. Computer fluid dynamics (CFD) yields the most accurate calculations. Although CFD requires a high level of computational effort, it is now widely used within the sector by various stakeholders, ranging from academia to railway companies. However, CFD itself does not directly provide the level of noise emission, as it is generally used for computing the generation of the turbulent flow around the component to be investigated. Component-based modelling [19] offers an alternative, more straightforward approach.
A comparison between measurements and predictions in the D3.9 – Source model for pantograph and bogie aerodynamic noise for inclusion in the global simulation model, one of the deliverables of the ACOOUTRAIN project [20], revealed that the proposed model is suitable for predicting aerodynamic noise generated by generic pantographs. However, further validation using wind tunnel or in situ measurement data for each individual component is required.

Wind tunnel tests are generally used in combination with “in situ” measurement and/or source specific simulation to better understand the noise source mechanisms and design mitigation solutions. Examples can be found for bogies in [97] and pantograph designs in [98].

Dedicated field measurement techniques are used to validate the models and to characterise noise sources (on-board microphones [21], microphone arrays [22]). However, these methods do not enable separation of, or distinction between, rolling noise and aerodynamic noise. Measurements taken within a perimeter in close proximity to the train [23] show a marked and progressive evolution in pantograph noise directivity, clearly increasing with speed [24].

Measurement approaches using microphone arrays have been successfully applied for the validation of models of the aerodynamic noise sources of train upper parts (i.e. for pantographs) [99]. On the other hand, these approaches have not been successfully applied for validation of aerodynamic noise generated in the lower parts of the train, because they do not currently allow the separation and allocation of the rolling noise component.

**Local phenomena: squeal and bridge noise**

Squeal is a localised rail noise phenomenon that can occur when the train is running on curves. The mechanisms involved are complex and include friction-induced instability at the wheel/rail contact and mechanical coupling between the structures.

Rudd identified three possible excitation mechanisms in 1976 [25], and unsteady lateral creepage at the wheel-rail contact has since been identified as the main cause of squeal. A number of prediction models have been developed on the basis of Rudd’s early work [26], [27], [28].

Even though squeal noise has been studied for many decades, it is still an active field of research for railway noise.

Contact between the wheel flange and the rail gauge face may also occur on sharp curves and can generate “flange squeal” [29].

Bridges are a further common source of noise generation. They can cause noise increases of up to 10 dB [4] and are therefore considered as hotspots in noise maps, for example. Noise increases on bridges are primarily caused by radiating bridge vibrations during train pass-by and significant levels of rolling noise along the bridge due to its distinctive fastening system.
Classical rolling noise models can be used to predict rolling noise on bridges by taking account of track parameters. Vibration transmission between the track and the bridge must first be assessed in order to predict noise coming from the bridge structure. The assessment can be carried out in various ways, e.g. using coupled beams [30], finite elements (or waveguide finite elements) [31], statistical energy analysis, etc.

In terms of bridge noise, single-box and twin box girder types produce an average of 2.4 and 4.2 dB(A) less noise than the U-shaped girder types, because displacements of the U-shaped bridge (discounting the track superstructure ones) are greater than those of the box girders [100].

DB has recently developed a guideline in order to mitigate noise generated on bridges [111]. The guideline is intended to define the noise protection level required for the construction, renewal and repair of railway bridges.

Mitigation measures

Various mitigation measures have been developed on the basis of the knowledge available with the general objective of reducing railway noise. Such measures include noise barriers, rail and wheel dampers (see Figure 4), acoustic shielding, absorptive matting, track dynamics control, etc. Information on such mitigation measures and the associated costs is outlined in a UIC study [32].

Numerical and experimental studies, such as those performed within the scope of the SILENCE EU-FP6-SUSTDEV [33] and QCITY EU-FP6-SUSTDEV [34] projects, have shown that rail dampers and wheel dampers can be expected to reduce noise at pass-by by around 3 dB and 2dB, respectively.

The results rely on the rail and the wheel vibration damping when using tuned mass-spring resonators. For the wheel, the most dominant vibration modes of the wheel are damped. However, when applied to the rail, the track decay rate is increased within some specific frequency bands.

Based on this principle of increasing the track decay rate, specific rail pads can be used for the track in order to reduce rolling noise. Using appropriate stiffness and damping, especially around the so-called pinned-pinned frequency, a noise reduction of more than 3 dB has been achieved in [103] compared to a regular rail pad.

A number of studies [35], [36] have been focused on the acoustic performance of low height barriers report insertion loss ranging from 3 to 7 dB, depending on the speed of the train. Low height barrier acoustic performance can also be improved using diffracting elements [101].

Low height barriers closer to the source may provide benefits such as reduced visual impact and improved passenger experience but can be difficult to use due to their impact on railway construction, operation, maintenance and safety.

In addition to the above-mentioned projects and studies, the UIC report, Rail Dampers, Acoustic Rail Grinding, Low Height Noise Barriers: A report on the state of the art, published in 2012 [37], is an important source of information on rail dampers and low height barriers.

In this context, the STARDAMP project [40] was initiated to facilitate practical application of R&D on wheel and rail dampers. A detailed study was carried out on wheel and rail dampers and included testing of methods for damper performance assessment based on standardised laboratory measurement and calculation techniques. Maintenance issues were also addressed in terms of life cycle cost (LCC).
The noise reduction predicted with the STARDAMP method has been shown to be underestimated in the case of slab tracks with soft fastening systems [104]. This was attributed to the fact that measured track decay rate can lead to an underprediction of rolling noise up to around 4 dB for slab tracks [105].

Measures implemented at the propagation path, such as general noise barriers, are well accepted and deployed. They are acoustically efficient in almost all cases, offering noise reduction of approximately 10 dB, and tend to meet people’s approval because they are perceived as effective on account of their visibility [38].

On the other hand, measures at source, such as rail or wheel dampers, can be difficult to deploy for the following reasons, among others:

- They offer less acoustic efficiency, and efficiency tends to vary [39]
- They have less visual impact
- Infrastructure and rolling stock managers may be reluctant to use them

Indeed, they represent additional components requiring specific maintenance.

Noise barriers affect noise on the propagation path. Rail and wheel dampers decrease vibration and, thus, acoustic energy in radiating structures. Another option for mitigation is to implement acoustic isolation at the destination, using double glazing, for example.

The pantograph and leading bogie are the two main sources of aerodynamic noise at high speed. In respect of high-speed trains, noise barriers less than 4m in height are insufficient in terms of impact on noise sources at the top of the vehicle, such as the pantograph and pantograph recess.

Various mitigation measures have been developed and are now in industrial use, particularly in Japan. Such measures include a low-noise pantograph [42]. Pantographs may be shielded (see Figure 5) and/or specifically designed to achieve noise reductions of 5-10 dB [43], [44].

A study on Aerodynamic Noise Reduction using Porous Material and their Application to High-Speed Pantograph [45] shows that porous covers (see Figure 6) can be an effective measure for reduction of aerodynamic noise from pantographs.
Aerodynamic noise can also be reduced by streamlining covers for the bogies, avoiding extruding parts or gaps along the train, as well as the front of the vehicle [96]. Recent generations of high-speed trains demonstrate improvements in this field, offering both reduced noise and lower energy consumption. Further streamlining is possible but is costly, particularly in terms of maintenance.

The most common and efficient measures for mitigating squeal consist of friction modifiers and vibration dampers for both wheels and rails, which reduce the friction coefficient and, thus, the amplitude of creep forces.

A number of designs have been tested in both laboratory and real on-track conditions by the UIC NNV experts, and the outcomes are summarised in the *Combating Curve Squeal - Phase 2* report [46]. Wheel dampers are particularly effective because they can be tuned and, therefore, can reduce wheel vibration.

The following measures may be considered for mitigation of bridge noise (see Figure 7):

- Track fastening optimisation in order to reduce rolling noise (rail dampers, appropriate rail fastening, etc.)
- Track optimisation in order to reduce the energy transmitted to the bridge structure (appropriate rail fastening, under ballast mats)
- Vibration absorption on the bridge structure (tuned absorbers)
- Acoustic shielding

These mitigation measures were tested as part of a case study conducted by SNCF on the Gavignot bridge in France [47].

Figure 6 – Porous coating of pantographs [45]

Figure 7 – Mitigation measures tested on the Gavignot bridge (France). Left: absorbers on bridge desk. Centre: low transmission baseplates. Right: acoustic screen
## Table of standards

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<td>EN ISO 3095:2013</td>
<td>Describes the procedure for pass-by noise measurement, including microphone location. Mandatory in TSI Noise.</td>
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<tr>
<td>Parking noise</td>
<td>EN ISO 3095:2013</td>
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<tr>
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<td>Parking noise</td>
<td>ACOUTRAIN D1.1</td>
<td>Clarification of the simplified method in the partial revision of the TSI. Not mandatory but referenced in TSI Noise.</td>
</tr>
</tbody>
</table>
Table 1: Standards (pending or published) and legislative documents related to noise source generation, rolling noise and aerodynamic noise

Open points in standards

Acoustic efficiency of innovative noise barriers

The acoustic efficiency of innovative noise barriers and low height noise barriers is not assessed within the context of European standardisation. A broadly accepted measurement protocol would enable various types of barrier to be compared in real conditions, thereby increasing competitiveness in the sector.

Noise monitoring

Noise monitoring is now being addressed in CEN Working Group 3 as working item WI00256879. The UIC HRMS (Harmonisation of rolling behaviour and noise measurement sites) project [48], which aims to develop a harmonised noise monitoring system to reduce noise disturbance for people living near main railway lines, has already produced a number of inputs. In the event that additional results are required by the CEN working group, a complementary study could be undertaken by the TTI Acoustics group.

Application of EN 15610 and EN 15461 in China

Application of EN 15610 and EN 15461 to the Chinese high-speed network gives rise to unusual track decay rates and rail roughness.

The question of the relevance of European standards to networks outside Europe needs to be addressed. Either China could adapt both EN standards, which would require extensive research, or the specific circumstances arising in China could be taken into account in the EN standards.

Brake block selection

Acceptance of braking blocks in accordance with acoustic criteria is an open point in the TSI Noise and in the context of standardisation. Under the European Commission mandate relating to the revision of the TSI Noise [49], a procedure for testing the acoustic performance of composite brake blocks shall be included in the TSI. The method described in [50] is expected to be referenced in the NOI TSI and may require further innovative test methods, to be developed by the railway sector, in order to reduce certification costs (e.g. replacing line tests with bench tests).
CURRENT RESEARCH PROJECTS

European level

The Shift2Rail FINE 1 (Future Improvement for Noise and Energy) project [52] is a European project funded under the Horizon 2020 programme. It began in 2016 with the objective of reducing railway operating costs by reducing rail traffic-related energy use and noise.

In particular, FINE 1 project activity shall support the innovation process by providing methodologies and know-how to enable development of low noise and low energy technical demonstrators. Modelling and characterisation of external noise sources are addressed in its Work Package 8: Sources and assemblies.

Noise separation techniques have also been developed and tested within the scope of the Roll2Rail lighthouse project [52]. Also worthy of mention is the DESTINATE project [53], particularly its WP3 - Development of methodologies, tools and technologies for noise prediction and mitigation and WP4 - Validation and integration of proposed solutions.

SNCF is updating the source terms for rolling stock in accordance with CNOSSOS-EU requirements in the context of strategic noise mapping. The aim of this project is to develop and validate a methodology in order to translate the source terms currently used in France into source terms compatible with CNOSSOS-EU requirements. Based on pass-by measurements and simulation results, this hybrid methodology will offer an alternative to the use of tabulated or outdated input values.

National level

In France, the SNCF MEEQUAL project is focused on on-board roughness and time-domain reflectometry (TDR) measurement using microphones placed close to wheels and axle box accelerometers [54]. This three-year project began in September 2017.

This methodology will be used to provide input data for strategic noise mapping in accordance with CNOSSOS. The results will also enable a general survey on roughness evolution on the French network in relation to track conditions (fastening, traffic, etc.).

Also in France, the acoustic performance of various rail grinding techniques was studied in a four-year research project involving SNCF and grinding companies [55], and an optimised grinding technique was developed. This has resulted in adaptation of grinding policy in France, taking into account the results of the aforementioned study.

The two-level acceptance criterion developed as part of the project considers the roughness spectrum after grinding in terms of (i) emergence of grinding peaks and (ii) global roughness level through the SNARRM indicator. The SNARRM (single number acoustic rail roughness metrics) indicator developed within the framework of the project represents the noise level increase at pass-by for a given case compared with a reference case based on the TSI roughness spectrum [56].

In Germany, the acoustic annoyance due to the presence of grinding marks has been investigated using listening tests based on simulated audio signals. As a result, a combination of several indicators associated with limit values has been proposed in order to appraise the acoustic quality of a grinding technique [106].
These indicators include a limit curve on the rail roughness spectrum as well as a limitation on the number and emergence of tonal components. A collaborative work undertaken between DB and SNCF has for objective to combine their own two approaches and converge towards a common indicator to assess the acoustic performance of a grinding technique.

In the UK, HS2 has been investigating a new experimental methodology for characterisation of high-speed rolling stock [23]. This methodology is aimed at achieving a more detailed acoustic characterisation of high-speed trains, without resorting to the use of sophisticated technologies with complicated post-processing (e.g. acoustic holography or beamforming).

The preliminary results show promise. With a relatively simple setup, it has been possible to achieve a level of noise source discrimination that had only been achieved previously using far more complex approaches. It is thought that with some further development, a consistent and repeatable characterisation methodology can be developed.

In China, tests are being carried out to assess roughness and TDR in relation to train and track type.

IDEAS FOR FUTURE RESEARCH PROGRAMMES

Rolling noise

Rolling noise for non-ballasted tracks

Due to a lack of data, rolling noise prediction for slab tracks is not sufficiently understood. Employed in only a few cases in the past, slab tracks are now widely used — in China, for example — and may therefore merit further research, taking acoustic reflection at the ground surface into account. Such research may, in turn, have an impact on prediction tools and experimental assessment [57].

Rail roughness

Rail roughness is a very important input data point for any railway noise and vibration assessment study. Up to now, roughness has been measured on an ad hoc basis, but long-term studies have not been carried out, apart from studies to assess the influence of rail dampers on roughness development and the influence of grinding techniques on roughness, for example. Though some of the projects undertaken in the past have attempted to quantify this issue, they have not given rise to consistent results. A statistical approach may therefore be prudent.

Using data from previous projects already collected by members, as well as large-scale data collection from on-board systems, the following points could be studied:

- Track characteristics (components, route)
- Traffic (speed, weight, rolling stock type)
- Grinding policy
- Mitigation measures
Wheel roughness

Although there is broad agreement that use of composite brake blocks results in less wheel roughness than use of cast-iron blocks, there are still no acceptance criteria for brake blocks that take noise into account.

Following the UIC NICOB (Noise impact of composite brake blocks) project [16], a second project proposal to work on noise acceptance of brake blocks (NABB) has been developed.

The objective is to develop a method to assess the acoustic performance of brake blocks prior to industrial deployment. The main difficulty lies in efficiently combining numerical models, laboratory tests and field tests in order to minimise effort and costs. If the project were to result in specifications for the manufacturing process, this would be very much welcomed by brake block suppliers. It would also be useful to take advantage of bench tests wherever possible in order to reduce manufacturing costs.

However, the main priority for most experts in this area is to develop a common position on the exchangeability and homologation of both K and LL brake blocks, with special attention to composite brake blocks. This is not only related to noise emission, but to a fragility phenomenon appearing when operating under winter conditions, which could lead to safety concerning issues.

Benchmarking reports on this type of brake could include questionnaires covering topics such as noise, collecting actual data from members and incorporating summaries in the report.

Curve squeal

Curve squeal monitoring involves complex numerical and mechanical formulations. This highly skilled work is generally carried out by research institutes. However, given the increasing prevalence of monitoring cars equipped with microphones and accelerometers, a general UIC member survey may be relevant at European level. The objective would be to statistically access the influence of track parameters on curve squeal using a large database of data recorded on board. Part of the project would involve developing this European database.

In addition to traditional methods of noise and vibration reduction, DB is conducting research into other innovative techniques that may become mainstream if they prove effective. At Grünstadt and Freinsheim stations in the German federal state of Rhineland-Palatinate, close to Mannheim, DB is testing three technologies designed to reduce wheel squeal through curves, including two rail lubrication systems from different manufacturers and a rail damper [62].

Aerodynamic noise

Numerical models and measurement methods for assessing aerodynamic noise are not typically used by railway operators. However, there is a need for better specification and validation (acceptance on commissioning) of rolling stock characteristics in relation to aerodynamic noise sources.

In this context, the choice of numerical and experimental tools should not be left to rolling stock manufacturers without being sure of their relevance. A quick and simple benchmarking exercise could be helpful to UIC members. Case studies could be proposed and various numerical tools tested and validated through specific measurements.
This proposal has been submitted to the UIC opt-in 2020 process as the AERONOISE project, with five key objectives:

- Produce a benchmark of the acoustic performance of the new generation of high-speed rolling stock. This includes a focus on the design of the relevant zones for aerodynamic noise, the mitigation measures available, and collection of existing data in order to provide further guidance on acoustic requirements reflecting the current state of the art.
- Identify current gaps in standards to more effectively evaluate rolling stock emissions at high speed and produce a benchmark of relevant measurement and analysis techniques to fill these gaps.
- Improve knowledge on the effectiveness of noise barriers for aerodynamic noise along high-speed lines.
- Produce a guidance note on cost-effective measurement and analysis techniques for categorising rolling stock emissions at high speed in order to address gaps in standards.
- Demonstrate measurements for characterising rolling stock emissions at high speed.

**Bridge noise**

UIC Code 717: *Recommendations for the design of bridges to satisfy track requirements and reduce noise emissions* could be updated in the form of a new IRS, taking account of the current state of the art and technologies developed over the past 25 years to reduce this particular type of noise production.

The updated document could include general information on noise generation and sources of noise, drawing from new research and WHO/EU directives, as well as information on radiation and measures to limit both generation and radiation of noise, taking into account the general principles and rules to be adopted, best practices and any precautions to be taken.

**Mitigation measures**

In addition to ordinary noise barriers, which are widely used, new and innovative barrier designs have been developed [58] and tested [59], including low-height noise barriers [60].

The EN 1793 series of standards provides a laboratory protocol for measurement of acoustic performance, though conceived for classical road noise barriers. EN 16272 and EN 16951 were developed by CEN/TC 256/SC 1/WG 40, also for classical barriers. Noise barriers must conform with the TSI Noise in terms of acoustic and mechanical performance [61].

A standardised method for measurement of low height noise barrier efficiency has yet to be developed. In addition, it is not yet clear how low height noise barriers are to be taken into account in simplified prediction models such as CNOSSOS.

Any such development in this area could draw from the example of Dutch infrastructure manager ProRail, which is also testing noise abatement innovations such as low height noise barriers as a means of protecting the two million residents who live within 300 metres of its network. According to ProRail, use of the 75 cm-high barriers has come a step closer following two successful trials in Hilversum and Susteren, in which noise was reduced by approximately 5dB in both cases [62].
Acoustic comfort, subjective perception and psychoacoustic indicators

INTRODUCTION

Railway noise is perceived both inside and outside trains, affecting people in different ways:

- Exterior noise is mostly perceived as a source of annoyance by those living in close proximity to railway lines.
- Interior noise is a source of annoyance for passengers, but may also be designed to encourage certain passenger behaviours.

Exterior noise

Though numerous academic studies have been carried out on the perception of road traffic noise, comparatively few have focused on the perception of exterior railway noise. It is clear, however, that human perception of railway noise is a complex phenomenon involving numerous sociological, physiological and physical aspects [63]. Indicators representing human perception may, in the future, become just as important as physical levels of noise at pass-by for specifications. Modelling and predicting perception is therefore a key issue.

One of the few available studies on perception of exterior railway noise shows that annoyance is closely correlated with loudness (as measured within the framework of ISO 532), and that loudness is a more important factor than the sound pressure level in dB(A) in terms of annoyance caused [64]. This tallies with the results obtained in respect of other sources of exterior noise (road transport and aircraft flyovers), although sound pressure level is still the indicator most commonly used to measure annoyance caused by transport noise.

In this context, high-speed trains represent a very specific subject in terms of time signature and frequency content. Complaints related to high-speed operations often refer to a sudden noise [107] that is more surprising and therefore disturbing, than the noise from slower operations at the same equivalent noise level [108]. The frequency content is also of great importance, because of the low-end spectrum resulting from aerodynamic contributions.

The recent Environmental Noise Guidelines for the European region published by the World Health Organization [109] highlighted the ambiguous relationship between the impact on health and annoyance, more related to human perception. Even if railway noise has been largely considered as less annoying than other transport modes, WHO recommendations in terms of noise exposure do not reflect this difference.

Interior noise

Though it is well known that railway tracks contribute to interior noise, the extent of the phenomenon is not well quantified. Exterior propagation has a significant impact on interior noise in the case of tunnels and walls close to the track (increase of interior noise from 7 dB to 10 dB [65], [66] and [67]).
Loudness is a major contributor to passenger annoyance in respect of interior noise. Rattling, squeaking, humming, hissing, buzzing, etc. are further elements that can cause annoyance. Such noise components are often characterised by the characteristic tonal properties (one or multiple frequency components) of these sources.

Annoyance due to tonal components may be predicted using various standardised indicators (prominence ratio, tone-to-noise ratio, DIN 45681 procedure, ISO 1996-2 annex C and annex D).

It is also important to note that intermittent events such as footsteps, conversation, and doors closing and opening are also a major source of annoyance for passengers, as they prevent them from sleeping, reading, etc. [68]. Perhaps counter-intuitively, increasing the overall noise level (by increasing air-conditioning flow, for example) may in fact increase acoustic comfort by reducing the impact of such intermittent events [69].

Railway companies have differing priorities with regard to noise. For example, in most EU countries, exterior noise is the key issue because large numbers of citizens are exposed to high noise levels. In China, however, high-speed lines are mainly in the countryside. The key issue in China is therefore interior noise.

NORMALISATION/STANDARDISATION CONTEXT

<table>
<thead>
<tr>
<th>Topic</th>
<th>Standards</th>
<th>Comments</th>
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| Interior noise             | ISO 3381:2005                    | Specifies the conditions for obtaining reproducible and comparable measurement results for noise levels and spectra inside all kinds of vehicles on rails or other types of fixed track, except for track maintenance vehicles in operation.  
Revision as ISO/DIS 3381 in progress (EN and ISO parallel enquiry launched in July 2019). |
| Cab noise                  | EN 15892:2011                    | Specifies a type test method to measure noise levels inside the driver’s cabs of railway vehicles for assessing compliance with the relevant European legislation. This method is applicable to measurement of noise inside the driver’s cab resulting in external warning horns sounding when the vehicle is stationary, and measurement of noise inside the driver’s cab while the vehicle is running. Mandatory in TSI Noise. |
Acoustic landscape

ISO 12913-1:2014
Provides a definition and a conceptual framework for the concept of a soundscape. Explains factors of relevance for measurement and reporting in soundscape studies, as well as for soundscape planning, design and management.

ISO/TS 12913-2:2018
Specifies requirements and supporting information on data collection and reporting for soundscape studies, investigations and applications.

Annoyance

ISO 1996-1:2016
Defines the basic quantities to be used for description of noise in community environments and describes basic assessment procedures. It also specifies methods to assess environmental noise and gives guidance on predicting the potential response from a community to long-term exposure from various types of environmental noise.

Describes how sound pressure levels can be determined by direct measurement, by extrapolation of measurement results by means of calculation, or exclusively by calculation, intended as a basis for assessing environmental noise. Recommendations are given regarding preferable conditions for measurement or calculation to be applied in cases where other regulations do not apply.

DIN 45681:2005
Determination of tonal components of noise and tone adjustment for assessment of noise emissions.

Table 2: Standards (pending or published) and legislative documents related to acoustic comfort, subjective perception and psychoacoustic indicators

Open points in standards

ISO 3381 is being revised to include all of the EN 15892:2011 [70] requirements. EN 15892:2011 will be cancelled at the end of the revision process.

CURRENT RESEARCH PROJECTS

European level

Within the framework of the European Shift2Rail project, interior noise is addressed in Work Package 7 (Interior Noise Modelling) of the FINE 1 (Future Improvement for Noise and Energy) project, which deals with cross-cutting activities.

The objective of this work package is to develop methodologies for efficient and accurate predictions of interior noise, including a modular framework to handle sources, transmission paths and results from existing simulation tools. The task leader is Bombardier and the contributors are CAF and TALGO. The subtasks are as follows:

- Review the state of the art for industrial noise prediction
Define a modular framework to handle sources, transmission paths and results from existing tools

Define validation schemes for structural and air-borne sound transmission

Evaluate pressure field around car body

Evaluate interior sound field

A visualisation and auralisation tool, largely based on work conducted by the Swiss Federal Laboratories for Materials Science and Technology (Empa), has been developed and delivered within the scope of the DESTINATE Shift2Rail open call project [71].

The tool allows experiencing railway noise scenarios in a virtual environment, supporting various presentation modes such as Virtual Reality headsets and audio-visual labs [112] and was presented at the most recent UIC noise workshop held in March 2019 at UIC headquarters in Paris.

This relies on a physics-based approach and a pure artificial creation of sounds. For rolling and impact noise, the radiated sound is individually generated based on physical parameters such as rail and wheel surface roughness, wheel diameter and running speed [113].

This novel concept allows demonstrating in an intuitive way the effects of noise mitigation measures at the sources (e.g. rail grinding, composite brake blocks, rail dampers, speed reduction) and at the propagation path (noise barrier, rail shields, cutting).

**National level**

In France, a recently published regulation has stressed the necessity to include short term indicators in noise impact studies together with limit values. To avoid any premature and damaging implementation of such indicators and because of the lack of dedicated studies on the subject, a large survey has been initiated by SNCF about these types of indicators. An analysis was carried out to verify their potential for application and their correlation with annoyance. Initial results show that measured short term indicators could present a large dispersion, even for trains of the same type [110].

The various analysis tools used to predict annoyance due to tonal components have been compared by SNCF. Worthy of particular note are two projects on rattle noise modelling [72], and [73].

The French Scientific and Technical Centre for Building (CSTB) has developed an auralisation tool called MithraSON for urban soundscapes. This tool includes audio synthesis for all types of road vehicles, as well as trams.

A PhD project began in 2016 as a collaboration between SNCF, CSTB and Gipsa-Lab (Grenoble image, speech, signal and automation laboratory) with the objective of auralising railway noise sources. This is achieved by using physical synthesis for rolling noise and granular synthesis for equipment noise [74].

Studies by CARS on aerodynamic noise phenomena in China are focused mainly on the propagation path from exterior to interior noise [93].

In South Korea, a number of studies have been carried out on the relationship between railway noise and community annoyance [75].

The intelligibility of audio announcements used in public address systems has been also studied in Japan ([76], [77]).
IDEAS FOR FUTURE RESEARCH PROGRAMMES

Exterior noise

Annoyance due to multi-exposure

People are exposed to noise not only from railways but also from ground-borne vibration. Exposure to noise from multiple sources adds additional complexity to the issue. It may be useful to conduct a dedicated research project examining the multisensory aspect of annoyance as a basis for future standards.

Low frequency noise annoyance

There is a lack of knowledge in the domain of low frequency noise annoyance. Low frequency noise relates to noise at frequencies of less than 100 Hz. It may be useful to develop a specific indicator in this regard. A project proposal on this topic was submitted to the UIC opt-in process 2019 under the name “LOWFREQS”, but has not yet been approved. The objectives of the proposed project are as follows:

- Identification of existing indicators associated with annoyance resulting from low frequency noise
- Analysis of the frequency content of exposition situations potentially impacted by low frequencies
- Application of the identified indicator(s) to actual measurements to quantify levels of annoyance.

Short-term noise indicators

Some instances of noise exposure raise complaints due to the annoyance they create, despite being compliant with the applicable legislation. It is likely that short term indicators, such as \(L_{A_{\text{max}}}\) or \(L_{eq,Tp}\) will ultimately be used in European legislation, as is already the case in the Nordic countries [78].

Interior noise

Track contribution to interior noise

It seems that there is no clear link between interior noise and acoustic radiation from track components. The UIC Track Experts Group may be able to provide information on this issue. The approach taken in China to the use of transfer path analysis (TPA) for aerodynamic sources [80] could also be applied to the issue of noise emanating from tracks.

Interior comfort specifications for rolling stock

It may be useful to develop an indicator to specify interior acoustic comfort levels for rolling stock. This topic is not addressed in Shift2Rail FINE 1 WP7 [51].
Ground-borne vibration

INTRODUCTION

In November 2017, the UIC NNV published the Railway Induced Vibration – State of the art report [80], which has been used as the basis for this chapter.

Railway-induced vibration

In addition to noise coming directly from tracks, residents living close to railway lines are also exposed to vibration-related phenomena.

Railway-induced vibration is generated at the wheel-rail interface due to the interaction between the vehicle and the track, resulting in rolling noise.

According to the UIC NNV report, the main sources of vibration are:

- Quasi-static excitation due to loads moving along the track
- Dynamic excitation due to vertical defects on running surfaces (variation of track elasticity, track and/or wheel surface unevenness, rail corrugation and track singularity)

Ground-borne vibration can reach building foundations close to the track. This phenomenon is illustrated in Figure 8.

![Figure 8 – Exposure to railway-induced noise and vibration (example of a surface line)](image)

Vibration caused by vehicle-track interaction travels through the ground at varying speeds depending on the ground type; propagation is slower in softer soil. If the train speed exceeds the ground vibration propagation speed, this creates a ground-borne vibration “boom”, analogous to a sonic boom created when aircraft break through the sound barrier.

In practice, this means that there is a threshold train speed above which ground vibration increases sharply. In the case of peat and clay soil, this critical speed may be as low as 150 km/h. Bogie spacing and axle spacing also influence the critical speed [82].

In addition to track and/or wheel surface unevenness, which is the most significant source of dynamic excitation, vehicle on-track resonance frequency also plays an important role in vibration generation.
Vibration levels will depend largely on the track stiffness and soil properties. The track behaves as a natural low-pass filter with regard to ground vibration.

Railway-induced vibration can be modelled using a large variety of numerical models based on various hypotheses, each with specific advantages and drawbacks:

- **Finite element models (FEM)** allow simulation in the time domain with complex geometries. They consider transient phenomena, such as local defects, but are limited in terms of size and frequency. They are mostly adapted to focus on quasi-static excitation below a few dozen hertz or, rarely, up to 100 Hz. FEMs are typically used to model the track, while propagation in layered soil is modelled using boundary elements (BEM) [83].

- **Mass-spring semi-analytical models** can be used for preliminary calculations as they are easy to use and deliver results quickly [84]. They are applied mainly in the frequency domain and rely on longitudinal invariance in terms of track design. They are useful for absolute predictions only to a very limited extent but can provide reasonable estimations for comparative studies.

- **Using the same hypothesis of invariant track properties, 2.5D models** yield even more accurate results with almost the same computational efficiency. A model developed at KU Leuven uses a 2D FE model for the track coupled, with BEM (boundary elements method) for the ground [85]. The vibration velocity at the surface of the ground is estimated using a Fourier transform in the space domain.

- In some cases, the problem can be split into two or more parts and different models can be used for each phenomenon: the first estimating the force transmitted from the track to the ground, and the second measuring propagation in the ground or building vibration, for example. The complexity of the model can thus be adapted to the different stages of the process.

In the case of tunnels, other approaches are used in order to account for the interaction between the tunnel walls and the surrounding soil [87].

**Mitigation measures**

The principles for mitigation of vibration are similar to those for noise mitigation. They can be applied at source (vehicle and track), at the propagation path or at the destination.

Mitigation at source consists mainly of reducing dynamic excitation by means of running surface maintenance. The measures applied may include wheel re-profiling, rail grinding or track tamping.

Another excitation phenomenon that can be mitigated at source is quasi-static excitation when the train speed exceeds the ground wave speed. Train speed can be reduced, but this is not desirable. Alternatively, injections can be administered to stiffen the soil, resulting in an increase in ground wave speed.

One of the most common mitigation measures for ground vibration is to add resilience to the track. This can be achieved in various parts of the track by using specific components:

- Soft rail pads or soft fastening systems
- Embedded rail
- Under sleeper pads (USP)
- Under ballast mats (UBM)
- Floating slabs (for slab track)
- Column stabilisation and piling walls
On the propagation path, trenches and walls can block propagation of vibration waves, acting in a similar way to noise barriers. The trenches may be filled with concrete or other materials, built as sheet piling walls (see Figure 9), or constructed using jet grouting techniques as outlined in the EU RIVAS project [88].

Building vibration isolation is a highly effective mitigation measure that can be applied at the destination. It can mitigate against very low frequencies, but must be taken into consideration during building design.

Accurate input data must be used for models in order to predict exposure to ground vibration and to design potential mitigation measures, particularly in respect of the mechanical properties of track components and soil.

For the track components, a mathematically complex determination of stiffness, (where the real part corresponds to stiffness and the imaginary part refers to damping), is generally required for most of the models. This is also the case for rolling noise as the track’s elastic properties determine its decay rate, which is linked to the acoustic energy radiated by the track.

For rail pads, under sleeper pads and under ballast mats, for example, different stiffness values can be applied on the basis of the measurement procedures outlined in EN 13146 for static stiffness and low frequency dynamic stiffness. These values correspond to the behaviour of the elastic components under the static load of the train or under a moving load, respectively. They are obtained using low-frequency variable excitations (up to 20 Hz) at high amplitude (up to 68 kN).

For safety reasons, these measurements are necessary for product certification in terms of track deflection. They are not representative of the dynamic excitation responsible for noise and vibration, which occur at lower amplitude and higher frequencies.

Elastic material is known to stiffen with increasing frequency and preload. However, if the values obtained for static or low frequency dynamic stiffness are used as input to model noise or vibration, they will result in inaccurate predictions.

It is therefore important that manufacturers and laboratories be provided with a measurement protocol for acoustic stiffness. This is now addressed in an annex to EN 13146 (see Table 3).
## Table of standards

<table>
<thead>
<tr>
<th>Topic</th>
<th>Standards</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>USP</td>
<td>EN 13230-5:2016</td>
<td>Railway applications. Track. Concrete sleepers and bearers. Special elements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Defines the specific requirements relating to special elements, such as special sleepers, special bearers and reinforced concrete special elements. These are generally used in specific areas of the track in the case of ballastless tracks, bridges or with check rails, for instance. The document defines additional technical criteria and control procedures related to manufacturing and testing special elements.</td>
</tr>
<tr>
<td>USP</td>
<td>EN 16730:2016</td>
<td>Railway applications. Track. Concrete sleepers and bearers with under sleeper pads</td>
</tr>
<tr>
<td></td>
<td></td>
<td>This standard applies to systems comprising concrete sleepers or bearers and under sleeper pads in ballasted track and defines the relevant test procedures and evaluation criteria.</td>
</tr>
<tr>
<td>USP</td>
<td>IRS 70713-1</td>
<td>Railway Application - Track &amp; Structure “Under Sleeper Pads (USP) - Recommendations for Use”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contains recommendations for use of under sleeper pads in ballasted tracks with concrete sleepers. Provides recommendations for use and requirements for qualification and quality control procedures. Contains information on technical and economic findings based on recent experience. Also includes information on noise and vibration, as well as the interaction between under sleeper pads and other elastic components in the track superstructure, such as soft rail pads and under ballast mats (UBM).</td>
</tr>
</tbody>
</table>
Open points in standards

High-frequency dynamic stiffness

EN 13146-9:2009+A1:2011 outlines a methodology for the measurement of high-frequency dynamic stiffness in rail pads and fastening systems. High-frequency dynamic stiffness is measured up to 400 Hz, using dynamic excitation forces at low amplitude centred around a static preload value of high amplitude, (chosen between 10-70 kN) representing the wheel dynamic load.

In this context, stiffness is likely to be representative of fastening system behaviour regarding noise and vibration issues. A specific measurement apparatus, which cannot be used for the other measurements described in the standard, is required. High-frequency dynamic stiffness is therefore be dealt with in a dedicated standard. Relevant information will be included in an appendix to the next revision of EN 13146-9:2009+A1:2011 and will be removed from the document when a dedicated standard is published (work item WI00256880, see Table 3).

The procedure for measurement of high frequency dynamic stiffness is described in EN 16730:2016 for under sleeper pads and under ballast mats. The static and dynamic input force can be applied to the test sample in two different ways: using a flat plate, whereby each point is in contact with the sample, and using a geometrical ballast plate (see Figure 10), simulating the contact between the ballast and the pads [89].

The results from the flat plate and the ballast plate will obviously differ; the question is to determine which is better suited to each application.

![Figure 10 – Geometrical ballast plate for measurement of UBM and USP stiffness](image)
Increased vibration following noise barrier installation

Complaints in relation to increased vibration are likely to increase following installation of noise barriers or large-scale facade insulation (soundproof windows). There is no physical reason that explains this phenomenon.

CURRENT RESEARCH PROJECTS

European level

The European Commission has developed a common methodology for strategy noise mapping, called “CNOSSOS”, for its member states. Applying the same principles, a common prediction model for ground-borne vibration could be developed within the context of the EU S2R-OC-CCA-01-2019 Noise & Vibration 2019 call for projects.

The Unified calculation model for railway induced vibration — Opportunities for development project, managed by the Netherlands National Institute for Public Health and the Environment (RIVM) [90], is of particular note here.

National level

The SNCF track laboratory is currently investigating the feasibility of performing acoustic stiffness measurements using a single hydraulic jack capable of delivering controlled excitation up to 250 Hz. The proposed methodology for under ballast mats and under sleeper pads consists of reducing the number of measurements taken by estimating stiffness evolution with respect to preload and frequency.

Rail pads are stiffer than USP and UBM and their stiffness is less dependent on frequency. Instead of measuring each frequency, alternative methods can be proposed using a single frequency measurement per preload [91] if the frequency is sufficiently representative of the component (i.e. for rather stiff pads).

Under sleeper pads are one of the few measures available to mitigate ground-borne and structure-borne noise. Noise has been shown to increase following installation of under sleeper pads, notably in the context of projects run by SBB (Switzerland). The situation should be addressed — not only in Switzerland, but also in other countries — in order to ascertain which types of USP are potentially responsible and how the issue can be avoided. DB is also conducting research in this area.

IDEAS FOR FUTURE RESEARCH PROGRAMMES

High-frequency dynamic stiffness measurement in the context of ground-borne vibration

In light of the results obtained from the SNCF research project, it would be interesting to quantify the influence of high-frequency dynamic stiffness in studies on ground-borne vibration. Research in this area could help to ascertain the consequences in terms of ground-borne vibration of using low-frequency rather than high-frequency stiffness.
The question remains as to which type of load transmission plate (flat or geometrical ballast) most accurately represents the actual loads expected on track. Potential projects to examine this issue may be based on SNCF database information, using in situ measurements and numerical simulation to assess the geometrical ballast plate compared to the flat plate in relation to actual excitation on track.

**Increased vibration following noise barrier installation**

It would be useful to begin research to better understand vibration emissions before and after installation of noise protection measures by conducting a survey of people living close to railways and by developing a project to calculate levels of vibration following noise barrier installation.

**Increased noise following installation of under sleeper pads**

There is scope for further campaigns to measure noise emissions before and after USP installation. Theoretical calculations to examine how noise is generated in this context would help to better understand this issue. The material used to manufacture the USP (rubber, polyurethane, etc.) should be taken into account when developing specifications.

**Knowledge database for collection of data and measurements**

The various railways and IMs have collected the results of research and measurements over time. Collecting all of this data in a common database and making it available to the partners involved would be a valuable initiative.

Some railways have internal and/or national databases or document sharing systems (e.g. SBB, ProRail database of mitigation measures, etc.), but such systems are not interlinked.

Any initiatives in this area could be expanded to include the development of guidelines to be used by IMs and RUs, encouraging the use of solutions that already exist in the industry where possible.
CONCLUSION

Experts in acoustics from the UIC TTI Sector drafted this White Paper with the objective of highlighting various technical issues, having reviewed cooperative research projects within UIC and the EU and projects funded at national level, as well as cost-benefit analyses, academic research, etc. Exterior noise, interior noise and ground vibration have been addressed in terms of the state of the art, current studies and open points in standards.

The state of the art in relation to exterior noise sources shows that the physical phenomena that determine railway noise are well understood. Modelling tools and measurement techniques have contributed to the development of a very strong framework in relation to this topic, both in terms of the standardisation and legislative context and the numerous and efficient mitigation measures that have been developed.

Noise at pass-by has been reduced by more than 10 dB overall since noise emerged as a major issue for the railways. The ideas for future projects outlined in this White Paper relate to very specific topics that present challenges from a modelling point of view, such as roughness generation and growth or squeal noise, for example. A number of more classical topics have also been identified requiring new data so that the relevant standards can be updated. Such topics include low-height noise barriers and slab tracks, for example.

Despite the noise reduction achieved over the past few years, complaints in relation to noise have continued to increase. This would suggest that railway noise is no longer considered simply in terms of decibel levels, but rather as a specific stimulus perceived by others. While extensive, relatively straightforward physical measurements have been developed in this area, there is a general lack of metrics for assessment of human perception. As highlighted in this White Paper, some indicators exist but are not currently in widespread use. The authors propose that projects be developed to define specific indicators in this area, as well as in relation to interior noise, which is also related to perception.

Railway-induced ground vibration does not have the same broad technical background as noise. The main reason for this is that the applicable national regulations are only just beginning to take ground vibration into account. Thus, efforts to understand and mitigate them have not been deemed a priority in comparison to noise, for example. However, based on the scientific progress made in relation to the various aspects of the issue (structure and soil mechanics, numerical modelling, train track interaction, etc.), high levels of technical and practical knowledge have been amassed in relation to this type of vibration in a short space of time.

Numerous mitigation measures have been developed that have not been deployed on tracks. As with noise, ground vibration is currently being addressed at national level in terms of legislation and modelling. Despite a number of collaborative projects such as RIVAS and CARGOVIBES [92], which have produced quality results in recent years, a shared vision for modelling and standardisation at European level remains a key challenge. The ideas for future research proposed in this White Paper go in this direction.

A number of proposals for projects, such as AERONOISE and LOWFREQS, have already been prepared and submitted to the UIC opt-in process on the basis of the work delivered by the UIC TTI Sector’s acoustics experts and presented in this White Paper. However, the ideas presented here could potentially be developed not only by the UIC TTI Sector or the NNV but also by other UIC sectors or departments, and may be incorporated in other projects, such as those conducted for the purpose of standardisation within CEN/ISO or other international cooperative framework projects such as H2020 or S2R.
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