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Report on a noise emission monitoring solution for steel railway bridges

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Name	Beneficiary Short Name	Details of contribution
Jenny Boehm	TUB	Description of bridge sound generation process, noise emission measurement system, processing of acoustic measurements. Contribution to other parts of the document.
Christoph Gramowski	S&V	Considerations and method application to noise damper development. Contribution to other parts of the document.
Marian Ralbovsky	AIT	Description of vibration measurement system and processing of vibration measurements. Contribution to other parts of the document.
Luca Rizzetto	DICEA	Defining objective and aim of this document.
Rok Rudolf	ZAG	Document structure, introduction, scope and conclusion. Contribution to other parts of the document.

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1. Executive Summary

Steel railway bridges represent a significant noise source, especially at low frequency ranges, producing a "thundering noise" sensation to nearby listeners. Steel bridges tend to vibrate at those ranges, producing large noise emissions that are difficult to reduce with conventional noise control measures like noise barriers. Due to long life-span of steel railway bridges - typically over 100 years- this problem will not go away any time soon.

To tackle this problem, we must first devise a noise monitoring system specifically for railway bridges. Since a large part of noise comes from vibrating bridge structure, a monitoring system needs to include vibration as well as airborne noise monitoring sub-systems. To make this system easy to use in practical settings, it is important that it causes the least possible interference with regular rail traffic over the measured bridge. Thus, a contactless system measuring both noise and vibrations of the bridge is proposed.

This report provides a description of such a system, utilizing both a microphone based and a laser-Doppler vibrometry solution to measure airborne noise and vibration characteristics of steel railway bridges respectively. The presented setup and the suggested approach represent a complete solution for the measurement and monitoring of bridge noise emissions, developed specifically to provide a basis for noise control using dampers that reduce bridge vibrations.

2. Abbreviations and acronyms

Abbreviation / Acronyms	Description
NEM	Noise Emission Monitoring
SVM	Structural Vibration Monitoring
LDV	Laser-Doppler Vibrometry
BPB	Bridge Pass-By, associated with bridge pass-by time, the time it takes from when the first part of the rolling stock enters the bridge until last part of the rolling stock leaves it.

3. Background

The present document constitutes the Deliverable D1.2 "Report on a noise emission monitoring solution for steel railway bridges". It was prepared in the framework of task 1.2 of the Technical Demonstrator 3.5 (TD 3.5), defined in Shift2Rain Master plan Innovation Programme 3 (IP3) in line with Multi-Annual Action Plan (MAAP).
It contributes as well to task 4.2 of TD 3.5, of IP3.

4. Objective/Aim

This document has been prepared to provide a description of a noise emissions and vibration monitoring solution for steel railway bridges.

The aim is to provide a stable and robust noise monitoring platform that could be utilized on a variety of bridge setups of acoustic interest, to provide a comprehensive description of noise emissions due to traffic over it, and thus obtain all necessary data for development, implementation and quality assessment of noise reduction measures – specifically, noise dampers. The selected noise monitoring solution is contactless and operationally oriented towards frequency ranges of particular interest.

The solution is a monitoring protocol that uses two different monitoring subsystems, one for air-borne noise emission and the other for vibration monitoring, that can be employed when investigating bridge and crossing trains noise emissions. The solution is able to identify emitted noise energies at different frequencies, to separate contribution of noise specific to the bridge from other train noise, as well as provide insight into bridge noise breakdown by different emitting sources - different bridge elements.

The monitoring system will be tested on two steel railway bridges and further demonstrated on one such bridge within WP5. Design of the final measurement system will be updated at the end of this project (M24), derived by selecting data streams that prove to be most effective in noise analysis. The system will be developed in close coordination with the development of noise dampers carried out within WP4, to ensure full compatibility.

5. Noise emission monitoring solution for steel railway bridges

5.1 Introduction

Steel railway bridges represent a significant and distinctive noise source. This document describes a combination of test methods that can be used to comprehensively characterize noise emissions intrinsic to steel railway bridges, providing a specialized noise monitoring solution for them.

To this aim, the solution utilizes airborne noise measurements near a bridge and at a reference point away from the bridge, using the comparison to distinguish the bridge structure specific noise from the railway track noise where no bridge is present. Additionally, the method prescribes vibration measurements on bridge structure itself, to identify parts of the bridge with high noise emissions and their respective noise spectrum.

Results from these measurements can be used along with results from airborne noise measurements to ease the selection of specific structures suitable to noise control measures – specifically noise dampers, as well as to give information to noise damper developers on what kind of dampers are required as part of a tuning process. The solution is developed with this application in mind. Furthermore, the methods used are selected to be applied in ways to make the monitoring solution least disruptive to regular rail traffic over bridges under testing.

During development of this monitoring solution, a number of measuring technologies have been considered, both for airborne noise as well as for vibration parts of the system. Noise measuring microphone arrays, near-field aerodynamic microphones, induction-based vibration measurement systems as well as conventional accelerometers have all been considered for their application from a variety of angles. Additionally, we collaborated with a complementary S2R project (In2Track2), to harness the expertise and previous research results obtained there.

The two methods selected at the end of this process are:

- a microphone-based method altered from a standardized constant speed test method in EN 3095 for airborne noise [1], as applied by In2Track2 partner DB Systemtechnik [2][3],
- a contactless measuring method using Laser-Doppler vibrometer for bridge structure vibrations.

As the noise emitted can depend on many other factors (rolling stock design, operating conditions, track type and condition etc.), this document also describes the measures that can be used to minimize or account for these influences including statistical analysis over different train types and speeds and rail roughness measurements. The document also gives guidance on how to apply these additional measures to provide an emission monitoring solution for steel railway bridges.

5.2 Scope

Steel railway bridges represent a distinct noise source and methods described are a specific monitoring solution for this source.

The results obtained by this monitoring solution can be used to:

- determine the intrinsic characteristic of airborne noise emitted by a steel bridge,
- determine the specific parts of bridge structure that emit noise and their respective vibration spectra,
- provide a noise-based comparison tool for steel railway bridges,
- provide the basic information needed to design and tune noise dampers for specific bridge,
- verify the performance of noise reducing devices installed on steel railway bridges, focusing on noise dampers but could also apply to other devices (resilient rail fastenings, under sleeper mats, under ballast mats, noise barriers…) .

This monitoring solution was developed with steel railway bridges in mind and is to be tested and validated on such during this project. The reason for this is simply because steel bridges tend to produce more airborne noise then other bridge types. While it is probable that this monitoring solution, in whole or in parts, can be applied to other types of railway bridges, testing on non-steel bridges is outside the scope of this project.

5.3 Sound generation process of a steel railway bridge

This section gives a short overview of the sound generation process when a train passes a steel railway bridge. The aim is to point out aspects that need to be considered when conducting bridge measurements and implementing noise control measures (bridge dampers). The terminology chosen for this report follows the terminology proposed by Thompson, D.J. in "Railway Noise and Vibration" [4]. Figure 1 shows a model of the sound generation process when a train passes a bridge. It can be seen, that the total sound consists of two components named bridge noise and train noise.

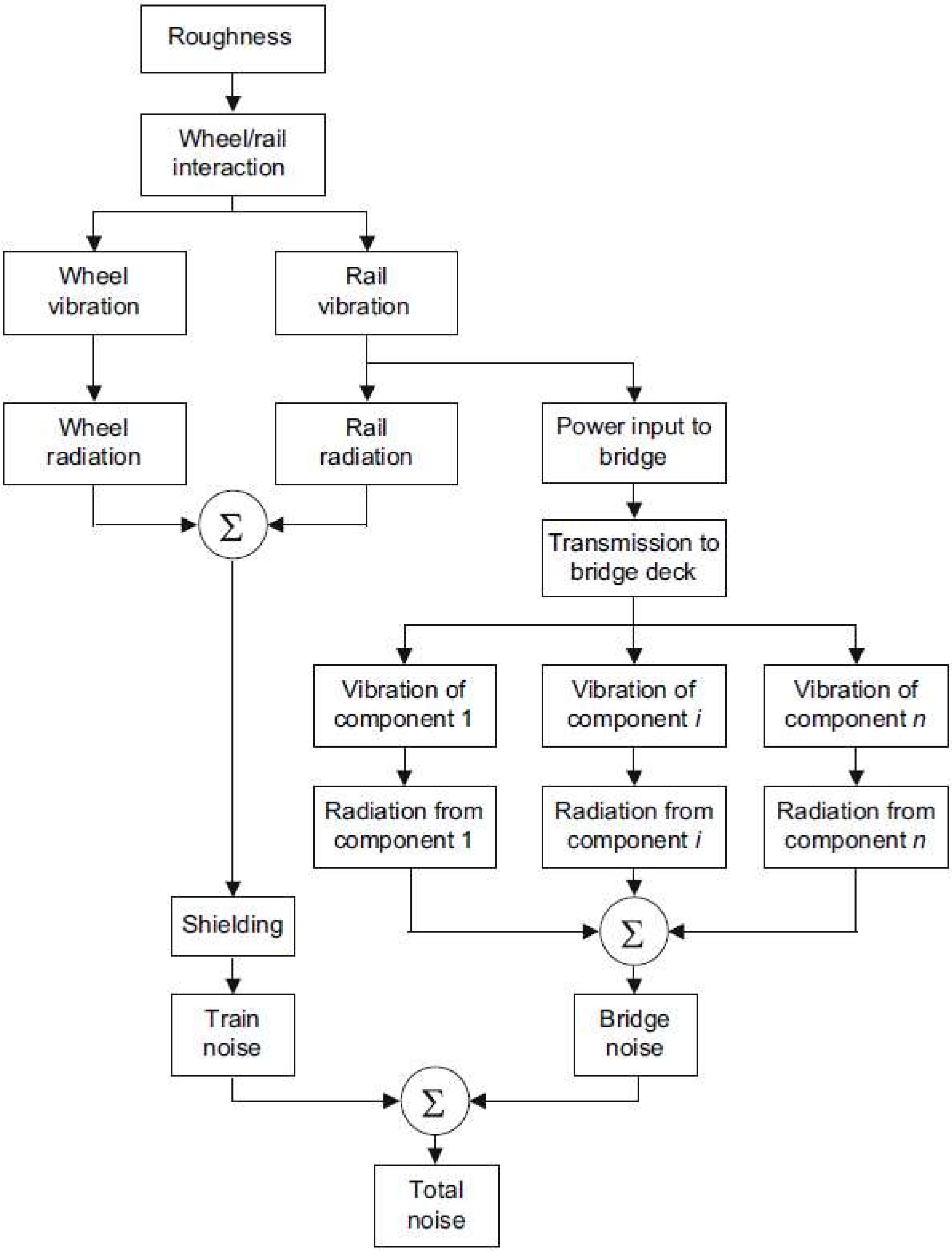

Figure 1: Model of the sound generation process when a train passes a bridge. Picture taken from Thompson [4].

Train noise is the sound generated by the wheel/rail interaction and radiated by the track (mainly rail, but also sleeper) and the train (mainly wheel). This train noise model is similar to the rolling noise model in [4] for a train passing a straight, plain track. The main excitation is caused by the combined roughness of wheel and rail - the higher the roughness amplitude, the higher the excitation. The excited frequencies depend on roughness wavelength and train speed. The roughness excitation causes the wheel and rail to vibrate. The vibration amplitude depends on the roughness amplitude but also on the frequency dependent, passive dynamic properties of wheel and rail (e.g. mobilities - ratio of vibration amplitude and exciting force). The vibrating structures radiate airborne sound that can be perceived as noise when it reaches a receiving person. In the low to mid frequency range, the rail is usually the dominant sound source and in the higher frequency range it is the wheel. On a bridge, the train noise may be shielded by bridge parts or

noise barriers on the bridge, which would lead to a decrease of this sound component in comparison to a straight, plain track. Shielding is more efficient for higher frequencies. On the other hand, the train noise can be increased on a bridge because the rail is often less damped (lower track decay rate) and emits more sound. This would lead to an increase in train noise in the low to mid frequency range compared to a straight, plain track.
Train noise may also be increased at non-ballasted bridges due to the missing air borne sound absorption of the ballast bed. In this case, application of absorbing material at the track may be useful.

Bridge noise is the sound radiated by the bridge structure. It has the same source of excitation (wheel/rail interaction). In addition to the combined roughness, the parametric excitation of varying track stiffness (sleeper passing frequency) and the resonance of wheel mass and track stiffness are important excitation mechanisms. The vibrating rail transmits power to the bridge structure. The structure-borne sound propagates and causes the different bridge components to vibrate. It is radiated by the bridge as airborne sound. Because bridge components have larger dimensions than the wheel and rail, the bridge noise often dominates at low frequencies. This can cause a very annoying sensation termed “bridge thundering” (German: “Brückendröhnen”).

Beside the above-mentioned constructive parameters, the total noise is dependent on train speed and train type. It is important to keep this in mind when it comes to characterising the bridge.

Other noise sources can also become important at bridge passing events. At low speeds traction noise is often dominant and at high speeds aerodynamic noise. There is also impact noise caused by rail joints, switches etc. and noise associated with curve negotiation. It is obvious that bridge dampers can only reduce the bridge noise. In cases where traction noise, aerodynamic noise or train noise are dominant, bridge damping will show no effect on overall noise levels. This is especially important as the increase in the total noise may also be caused by an increased rail vibration and radiation. In this case, it would be more efficient to apply rail dampers.

Since bridge structures like trusses or girders typically emit low-frequency noise, total noise spectrum from all above-mentioned sources tends to show more low-frequency noise at steel railway bridges when compared with noise of plain track.

5.4 Terms and definitions

Thundering peak frequency (f_P [Hz]) – frequency of a localized peak in a noise spectrum that typically occurs at 50~200Hz on steel railway bridges (depending on bridge characteristics) and causes thundering noise sensation to nearby listeners, that can cause an annoying sensation (German: “Brückendröhnen”).

5.5 Instrumentation and calibration

Noise emission measuring (NEM) system – Minimum of two to four class 1 microphones (in accordance with IEC 61672-1 [5]) with free field characteristics and adequate windscreen. Multichannel data acquisition system, with anti-aliasing filter and sufficiently high sample rate to capture the highest relevant frequency. Class 1 sound calibrator (in accordance with IEC 60942 [6]). Calibration of the measurement chain for each microphone before the start and after the end of the measurements. The difference shall not exceed 0.5 dB.

Cable or other signal transfer means to allow for at least one or two microphones to be mounted at least 100 m away from bridge for designated reference point measurements. At this distance the contribution of bridge noise should be negligible compared to other rail noise.

Structural vibration measuring (SVM) system - Laser-Doppler vibrometer, allowing for contactless vibration measurement on a fixed point of the bridge structure in 5~100 m range with sample rate at least 5 kHz, equipped with hardware or software signal analyser capable of obtaining vibration spectrum. Additional vibration sensor/device, recording structural vibrations at a fixed reference point, using either additional contactless (Laser-Doppler vibrometer) or mounted measurement device (accelerometer fixed via magnet).

A system to measure train speed between starting and ending points of bridge span and at reference point e.g. photocell system with reflecting surfaces using two beams interrupted by rolling stock or GPS based system with accuracy allowing for a maximum 3% error.

Other parameters

Train type (high-speed, regional, freight, etc.) shall be documented.

Meteorological conditions shall be recorded at representative times during the measurements: temperature, humidity, barometric pressure, wind speed and direction at the level of the highest microphone. Any precipitation needs to be documented.

Rail roughness measuring system in accordance with EN 15610 [7]. System shall be capable of measuring the wavelengths specified in ISO 3095 [1]: for train speeds up to 190 km/h 0,003 m to 0,10 m and for higher speeds to 0,25 m.

5.6 Test procedure

Measurements are carried out during a rolling stock crossing of the tested bridge at constant speed. Two sets of measurement results are recorded simultaneously, one for airborne noise and another for bridge structure vibrations. First set is obtained with a NEM (see 5.6.1) and second with a SVM system (see 5.6.2). Additionally, airborne noise measurement results are also obtained at a reference point away from the bridge, for the purpose of comparing bridge noise with train noise using the same rolling stock. The analysis should be done in third-octave band spectra to keep the spectral information. Frequency Linear (Z) weighting and Fast (F) time weighting ($L_{ZF,\dots}$) should be applied unless otherwise stated. Typically, sound levels are calculated using A-weighting. However, this reduces the low-frequency content typical for bridge noise. Therefore, comparison of A-weighted single-value (frequency averaged) levels of bridge noise and train reference noise is less meaningful.

The main objective is to provide acoustic characterisation of the bridge: the increase in total noise of a train pass-by compared to a straight plain track. As was pointed out earlier the total noise is dependent on train speed, train type, wheel and rail roughness. These parameters must be comparable, or they must be accounted for in post-processing.

In the preparation stage, large parts of the tested bridge structure, which are judged to vibrate and represent the biggest contribution to noise emitted in the 50~200Hz frequency range, are identified – typically steel girders or trusses. These parts are designated as "measured parts" and are typically also the main candidates for noise control application of noise dampers. The main objective of performing vibration measurements on these structural members is to generate input data for bridge damper development: bridge dampers reduce the vibration amplitude of bridge resonances and need to be tuned to the resonance frequencies that dominate sound radiation. The location of the dampers needs to be adapted to the mode shape.

If the NEM/SVM also has to cover bridge damper issues, further measurements at the potential damper locations are necessary. Measurement parameter is (by today's state of knowledge) the mechanical impedance in the frequency range up to 500 Hz. This measurement is executed with an acceleration sensor (see above) and an instrumented impact hammer. No adjustments at the bridge structure are necessary. Usually, the main challenge is to reach the bridge locations by a cherry picker etc. to apply the impacts at the plates. If several plates at e. g. the longitudinal girder are equal (same size, same thickness), it is not necessary to analyse all plates, see also chapter 5.6.2. The reason is the very similar excitation along the bridge length.

5.6.1 Noise emission measurement

Measurement of the radiated airborne sound is necessary, because it is difficult to predict the radiated sound from only vibration measurements and because it will usually not be possible to measure the vibration of all bridge components. The noise emission measurement has three objectives: First to characterise the bridge acoustically, second to assess the performance of noise reduction measures at the bridge and third to generate input data for bridge damper development. The method described below focuses mainly on objectives one and two. The measurement results can easily be used for bridge damper development if narrowband spectra are calculated by Fourier Transformation of the recorded time signal.

The method proposed in this document is the result of research and discussions within Assets4Rail and with the complementary project In2Track2. In2Track2 partner Deutsche Bahn proposed a method to assess bridge noise reduction measures as a result of a previous German national research project. The method proposed in this document is based on the method proposed by DB and will be further tested and evaluated in the upcoming measurements in Assets4Rail.

Environmental conditions

The environmental conditions listed below are based on the requirements in ISO 3095 [1] chapter 6 "constant speed test". Free sound propagation conditions shall exist in the triangular area between the microphone and the track with a length of twice the microphone distance to either side. Therefore, no sound absorbing materials shall be in the propagation path like snow, tall vegetation or persons and the ground shall not be reflective (no concrete, water, ice). No large reflective objects like noise or other barriers, hills, rocks or buildings shall be within a radius of at least three times the measurement distance. Shielding and reflection from the bridge structure itself is obviously intended to be measured.

Heavy rain and wind speed above 5 m/s raise the background noise level and may affect the measurement results. The microphones used during the measurements in Assets4Rail need to be dismounted or covered during heavy rain due to technical reasons. Therefore, measurements are only possible in dry weather conditions.

The background noise level measured over 20 s needs to be at least 10 dB lower than the pass by noise level, also in each third-octave band of interest.

Track Conditions

The track conditions are based on the requirements in ISO 3095 [1]. Obviously, on a bridge not all conditions from ISO 3095 need to be fulfilled. Also, the aim of the measurement is not the type test of trains but the characterisation of the bridge and the effect of the mitigation measures.

Therefore, the track parameters rail roughness and track decay rate do not need to meet the curves in ISO 3095 [1]. However, in order to characterise the bridge structure, it could be useful to eliminate the influence of the track by ensuring a low rail roughness (e.g. by acoustic rail grinding) and a high track decay rate (e.g. through rail dampers). On the other hand, one could argue that a low track decay rate on the bridge should be considered as inherent to the bridge and should therefore not be altered purely for the measurements. If the reference point fulfils ISO 3095 [1] track requirements the influence of the track on the emitted sound is minimised and the acoustic characterisation of the bridge is comparable. Alternatively, one could attempt to account for track parameters in post-processing calculations.

The following conditions are recommended for the reference point. Deviations shall be documented. Consistent superstructure over minimum length of twice the microphone distance. Minimum curve radius in accordance with chapter 6.2.2. Ballasted track. No rail joints, free of visual defects, no loose sleepers.

The bridge track conditions shall be documented.

Vehicle conditions

Measurements with the aim of acoustic characterisation of the bridge and determination of the effect of mitigation measures are only valid for trains running at constant speed and at the same speed at the reference section and on the bridge. The deviation of train speed at reference section and bridge shall not exceed 5 %.

Measurement procedure

The microphones are to be positioned horizontally and oriented towards the track. They have to be equipped with a windscreen.

Microphone positions:

- In accordance with ISO 3095 microphones shall be located at a distance of 7.5 m and if possible also at 25 m from the centreline of the track at a height of 1.2 m and 3.5 m above rail head respectively [1]. The measurement plane at the bridge shall be located between ½ and 1/3 of the bridge span to minimise possible noise contribution from specific elements at bridge endpoints in line with [2].
- One or two microphones at ISO 3095 positions [1] at a reference measurement plane at the free track that is located at a minimum distance of 100 m from the bridge (reference point). The distance shall be large enough, so that the reference measurements are not disturbed by the bridge noise emissions. Trains and train speed at bridge and reference point need to be the same.
- Optional: one microphone below the bridge between ½ and 1/3 of the bridge span at a height of 3 m below the rail head.

Time signal of the sound pressure *p(t)* is measured at this locations over the train pass-by time as defined in ISO 3095 [1].

5.6.2 Vibration measurement

Laser-Doppler Vibrometry (LDV) system will measure vibration of selected bridge parts. Choice of measurement points shall be done by first selecting relevant structural elements ("measured parts"), and then selecting the measurement points on each structural member.

Selection of measured parts

Structural members with high contribution to the bridge acoustic emissions should be selected as measured parts. Their identification can be performed based on engineering judgement. Here, members with low bending stiffness should be favoured, such as high girder webs or other members with low thickness (like steel-sheet footpaths). The relevance of various member types is also influenced by their total sound-emitting (vibrating) area. Usually, perforated steel sheets are not relevant in sound emission.

The engineering judgement can be aided by a confirmation tool for simplified estimation of sound energy emitted by different bridge members, which is possible to implement in an Excel spreadsheet. With the purpose of analysing the sound emission, a steel bridge structure can be divided into individual rectangular vibrating plates with repeated geometries. Plates with equal geometry and boundary conditions are henceforth referred to as "plate type". The relative distribution of emitted sound energy can be estimated and bridge members with largest contributions can be selected as "measured parts". The simplified estimate is based on principles of Statistical Energy Analysis, with the assumption of strong coupling between all bridge members. The sound energy radiated by each plate (W_{rad}) can be estimated based on the spatially averaged mean-square vibration velocity $\langle v_i^2 \rangle$ of that plate as described by Thompson [4]. Note that the accuracy of this estimate at very low frequencies may be limited as it depends on formulas for simplified estimation of the radiation ratio σ that do not account for boundary conditions of the plates.

It follows from the assumption of strong coupling that all plates of the same type should vibrate with equal amplitudes. This assumption should be verified by measuring at least two plates of same type along the bridge length. Recommended locations are near 1/6 of bridge span and near mid-span.

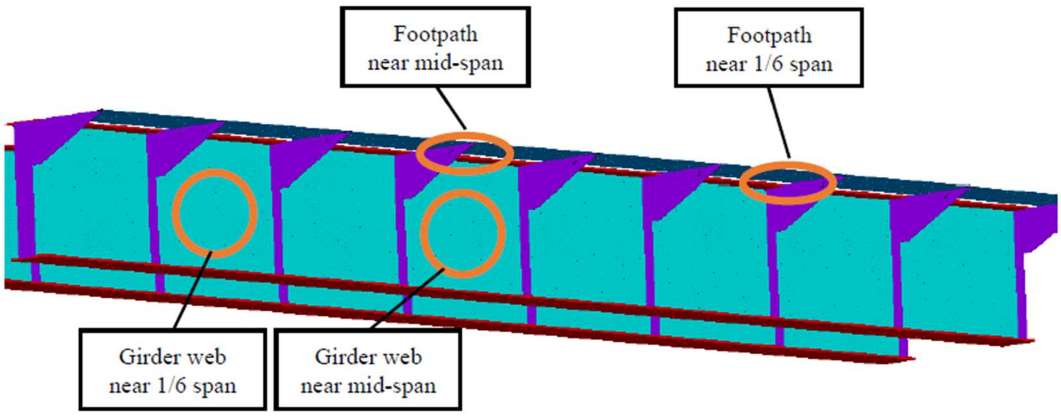

Figure 2: Schematic example of measured parts selection

This project has received funding from the Shift2Rail Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement no. 826250 Assets4Rail).

Selection of measurement points

Vibrations shall be measured on several points on each of the selected measured parts. The selection of measurement points should allow us to estimate the spatially averaged mean-square vibration velocity $\langle \overline{v_i^2} \rangle$ in the relevant frequency range. The measurement points shall be selected at locations where highest vibration amplitudes are expected. Since these locations differ between vibration modes (Figure 3), a combination of expected amplitudes from all vibration modes in the frequency range of interest can be used to estimate suitable locations. Weighting factors may be used in the combination of modes to emphasize certain frequency range.

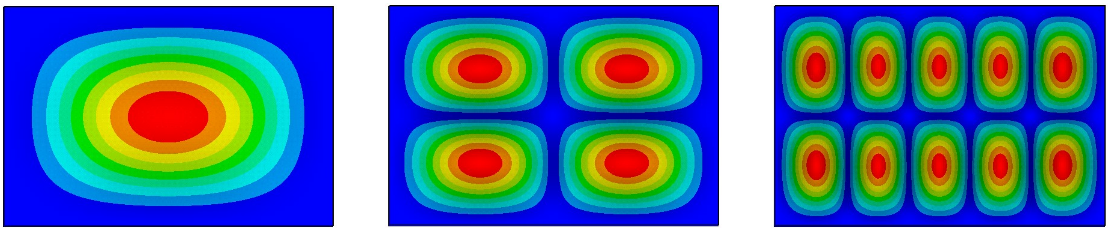

Figure 3: Distribution of vibration amplitudes in a steel plate: mode 1 at 93 Hz (left), mode 5 at 275 Hz (middle) and mode 13 at 611 Hz (right).

Figure 4 shows expected combined vibration amplitudes of a rectangular plate 1800x1200x20 mm with fixed boundary conditions, together with selected measurement locations. In the left are first 5 modes combined (frequency range 0 – 300 Hz), in the middle are first 10 modes combined (frequency range 0 – 480 Hz), in the right are first 20 modes combined (frequency range 0 – 820 Hz).

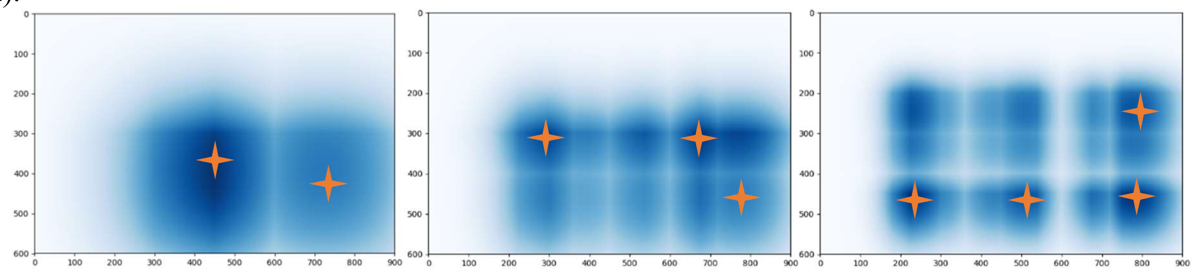

Figure 4: Expected vibration amplitudes and selected measurement locations (orange stars) in case of first 5 vibration modes (left), first 10 vibration modes (middle) and first 20 vibration modes (right). Due to symmetry, only ¼ of plate with dimensions 1800x1200 mm is displayed. All axes in [mm], vibration amplitudes normalized to maximum shown as shade of blue (0 - white, 1 – dark blue).

At least 2 measurement locations shall be selected for each measured part; recommended are 4 locations per measurement part. Symmetry conditions shall be exploited, which means that locations reflected by the symmetry axes shall not be selected as regular measurement points.

On the whole bridge, at least 20 measurement points shall be selected.

Position of actual measurement locations shall be documented with an accuracy of less than 2 cm. The angle between the LDV ray and the measured surface shall be determined and documented. The required accuracy of the determined angle is 10° if 75°<angle<90°, 5° if 60°<angle<75° and 3° if 45°<angle<60°. The position of the LDV must be chosen such that the angle is at least 45° at all measurement points. Repositioning of the LDV between different measuring points is allowed. Vibrations of the LDV device shall be recorded using an accelerometer mounted on the LDV in the direction of the measurement ray.

Bridge vibration reference point

One location shall be selected as the reference point. Structural vibration at this point shall be recorded during all investigated train passages. The reference point shall be selected at the plate type with highest estimated relevance for sound emission, preferably at a member located near the middle of total bridge span. Most suitable location at this plate shall be selected according to the above stated recommendations for the selection of measurement points.

Measurement procedure

At least one full train passage shall be recorded at each measurement point. Vibrations at the reference point shall be acquired in all records. Therefore, simultaneous measurement of vibrations on at least 2 points (1 reference point and 1 varying point) is required. Simultaneous measurement of more reference points or more varying points is allowed, which would require additional sensors / measurement devices.

Vibration signal time-histories shall be recorded using sampling rate of 5 kHz or more. Antialiasing filter shall be activated in the acquisition system. The recording must start before first axle enters the bridge and must end after last train axle leaves the bridge.

5.6.3 Additional measurements

- Train speed and pass by time shall be measured (e.g. with photocells). Speed shall also be measured at a reference point.
- Measurement of rail roughness in accordance with EN 15610 [7] at the bridge and reference measurement plane
- Detection/Documentation of train type.
- Optional: structure-borne sound measurements with accelerometers at the bridge (between ½ and 1/3 of bridge span) and the reference point to compare track vibration.

5.6.4 Bridge conditions

For measurements to be performed, the bridge under test must meet the following requirements:

1. Has to be a steel railway bridge.
2. Has to be operational for rail traffic or other rail vehicles in constant speed.
3. Must not have a noise barrier because the results validity is limited related to non-noise-barrier bridges (conventional noise barriers on a bridge are expected to shield train noise much more then bridge noise). However, if a solution for a specific bridge with noise barrier is searched, the noise barrier at this bridge is OK, of course.
4. No rivers or other water surfaces, or very dense vegetation under the bridge that would prevent positioning of measurement systems. Creeks or canals that cover only narrow part under bridge-span might be permissible, depending on bridge length. Ground must be solid and even enough to mount microphone stands up to about 30 m from track centreline.
5. The procedure is developed with relatively short bridges in mind; with bridge span < 40 m. While methods used can be applied to longer bridges as well, obviously more effort would be required to measure them. Measuring on bridges with spans 100 m or more would likely prove impractical in many cases, both from this additional effort required and from other considerations like height or presence of water.

6. Free sight (no objects or vegetation) within a triangle with equal sides of L = bridge length, in order to perform LDV measurements. If this cannot be guaranteed, a more detailed planning of the position of LDV can be performed, such that free sight is guaranteed between each measurement point and the LDV. The LDV can be repositioned between train passages if necessary.
7. Max height 10 m from rail to most of the ground under the bridge with possible exemptions for localized ditches, drainage holes or narrow canals. This allows for relatively simple measuring location placing of microphones using microphone stands - permitted ground is level and solid enough. Beyond this limit, stands become impractical, and microphones would have to be placed on specialized construction fastened to bridge itself.
8. No large buildings, barriers or other structures near the bridge and reference measurement point (100 m range to avoid noise reflections). Trees or other smaller structures that can be judged to offer negligible noise reflection are permissible.
9. Additionally, the ground at a reference point should be at most 2 m under rail head, without large sound absorption or reflection objects in a 100 m radius (linked to requirements in chapter 6.1 and 6.2 of ISO 3095 [1]).
10. No large noise sources under or nearby – including large roads or highways. Very small or forest roads might be ok, as long as there is enough room under the bridge to mount microphones (~30m away from roads, linked to requirements in chapter 6.1 of ISO 3095 [1]).
11. The reference point has to be passed by the same trains as the bridge, each traveling with the same speed on both measurement points (bridge, reference).

5.6.5 Other conditions

All other conditions (environmental, track, vehicle) other than those related to train composition, will fulfil the requirements set forth in chapter 6.1 and 6.2 of ISO 3095 for both the bridge as well as reference point measurement positions [1])..

5.7 Data processing

5.7.1 Processing of acoustic measurements

The time signal of the sound pressure $p(t)$ (raw time date) is measured. From this data the pass by noise level shall be calculated according to ISO 3095. Furthermore, the third-octave band spectra of the bridge pass-by measurements shall be calculated. For damper development narrowband Fourier spectra shall be calculated from the raw time signals.

To characterise the bridge acoustically the difference $\Delta L_{br\text{-}ref}$ between the bridge pass by noise level at each microphone i, and the pass by noise level at the reference point will be calculated. The arithmetic average of ΔL is then calculated separately for all microphone positions, train types and speed categories.

To determine the effect of noise dampers $\Delta L_{br\text{-}ref}$ is determined before and after damper installation. The level difference characterises the damper effectiveness. Comparison in third-octave bands shows the spectral effectiveness of noise dampers and gives more physical insight.
For a better acoustic characterisation of the bridge, the rail roughness difference between bridge and reference point should be accounted for. A method to do so will be researched in Assets4Rail.

Additionally, if noise level dynamics during train pass-by need to be studied, airborne noise emissions are to be processed as $L_{ZF,100ms}$ spectrum in 1/3rd octave bands. Most likely this would be needed in case of reoccurring noise maximums (bumps) that can signify localized track or bridge faults that generate additional noise.

5.7.2 Processing of vibration measurements

Narrow-band spectra (FFT) of records at all measurement points shall be evaluated and a put into ratio to the reference point.

Narrow-band spectra (FFT) of records at the reference point, which were acquired during different train passages, shall be combined to form mean spectra. In here, weighted mean can be used to account for expected quantities of different train types.

From this, mean vibration amplitudes at all points shall then be evaluated, and further also the spatially averaged mean-square vibration velocity amplitude for all measured parts and all frequencies of the narrow-band spectra. Using Thompson [4] formulas, emitted sound energy with dependence on frequency shall then be estimated for each plate type *i*.

Estimate of total emitted sound energy shall be formed as the sum of sound energy emitted from all bridge plates:

$$\boldsymbol{W_{rad}(f) = \sum_i n_i \cdot W_{rad,i}\,(f)}, \tag{1}$$

where:

n_i.........number of plates of type *i* in the whole bridge.

From the narrow-band spectra of W_{rad}, third-band octave spectra shall be constructed.

This procedure does not account for effects beyond sound emission. The propagation of sound to the immision point is determined by the geometry of the bridge and its surroundings and is not considered in the evaluated sound energy emission W_{rad}.

5.7.3 Combining acoustic and vibration measurements

Recorded noise spectrum for each bridge shall be compared against vibration spectrum with the goal of identifying a common spectral maximum in the 20~300Hz range. This would indicate a presence of a natural frequency of parts of the bridge structure or more likely one of its higher orders that falls into that frequency range – a thundering peak frequency f_P.

To help rank bridges according to their "radiation efficiency", a bridge index (*BI*) can be introduced. This index is a weighted difference between bridge-specific noise and sound energy emitted by the bridge – both at the thundering peak frequency. Bridge-specific noise is expressed as a difference between bridge and reference point noise levels (from NEM measurements – see 5.6.1, 5.7.1). Total sound energy from the bridge will be assessed from SVM measurements (see 5.6.2, 5.7.2), weighted relative to some reference value for steel railway bridges – to be assessed and declared during the course of the project.

The introduced bridge index assessed at other frequencies can also be summed up to give us a bridge value over a larger spectrum range (BI_T).

Note that bridge index *BI* or value BI_T provides a measure of how much of the vibration measured on bridge parts gets transmitted as airborne noise, using some basic assumptions on radiation efficiency and for a whole bridge. This can be useful in comparing different bridge designs using different types of parts or structures.

6. Conclusions

This section will be updated and revised as research progresses at least once on next deliverable update on M24, with possible edits in between as new conclusions are reached.

In current form, this report describes the measurement procedure for steel railway bridges as envisioned by contributing partners. It is based on literature and state-of-the-art review as well as our expertise and experience with subject matter. It is however still just an idea about how the final procedure will be realized and as such is subject to change.

While contributing partners are confident methods described in this document can provide a quality measurement procedure it is nevertheless quite probable that some parts of it will be edited or revised. The need for changes will most likely emerge during analysis of measured results and experiences gained during application on two pilot bridges. The document is scheduled to be updated to its final form in M24 of this project.

7. References

[1] Standard EN ISO 3095:2013 "Acoustics -Railway applications -Measurement of noise emitted by railbound vehicles"

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[3] "Grundlegende Anforderungen an Nachweismessungen zur quantitativen Bewertung von infrastrukturbasierten Innovationen zur Minderung des Schienenlärms" by DB Systemtechnik, document number 08-P-6835-TTZ112, date: 22.07.2010

[4] Thompson, D.J. – Railway Noise and Vibration: Mechanisms, Modelling and Means of Control, ISBN 978-0-08-045147-3, Elsevier, 2009.

[5] Standard IEC 61672-1:2013 "Electroacoustics - Sound level meters - Part 1: Specifications"

[6] Standard IEC 60942:2017 "Electroacoustics - Sound calibrators"

[7] Standard EN 15610:2019 "Railway applications. Acoustics. Rail and wheel roughness measurement related to noise generation"