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Auralisation of combined mitigation measures in railway pass-by noise

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ABSTRACT

To reduce noise exposure along railway lines various combinations of noise mitigation measures can be considered. However, predicting and assessing their effects is non-trivial and the potential need for multiple measures is difficult to communicate to stakeholders. Auralisation is a promising tool that can help to support communication and decision-making, and enable psychoacoustic evaluations. This paper presents developments of a physics-based auralisation model for train pass-bys that allows various mitigation measures to be included. The work is conducted within the European research project SILVARSTAR. The proposed model includes contribution from rolling noise, impact noise, traction, auxiliary systems, and aerodynamic noise. It is physically based and allows a direct assessment of pass-by parameters such as speed, roughness, wheel flats and track design. Based on the TWINS model, five structural transfer paths for rolling noise are considered to integrate mitigation measures such as wheel and rail dampers. Shielding by noise barriers is simulated with analytical models. Reflection at different ground types is considered and can account for track embankments. The results can be coupled to an immersive Virtual Reality environment, by first panning the synthesised sounds to a small virtual speaker array and subsequently dynamic binaural rendering for headphones.

1. INTRODUCTION

Auralisation is the acoustical counterpart to visualisation and allows users to audibly experience situations that do not necessarily exist (yet). The term was introduced by Kleiner et al. [1] and it involves rendering an audible sound field emanating from acoustic sources located within a virtual environment. Auralisation has a long tradition in the planning process of concert halls and opera houses [2].

During the past decade, there has been increasing interest in environmental acoustics applications of auralisation. Auralisation provides much more information than noise levels regarding the acoustics and the quality of the sound environment. It can be used to characterise different acoustical scenarios using psychoacoustic parameters. It can also be combined with visual information, thereby

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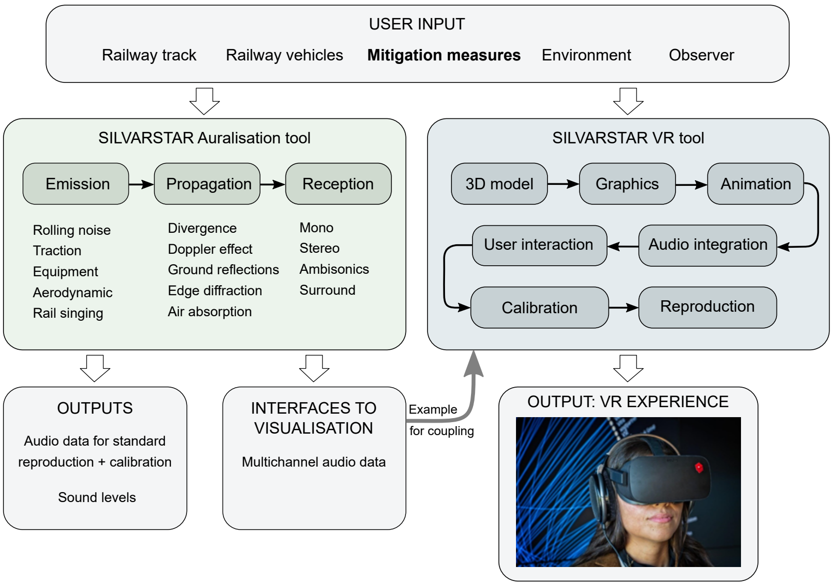


Figure 1: Concept of the SILVARSTAR auralisation and VR simulation.

achieving a more thorough evaluation of a virtual environment using current Virtual Reality (VR) technologies. As a communication tool, auralisation can be used in noise control engineering to provide an audible impression of the effect of a future noise mitigation measure instead of demonstrating the reduction graphically or in terms of decibel values. This will allow the relevant parties involved in future developments (public, decision makers, vehicle customers and designers) to have a full immerse experience of the effect of the mitigation measure and obtain much better insight than sound pressure levels or other acoustic quantities, which are difficult to communicate to an audience without an acoustics-related background. Existing operational railway auralisation models lack the possibility to simulate various combinations of different mitigation measures [3, 4].

This paper presents some first developments that are conducted within the European research project SILVARSTAR. They are based on previous work from the authors, combining expertise in railway noise modelling [5] and acoustic VR. Technical objectives of SILVARSTAR are the development of models for realistic physics-based railway auralisation that allow the inclusion of combined mitigation measures. Intuitively understandable demonstrations of railway noise mitigation will be achieved by coupling the auralisation models to 3D visualisations creating an immersive, interactive VR environment. The concept is illustrated in Figure 1. To achieve this, advances in sound synthesis, propagation filtering, and on sound reproduction are required.

2. SYNTHESIS OF TRAIN PASS-BYS

In most relevant exposure situations, a train has to be regarded as an extended acoustical source. For the horizontal extension this is due to the train length being comparable or greater than the distance between the track and the observer. Vertical source extension typically becomes relevant in cases where a noise barrier provides shielding to rolling noise, while having little impact on sources on top of the train such as HVACs. The chosen auralisation process thus consists of three modules that separately describe sound emission, sound propagation and sound reproduction. Equivalent sources are distributed in a virtual environment. The sources are attributed to a certain location with a certain orientation. A source signal describes the sound pressure as radiated by each source.

Auralisation requires a procedure to generate sound samples. Relying on audio recordings for railway auralisation is rather limited with respect to the representation of different scenarios and for different applications. Sample-based synthesis may partially help to overcome these limitations. The

ID	Type	Size	Composition	Length	#Axles	Speed range
1	Regional	Short	5 coaches	90 m	12	80-200 km/h
2	Regional	Long	10 coaches	180 m	24	80-200 km/h
3	Intercity	Short	2 locs + 6 coaches	200 m	32	80-200 km/h
4	Intercity	Long	4 locs + 12 coaches	400 m	64	80-200 km/h
5	Freight	Short	1 loc + 16 wagons	300 m	72	60-100 km/h
6	Freight	Long	1 loc + 21 wagons	550 m	110	60-100 km/h

Table 1: Descriptions of virtual test trains and their speed range.

most versatile approach however is to use parametric or physics-based synthesis. These allow various railway scenarios to be reproduced but require calculation models of adequate fidelity. This section briefly introduces the scenarios and the modelling approaches.

2.1. Scenarios

A scenario is understood here as a parametric description of an outdoor situation where a single train travels in front of a non-moving observer. The parameters describing the scenario are related to the railway vehicles, the railway track, the environment and the observer. The mitigation measures that are currently explicitly covered by the model are

1. Rail grinding
2. Composite brake blocks on freight wagons
3. Avoidance of wheel flats
4. Wheel dampers
5. Rail dampers
6. Rail shields
7. Low height barrier
8. Noise barrier
9. Secondary sources attenuation.

The listed mitigation measures can be combined apart from 5+6 and 7+8 as these are not used together in real situations. Regarding railway vehicles, Table 1 introduces six virtual test trains. There are three different train types consisting of a regional, an intercity and a freight train. Each train type is implemented in two different lengths. The total lengths, numbers of axles and the compositions were chosen based on statistical analysis of a large datasets of international train pass-bys operating on the Swiss network. In the simulations, the trains operate at constant speed v. Acceleration phases or standstill are not supported. The track can be specified in terms of track type (slab or ballast), sleeper type (concrete monoblock or biblock) and stiffness of the rail pad (hard, medium, soft).

2.2. Rolling noise synthesis

The flow chart in Figure 2 illustrates the synthesis of rolling noise source signals. Rolling noise is caused by the roughness on the wheel-rail surfaces which impose a relative displacement at the contact point [5]. The finite size of the contact patch introduces a spatial filtering effect. The roughness extends over the rail surface and around the wheel circumference and is transformed into the time domain using the speed v. The wheel/rail roughness and possible discontinuities on them, such as rail joints or wheel flats, are generated following an earlier approach for rolling noise synthesis as outlined in [3]. Separate transfer path filters are created for radial wheel vibration, axial wheel vibration, lateral rail vibration, vertical rail vibration and the sleepers. These are calculated using the TWINS

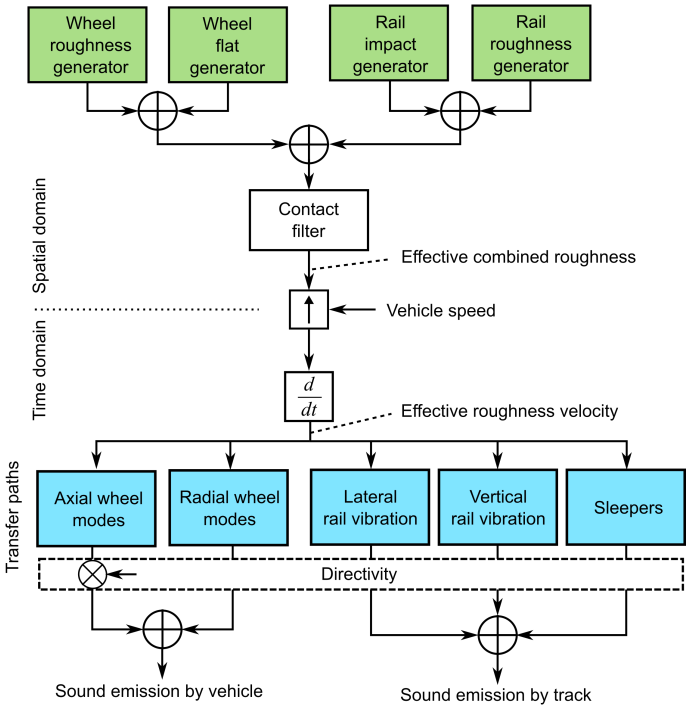


Figure 2: Flow chart of the physics-based rolling noise synthesis model to create artificial source signals of a single wheelset pass-by.

model where the track is modelled analytically as a Timoshenko beam over a continuous or discrete support and the wheel is included by means of its modal properties obtained with finite element calculations [6]. To design the wheel transfer path filters, idealised rolling damping [5] curves are used that were derived from wheel vibration measurements and TWINS simulations. Finally, the sound pressure signals of the different contributions are modulated by directivity functions to account for their free field source directivity and possible shielding by the vehicle body. The resulting source signals are used as inputs into the propagation filtering.

Because rolling noise is the dominant source in many situations, seven measures from the list above relate fully or primarily to rolling noise. Measures 1-3 concern the roughness excitation of the wheel/track system. They are included in the sound synthesis model by modifying the roughness generator at the start of the auralisation process. Rail and wheel dampers (Measures 4 and 5) modify the vibrational behaviour of the wheel/track system. These are accounted for by adjusting the track decay rates [7] or by altering the structural damping ratios of the wheel [8] in the TWINS simulations. The rail shields (Measure 6) are introduced as a spectral insertion loss applied to the rail components [9].

2.3. Synthesis of other sources

Source signals for traction, equipment and aerodynamic noise are generated by subtractive synthesis, with the exception of specific tonal components. The basis are sound powers in 1/3 octave bands and corresponding source directivities. To interpolate between different vehicle speeds v, the sound power level L_W in dB of source i and frequency band j is modelled as

$$L_{W,i,j}(v) = L_{W,i,j,v_0} + \beta_{i,j} \log_{10}\left(\frac{v}{v_0}\right). \tag{1}$$

with the sound power L_{W,i,j,v_0} at reference speed v_0, and the speed coefficient β.

Rail singing was earlier found to be relevant for auralisation [4]. It is observable around 1.2 kHz

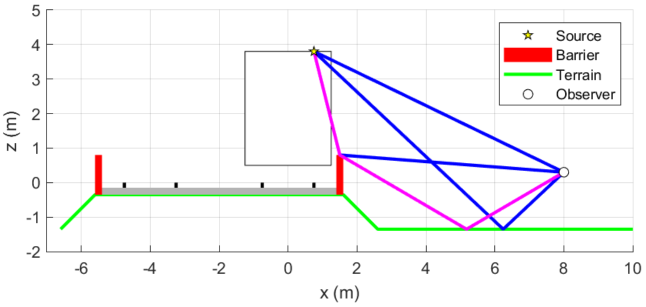


Figure 3: Vertical cross section of an example idealized propagation geometry for an HVAC source (star symbol) on top of a train and four propagation paths (solid lines) to the observer location (circle). Sound is diffracted at the edge of the low height barrier (red) and reflected at the ground (green). The magenta line shows the combined diffracted-ground reflected path.

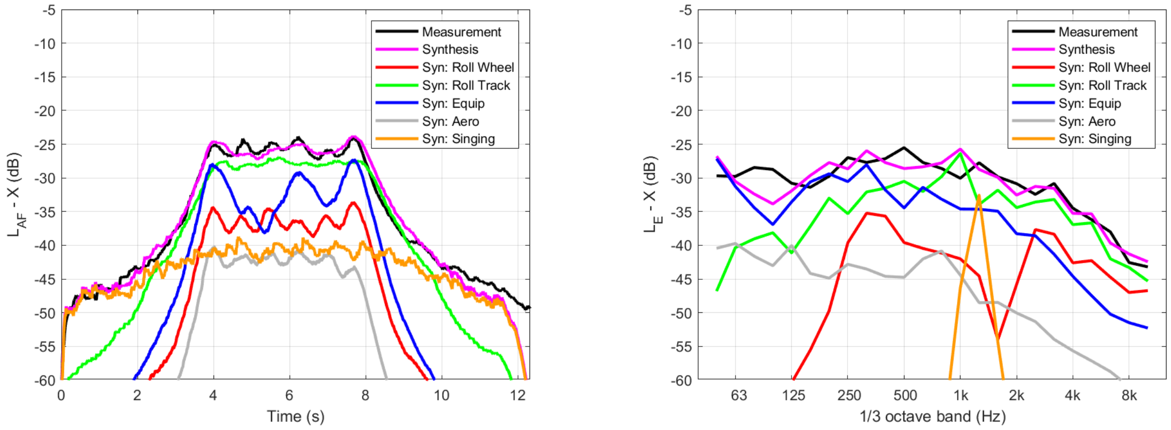
and related to highly propagating waves in the rail. Due to its large horizontal source extension, it is modelled as a coherent time-varying line source. The rail singing source signal is synthesized by narrowband noise which is slowly modulated in amplitude in accordance with the low track decay rate.

2.4. Propagation filtering

Sound propagation simulation is performed in vertical cross-sections. The propagation effects from source to receiver are applied to each source signal individually. This is realised by processing the source signals with a set of digital time domain filters. Due to source motion, all propagation effects change over time which means that time-variant filters are used. The model considers Doppler effects, propagation delay, geometrical spreading, ground reflections, edge diffraction and air absorption. Standard noise barriers or low height barriers (Measures 7+8 from the above list) are simulated by modelling the sound diffracted by the barrier top, and the inherent changes to the ground effect. The ground effect is also affected by a possible track embankment, the observer location and the ground properties. In the absence of a barrier, the embankment edge may also shield low height sources such as the rail. Figure 3 illustrates the four propagation paths considered. These paths are used to model the sound pressure p at the observer location at time t caused by source i. The total sound pressure is the sum of the corresponding four partial sound pressures for direct, reflected, diffracted and diffracted-reflected sound:

$$p_{i,\mathrm{tot}}(t) = p_{i,\mathrm{dir}}(t) + p_{i,\mathrm{refl}}(t) + p_{i,\mathrm{diff}}(t) + p_{i,\mathrm{diff/refl}}(t). \tag{2}$$

If there is no line of sight between source and observer, $p_{i,\mathrm{dir}} = 0$, and analogously for the ground reflected sound. Each term in Eq. 2 is computed with its individual time-dependent Doppler effect, propagation delay and geometrical spreading. For the ground reflected sound, spherical wave reflection at a finite impedance plane is assumed. The complex frequency dependent ground impedance is calculated as a function of the ground type using Miki's model [10]. Single-edge diffraction is modelled based on Pierce's analytical frequency domain expression [11]. To simulate air attenuation, spectral air absorption coefficients are calculated with ISO 9613-1 [12] assuming a homogeneous atmosphere. Reflections and diffraction from objects, such as buildings, barriers or walls, the ballast effect, scattering, wind and turbulence effects are neglected.



(a) (b)

Figure 4: Measured and simulated sound pressure levels of an electrical multiple unit (EMU) train passing by with 78 km/h at the measurement position 'A' according to ISO 3095 [14]. All levels are shifted by an arbitrary value *X* for confidentiality reasons. (a) A-weighted FAST-time weighted level time histories, (b) 1/3 octave band spectra of sound exposure level.

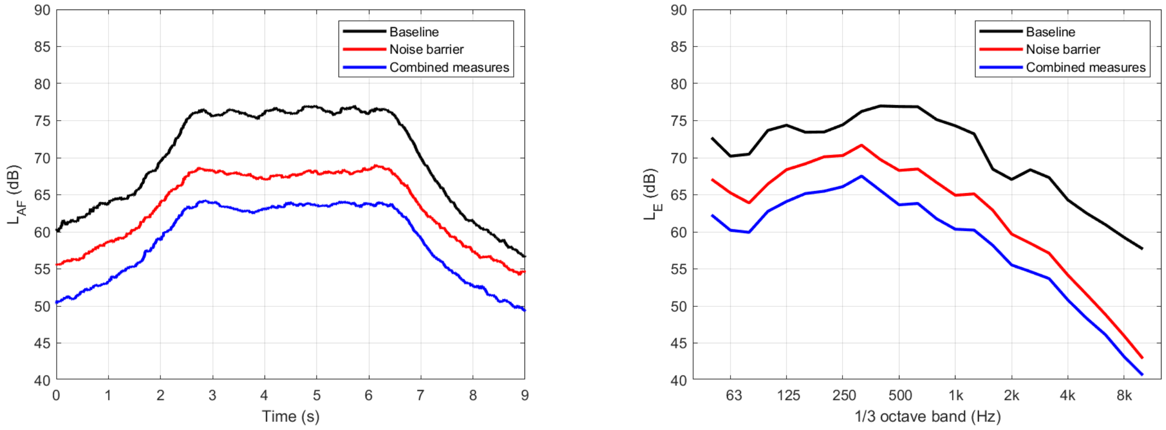
2.5. Reproduction rendering

To support different reproduction systems, different rendering strategies and output formats are used. The sum of all observer sound pressure signals is useful for monophonic playback and to compute acoustical or psychoacoustic parameters. For two-channel loudspeaker playback, a stereophonic ORTF rendering is done [13]. First Order Ambisonics (FOA) is a compact scene-based audio format that can be used for web-based video platforms like YouTube. For interfacing with the VR environment, a tailored intermediate audio format has been developed. For compactness and simplicity, a channel-based format is used where all observer sounds are panned to a 2D array of virtual speakers. The virtual speakers are located on a tilted semi-circle facing the track. This array is recreated in the VR environment where binaural rendering for headphones is achieved through dynamic HRTF filtering.

3. RESULTS AND COMPARISON TO MEASUREMENTS

As a means of model verification and validation, comparisons to pass-by measurements are made. During the auralisation model development, first comparisons to vehicle certification pass-by measurements according to ISO 3095 [14] without mitigation measures are performed. As an example Figure 4 compares sound pressure levels of a measurement (black curves) to the corresponding synthesis (magenta curves). A very good agreement of the overall temporal and spectral behaviour can be observed. The partial source contributions of the synthesis are also shown. They indicate that the rolling noise contribution from the track (green curves) is mainly dominating the A-weighted level and the spectrum above 500 Hz. At lower frequencies, traction and equipment noise (blue curve) dominate the overall spectrum. Two seconds before and after the pass-by rail singing (orange curve) is dominant. Listening to the partially summed sounds revealed that also the wheel contributions are clearly relevant as these are dominant in the higher frequency range. These observations point towards the importance of considering all the different sources in auralisation.

Figure 5 shows results from auralised train pass-by scenarios with different mitigation measures. In all scenarios, an electrical multiple unit (EMU) train is operating at 80 km/h on a ballasted track within a rural environment. The observer is located at 12 m distance to the track at 5 m above ground. As mitigation measures, a noise barrier of 2 m height above rail, smooth rail roughness and a 5 dB



(a) (b)

Figure 5: Sound levels of auralised scenarios that are without measures (black curves), with a 2 m noise barrier (red curves), and three combined mitigation measures (blue curves). The combined measures consist of 2 m barrier, smooth rail roughness and attenuated secondary sources. (a) A-weighted FAST-time weighted level time histories, (b) 1/3 octave band spectra of sound exposure level.

Figure 6: Example 3D visualisations a freight train on different track types with mitigation measures rail shields, low height barriers and standard noise barriers.

attenuation of the secondary sources are used. The selected mitigation measures achieve broadband level reductions. They affect the time structure and the frequency content of sound pressure at the observer (see Figure 5).

4. IMMERSIVE VIRTUAL REALITY ENVIRONMENT

To create immersive audio-visual experiences, the auralisations were coupled to 3D visualisations of outdoor train pass-by scenes as illustrated in Figure 6. An operational VR system was set up that will be used as a demonstrator. The VR system allows for user interactions like head rotation, resetting the train location, and immediate switching between scenarios. The user can for instance toggle on and off a mitigation measure, or a series of combined measures, or switch between different measures. These immediate changes during the virtual train pass-by allow for direct AB comparisons.

The VR system consists of hardware and software. The auralisations are reproduced by dynamic binaural rendering for headphones using the intermediate audio format. The open-back circumaural headphones of type Sennheiser HD650 were equalised and calibrated using measurements with a KEMAR head and torso simulator. The 3D visualisations are displayed with a head-mounted display of type Oculus Quest 2 allowing for stereoscopic panoramic view and head tracking. The scenario switching is achieved through hand-held motion controllers. The user initiates changes by pushing a virtual button in the scene by hand, or by pressing physical buttons on the controller. The VR application was developed in collaboration with the Swiss company Bandara VR using the commercial game engine Unity. First impressions of the prototype system including binaural sound are available on the web-based video sharing platform YouTube here.

Similarly as demonstrated here, the auralisations can be coupled to other existing or future 3D visualisation systems to create immersive audio-visual VR environments.

5. CONCLUSIONS

A new VR simulation framework is introduced that allows for demonstrating combined mitigation measures in railway pass-by noise. The physics-based auralisation model will be validated against field measurements. The developed VR tools will be released as software as an output of the SILVARSTAR project. These tools may help the railway sector to support communication and decision-making, and enable psychoacoustic evaluations of different railway noise mitigation strategies.

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