Sound propagation and distribution around typical train carbody structures

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Summary

Within the European rail initiative Shift2Rail, funded by the European Union, the FINE1 project aims at improving energy efficiency and state-of-the-art noise modelling and control for railway systems. For high energy efficiency, it is vital to reduce the mass of the trainsets. With this mass reduction the challenge to achieve high sound transmission losses of the carbody structures increases. To meet the rising demands for acoustic comfort inside the trains while fulfilling the more stringent mass targets, the need for accurate interior noise prediction methods is growing. Current industrial interior noise prediction methods rely on a mixture of empirical, analytical, statistical and numerical approaches.

One important aspect of the interior noise prediction is the sound distribution around the carbody for source excitations from different geometrical positions, e.g. the sound pressure field on the carbody structure generated by a sound source in the underframe. The paper presents the results of simulations of the pressure field around the carbody for either artificial sources or real operation in free field and tunnel. The practicality and validity of using different calculation approaches like BEM, ray tracing, SEA and standardized outdoor sound propagation is investigated in combination with selected validation test results. Due to the large variety of parameters involved, further work is needed to deduce processes for general application in free field and tunnel. By investigating the influence of a coarse and more detailed geometry some recommendations for future modelling are given. The resulting generalized transfer functions shall form a basis for refining the actual interior noise prediction tools used in the railway industry.

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1. Introduction

Within the European rail initiative Shift2Rail, funded by the European Union, the FINE1 project (Future Improvements for Noise and Energy) aims at improving energy efficiency and state-of-the-art noise modelling and control for railway systems. There is a collaboration with the complementary open call project called DESTINATE (Decision supporting tools for implementation of cost-efficient railway noise abatement measures).

The work presented is carried out partly in the "Interior noise prediction" work package of FINE1. This work package deals with interior noise predictions in the industrial context of the railway industry. The challenge is to find a compromise between needed accuracy and modelling effort taking the specific aspects of the railway vehicles for sources, transmission path and interior sound field into account. A literature review for interior noise predictions and the current state of the art used in the European railway industry including the implementation of pressure field around carbody is given in [1]. To meet the rising demands for acoustic comfort inside the trains while fulfilling the more stringent mass targets, the need for accurate interior noise prediction methods is growing. Current industrial interior noise prediction methods rely on a mixture of empirical, analytical, statistical and numerical approaches.

The work presented here deals with one important aspect of the interior noise prediction, namely the sound distribution around the carbody structure (close to surface) for source excitations from different geometrical positions, e.g. the sound pressure field on the carbody structure generated by a sound source in the underframe. Nowadays, the transfer functions (TF) implemented are often based on measurements with a limited number of parameter variations. The aim is to find reliable calculation approaches for the sound pressure around the carbody structure in free field and tunnel environment. The available methods for quantifying the sound distribution around the car-body are huge, reaching from measurement methods to a number of analytical/numerical prediction tools.

The objective is to define transfer functions (in 1/3 octave band resolution) from all relevant exterior source positions to the complete surface of the carbody structure (underfloor, sidewalls, car ends and roof). There are different challenges related to this task. One aspect is that a full parameter space would be huge so that it is not practical to do these calculations for the complete parameter space. Hence, reasonable simplifications and assumptions have to be taken which should be based on the identification and quantification of the dominating parameters and relevant physical effects. Another aspect is the wide frequency range which shall cover 20 to 5000 Hz and the large geometries involved (compared e.g. with automotive applications). It is therefore vital to investigate which methods and tools are best suited for this application, potentially split for frequency range and application cases (section 2). A problem definition is given in section 3. In the remaining part of the paper (section 4), results of different calculation and validation examples are shown. Finally, preliminary conclusions are drawn and an outlook is given for future work within FINE1.

2. Potential prediction methods

In this section a rough overview of prediction methods to be applied for this task is given.

2.1 Empirical / analytical methods

Toepfer provides several empirical formulas for the sound pressure level (SPL) distribution around railway vehicle carbodies [5]. The standard ISO 9613-2 [2] specifies an engineering method for the prediction of outdoor sound propagation for a variety of sources of known sound power emission in octave bands at defined locations. The standard covers the physical sound attenuation mechanisms and provides equations for the calculation (e.g. geometrical divergence; atmospheric absorption; ground effect; reflection from surfaces; screening by obstacles and a variety of meteorological conditions). The standard includes single and double edge diffraction including sound barriers. Required input parameters are the geometry of source and environment, ground surface characteristics and sound power spectra. As the usual application of this standard is for outdoor sound propagation over larger distances, a number of simplifications are used in the calculation procedure and it needs to be checked if it can be applied successfully for the calculation of the pressure field around a carbody in free field. Some example results using CadnaA are presented in section 4.4.

2.2 Wave based method - BEM

The boundary element method (BEM) is in general a wave based method (meaning the quantities are fully defined as functions of space and time). BEM uses elements for discretization on the boundary surface only. The air itself is not discretized with volume elements in contrast to the finite element method (FEM). In general BEM computes the acoustical quantities on the boundary surface of the acoustic domain instead of the acoustic domain itself ('the air'). The latter values are computed based on the boundary solution by using surface integrals over the domain boundary. The microphones (field points) can be placed at any position within the domain. The boundary conditions for the indirect (variational) IBEM relate acoustic pressure, normal velocity, and normal impedance to single- and double-layer potentials. Both sides of the boundary surface are considered simultaneously even though only one side of the boundary may be in contact with the fluid. IBEM does not distinguish between interior and exterior computations. The direct (collocation) DBEM uses directly sound pressure and normal velocity on the side of the boundary surface in contact with the air. In DBEM differences exist between interior and exterior computations and the boundary surface needs to be closed. These BEM approaches have principally no limitations in the frequency range, the geometrical model size or shape of interest, but are practically limited by mesh size and computational resources. BEM is considered a slow method for large models. The Fast Multipole Method (FMM) is one solution to accelerate the computation by reducing the number of computational operations and optimizing the use of memory. BEM provides - due to the solution of the Helmholtz-equation - a full physical model including the radiation, (partial) reflection, diffraction, interference and absorption. BEM Software tools used in this work are LMS VirtualLab, ANSOL COUSTYX [4] (section 4.1) using FMM DBEM solver and ESI-VAOne (section 4.2) using standard BEM solver.

2.3 Ray acoustic methods

Ray (or beam) acoustics (a consideration of geometrical acoustics) uses the concept of a sound ray with a certain amount of acoustics energy (very similar to geometrical optics considering a free straight light ray propagation as an equivalent for a light wave). The main feature of this idealization is a defined propagation direction following propagation laws (e.g. geometrical divergence, air absorption, reflection). Since the acoustic wave length is often of the same order as the dimensions of the interacting objects the principle is strictly valid for high frequencies only. Depending on the implemented method rays are collected in a beam (e.g. pyramids, cones with different cross section). The propagation physics of the classical ray acoustic concept given does not include sound diffraction (and interference) which is in general relevant for surfaces similar or smaller than the wavelength. Scattering (in general caused by objects smaller than the wavelength) is quantitatively included by using scattering models. The ray acoustic tools used in this study are ODEON [3] (section 4.1) and ICARE (to be used for study presented in section 4.2). Sound diffraction is in general relevant for surfaces similar or smaller than the wavelength and can be included in a simplified way in ODEON and ICARE using low order diffractions (ODEON up to second order / ICARE up to third order).

2.4 Statistical methods

Statistical energy analysis (SEA) is an energy based collection of methods for the analysis of complex acoustic systems. The analysis is not done for 'specific', but for typical systems (in a statistical sense). In tendency, the method is used for high frequency applications to assure the needed properties and conditions (e.g. modal density, modal overlapping, weak coupling) in the systems. The diffraction problem is currently solved with engineering means (e.g. adapted coupling factors, creating the necessary boundary for a kind of diffuse field). In this paper, VA One using SEA subsystems is used in section 5.3 for a tunnel application.

3. Problem definition

The concrete problem of an external sound field distribution can on the one hand be solved for a specific combination of external sound sources and carbody (a kind of signal analysis with sources and carbody as close to reality as necessary) or by an equivalent (simplified) system description with idealized sound sources and carbody geometry. The topic 'pressure field distribution around an object' could from the acoustics engineering point of view be loosely considered as propagation acoustics: starting with the sound radiation and successive sound interaction with objects (e.g. carbody). Full or partial reflection, diffraction (scattering), transmission and absorption are the distinct processes of the propagation physics. The radiated sound interacts also with other sound sources or with reflected or diffracted sound. The wavelength dependence of the SPL distribution around the carbody, the closeness of other objects (e.g. ground, tunnel walls) complicates the propagation process occasionally

up to a change of the sound field character (giving also the sound field below the carbody a technical distinction). The SPL around the carbody is not only captured by direct sound of ‘visible’ sources, but also by the sound going ‘around the corner’ (the diffracted part). These general technical remarks set certain requirements and questions for measurements and predictions of SPL distributions. Only a few examples will be given here: what additional parts (e.g. bogie or underframe equipment) shall be used for measurement/prediction of the pressure field? What contribution is of major interest: the incident field, the grazing field? At what distance should the pressure be measured/calculated, which microphone type to be used?
At the current state of the FINE1 project two requirements for the SPL distribution are fixed: the general source characterization by spectral sound power (1/3 octave bands) and the simplification as point sources. In this work different approaches are tested to investigate feasibility and reliability of the methods for several target applications in free field and tunnel (see section 4). Specifically, in section 5.1 the question of geometrical details to be included in the models and the influence of track absorption are tackled.

4. Application cases

4.1 Regional train - BEM / Ray acoustics in Free field (Bombardier)

Figure 1 shows two geometries in combination with a more complex model of a regional rail vehicle. The computations shown are performed with these geometries (only plane walls, no further components or parts) and a single point source near a wheel/rail contact position. Two detailed SPL distributions of BEM and ray-acoustics are displayed in Figure 2 (examples of full range 100 – 3150 Hz).

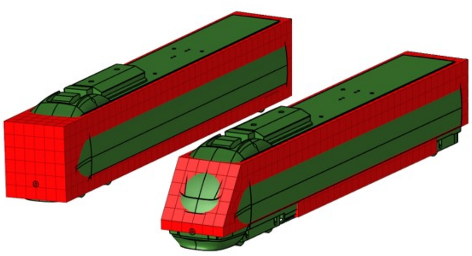

Figure 1. Simplified (left) and more detailed (right) meshed geometry of carbody in red in comparison to real train geometry (in green)

The spatial SPL distribution in BEM is much more distinct. In Figure 3 one exemplary result presentation after post processing is shown (spatial / frequency averaging): the local SPL distribution for a specific spectral SWL at a certain position (SPL – SWL). Ray acoustics provides a similar SPL distribution (not shown here) with differences mainly in roof and front window areas.

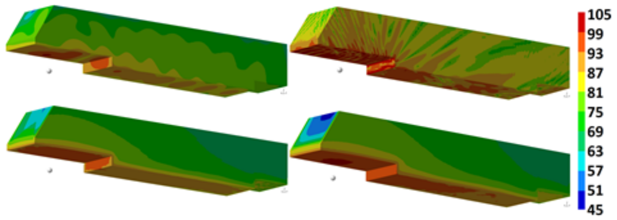

Figure 2. SPL distribution on carbody for source at right front wheel/rail contact at 100 and 1000 Hz (105 dB SWL per frequency assumed). Left: 100 Hz, Right: 1000 Hz. Top: BEM, Bottom: Ray acoustics

Figure 4 shows the influence of the geometry change (simplified to more detailed). In tendency the influence of geometric changes is lower in the high frequency range. But it needs to be kept in mind that the geometries investigated are still not taking into account e.g. the rounded sidewalls and other geometric details.
The simplified case results always in higher SPL here. Although only the geometry in bogie sections and at train head are changed, the changes in SPL distribution are visible in almost all areas. The highest differences occur in underfloor and front areas.

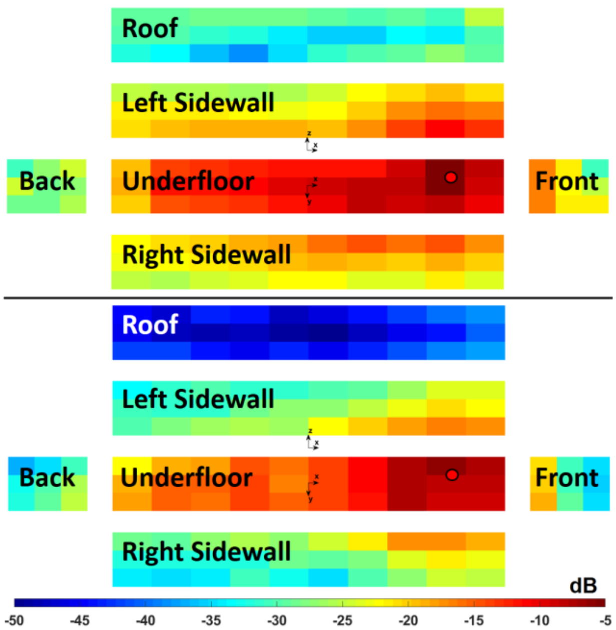

Figure 3. BEM calculated TF (SPL – SWL) for source at left front wheel/rail contact. Detailed geometry. Top: 100 Hz, Bottom: 1000 Hz

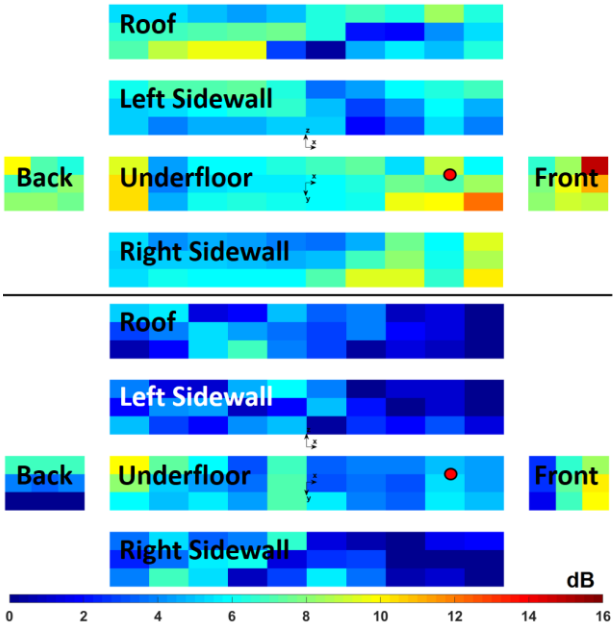

Figure 4. Geometry influence (SPL difference) calculated with BEM. Top: 100 Hz, Bottom: 1000 Hz

4.2 Metro train - BEM in free field (Alstom)

Previous work done within Alstom [6] showed promising results for wall pressure numerical simulations with two different computation techniques, beam-tracing and FMM BEM. Within the FINE1 context a complete validation study is planned. The objective is to compare SPL experimental values of an existing train (Metro type) in standstill and running conditions with results obtained by two computation techniques (Beam-tracing and BEM). The presented work shows first results of this ongoing study.

4.2.1 Experimental set-up

At standstill wall pressure measurements in free field on a ballasted track have been done on a Metro using an artificial pink noise omnidirectional loudspeaker with known sound power level (SWL) at different distinct positions. The objective is to have experimental results with a controlled excitation to avoid the uncertainties on real sources in dynamic conditions. Several microphones have been placed in different positions (underframe, sidewall, roof). Figure 5 shows the mesh of sensors and the source in one of the locations.

In a second step dynamic tests with the same Metro have been performed at several speeds and in different environment (free-field, tunnel and viaduct). All the input data needed to quantify acoustic sources as track and wheel roughness, track decay rate, train equipment etc. have been characterised in order to have detailed inputs for the simulation models.

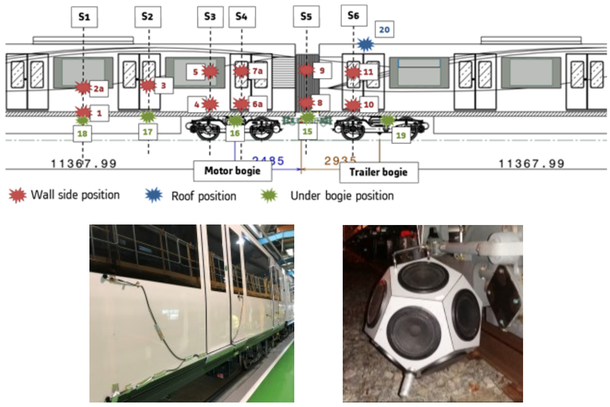

Figure 5. Metro at standstill - measurement set-up with omnidirectional loudspeaker beside the bogie.

4.2.2 Simulations

Two simulation technologies shall be evaluated: beam-tracing (ICARE software, not shown here) and BEM (ESI VAOne). The BEM simulation has been started but only results for the standstill condition with loudspeaker excitation until 500 Hz are available so far. For this frequency range the standard BEM solver of VAOne is used. A model with the geometry of the Metro, the ground including its impedance (ballasted track absorption) and the acoustic source modelled as a monopole with the corresponding SWL is created. The number of wetted nodes are around 26000. A computation from 40 Hz to 500 Hz with one frequency per 1/12 octave band has been performed. The computation time is 7 hours on a 4-core machine (CPU Intel E5-2643 with 64 GB RAM). Figure 6 shows the overall SPL distribution for the BEM calculation.

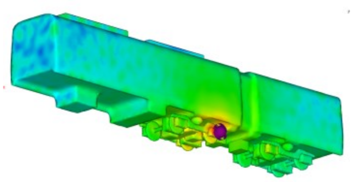

Figure 6. Metro BEM model including source location and overall SPL distribution (40-500 Hz).

The comparison of test vs. simulation for several points and one of the source positions (laterally in front of one wheel, see Figure 6) is shown in Figure 7 for A-weighted overall levels. The propagation is well captured, with differences in overall level mainly between 0 to 2 dB having a maximum difference of 4 dB.

The comparison of spectra on the points in two sections are shown in Figure 8 (dotted line is experimental results and continuous is simulation).

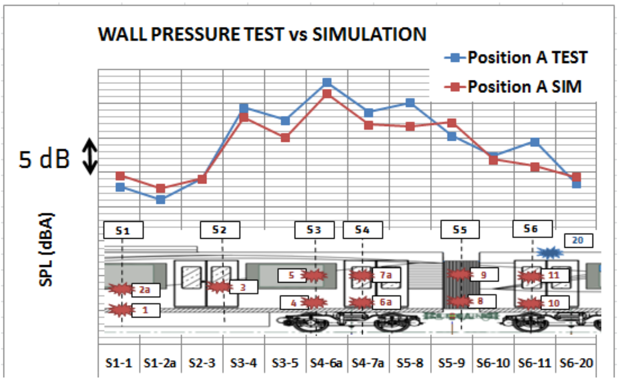

Figure 7. Wall Pressure overall punctual results.

About the points of section 4: one is located on the lateral side where the excitation is (7a), the second one is symmetric to the first one on the opposite side (7b), and the third one is in the underframe (16). For section 1 both points are located on the lateral side. In general the trend is well captured. The higher differences in some frequency bands correspond to the point located on the face opposite to the excitation. In general results for these low frequency bands are promising with this type of simulation but a deep analysis of the spectra for all the measured cases is still pending.

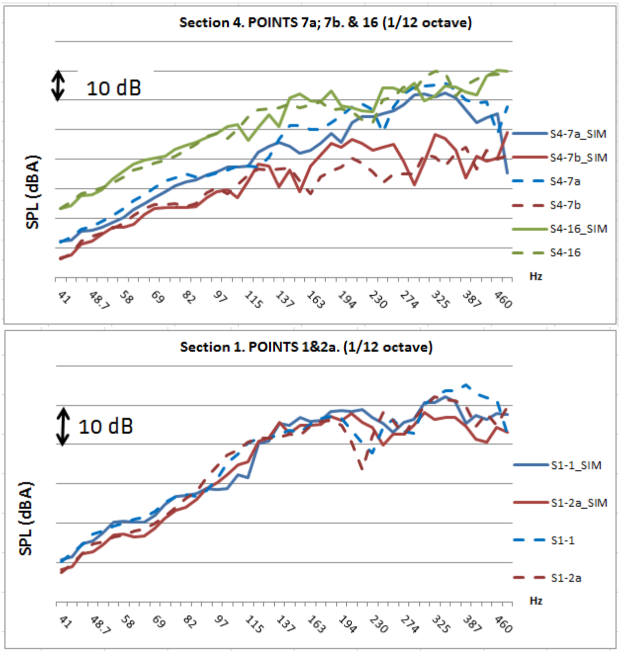

Figure 8. Wall pressure spectral results for S1 & S4 (for positions see sketch in Figure 7)

As a next step calculations with BEM for higher frequencies and beam tracing using ICARE will be performed checking the viability to reach the complete frequency band of interest, the accuracy and evaluating the computational cost for the standstill case. The limitations of each of the methods should be obtained. The same process will be done for dynamic conditions in different environments. In this case an additional effort should be taken to simulate correctly the different acoustic sources as rolling noise and equipment in general.

4.3 Metro train – SEA in Tunnel (CAF)

In this section, the software VAOne is used in order to evaluate the possibility to predict wall pressures for a vehicle running at 80 km/h through a tunnel using SEA. The vehicle geometry is modeled by panels characterized by the transmission loss measured in-situ. Figure 9 shows the geometry of the coach to be studied, which corresponds to a metro-type vehicle trailer coach. The exterior acoustic field is represented by acoustic cavities.

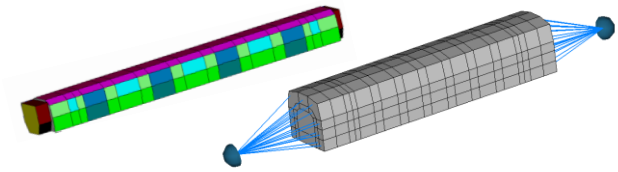

Figure 9. VAOne model of a metro trailer coach (left) and exterior acoustic cavities (right)

The absorption coefficients of the tunnel is deduced from spatial decay measurements with one loudspeaker and measured SPL at different positions. This results in frequency dependent absorption coefficients in the range 0.03 to 0.13.

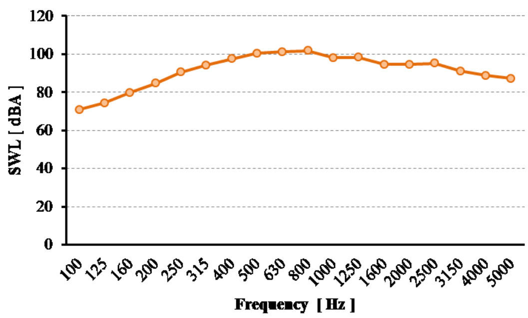

Figure 10. Rolling noise SWL spectrum of a metro wheelset running at 80 km/h.

The acoustic loads are introduced into the model as SWL in 1/3 octave bands. For a vehicle running at 80 km/h, the predominant sources are rolling noise and traction equipment. The wall pressure measurements were made on a trailer car, thus only rolling noise sources are considered, whose spectrum was derived numerically and is shown in Figure 12. The resulting calculated wall pressures are compared to the experimental pressure levels measured with microphones in a dynamic test at 80 km/h. The microphone locations are detailed in Figure 11. Microphones 11 and 21 are located on the sidewall, microphone 10 is in the underframe close to the bogie and 20 is located also in underframe but at the center of the car.

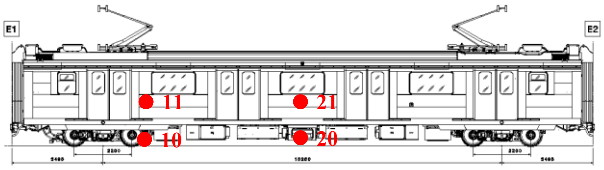

Figure 11. Trailer car exterior microphones.

Figure 12 shows the comparison between the calculated and measured SPL for the microphones located at the center for which the largest divergence between measured and calculated results is expected as they are the farthest points from the noise source. Significant deviations are found at low frequencies. The reason is that SEA models require the subsystems to show a minimum of modes per band. In the current model, this is fulfilled for frequencies above 315 Hz. For higher frequencies, there is an acceptable agreement between the calculated and measured results.

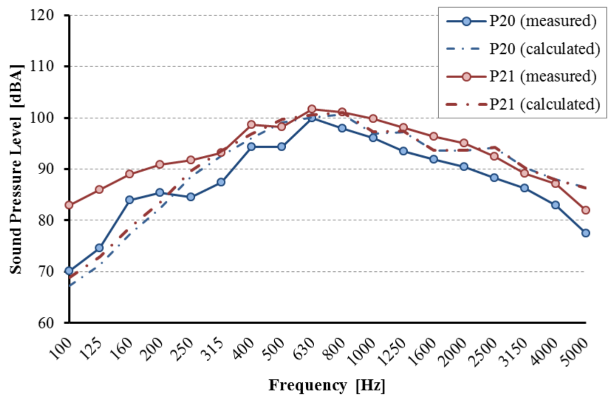

Figure 12. Measured vs. calculated wall pressures at microphones 20 and 21.

In terms of total values, Table I shows that sidewall SPL are more accurately predicted, while the difference for underframe SPL are up to 2.5 dB(A). Based on these results, SEA provides an interesting alternative to predict wall pressures in tunnel in the early design phase of new projects offering a good balance between accuracy and computation time.

Table I. Measured and calculated wall SPL in dB(A).

	P10	P11	P20	P21
Measured	107.9	109.9	105.2	108.7
Calculated	110.4	110.3	107.5	107.9
Difference	2.5	0.4	2.3	-0.8

4.4 Metro – Tunnel: ODEON / Free field: CadnaA (DESTINATE - Müller-BBM)

The FINE1 partners prepared a data set for the noise emission of the bogie in form of 1/3 octave band values of SWL in the frequency range 100 Hz to 5000 Hz. The data was given for the noise emission on a track in free field and on a track in a tunnel. Also the geometric data and absorption coefficients for the concrete tunnel wall were provided.

4.4.1 Tunnel simulation with ODEON

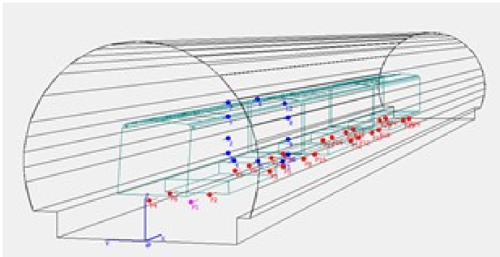

Figure 13. Geometric layout of input data (tunnel shape, carbody with three cars, red dots: sound source for each wheel; blue dots: receiver positions.

Figure 13 shows the geometric layout of the input data for the simulation of the sound field using ray tracing (ODEON [3], version 14.03, 2017-06-01) in the tunnel with two tracks. All walls and the floor are treated as hard concrete walls under acoustic aspects. The absorption coefficient for the walls is very low (α~0.02 at low frequencies, α~0.1 at high frequencies). Also a fully reflecting surface was assigned to the modelled shape of the train. For the calculation the value of the sound power of the bogie was equally distributed to the 4 wheels, no directivity index for the wheels was considered.

4.4.2 Free field simulation with CadnaA

Whereas the software ODEON is optimized for the calculation of the sound propagation in rooms and was used for the tunnel case, the calculation under free field conditions is performed with the software CadnaA. With this software the sound propagation is calculated based on ISO 9613-2 [2].

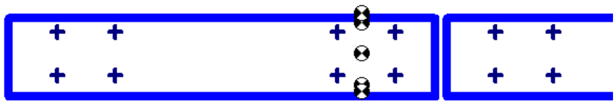

Figure 14. Side view of the geometric layout of input data (carbody, sound sources and receiver positions) for the calculation in free field. The carbody is simulated as a vertical noise barrier.

Due to the fact that diffraction can be calculated only with horizontal edges the y and z coordinates of the train had to be replaced compared to the simulation in the tunnel (see Figure 14).

4.4.3 Results

For an overview the A-weighted SPL on the carbody were categorized in positions under coach, sidewall and roof. In Table II the simulated total SPL results are compared with the tunnel and free field measurements. There is a good correlation (less than 0.5 dB difference) between the measured and calculated results for the tunnel situation. The span of the absolute SPL from positions under the coach to the roof is less than 4 dB.

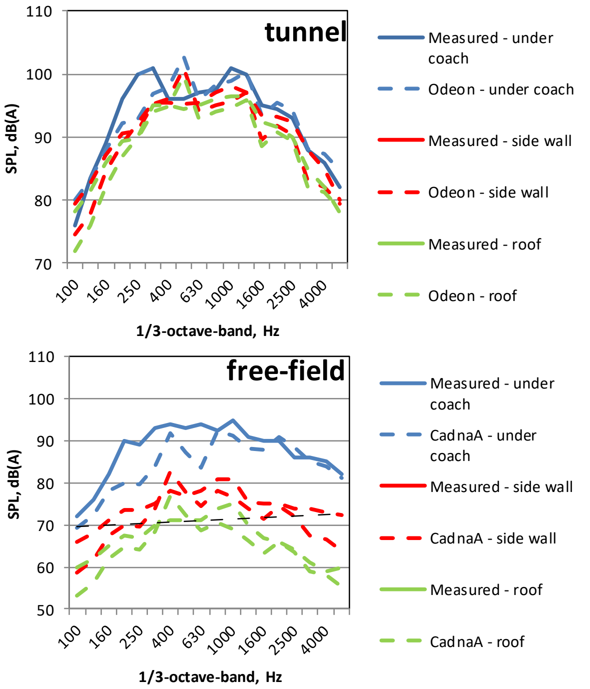

Figure 15. Measured and calculated 1/3 octave band SPL on carbody surface areas in dB(A) (top: tunnel, bottom: free field).

In free field the calculation results for positions in the area under the coach show about 1 to 3 dB lower levels than measured.

Table II. Measured and calculated SPL on carbody surface in dB(A).

		Under coach	Sidewall	Roof
Tunnel (ODEON)	**Measured**	108.9	106.1	105.0
	Calculated	108.7	106.1	105.0
	Difference	-0.2	0.0	0.0
Free field (CadnaA)	**Measured**	103.1	88.5	81.6
	Calculated	99.9	87.3	80.9
	Difference	-3.2	-1.2	-0.7

1/3 octave band spectra of measured and calculated SPL are shown in Figure 15. It seems that in the frequency band around 250 Hz the simple free field simulation is not sufficient and that cavity effects below the bogie should be taken into account. For the positions on the sidewalls and on the roof, the calculated values are in the range of the measured data.

5. Conclusions and Outlook

Based on the preliminary FINE1 results presented it is shown that different approaches and methods to calculate the pressure field around the carbody can be used with acceptable accuracy. Still, a lot of simplifications and assumptions are inherent in the related calculations. No thorough physical understanding is gained yet which effects need to be included in the calculations to capture the mostly relevant parameters and cope with the complexity of the problem. This is required for the deduction of more generalized transfer functions to capture the complete practical parameter space for real vehicle designs and operating conditions. An important aspect that remains is the reduction of modelling efforts for general applications and the integration in the interior noise prediction schemes. Moreover, it needs to be checked how the resulting SPL distributions shall be used properly to characterize the sound transmission process to the vehicle interior. These are topics for future work within the FINE1 project and beyond.

Acknowledgement

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