Acoustical Source Modelling for Rolling Stock Vehicles: the Modeller's Point of View

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Summary

In the framework of the European project Acoutrain, a deep study of the validity of current, state-of-the-art predictions of the exterior noise of rolling stock vehicles has been performed. Although different international standards exist to measure the sound power level of noise sources, this quantity alone is insufficient to create reliable source models, as directivity information is also required. The same measuring techniques used in these standards can be adapted to obtain the data needed for accurate source modelling. In this paper we address the issue of source modelling for the case of rolling stock vehicles; we present the mostly widely used techniques used in this sense and compare their results with measurements both at source level and at train level, showing the impact this has on full train noise prediction. Lastly, we discuss the relation between source modelling in general and the experimental characterization of the sources, including an analysis of the consequences this has on current practices in this domain and on standardization of testing techniques.

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1. Introduction

The main objective of the European project Acoutrain [1] was the development of methodologies to introduce elements of virtual validation in the certification of trains according to TSI NOISE. This should be based on calculations capable of predicting noise levels with accuracy at least comparable to that of the measurements on the train. Clearly, one of the most important challenges to reach this objective is the availability of reliable models of the train's noise sources. In particular, one of the objectives of Acoutrain was the minimization of the measurements required at train level: we would like then to be able to characterize single sources in free-field and then place them 'virtually' on the train and calculate the global level of the train. This study presents the analyses done for the HVAC unit of an EMU train used for part of the validation activities done in Acoutrain; the unit was characterized alone in free-field in a first test campaign, and then measured when installed on the train.

Two calculation tools have been used within Acoutrain and in this study: SITARE and ACOUTRAIN-tool. The first one, SITARE, has been developed exclusively for ALSTOM and since many years it is the reference tool for exterior noise calculations of ALSTOM [2]. ACOUTRAIN-tool has been developed by ISVR specifically for the Acoutrain project. The two tools share the main approach to the calculation of noise levels:

- Sources can be modelled in different ways, mostly based on combinations of monopoles and dipoles (with a given directivity, if required) of given sound power level expressed in 1/3 octave bands.
- Noise propagation is evaluated using theoretical propagation in air [3] from sources to receivers in three dimensions.
- Noise reflection on the ground is evaluated on the basis of a Miki model [4].

2. Experimental data

Experimental data for this study are available from two test campaigns: the unit characterization, done in free field on the unit alone, and measurements on the unit installed on the train. This section describes these two measurement setups.
The HVAC unit was characterized by Bombardier Transportation and KTH in free-field conditions when located 0.8 m above an asphalt surface. The unit itself is approximately 3 m long, 2 m wide and 0.5 m high.
Two measurements were performed in these conditions (for more details please refer to [5]):

1. Sound Power Level according to ISO 3744 [6], based on 9 pressure measurements on a parallelepiped at 1.2 m from the reference box/unit surface.
2. Sound Pressure Level at various points on a hemisphere centred on the evaporator fan, on the top surface of the HVAC. The points were taken every 30° in 3 perpendicular planes, corresponding to the unit's main axes. The total number of points is 21.

The first measurement represents the standard kind of data commonly available from machinery suppliers: sound power level in 1/3 octave bands, with no information about the directivity. The second measurement aims at giving an estimation of the directivity (which for this kind of equipment is pronounced), but there is no standard defining how directivity patterns should be extracted from these data for relatively large sources as in this case. At least two remarks must be made regarding the second measurement setup:

- The directivity thus measured includes the effects of ground reflection which for the HVAC unit is not representative to its installation in the train.
- The measurement setup maximizes the information on the directivity in directions above the unit, while the unit will be mounted on the train's roof and thus it would be also useful with a measurement of directivity patterns below it.

These limitations are difficult to overcome without lifting the unit. Measurements with the unit installed on the train were performed by SNCF [5]. Five microphones were placed on a semicircle of radius 2.5 m, at 4 m height, the centre microphone being placed in front of the geometrical centre of the unit and the others at +/-20° and +/-40° with respect to this. A sixth microphone is placed at 7.5 m from the centre of the track, at 1.2 m height.

3. Modelling

From the data obtained in the source characterization tests, this study aims at creating several models and see how they compare to the measurements on the train. The objective is to find the simplest model capable of giving sufficiently good results.
Five ways of modelling have been investigated in this study:

1. A single monopole with sound power level based on the ISO 3744 measurements. Calculations have been done with SITARE.
2. A single monopole with sound power level based on the measured sound pressure levels. The source is placed in a model of the source directivity characterization tests and the effect of ground reflections (the ground being assumed to be fully reflecting) are considered in the estimation of the differences Lw-Lp. Calculations have been done with SITARE.
3. The sum of a monopole plus a half-dipole pointing upwards. This model is based upon the observation that the source characterization gave a rather circular pressure distribution in the x-y plane, while sound pressure was higher at the point above the unit. This is due to the main source being the evaporator fan placed on top of the unit that will have a directivity mainly pointing upwards. Similarly to what was done in point 2, a model of the characterization tests was built and the sound power levels for the two sources were defined from the best fit with measured sound pressure levels. Calculations have been done with SITARE.
4. The sum of a monopole plus a "fan source" pointing upwards. The scheme is the same as in the previous model, but the half-dipole is substituted by a point source with a given directivity, typical of a fan source, coming from

ALSTOM internal measurement databases. Calculations have been done with SITARE.

5. A "box source", where five half-monopoles are associated with the 5 faces of the source (bottom excluded) and placed in the middle of the face. The horizontal sides of the unit have been arbitrarily chosen to be 1.2 m long. The sound power level of the whole unit is derived from the ISO 3744 measurements and the relative weight of each source is obtained from the directivity measurements. This calculation is done with ACOUTRAIN-tool.

Table I. Sound Power Level for each source model.

MODEL		*SWL(A) TOT*	*SWL(A) TOP*	*SWL(A) REST*
1	MP ISO3744	89.1		
2	MP SPHERE	86.1		
3	MP + DP	86.9	84.4	83.4
4	MP + FAN	87.3	86.2	80.6
5	BOX SOURCE	89.1	87.4	84.1

It is important to remark that the sound power level associated with the unit is different for each of the five models (except the first and the fifth because they are equal by construction). Indeed, the estimated sound power level of a source depends on how data are treated, which means that when modelling a source the actual measured spectra are needed, as different modelers using different source models will take different assumptions and obtain different input data for their computation tools.
In Table I the sound power level obtained from the calculations discussed in section 4 is shown. When possible, the sound power directed upwards (dipole, fan or upper face of the box source) is compared to the sound power radiated on the other sides.

4. Model results on sources alone

In this section are shown the result of the models when compared with the directivity source characterization measurements. In this case, the results are presented grouped by their height, as the measurements were quite symmetric with respect to the angle in the x-y plane. Figure 1 reports the maximum and minimum measured sound pressure level around a circle at a given height from the x-y plane and shows the comparison with the simulated results.
Unsurprisingly we find that simple models (pure monopoles) are less accurate, while by increasing the complexity of the modelling a very good match can be obtained. Note however that the models were built to match exactly these measured spectra.
To quantify the performances of the different models, we present in table II the maximum and average absolute values of the difference between measured and calculated values, for both the global level and per 1/3 octave bands. The values are averaged over the 21 considered pressure points.

Table II. Absolute difference between calculations and measurements for the source directivity test. For each case, the maximum and average of the modulus of the level difference is given, for both the global level and the single 1/3 octave bands.

MODEL	*GLOBAL dB(A) LEVEL*		*PER 1/3 OCTAVE BAND*	
	$\lvert\Delta L\rvert$ max	$\lvert\Delta L\rvert$ average	$\lvert\Delta L\rvert$ max	$\lvert\Delta L\rvert$ average
MP ISO3744	8.4	3.6	13.2	4.2
MP SPHERE	5.6	3.1	11.2	3.5
MP + DP	2.9	1.3	9.9	1.8
MP + FAN	2.7	0.6	9.8	1.5
BOX SOURCE	5.0	2.27	15.1	2.7

The clear trend is an improvement in the quality of the prediction with the increase of the complexity of the model.

5. Model results on the train

In this section are shown the results of the different source models, with the unit installed on the train and measured *in situ*. A number of difficulties arise for such measurements, among which: the geometry of the test has higher uncertainty, there is no standardized procedure to measure installation effects (which in this case were anyway not evaluated), it could be difficult to control spurious sources.

In particular for the first two points, their control is closely linked to how these effects (geometry and installation) are dealt with in the calculation tool.

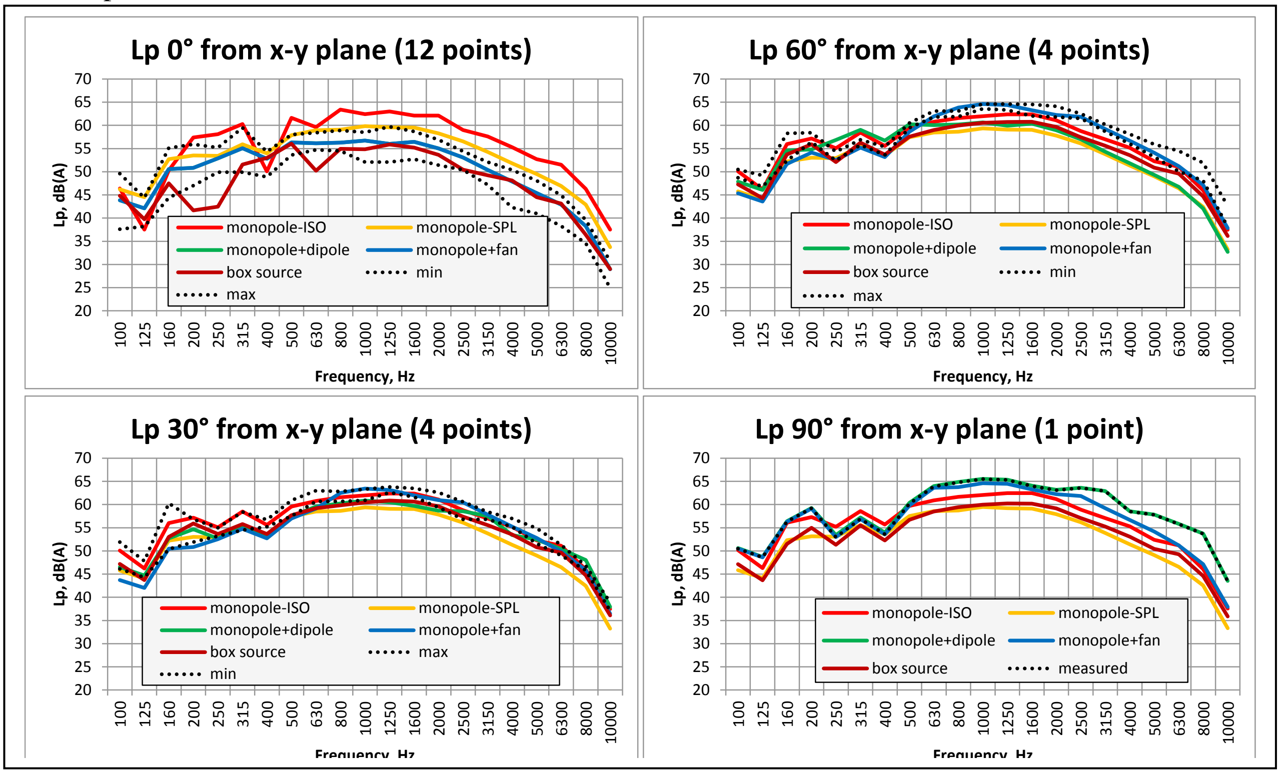
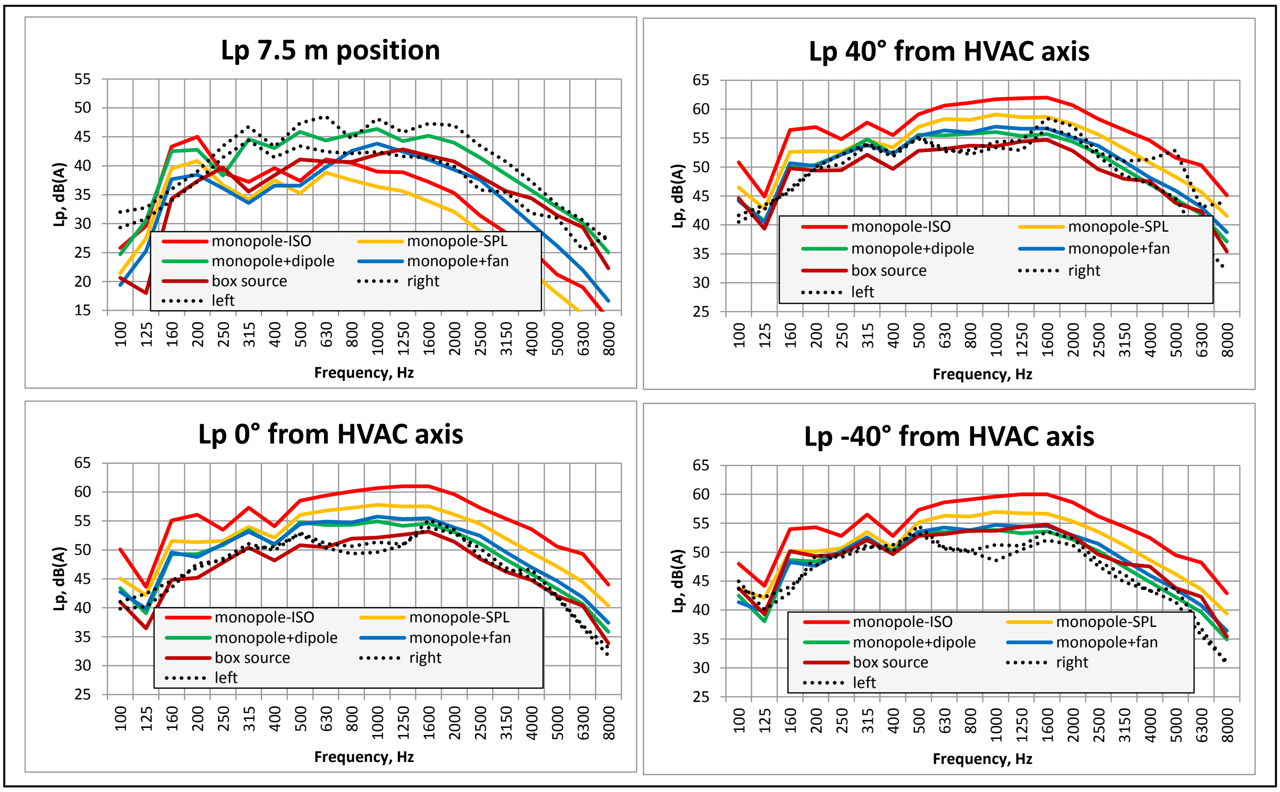


Figure 1 (above). Comparison of measured and calculated sound pressure levels for the directivity source tests. “Min” and “max” refer to measured levels.

Figure 2 (below). Comparison of measured and calculated sound pressure levels for the in situ tests. “Left” and “right” correspond to the train’s sides.



This suggests that vehicle procedures to minimize errors due to these effects should be defined on the basis of the model that will be used in the calculation, as depending on the model chosen the different effects might have a different impact.
Results are quite satisfactory, as can be seen in Figure 2. Results are markedly better with increasing model complexity, even if some features of the test results cannot be found with any calculation, like the unexpected region between 630 Hz and 1250 Hz, rather flat with relatively low values.

Table III. Absolute difference between calculations and measurements for the *in situ* test. For each case, the maximum and average of the modulus of the level difference is given, for both the global level and the single 1/3 octave bands.

	GLOBAL LEVEL		1/3 OCT. BAND	
|ΔL|	max	mean	max	mean
MP ISO3744	8.8	5.9	14.0	6.7
MP SPHERE	6.2	4.0	17.3	5.4
MP + DP	5.5	2.2	8.9	2.7
MP + FAN	4.7	2.8	13.0	3.9
BOX SOURCE	3.3	1.6	13.8	2.4

The results show that the uncertainty linked to such measurements can be higher than expected: results on the two sides of the train at 7.5 m distance are for example quite different, with no clear explanation for this.

To quantify the performances of the different models, we present in Table III the maximum and average absolute values of the difference between measured and calculated values, for both the global level and per 1/3 octave bands. Values are averaged among the 6 considered pressure points.

6. Uncertainty evaluation

One of the results of this study is an estimation of the uncertainty linked to source modelling in noise calculations. One of the objectives of Acoutrain was the development of a procedure to incorporate elements of virtual testing to replace rolling stock noise testing with the objective of having results with uncertainty similar to that of measurements.
While some elements are still missing (for example a better estimation of measurement uncertainty), until now there was no estimation of the uncertainty to be considered due to source modelling. The results presented here are not conclusive, as they are based on a single source, but can be taken as a first estimate where no other information is available.
It is useful to divide the spectrum into three bands: the low, mid and high frequencies. At low frequencies, the results are less good than in the rest of range due to the higher uncertainty on the sound pressure values, including for example coherent effects due to reflections. The mid frequencies are those where the calculations are most reliable, and also those where A-weighted sound power levels are higher for typical rolling stock sources. High frequencies again have higher variability, mostly linked to the directivity pattern that could be too complicated to model with only the 21 points measured in the source characterization tests, in particular for the in-situ receiver points below the plane of the unit.
The absolute level differences between measured

Table IV. Absolute difference between calculations and measurements (*in situ* test) per frequency range.
Maximum and average of the modulus of the level difference given, for the global level and the 1/3 octave bands.

	GLOBAL LEVEL		100-315 Hz		400-5000 Hz		6300-8000 Hz	
Level difference |ΔL|	max	average	max	average	max	average	max	average
MP ISO3744	8.8	5.9	12.3	6.1	11.2	6.5	14.0	9.7
MP SPHERE	6.2	4.0	12.0	4.9	14.1	5.2	17.3	8.1
MP + DP	5.5	2.2	7.6	2.9	7.3	2.5	8.9	4.0
MP + FAN	4.7	2.8	13.0	4.9	8.9	3.2	10.8	4.9
BOX SOURCE	3.3	1.6	13.8	2.8	5.0	1.9	6.4	4.0

and calculated values per frequency range are shown in Table IV. As the data are not homogeneous, a correct statistical analysis cannot be done. Under the hypothesis of an underlying normal distribution, its standard deviation can be obtained by assuming that the mean quantities in table IV correspond approximately the 25^{th}-75^{th} percentile interval of the distribution and thus correspond to 0.7 standard deviations (+/-0.7σ being approximately the interval corresponding to half of the entire population).
A reference variability is then evaluated for simpler models (i.e. single monopoles), and for more complex models (combination of elementary sources to take directivity into account), as the average of the results in the previous table, divided by 0.7, as shown in Table V.

Table V. Reference variability standard deviations in decibels that can be used when simple or more complex models are used, as derived from the in situ evaluations.

MODEL	GLOBAL LEVEL	100-315 Hz	0.4-5 kHz	6.3-8 kHz
SIMPLE	7	8	8	13
COMPLEX	3	5	4	6

An important remark to be considered is that these are not just uncertainties related to source modelling, as they include also the effect of uncertainties from source characterization testing, source installation on the train and on-train testing.

7. Conclusions

In this paper we present the effects of different source modelling approaches on the prediction of rolling stock noise. It was shown that simple models based on single monopoles cannot reproduce reliably the noise emissions of a typical source found on a rail vehicle. More complex models that take into account the source's directivity yield better results, but require source characterization tests that are not described in current international standards. On the basis of these results, an estimation of uncertainty linked to source characterization, modelling approach and installation is derived, which can be used as a basis for future analysis.
Depending on the desired accuracy of the match between measurements and calculations, it is clear that if on one hand source models must have a sufficiently high degree of complexity to be able to reproduce the main characteristics of the source in terms of sound power and directivity, on the other hand measurements (both on the train and characterization ones) must have a degree of accuracy that is not always possible to obtain and that anyway is not required by the commonly used international standards cited in this study.
Within the Acoutrain project it has become clear that current ISO standards for sound power estimation are not developed for vehicle source modelling and do not provide sufficient detail for such purpose. But this study shows that different data sets can (and should) be used differently by different modellers using different calculation tools. It is thus suggested to improve the current standards by adding guidelines on how the existing methodologies can be adapted to obtain the data that modellers need to create sufficiently accurate representation of the noise source. For the purpose of source modelling it is also suggested to keep a strong link between simulation and testing (ultimately these tasks should be done by the same person). The quality of source models is strongly dependent on the quality of the input data and accordingly on the direct knowledge of the circumstances of the tests and of any difficulties associated with those, in particular for non-standardized tests.

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