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Intelligibility prediction in rolling stocks using ray tracing method

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In public transport, acoustic intelligibility is extremely important as passengers have to be able to understand the different messages delivered by PA systems. An estimate of this acoustic property can be carried out by determination of STI or RASTI indexes. In this paper, a simulation based on the ray-tracing method and use of a commercial software is proposed (ODEON). While this method is usually relevant in large rooms, its implementation in a narrow room, like a train, with many internal obstacles may lead to erroneous results (diffraction effect, interference etc.). A case study is presented here and compared with measured values during commissioning. Limits and first order parameters for this type of study will consequently be discussed. In conclusion, basic guidelines for favourable intelligibility with regards to different simulations on several types of rolling stock will be suggested.

1 Introduction

Acoustic Intelligibility, or how comprehensible a speech is, is one of the numerous items that have to be considered during the acoustic design of rolling stocks. Achieving a low ambient noise is essential for comfort, but assuring an acceptable quality for understandable voice announcements must not be neglected.

To fulfil this requirement, the Public Announcement system (PA system) on board has to deliver a certain sound pressure level, above background noise, which is the same at all passenger locations. The acoustic properties within the rolling stock must ensure that acoustic perturbation does not interfere or obscures the message. Both rolling stock builder and PA supplier have to collaborate. Predicting intelligibility at an early stage is therefore a necessity to facilitate the integration of the PA system and to avoid substantial expenses or refit at a later stage in the project.

Determination of Rapid Speech Transmission Index (RASTI) is one of the tools commonly used throughout the industry, in the architectural and building stream as well as in transportation to quantify the speech intelligibility or privacy. RASTI is a condensed version of STI standardised by IEC 60268-16 [1]. As a matter of fact, these indexes are usually defined as the requirement for intelligibility specification.

This article aims at presenting a complete study of intelligibility prediction in a rolling stock, from the simulation to the comparison with commissioning measurements performed on London Underground S stock (SSL). We show that under certain conditions the ray tracing method gets reliable results and can be employed to ensure proper intelligibility level on board by fast investigation of different configurations.

2 Numerical prediction of intelligibility

2.1 What is RASTI index?

The STI index is an objective way of rating the speech intelligibility. This index lies in a [0-1] interval and has been validated after comparison with other subject-based methods [2]. In this method, different test signals consisting of amplitude modulated signal reproducing natural human speech patterns are emitted from a source to a receiver: basically 7 octave band signals from 125 Hz to 8 KHz through 14 modulation frequencies from 0.63 to 12.5 Hz, corresponding to broad band spectrum generated by the vocal cords and modulated by the mouth. Background noise and acoustic environment such as reverberation in room or distortions in sound system will both affect the acoustic response and will reduce the modulation present in the signal. This degree of loss in the modulation intensity is expressed by the modulation Transfer Function (MTF) from which STI is inferred.

RASTI is a condensed version of the STI often employed in which only the 500 and 2000 Hz octave band signals are taken into account. It actually prevails on STI in many applications for historical and technical reasons (measurement capabilities). Table 1 presents the relationship between subjective intelligibility and RASTI indexes.

Speech Intelligibility	RASTI
Excellent	>0.75
Good	0.60 – 0.75
Fair	0.45 – 0.60
Poor	0.30 – 0.45
Bad	<0.30

Table 1: equivalence between speech Intelligibility and RASTI

Within the particular application of public announcement in rolling stocks, the deterioration of RASTI indexes (i.e. speech intelligibility) is pragmatically caused by performance of a PA system (delay, distortion) and the influence of the internal acoustics in the vehicle such as noise, echoes and reverberation.

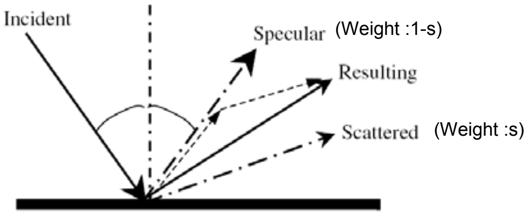
2.2 The ray tracing method

The ray tracing method is one of the alternatives commonly used for predicting room acoustics. It covers quite a large frequency range and gives acceptable accuracy in the prediction of different parameters in acoustics such as Reverberation Time, Intelligibility, Early Decay Time. It has been shown that this method yields to relevant STI estimates in industrial Halls and large rooms.

The method is roughly the following: a large number of rays are emitted in either random or deterministic approach from a source. Each ray is followed as it propagates through the room, being reflected in a specular way or scattered by surfaces, barriers and furnishing until it reaches a receiver. The energy carried by any of them is attenuated according to spherical divergence, material absorption and air. The relation between the absorption part and the scattering part of the energy is usually defined by the equation:

$$(1-s)(1-\alpha)+\alpha+s(1-\alpha)=1 \qquad (1)$$

Specular absorbed scattered



In ODEON, an image method can be used for calculating the first reflections, before switching to ray-tracing method beyond a so-called Transition order (hybrid method). The scattered coefficient s is a weighted sum of intermediate coefficients in order to account for surface and edge scattering, respectively user-defined and automatically calculated by the software [3]. At last, several computation algorithms allow composing with the specular and scattering parts.

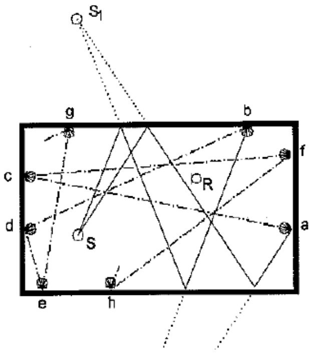


Figure 1. Example of resulting reflection sequence between source and receiver [4]

The limitations of the ray tracing methods are explicit in the definition itself: Being an energy-based method, all phenomena based on the wave nature of sound such as interferences close to surfaces, standing waves, are omitted. This leads to poor accuracy at low frequencies [4,5]. Another critical point is the diffusion and diffraction effect. It has been accepted that accounting for these effects improves the prediction with respect to specular reflections. The scatter effect originates in the ratio between surface size, edges and the wave length in the low frequencies and the surface roughness and the small wave lengths at higher frequencies. The use of scattering coefficient for the different surfaces is a common technique in ray-tracing software for encompassing this effect. It is nevertheless extremely difficult to get proper values for scattering coefficients. Experience is invaluable in this respect.

Considering these different limitations, application of such a method in a rolling stock is challenging. Indeed, the internal space is quite small: distances between surfaces are short, potentially leading to interferences and the scattering and diffraction effect around seats may be important.

2.3 Case study: SSL London Underground

The intelligibility study presented in this article was performed on behalf of PA system manufacturer Axion Technology, who provided the communication system for the SSL train. This line, which is now under construction by Bombardier, will gradually replace the A60 trains of London Underground. The SSL train consists of an 8-vestibule coach configuration which includes 3 different types of cars (variation in overall length and general arrangement). The different loudspeakers for Public Announcement were integrated in the lighting ceiling panels. The results for one car type will be presented here.

Picture 1: Internal view of the SSL (mock-up)

In terms of Intelligibility, the requirements onboard the SSL line consists of a minimum RASTI index at selected seated position and standing in the vestibule, as well as a uniform sound pressure distribution from the PA system.

The numerical model for the ray-tracing method is based on the general layout of the car: the main fittings such as geometry, cross section, seats, and barriers are included in the 3D model, and the material acoustic properties are assigned to any relevant surface (provided by Bombardier or from our database). The first challenge for such a model is the degree of details to be considered with the geometry and the particular end surfaces for a vestibule coach that is normally open (indeed, the volume studied in a ray tracing method has to be closed to avoid rays from escaping). The geometrical details and precision to be accounted for are directly dependent on the frequency of interest and the wave length, e.g. the influence of the handles and bars on the internal sound field can be considered as insignificant. The extremity surfaces are modelled with a specific absorption.

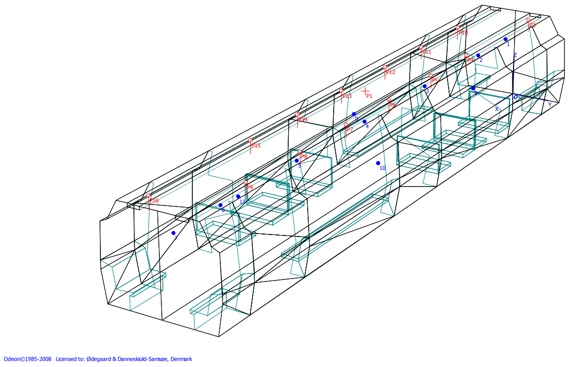


Figure 1: Numerical model of M1 car (ODEON v.9)

The relevance of the geometrical model and basic acoustic properties are validated by the comparison between specified and computed Reverberation Time (through classical method available in Ray Tracing Software), as presented in figure 2. The Reverberation Time measured on board is also displayed.

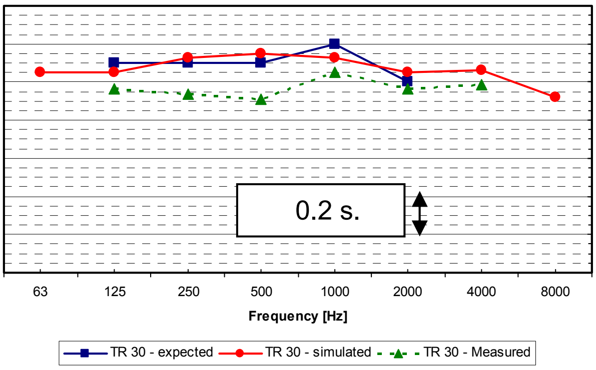


Figure 2: Comparison RT specification/RT computed/RT measured

The Loudspeaker characteristics make up the necessary input for the model in terms of the sources: Transfer function $L_{W\ acous}$/$L_{W\ elec}$., directivity pattern (that can be measured or provided by the PA system supplier) and also the mounting condition. Indeed, fixation and perforated protecting panels usually employed can have considerably influence on the frequency response of the loudspeaker and have to be examined in order to assign the right properties to the virtual source of the model. Each loudspeaker in the SSL train is therefore modelled by a monopole source with a specific directivity pattern and associated transfer function.

Ultimately, the last but not the least critical point is the scattering effect, as discussed in 2.2. The internal domain is extremely narrow compared to usual application for the ray tracing method, and possible screening, diffraction, or near field effect can spoil the prediction, especially in the seated areas where absorption, edges and small surfaces are present.

The model is used to assess the right number and location of speakers to comply with RASTI specifications.

3 Validation of the ray tracing prediction

3.1 Measurement procedure

Different methods exist for measuring the Modulation Transfer Function used in STI and RASTI assessment. A practical one was presented by Schroeder [6] and facilitates or enables the assessment of the Modulation Transfer Function by determining the impulse response between the source and a receiver for a linear and time invariant system:

$$MTF(f) = \left| \frac{\int_0^\infty h^2(t) e^{-2\pi jft} dt}{\int_0^\infty h^2(t) dt} \right| \tag{2}$$

Nevertheless, the direct implementation of this equation does not consider of the influence of background noise on RASTI index and it has to be added afterwards. The necessary impulse response is assessed using Maximum Length Sequence signal [7]. This technique is of great interest in rolling stocks at it allows to post process the Modulation Transfer Function measured on board and assess RASTI indexes extremely rapidly for different background noise levels, i.e. different rolling conditions.

3.2 Measurement results

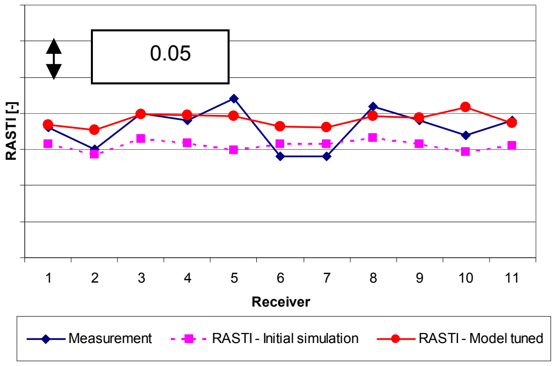
The intelligibility of PA system in SSL line was tested at Bombardier facility in Asforby (UK) on a completely outfitted train. The train was at standstill in the workshop, with all auxiliary equipment at full load.

For measurement, a specific mouth simulator whose directivity is close to the human mouth pattern was used to produce the test signal in the driver cab, both in wall microphone and handset (see picture 2).

Picture 2: Mouth simulator used with the driver's handset

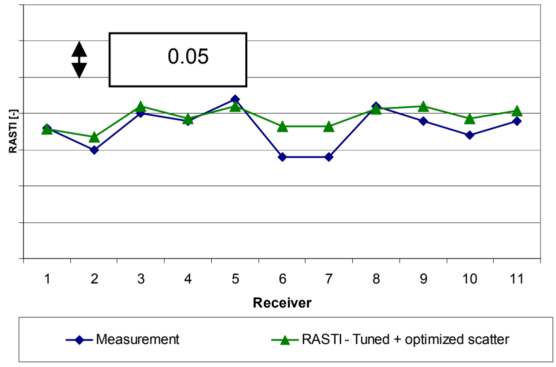
Resulting sound pressure in the M1 car was measured with a sound level metre at investigated locations. Post processing of the data is performed using an in-house developed software. The measurement uncertainty is expected to be around 0.03. For comparison, it was reported that the deviation between STI index and subjective subject-based intelligibility test is about 0.06 [6].

A comparison between different RASTI simulations and measured indexes is presented below for the eleven receivers defined in the M1 car (including seated and standing positions) and for different simulation cases.



(a)

(◇ Measured/□ Initial simulation /○ Model tuned)



(b)

(◇ Measured / △ Model Tuned +optimized scatter)

Figure 3. Comparison on RASTI indexes measurement/computation

The average RASTI index measured in the car is defined as R_{av}. Computation results are compared to this average in table 2.

Speech Intelligibility	Deviation to R_{av}	Correlation
Measurement	-	-
Initial prediction	-0.06	0.31
Model Tuned	-0.01	0.62
Model Tuned + opt. scatter	+0.02	0.82

Table 2: Comparison RASTI measured/RASTI computed Average R_{av}– Correlation coefficient

In (a), the measurements are compared to the initial computation using background noise level and Reverberation Time allocated by Bombardier, and after tuning with the real measured values. Both simulations are performed with standard scattering parameters for material and computation [3].

With respect to the measurement uncertainty, the initial prediction delivers satisfying results in terms of RASTI. Deviation of the average RASTI index is dropped from 0.06 to 0.01 after tuning of background noise and reverberation time parameters. Nevertheless, these predictions do not perfectly reflect the intelligibility spatial pattern on board, as it can be emphasized from correlation coefficient in table 2.

An optimization of the model can then be achieved by the scattering parameter introduced in the model as presented in (b) and leads to very satisfactory results: the average RASTI values predicted are extremely good (2% deviation) and the values at different locations correlate well with measurement (r=0.82).

A maximal deviation of 0.05 is found on receivers 6 and 7. These points are located respectively at the extremity vestibule and close to the gangway. To enhance the results, the model should be extended to the neighbouring car to limit the effect of the end surface (vestibule coach configuration, fully open on gangway).

3.3 Sensitivity analysis

As already verified for other acoustic applications, scattering is a key factor to get the most relevant results out of simulation (after proper background noise and relevant absorption properties). The overall influence of scattering on the computation results is now verified.

In figure 4 the results for different scattering algorithms offered by ODEON are presented, as well as realistic variation of surface scattering coefficients which is a user controlled parameter (as defined in [3]).

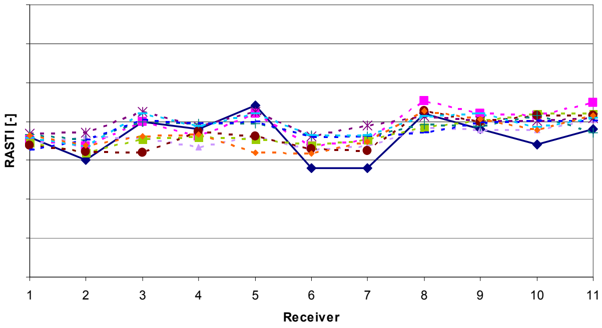


Figure 4: Effect of scattering on RASTI indexes computation algorithms / surface scattering variation (◇ Measured)

For these different simulations, the inferred RASTI indexes lie in a maximum of 0.05 deviation, and the average RASTI index over all receivers is in a 5% deviation from the measured one. Correlation coefficient can nevertheless drop to 0.3.

With these results and compared to measurement and subjective uncertainty, a reliable average RASTI value can therefore be inferred using ODEON on such applications and rooms, without too much attention to scattering. Nevertheless, if intelligibility is requested at specific spots or has to be precisely assessed, this parameter has to be taken into account.

4 Perspective and extrapolation

Results in SSL London underground are really satisfactory (Excellent speech intelligibility). For this application, it was found that the high number of loudspeakers and their homogeneous distribution in the car ensure a rather high sound pressure level with respect to a low background noise level. It is actually interesting to investigate the range of deviation for other configurations: how will intelligibility vary for higher background noise, or with different internal acoustic properties? It is obvious that very particular geometry, arrangement or cross sections will strongly influence the acoustic properties in local spots. Nevertheless, one can expect the average intelligibility prediction on this model to give reliable order of magnitude and tendencies.

4.1 On the effect of background noise

In this section, the effects of various spatial, environmental and rolling conditions are investigated (acoustic properties of the vehicle and loudspeakers are kept constant) amongst them:

- Receiver Location with respect to bogie area
- Free field/tunnel condition
- train speed

The RASTI indexes for these conditions are established by post-processing the intelligibility data of the simulation presented in section 2 with background noise levels, measured on similar vehicles. We assume the average RASTI value computed R_c in section 2 is the reference value, assessed far from the bogie area. Results are presented in table 3 in terms of deviation with respect to this value, as well as S/N values in the relevant frequencies bands.

Rolling condition	S/N 500 / 2kHz	Deviation To R_c
Initial condition Standstill – equipment on	>20/>20	**0**
Free field max. speed <100 km/h	18/>20	**-0.01**
Free field, above bogie max. speed <100 km/h	15/>20	**-0.02**
Classical concrete tunnel max. speed <100 km/h	9/16	**-0.05**
Free field max. speed 140 km/h	10/>20	**-0.05**
Classical concrete tunnel max. speed 140 km/h	3/11	**-0.17**

Table 3. Effect of rolling conditions on the intelligibility

As the background noise increases, the RASTI index and hereby the intelligibility will drop inside the car: With the previous acoustic properties of the car and constant properties of the loudspeakers (for instance no Automatic Gain Control based on background noise which is common in metro lines) a decrease of 0.05 can be expected in free field for typical metro speeds and up to 0.17 when the vehicle is running at maximum speed in tunnels.

4.2 On the effect of reverberation time

In this case, the geometry and background noise are kept constant as defined in section 2. The effect of Reverberation Time is investigated by modification of the main absorption area at frequencies of interest, i.e. the seats. In addition to a quite absorbent upholstered seat configuration for the initial model are also tested:

- A leather finishing (usually old metro lines)
- A light stainless steel (Delhi metro for instance)

These configuration leads respectively to longer Reverberation Time by reducing the acoustic absorption properties in the vehicle. Results are presented in table 4 in terms of deviation to the average RASTI value assessed in section 2. Deviation on Reverberation Time in the 500 Hz frequency band is also given as indicative value.

Seat configuration	RT 30 500 Hz	Deviation to R_c
Initial configuration Absorbent upholstered seat	-	**0**
Configuration 2 Leather finishing	+0.15 s	**-0.04**
Configuration 3 Stainless steel finishing	+0.4 s	**-0.12**

Table 4. Effect of Reverberation Time on intelligibility

As the Reverberation Time increases, the intelligibility and RASTI index diminished on board. For a reverberant vehicle (stainless steel finishing for the seat) a drop of more than 0.1 for the average RASTI is expected compared to the initial model.

If we now combine both effects, i.e. a highly reverberant vehicle with a restricting background noise level such as high speed in a concrete tunnel, a drop of 25% can be expected for the average RASTI index.

Configuration	Deviation to R_c
Stainless steel finishing Classical concrete tunnel max. speed 140 km/h	**-0.23**

Table 5. Effect of restricting conditions on intelligibility

These values are obviously indicative and will be influenced by the entire acoustic design of the car, internal and external (not the purpose of the study here).

5 Conclusions

The objective of this article was to investigate the means to predict intelligibility in rolling stocks thanks to RASTI index assessment. A commercial software is used in order to do so, and the influence of parameters such as absorption and scattering are discussed. Numerical results for a metro line are compared to RASTI measurements performed on board.

The work performed suggests that ray tracing method can give a good average prediction in terms of intelligibility in narrow rooms such as rolling stocks. For an overall value within the vehicle, Scattering will be a second order parameter as long as a good approximation of Reverberation Time and background noise is known. Nevertheless, if intelligibility is requested at specific spots or has to be precisely assessed, this parameter has to be taken into account.

Finally, several standard material configurations and rolling conditions for common metro lines are evaluated: with respect to background noise, an average drop of 0.05 can be expected for the RASTI index in free field for typical metro velocities and up to almost 0.2 when the vehicle is running at maximum speed in tunnels. In a reverberant vehicle, this value can go down by 0.25. These values are indicative still, and will obviously depend on the considered vehicle characteristics and the PA system arrangement.

Acknowledgements

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