RAILWAY NOISE:
MEASUREMENT TECHNIQUES
AND STANDARDIZATION
The new CEN-ISO Proposal of Standards

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The new ISO-EN 3095 standard is the result of a Working Group originally supported only by CEN TC 256, then completed with members selected by ISO. This WG, sponsored by UNIFER, began to work in Florence about ten years ago with the objective of refreshing the previous standard but suddenly it was realized its original defect, due to a lack of definition of the track on which wagons were running during the acoustical measurement campaign. It is well known that a large amount of the noise radiated by a wagon running on a rail takes origin from the contact between the wheel and the rail, and that the vibration due to the roughness of the rail is amplified by the quality of the track, determined by the whole system of rails, fasteners, sleepers and ballast. So it was decided to wait for the research work of METARAIL, a European Research Project that was investigating, among the others, on the influence of the track on the whole noise radiated during the passage of a train.

This paper will explain the procedure adopted to meet the result of keeping out the influence of the track from the result of measurements taken during the passage of a steel-wheeled vehicle on a track in normal state of maintenance.

It was about the autumn of 1990 when the CEN TC 256 WG 3 began to work, sponsored by UNIFER, aimed to write a modernized edition of the ISO standard dealing with the measurement of outdoor noise generated by the passage, or the stay, of vehicles running on a railway [1]; the same WG was charged also to write a new version of the standard devoted to the measurement of noise exposure within vehicles running on a railway [2].

The decision taken by CEN to start a WG with the up mentioned scope was taken in the respect of the Vienna Agreement between ISO and CEN, so now the two standards are following the ISO-CEN procedure for comments from the Member Bodies.

Till from the beginning of the work it became clear that there were chiefly two problems, one of metrological nature, the other of better specification of the experimental set-up.

The reason of the first problem derived essentially from the availability of new technologies of measurement, that is to say short $L_{Aeq}$ and the measurement time for SEL, related to the associated factors length and speed of modern trains; some other problem was rising up due to the increase in speed of trains related to the distance of the microphone from the rail.

The second problem derived from the necessity to better specify the track conditions, as the increased quality of the coaches and of the breaking system get more and more clear that the relevant source of noise was the contact between wheels and rail, so the roughness of the rail and the railway system in the whole deeply influence the passing by noise radiated from a train.

The problem of the distance of the microphone from the rail was linked to the ground effect, so the larger the measurement distance, the stronger are the effect of the absorption or reflection from the ground, and the measurement uncertainty grows up. Furthermore, with a shorter distance it is better possible to pick up the noise generated by a particular type of coach inserted in a train of suitable length and composition.

Except for the problem of the distance, it is clear that a better characterization of the experimental track influences the exposure to noise within the train, a very important parameter for judging comfort for passengers and safety for the workers.

While the WG 3 was at work, an European research program started with the aim to study the same problems, so it seemed useful to wait that the METARAIL project finished its researches and its results were of public domain: this is the first reason that justify the long time taken from the WG3 to send a final draft of the two standards to the CEN TC 256 Secretariat.

More then one suggestion derived from these results, but among them I want to remember here the definition of a new parameter, called TEL, and the definition of limits for the roughness spectrum of the rail, able to reduce the uncertainty of measurements under 2 dB.

TEL is like SEL, but the integration time $T_p$ depends only from the length $L$ of the train and its velocity $V$, as shown in figure 1.

Having in mind this new parameter, the metrological scheme is now that represented in figure 2.

From a round robin test developed in four different countries with the same set of trains, METARAIL deduced either a procedure to separate the contribution of the vehicle from that of the track, or a limit for the
spectrum of the roughness of the rail: these two methods are till object of research, in the frame of the European project STAIRRS.

- Equivalent sound pressure level
  \[ L_{eq,T} = 10 \log \frac{1}{T_R} \int \left[ \frac{p(t)}{p_0} \right]^2 dt \]
- Transit Exposure Level TEL
  \[ TEL = 10 \log \frac{1}{T_R} \int \left[ \frac{p^2(t)}{p_0^2} \right] dt, \quad T_R = \frac{L}{V} \]
- \( L_{PAFmax} \)

FIGURE 1 - The descriptors utilized in the new drafts

![Diagram of measurement quantities](image1)

Stationary vehicles

- \( L_{PAeq,T} \)

Moving trains

- Constant speed
- Accelerating or decelerating

Whole train

Part of train

TEL

- \( L_{PAeq,T} \)

FIGURE 2 - The metrological scheme of the new drafts

![Diagram of metrological scheme](image2)

Microphone positions

- Vehicles with constant speed

Sound sources in upper part vehicle U.T.?

YES

Second microphone position h=3.5 m recommended

NO

FIGURE 3 - The scheme for positioning the microphone

To try to better qualify the contribution both of track structure and rail roughness, METARAIL propose a procedure based on the use of a “silent vehicle” defined as a vehicle whose noise emission is practically ininfluential on the whole emission of the system vehicle-rail, then the measurement of the vertical vibration of the base of the rail together with the measurement of the noise emitted during the passing by phase of the vehicles, both silent and under test.

In 1996, the UE undertook a big work [4] towards the settlement of common rules for an European noise control policy, so a new UE/ WG 6 started its work dealing with railway noise, with particular attention to high speed train set and freight trains.

FIGURE 4 - The procedure to qualify a rail as “smooth”

At the moment, the two Drafts are in the phase of inquiry for comments, while the WG6 is delivering the results of a study developed essentially by TNO TPD [3]: as the European Directive on noise control policy is going on, while some State has already issued regulations with limits, it is very important to arrive as soon as possible to the publication of the two standards, in particular CEN ISO 3095 is already claimed by the TSI on high speed rolling stock [5].

REFERENCES

2. ISO - Standard 3281/XY - Measurement of noise inside railbound vehicles, 19XX
Train noise measurement activity carried out by Italian railways is oriented to the following aims: measurements of immission levels as a consequence of the present Italian laws relating to acoustic pollution; research about the origin, propagation and reduction of noise. As far as the first item is concerned, the publication last November of the law on noise abatement planning has completed the Italian legislation on railway noise. Over the next few years a large part of measuring activity will be aimed at the design of noise abatement systems. To this end measurements will be essential for obtaining noise levels before and after the construction of barriers and for applying calculation models. Thus it is extremely important to build up a wide and reliable database containing train noise emission values.

**RAILWAY NOISE MEASUREMENT METHODOLOGY**

In most environmental noise problems, it is often necessary to distinguish the different contributions of several sources. This procedure is important because, in conformity with the current Italian legislation on noise, every polluting subject must reduce its own part of noise in order to bring the total environmental noise within limits of the law.

It is well known that railway noise is composed of generally easily identifiable sound events generated by single train transits. Thus it is simple to measure the sound energy value \((L_{AE})_i\) or \((L_{Aeq})_i\), related to the \(i\)-th single event. Eq. (1) gives the values of the equivalent sound level \(L_{Aeq,TR}\) calculated on the two reference periods \(T_R\): day-time (06-22) and night-time (22-06):

\[
L_{Aeq,TR} = 10 \log \left[ \frac{1}{T_R} \sum_{i=1}^{n} 10^{0.1(L_{AE})_i} \right] \text{dB(A)} \tag{1}
\]

where \(n\) is the number of transits during the \(T_R\) period.

In case of spurious events, that is to say events that could not be clearly associated to a train pass-by, the inspection of their time-history usually makes a decision possible. If there is still a residual doubt or if some events show evident anomaly due to, for example, the overlap with noise generated by other sources, then those events have to be rejected from the calculation. The rejection procedure could introduce some approximations but these can be minimized. In fact it is possible replace the rejected values with the arithmetic mean value obtained by the \((L_{AE})_i\) values definitely associated with the train transits. On the other hand, if there are relatively few uncertain or spurious events, for example 5% of the total train transits, then they can be left out of the account. The calculation error is small.

The outlined measurement procedure can be applied straightforwardly in those situations where the railway noise source is the only one or it is decidedly prevalent in comparison with other ones. But very often there is a multiplicity of almost equivalent noise sources. Urban areas where a railway and roads can be very close to each other represent typical cases. It becomes difficult to discriminate the single source contribution in the total environmental noise. In spite of the complexity, in many situations it is still possible to measure only the railway noise. The measuring geometry is schematically represented in Fig. 1.

There are at least two measurement points \(P_e\) and \(P_i\). The first one (reference point) is close to the railway tracks; the second one (noise immission point) is on the facade of a building which is usually far from the railway. Otherwise the simplified procedure above could obviously be applied.

**FIGURE 1.** Geometry of the system tracks - \(P_e\) - \(P_i\)
The calculation of $L_{Aeq,TR}$ on the building facade is based on the following equations:

$$[(L_{Aeq,TR})_i]_{P_i} = [(L_{Aeq,TR})_i]_{Pr} - \Delta_i \ dB(A) \quad (2)$$

$$L_{Aeq,TR_k} = 10 \log \left[ \sum_{j=1}^{k} 10^{A_{AE} \ (L_{Aeq,TR})_j} \right] \ dB(A) \quad (3)$$

The term on the left in Eq. (2) is the sound equivalent level at $P_i$ due to trains passing on the $j$-th track. It is given by the value of the same acoustic magnitude measured at $P_r$, taking into account the attenuation $\Delta$ due to the noise propagation effects between the two considered points. It can be calculated as the average of the differences between $L_{AE}$ values measured at $P_i$ and $P_r$ for a few train transits. Eq. (3) gives the whole sound equivalent level at $P_i$ as a sum of contributions of the $k$ sources ($k$ tracks). Some conditions have to be in place so that the procedure can give reliable results:

- $P_r$ has to be in an acoustic free-field as much as possible;
- simultaneous measurements have to be carried out at $P_i$ and $P_r$ points for at least a few transits (see below);
- the duration of the measurement at $P_r$ must be at least 24 hours;
- the transit tracks must be distinguished exactly in order to proceed to a correct calculation of $\Delta$ values (see the conditions on the distances below the drawing of Fig. 1);
- well identified railway noise events have to be measured only at the $P_i$ point (at $P_r$ there is no problem of this kind) for a statistically significative number of passenger and freight train transits on every track (*) .

### Measuring equipment

Other important information can be obtained by the measurement at $P_r$ point: the acoustic behaviour of the railway sources described by the noise spectrum in octave or 1/3 octave band. It is also necessary to measure the speed and length of the trains.

The measuring equipment used is partially shown in Fig. 2. There is also a video camera triggered by a signal generated by the approaching train and an electronic system for measuring train speed and length (start and stop clock signals are given by two pairs of IR cells fixed at a well defined distance).

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1 From the acoustical point of view “well identified” means that the sound level produced by the train transit is 10 dB(A) higher than the background noise level due to the other sources.

### A GSM modem links the remote measuring system to a computer. The data recorded by the sound analyzer is periodically transmitted to the computer, which can also send setting up, and controlling signals. Short films (a few seconds long) recorded by a video camera allow inspection of the type of train (ETR500, Intercity, etc.) and, above all, the ability to distinguish which transit track is used. So it is possible to establish the distance between the train and the measuring point.

The spectral compositions of the noise generated by train transits are organized in a data base using the prediction model of railway noise applied to sound abatement design systems, e.g. acoustic barriers.

### Some results of sound emission of FS trains

Table 1 reports sound emission values of some FS main trains. The $L_{Aeq}$ values are referred to the time exposure defined as the interval between the two instants where the function $L(t)$ values are 10 dB(A) below $L_{Amax}$ value.

### Table 1. Mean and S.D. values of speed and noise levels

<table>
<thead>
<tr>
<th>Train type and usual composition</th>
<th>Speed (km/h)</th>
<th>$L_{Aeq}$ [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC/EC/EN (Loc + 12 cars)*</td>
<td>197 ± 4</td>
<td>89.6 ± 1.0</td>
</tr>
<tr>
<td>Regional (Loc + 9 cars)*</td>
<td>90 ± 4</td>
<td>83.4 ± 2.1</td>
</tr>
<tr>
<td>Electric self powered (7 cars)*</td>
<td>117 ± 44</td>
<td>82.0 ± 1.6</td>
</tr>
<tr>
<td>Express (Loc + 15 cars)*</td>
<td>149 ± 3</td>
<td>84.5 ± 1.8</td>
</tr>
<tr>
<td>ETR 450/460/470/480 (9 cars)*</td>
<td>217 ± 40</td>
<td>88.2 ± 2.1</td>
</tr>
<tr>
<td>ETR 500 (Loc + 12 cars + Loc)*</td>
<td>209 ± 16</td>
<td>87.7 ± 1.3</td>
</tr>
<tr>
<td>Freight (Loc + 25 cars)*</td>
<td>100 ± 5</td>
<td>88.6 ± 1.1</td>
</tr>
<tr>
<td>TAF urban service (4 cars)+</td>
<td>107 ± 6</td>
<td>87.7 ± 1.8</td>
</tr>
<tr>
<td>Diesel self powered (4 cars)+</td>
<td>72 ± 8</td>
<td>84.7 ± 2.0</td>
</tr>
<tr>
<td>Diesel/Electric (Loc + 4 cars)+</td>
<td>67 ± 8</td>
<td>82.4 ± 0.8</td>
</tr>
</tbody>
</table>

* at 25 m from the track centre; 3.5 m above the rail level
+ at 7.5 m from the track centre; 1.2 m above the rail level
The STAIRRS Project

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The EU funded STAIRRS project includes three Work Packages. WP1 (Railway Noise Strategy Support System) will develop cost/benefit software to assess various noise reduction options (optimised wheels, new brake blocks, size/position of barriers) in order to identify optimal combinations of noise reduction strategies applicable at national or European level. A decision support system for noise policy makers supported by a European rail traffic database, topographical maps and cost data will be produced. WP2 (Characterisation & Classification Methodologies) will develop methodologies (measurement and calculation tools) for describing different types of railway track and vehicles separately and propose an appropriate classification system for trains and track types, aimed at determining the contributions of vehicle and rail to noise emission. Main output of the work will be a database containing train and track noise data from each participating country with analysis and assessment and a proposed classification system. WP3 (Consensus Building Workshops on Reducing Noise from Trains) will provide the relevant information to build a strategy and reach consensus on the priority action areas for noise source improvements and on the optimal balance between source noise reduction and noise abatement, discuss the opportunities for the optimisation of rules, legislation and voluntary agreements.

\textbf{INTRODUCTION}

In the last ten years there has been increasing pressure from residents, environmental lobbyists and legislators to reduce railway noise levels. In Switzerland, Austria and Italy (amongst other countries), legislation has been introduced that sets tight limits on the amount of noise railways are allowed to create (and inherently the traffic levels they can achieve). A number of Working Groups has been established by the EU’s Environment Commission to determine the EU’s future policy on potential noise legislation. Unless due consideration of all the factors (economic, technical, environmental) is taken into account, new legislation could have a potentially serious impact on rail transport and could particularly interfere with the environmentally encouraged growth of traffic from other sectors such as road and air.

The STAIRRS (Strategies and Tools to Assess and Implement noise Reducing measures in Railway Systems), funded within the 5\textsuperscript{th} Framework Program of the EU for the 2000-2002 triennium, aims at providing the relevant information needed for informed discussion and decision making required to ensure that a fair but effective solution is reached \cite{1}. STAIRRS builds upon the results of previous research projects (Silent Freight, Silent Track, EUROSABOT, EUROECRAN, METARAIL) that have done much to further understanding of railway noise generation mechanisms, to develop noise prediction and modeling software and to derive low noise components for potential application.

At the same time that the technical and environmental developments are taking place, the railways themselves have been undergoing a radical change. Previously single entity railway organisations are being split to establish separate companies with responsibilities for service operation and infrastructure management and maintenance. In this new environment, and given the legislative liability inherent in exceeding any prescribed noise limits, it is necessary to address the problem of how the responsibility for noise generation will be apportioned.

\textbf{WORK PACKAGES}

The STAIRRS program comprises of three distinct work packages, the contents of which is briefly described hereunder.

\textbf{WP1 - Railway Noise Strategy Support System}

The objective of WP 1 is to provide a Europe wide software tool to determine the large scale environmental impact of railway noise based on a common European database incorporating data on European rail traffic and their noise characteristics, topographical maps, and comprehensive cost data for the different noise mitigation options. The end user of the software will be decision makers at European and national levels as well as members of the consortium.

The software tool will provide the basis for addressing issues such as quantify the reduction of Annoyance for different noise policies (benefit),
consider the economic effects of policy options (cost), compare country specific solutions, determine night-time freight capacity, study the consequences of noise measures on the viability of rail transport, and assess the impact of operational measures.

WP2 - Characterisation & Classification Methodologies

Currently specified methods for measuring the noise from individual trains or vehicles in trains are limited in their ability to produce repeatable and reproducible data that can be reliable for the Cost Benefit Analysis of WP1, for legislative guidelines or for checking compliance. It is possible that in the future, financial bonus/penalty systems will be introduced for the use of quiet/noisy rolling stock and track types, and thus vehicle types and track superstructure types will need to be classified. To implement such a system requires a reliable method for measuring the noise creation of train/track combinations.

Investigation of this topic has been carried out in the METARAIL project [2] which focused on measurement methods for the assessment of railway noise creation. It was demonstrated that:

- It is feasible to improve the repeatability and particularly the reproducibility of railway pass-by noise measurements significantly, using basic methods by control of track roughness, train speed and site conditions concerning sound propagation.
- Methods could be developed and optimised through which it is feasible to separate the track and vehicle contribution to the overall noise level. However, these methods need further development and validation before they can be applied and accepted as industrial practice.

Remaining differences between measurement results of the same vehicle on different sites are estimated to be due to differences in:

- site propagation conditions,
- track dynamic behaviour,
- track roughness.

For more repeatable results the values of these parameters need to be accurately identified so that suitable corrections can be applied as necessary.

WP2 of the current proposal extends that work and has the following objectives:

- To provide methodologies with several levels of detail to enable characterisation of railway vehicles and railway track separately. By these means it will be possible to apportion responsibilities between infrastructure authorities and train operators, relate the effects of noise reduction measures on vehicle or track to different situations required for the Cost Benefit Analyses, enable data to be transferred from one situation to another, and propose a classification method
- To develop and validate the measurement and associated calculation tools needed to fulfil the methodologies mentioned above.
- To perform measurements, using the new techniques in order to demonstrate the classification methodology and to provide inputs to the railway noise data base developed by WP1.

Achievement of these objectives in the form of reports and proposals will be the deliverables for this Work Package.

WP3 - Consensus Building Workshops

Supporting WP’s 1 and 2, a number of consensus building workshops will be organised to take account of input from Railway operators, Infrastructure management, capacity regulators, UIC/CER/UIP, legislators from EU, national authorities and local authorities, industry, UNIFE, consultants and universities.

The intention of the workshops is for the various parties to reach agreement on how to balance the environmental needs of the Community with the available technical solutions and costs for implementation within a realistic timescale. They will further establish a consensus view of the priority areas of source noise improvements.

ACKNOWLEDGMENTS

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REFERENCES

Acoustic Characterisation of Railway Tunnel Portals
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The 78.5 km long, Bologna-Firenze High Speed railway runs in tunnels for 94% of its length. Knowledge on noise emission from railway tunnel portals is limited: thus, an experimental study aimed at verifying if and to which extent tunnel portals are a significant noise emission source has been necessary. The experimental campaign performed along the Firenze-Roma direct line has demonstrated that emissions are negligible when the High Speed or Intercity train runs inside the tunnel, while, during pass-by outside the tunnel, a reduction of 3 dB(A) Leq compared to fill sections was detected.

INTRODUCTION

The 78.5 km long, Bologna-Firenze High Speed (HS) railway runs in tunnels for 94% of its length. The studies on environmental noise impact, and the related noise abatement actions, have been aimed at the tracts running on fill or cut sections, on viaducts, and at tunnel portals.

Tunnel portals represent sound emission areas, whose characteristics do not fall into the standard types of sources treated by railway noise prediction codes, and for which the scientific literature [1,2], mainly addressed at road tunnels, proposes contrasting experimental data. It has therefore been necessary to:

a) Define if, and to which extent, the tunnel portal determines an increase of the sound pressure level compared to a fill section or viaduct (Phase 1).
b) Determine the sound power emitted by the tunnel portal (Phase 2a) and the vertical and horizontal radiation diagrams (Phase 2b).
c) Identify the best ways of simulating the source in a ray-tracing numerical simulation scheme (RAYNOISE code).

The experimental campaigns have been performed on the Firenze-Roma direct line (Galleria Castiglione, Viadotto Ascione), which is the only existing Italian railway infrastructure whose characteristics are similar to the future HS lines, and on which HS trains (such as the ETR 460 and ETR 500), as well as Intercity (IC) trains are presently in service.

EXPERIMENTAL CAMPAIGN

Phase 1 aims at determining the effect on sound level due to the presence of the tunnel. Measurements have been performed in 3 points at 3.5 m height above the track: P1, 25 m from the tunnel entrance, 25 m from the track axis; P2 and P5, on the axis of the fill and viaduct tracts, 25 m from the track. In this phase, synchronised audio recordings during 36 train pass-by have been performed.

In phase 2a, measurements have been made in the positions indicated in Figure 1. Points P1-P4 lay on the semi-arch of radius 8.60 m, centred on the geometric axis of the tunnel shaft and subdivided into sectors of 16° angular aperture, 3.5 m from the tunnel entrance; points P5 and P6, 25 m from the entrance, 3.5 m and 25 m from the track axis, 1.5 m and 3.5 m height; P7, in the niche about 100 m from the entrance, the microphone flush with the tunnel inside lining, 1.5 m high. Synchronised audio recordings during 49 train pass-by have been performed.

FIGURE 1. Position of the microphones

In phase 2b, measurements have been performed in points P8-P16 indicated in Figure 1. P8-P11 are situated on a horizontal arch obtained by cutting a sphere of radius 25 m and centre coinciding with the centre of the tunnel entrance with a horizontal plane at +3.5 m height; the microphones cover a 71.1° arch;
P12-P16 are situated on a vertical arch obtained by cutting a sphere of radius 25 m and centre coinciding with the centre of the tunnel entrance, with a vertical plane passing through the point 25 m from the tunnel entrance, at the minimum distance permitted by the tracks and the supply cables. P7 is in the niche about 100 m from the tunnel entrance with the microphone flush with the tunnel inner lining 1.5 m height; synchronised audio recordings have been performed during 52 pass-by.

The analysis of the experimental results allow to conclude that, during pass-by of HS trains such as ETR500 and ETR460, fill section tracts emit on the average 2.3 dB(A) more than the tunnel portal, with a standard deviation of 0.86 dB(A). Such trend is confirmed by data of IC trains: fill section tracts emit on the average 2.5 dB(A) more than the tunnel portal, with a standard deviation of 1.6 dB(A).

These average values have been calculated taking into account recordings of HS and IC pass-by having a speed differential between the two measurement points respectively less than 5 km/h (HS) and 10 km/h (IC). The variance of the acoustic data associated to such speed ranges is of the order of ± 0.5 dB(A).

The HS trains are characterised by an average value of pass-by Leq (considering a Lmax – 20dB(A) cutoff level) of 86.6 dB(A) in front of the portal and 87.2 dB(A) in front of the fill section. Spectral analyses confirm the presence of very low frequency components near the portal, of negligible significance in relation to legislative limits compliance.

The analysis of synchronised multiple spectra furthermore indicates that the SEL measured with the train outside the tunnel practically coincides (with differences of 0.2 dB(A) for HS and 0.3-0.4 dB(A) for IC trains) with the pass-by SEL. The fact that the portal is a negligible emission source is confirmed by the fact that the difference between the SEL values when the train is outside and inside the tunnel is about 14 dB(A) for HS and 11-12 dB(A) for IC trains.

**NUMERICAL ANALYSIS**

In order to extend the field results to the tunnel entrances that are present along the Bologna-Firenze tract, a technique capable of reproducing the measured sound field has been applied. Such technique is based on the ISO 9613 standard, i.e. on the concept that the environment acts as a transfer function between the sound sources and the microphones used for the field measurements. The unknown sound power values have been determined with a numerical model of the area facing the tunnel entrance, based on he Raynoise numerical simulation code, starting from the measured sound pressure levels.

The numerical scheme of the tunnel portal has been determined through trial simulations aimed at identifying the system of sources that best fits the objective of reproducing with an adequate degree of accuracy the sound field emitted by trains passing inside the tunnel.

The acoustic modeling of HS and IC trains that best fits the experimental data, for trains entering the tunnel, consists of one omnidirectional point source situated at the entrance section, in correspondence of the track axis 4 m above the track level, plus one directional point source (directivity angle of 30° with respect to the horizontal and vertical planes) on the axis of the opposite track, still on the entrance plane at 4 m height. Figure 2 shows the simulation of the acoustic field in proximity of the tunnel entrance during a HS train pass-by.

**FIGURE 2. SEL for HS train entering the tunnel**

For trains coming out of the tunnel, the emission sources consist of one omnidirectional point source situated at the entrance section, in correspondence of the track axis 4 m above the track level, plus one directional point source (directivity angle of 30° with respect to the horizontal and vertical planes) on the axis of the opposite track, still on the entrance plane at 4 m height.

Comparison between measured and simulated data show an overestimate of the model of 0.1 – 2 dB(A); only at some points near diffraction edges or remote from the entrance plane the differences reach 3 - 4 dB(A).

**REFERENCES**

The interior noise level in a rail vehicle affects significantly the comfort of the passengers. Even though high frequency components of the noise are successfully isolated in the coaches, low frequency components are still effective and passengers do have complaints. In this study (i) questionnaires were designed in order to assess first, the rating of the inside coach noise by the passengers then, their judgements about the traveller comfort (ii) interior noise level in each coach was measured (iii) saliva samples were taken from nine male volunteers just before and just after the voyage.

**ASSESSMENT OF NOISE CLIMATE IN RAILWAY COACHES**

A great deal of study has been done on the effect of noise caused by rail transportation and criteria for acceptable noise has been established [1]. Much, however, has been left to be done for the noise climate inside the railway coaches. Now, trains are more rapid and coaches are more lighter compared to the past. This gives rise to high levels of low frequency energy and thus a steep slope at low frequencies. Spectra, of a continuous noise, having a slope of $-5 \text{ dB/octave}$ is regarded as satisfactory [2] and articulation index=$0.5$ is assumed to be the threshold of comfort [3].

In this study, the noise environment of the rail coaches is assessed not only by the results of questionnaires but also by the measured spectra.

**Questionnaires**

The questionnaires (having 24 questions) are distributed and collected during a 4.5 hr voyage in an intercity train. 48% (52%) of the passengers were women (men). They were mostly young (36% at 20-29 yrs).

54% of the travellers have assessed the interior noise as "not high", but 30% were disturbed.

The passengers seemed to prefer "Reading" to "Talking with their neighbours". 31% of them were disturbed, while reading, by the noise level in the coach.

**Measured Spectra**

The noise level in the coach was measured at, at least, 3 points. Seat 1 was ~ on the bogies and just in front of the door. Whereas seat 34 was ~ at the middle of the coach. As can be seen the SPL level at $f\geq 25 \text{ Hz}$ is above the threshold level and the slopes of the spectrum, at $16 \text{ Hz} \leq f \leq 200 \text{ Hz}$, are steep for both seats. Independent of the seat location the turning, in this low frequency range, is at 40 Hz. The turning point
Disturbance of "Reading in 200 Hz ≤ f ≤ 10000 Hz is location dependent. It is at f=1000 Hz for Seat 1 and f=500 Hz for Seat 34. The spectrum slope of the seats, however, does not differ significantly. It is worth noting that, independent of "where they sit", 54% of the passengers have rated this noise level (72 dB(A) for Seat 1 and 61.6 dB(A) for Seat 34) as "not high".

Even though, passengers are more tolerant to the rail noise compared to the noise at home, they were not without stress. The analysis of the saliva of 9 male volunteers have shown that [K⁺]/[Na⁺] of 4 volunteers have increased (min:8%, max:85%) at the end of 4.5 hrs of voyage. But [K⁺]/[Na⁺] of 4 volunteers have decreased (min:8%, max:53%). The increase in [Na⁺] is more significant compared to [K⁺]. More volunteers have to be tested in order to arrive to a specific conclusion.

ACKNOWLEDGEMENTS

This work is dedicated to Ertuğrul Birlik.

REFERENCES

Measurements and Analysis of the Noise to which Passengers are Exposed in Istanbul Metro

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Recently, noise problems are gaining increasing importance in railway vehicles for passengers. The noise are controlled inside railway vehicles for one or more of four reasons, comfort, ease of voice communication, freedom from hearing damage risk, and ability to hear warning signals that originate outside. The internal noise levels in railway vehicles have been decreased step by step during recent years due to the fact that stiff requirements on passenger comfort. This paper presents the results of measurements and analysis of the noise to which passengers are exposed in Istanbul metro. These measurements demonstrate the role of wheel and rail maintenance in minimizing noise in the metro.

INTRODUCTION

Disturbance caused by noise is one of the most important environmental health consequences of the transport vehicles. Over a number of years, investigations in different countries have shown that noise affects different activities and causes a poorer life quality. There is thus a great need to control noise caused by transport. Investigations of the relationship between exposure to originating from different noise sources in the transport vehicles and effects among the exposed population form an important basis for technical measures to limit noise generation and to regulate noise levels. Such investigations have studied the extent of annoyance among persons exposed to different types and levels environmental noise.

Interior noise is often a problem in the railway passenger car during transportation. This noise may damage hearing if consistently of a high level or an impulsive nature, impair safety by making warnings difficult to hear, hinder communication between passengers, cause fatigue and loss of concentration and be annoying. At the same time, acoustic comfort in railway vehicles for passengers is becoming more and more important parameter. Engineering criteria for specifying acceptable noise levels and for rating them in those locations have been developed over the past half century.

Although, railway lines ensure high quality guidance, the track still has irregularities which cause noise and vibration, such as: defects in truck level, alignment or gauge, welding or rolling defects, rail joints, variable vertical stiffness of the truck (e.g., bridges), level crossings, acceleration and breaking.

Attaining better acoustic characteristics in future railway vehicles requires a better understanding of the sound phenomena taking place in those cars. The major problem is to prevent the noise generated by exterior sources, as the wheel-rail contact and traction system, from penetrating into the passenger compartments. This study reports interior sound measurements and analysis performed in operating conditions on the Istanbul Metro car.

MEASUREMENTS AND ANALYSIS IN THE RAILWAY PASSENGER CAR

Different types of measurements and ratings are used in the control and evaluation of noise depending on purpose. In this study manual measurements of noise levels were performed with a sound level meter in the metro car circulating with passengers on its usual route. One person made A-weighted sound level measurements directly from one station to the next during the time between 08:00 and 20:00, for a period of two hours, using a calibrated microphone on a stand at a level of 1.5 m above the ground.

The statistical analysis of the internal noise of the railway passenger car is shown in Figure 1. The results from the measurements show that, of 1470 measurements, the A-weighted noise level is concentrated around 65 dBA, the level of continuous noise. Corresponding internal noise levels for the railway passenger car are in the range 65-70 dBA, which represent a good compromise between low noise levels, good privacy and speech comprehensibility, but there are tonal and higher frequency components in the noise spectrum. Furthermore, there are interior noise level fluctuations during the transportation that are not desired.

Table 1 shows the equivalent continuous A-weighted noise levels $L_{eq}$, measured according to time intervals in the metro car circulating with passengers on its usual route from one station to the next. $L_{eq}$ is the A-weighted energy mean of the noise level averaged over the measurement period. The continuous steady
noise levels $L_{eq}$ are dissipating between 70.5 dBA and 80.7 dBA.

![Noise Level Distribution](image)

**FIGURE 1.** Statistical analysis of the railway vehicle interior noise.

Table 2 summarises the maximum A-weighted noise levels $L_{max}$ measured according to time intervals in the metro car circulating with passengers on its usual route from one station to the next. The maximum A-weighted noise levels $L_{max}$ are changing between 78.9 dBA and 92.1 dBA.

Table 1. Equivalent continuous A-weighted noise levels $L_{eq}$, measured according to time intervals in the metro car circulating with passengers on its usual route from one station to the next.

<table>
<thead>
<tr>
<th>Stations</th>
<th>Time Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>08 - 10</td>
</tr>
<tr>
<td>Ataköy</td>
<td>73,8</td>
</tr>
<tr>
<td>Başçekievler</td>
<td>72,9</td>
</tr>
<tr>
<td>Bakırköy</td>
<td>71,6</td>
</tr>
<tr>
<td>Zeytinburnu</td>
<td>74,7</td>
</tr>
<tr>
<td>Merter</td>
<td>70,4</td>
</tr>
<tr>
<td>Davutpaşa</td>
<td>71,0</td>
</tr>
<tr>
<td>Terazidere</td>
<td>70,5</td>
</tr>
<tr>
<td>Otogar</td>
<td>72,2</td>
</tr>
<tr>
<td>Kartalpınarı</td>
<td>72,4</td>
</tr>
<tr>
<td>Sağmalcılar</td>
<td>73,8</td>
</tr>
<tr>
<td>Bayrampınarı</td>
<td>74,5</td>
</tr>
<tr>
<td>Topkapı</td>
<td>76,6</td>
</tr>
<tr>
<td>Emniyeti</td>
<td>78,2</td>
</tr>
<tr>
<td>Aksaray</td>
<td>76,8</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

The internal noise levels of railway vehicles have been gradually decreased during recent years due to tougher requirements on passenger comfort, on external noise and an improved infrastructure. To modify and improve aural conditions in the metro car, the relationship between sound sources and the characteristics of the car must be understood. The reduction required in the railway passenger car depends primarily on the function of the inner part of the vehicle and the existing noise level within it. The overriding criteria, which must always be met, is that relating to hearing damage. In less noisy circumstances the allowable noise level may be defined by the requirements for adequate communication, passenger comfort, or avoidance of complaints from the passengers at large.

**REFERENCES**

Parametric Sensitivity Analysis of Railway Noise Impact Assessment Modeling

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This paper presents a parametric sensitivity analysis for the Comprehensive Community Noise Model (CCNM), as applied to simulate railway noise emissions. Various scenarios are explored including train technology, physical properties and speed, as well as barrier and receptor locations along the alignment to identify the worst performing parameters associated with the highest noise exposure levels.

INTRODUCTION

Railway noise constitutes a serious environmental concern in areas traversed by transit systems. The level of exposure to transit noise is a function of train technology and length, rail car type, vehicle speed, installed auxiliary equipment, type of track work, as well as the proximity of the railroad right of way (ROW) to existing buildings, or planned land use [3, 4]. This paper aims at defining railway parameters that are associated with noise exposure through the testing of a newly developed Comprehensive Community Noise Model (CCNM), which simulates noise levels at user specified receivers [2].

METHODOLOGY

A sensitivity analysis to changes in receptor and noise barrier locations, track length, and train characteristics was conducted. In all scenarios receptors were located midway along the track, at different distances along the track’s perpendicular bisector to obtain a noise profile up to 1,000 ft (305 m) away from the railway running surface. Average A-weighted noise levels were then obtained in terms of $L_{eq}$ and $L_{max}$ for each receptor point by simulating train passby incidents. Other noise sources, such as motor vehicles, aircraft, and other point sources, were assumed to be accounted for in the background level which means that the simulated values above background reflect the contribution of the transit system to ambient noise levels.

MODEL SIMULATIONS

Base Case Results

For the base case with a downtown background noise level of 70 dBA, predicted average noise levels ranged from about 75 dBA at 20 ft (6 m) away from the railway to 70 dBA at 1,000 ft (305 m), with maximum noise levels reaching 101.1 dBA close to the track (Figure 1). Average and maximum noise levels stabilize at 70 dBA and 100 dBA, respectively, at receptors located further than 500 ft (152 m) away from the track, implying that the noise emitted by a train passby incident converges to the background noise level. For background levels less than 70 dBA, there are some differences in simulated noise levels for receptors close to the track (up to 1.3 dBA at 20 ft (6 m)). These differences increase with receptor distance from the track, due to the influence of background noise levels, reaching up to 13.5 dBA at 1,000 ft (305 m). This stresses the significant role of the background noise level, which is a controlling factor of ambient noise perception.

<table>
<thead>
<tr>
<th>Noise level (dBA)</th>
<th>Receiver distance from track (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>0</td>
</tr>
<tr>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>75</td>
<td>200</td>
</tr>
<tr>
<td>85</td>
<td>300</td>
</tr>
<tr>
<td>95</td>
<td>400</td>
</tr>
<tr>
<td>105</td>
<td>500</td>
</tr>
</tbody>
</table>

FIGURE 1. Base case average noise levels

Sensitivity Analysis Results

Results of the sensitivity simulations to various parameters in terms of changes in noise levels with
respect to baseline conditions are summarized in Table 1. All receivers located at distances larger than 500 ft (152 m) away from the track experience the background noise level of 70 dBA.

This is illustrated by the increase in noise levels 20 ft (6 m) away from the track brought by the shift from 4 – 8 rail cars (0.7 dBA) versus that associated with the shift from 8 – 12 rail cars (0.5 dBA). While the number of additional cars was the same in both cases, the shift from a shorter train yielded a larger noise amplification. Furthermore, increasing the number of trains per day by 30, from 26 – 56, resulted in a 2 dBA increase in noise levels at 20 ft, whereas an increase of 36 trains, from 56 – 92, increased noise levels by only 1.6 dBA, implying that the increase in noise levels brought by an additional day train is not linear but rather larger for lower numbers of commuting trains per day. The noise contribution per rail car decreases further with increasing distance from track.

While the variation of other system parameters may yield relatively insignificant noise reductions, sometimes indiscernible to the human auditory system, appreciable noise reduction may still be achieved through their simultaneous application. This however, does not eliminate the need for intervention at the receiver level, through sound barriers and/or soundproofing.

### LIMITATIONS

The simulation exercise had several limitations, some pertaining directly to the model and others to the assumed parameters. The major drawback however, was the unavailability of transit noise measurements, necessary for model calibration. Furthermore, the point versus line source approximations of a train remain debatable. Other limitations to simulating real life cases include the assumption that all tracks were straight, the model’s limited range of acceptable track lengths, which led to the consideration of 20,000 ft long tracks, and finally, its inability to differentiate between day and night trains, which can be attributed to the early development stage of the software.

### REFERENCES


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Δ dBA from base condition at receiver location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track length (ft)</td>
<td>20 ft 50 ft 100 ft &gt; 200 ft</td>
</tr>
<tr>
<td>10,000</td>
<td>+0.9</td>
</tr>
<tr>
<td>14,000</td>
<td>-0.4</td>
</tr>
<tr>
<td>Locomotive type</td>
<td>Heavy diesel</td>
</tr>
<tr>
<td>GE E– 60CP</td>
<td>-2.4</td>
</tr>
<tr>
<td>British Rail Diesel</td>
<td>-1.3</td>
</tr>
<tr>
<td>European ASEA</td>
<td>-2.6</td>
</tr>
<tr>
<td>Number of engines</td>
<td>2</td>
</tr>
<tr>
<td>Rail car type</td>
<td>Disk brakes</td>
</tr>
<tr>
<td>Intercity Deutsche Bahn</td>
<td>-1.2</td>
</tr>
<tr>
<td>MkII, British</td>
<td>-0.3</td>
</tr>
<tr>
<td>Number of rail cars</td>
<td>4</td>
</tr>
<tr>
<td>12</td>
<td>+0.5</td>
</tr>
<tr>
<td>Train speed (mph)</td>
<td>30</td>
</tr>
<tr>
<td>110</td>
<td>+3</td>
</tr>
<tr>
<td>Number of trains per day</td>
<td>26</td>
</tr>
<tr>
<td>92</td>
<td>1.6</td>
</tr>
<tr>
<td>Night trains</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>-0.3</td>
</tr>
<tr>
<td>Sound barrier location (ft)</td>
<td>10</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>Receiver locations along track</td>
<td>0</td>
</tr>
<tr>
<td>0.05 L</td>
<td>-0.9</td>
</tr>
<tr>
<td>0.325 L</td>
<td>+0.2</td>
</tr>
</tbody>
</table>
Monitoring of sound levels of present day trains on the Spanish railway network

A. Gimenez, A. Marin, A. Sanchis, J. Romero, S. Cerdá\textsuperscript{b} and L. Faus\textsuperscript{a}

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\textsuperscript{b}Grupo de Acustica Arquitectonica, Ambiental e Industrial, Universitat Politècnica de Valencia. Spain

Within the Spanish state there no defined models for the measurement of the sound of railway traffic currently accepted by the government, for this reason it is possible to use any of the widely accepted international systems on new lines. In this study the intention is to find a simple model of sound evaluation made by trains which already use, or in the foreseeable future will use the Spanish railway network. Eight different kinds have been monitored in the study. The sound level of each train has been measured considering as parameters speed and length of the train and subsequently using the method developed in France and published in “Guide du Bruit”.

INTRODUCTION

Within the Spanish state there no defined models for the measurement of the sound of railway traffic currently accepted by the government, for this reason it is possible to use any of the widely accepted international systems on new lines. In this study the intention is to find a simple model of sound evaluation made by trains which already use, or in the foreseeable future will use the Spanish railway network. Our reference point was the French model [1] developed in 1980. This model uses speed and length to describe the train noise to determine how sound level decreases with distance. We chose this model because it is very simple. Noise measures were made and the French model was evaluated.

Measures description.

Measures were registered at eight different positions in the first season, and at five different positions in the second season. Sonometers were distributed as we could see in Figure 1. We measured $L_{eq}$, $v$ and $l$ for each train. The train sound was recorded and thus frequency analysis was possible.

GUIDE DU BRUIT MODEL

This model was published in 1980 [1]. Although it was made from measures that today are possibly obsolete, this model is very simple and thus it will be an appropriated model for our measures. According to this model, $L_{max}$ is a function of the kind of train, distance and speed. We could measure at a distance $d_0$ and speed $v_0$ the value of $L_{max}$, and then we can use the expressions

\[ L_0 = L_{max}(d_0, v_0) \]  
\[ L_{max} = L_0 - k \log \frac{d}{d_0} + 30 \log \frac{v}{v_0} \]

where $k$, considering no energy absorption and thence only geometric divergence, controls the attenuation of the noise with the distance. This parameter is a function of the kind of train. The model propounds concrete values for $k$ and $L_0$ for each kind of train and specifics $d_0$ and $v_0$. 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{distribution_of_measurement_points.png}
\caption{Distribution of measurement points.}
\end{figure}
To verify the model we used a reference distance $d_0 = 25 \text{ m}$, and the $L_0$ values obtained from the model for the mean speed of each train. Therefore the speed term in equation 2, vanishes. Using a linear regression model we can obtain the values of $k$ and $L_0$ that better adjust to the measures. These results are showed in Table 1.

Table 1. Model verification

<table>
<thead>
<tr>
<th>Train</th>
<th>$V$ (km/h)</th>
<th>$l$ (m)</th>
<th>$L_0$ model</th>
<th>$L_0^\text{exp}$</th>
<th>$k^\text{model}$</th>
<th>$k^\text{exp}_{dB(A)}$</th>
<th>$k^\text{exp}_{63\text{Hz}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave</td>
<td>275</td>
<td>200</td>
<td>101</td>
<td>87.9</td>
<td>15</td>
<td>19.7</td>
<td>11.6</td>
</tr>
<tr>
<td>Euromed</td>
<td>200</td>
<td>200</td>
<td>97</td>
<td>84.7</td>
<td>15</td>
<td>30.7</td>
<td>16.9</td>
</tr>
<tr>
<td>Talgo-2000</td>
<td>200</td>
<td>150</td>
<td>97</td>
<td>84.3</td>
<td>15</td>
<td>24.2</td>
<td>14.4</td>
</tr>
<tr>
<td>Talgo</td>
<td>200</td>
<td>135</td>
<td>97</td>
<td>88.9</td>
<td>15</td>
<td>39.9</td>
<td>17.0</td>
</tr>
<tr>
<td>Arco</td>
<td>200</td>
<td>125</td>
<td>97</td>
<td>90.0</td>
<td>15</td>
<td>35.8</td>
<td>18.5</td>
</tr>
<tr>
<td>Estrella</td>
<td>160</td>
<td>280</td>
<td>94</td>
<td>94.6</td>
<td>12</td>
<td>40.8</td>
<td>15.2</td>
</tr>
<tr>
<td>Short</td>
<td>160</td>
<td>80</td>
<td>94</td>
<td>82.0</td>
<td>17</td>
<td>38.1</td>
<td>19.4</td>
</tr>
<tr>
<td>Goods train</td>
<td>100</td>
<td>350</td>
<td>94</td>
<td>85.6</td>
<td>12</td>
<td>32.1</td>
<td>15.2</td>
</tr>
</tbody>
</table>

**MODEL EVALUATION**

To verify the model we used a reference distance $d_0 = 25 \text{ m}$, and the $L_0$ values obtained from the model for the mean speed of each train. Therefore the speed term in equation 2, vanishes. Using a linear regression model we can obtain the values of $k$ and $L_0$ that better adjust to the measures. These results are showed in Table 1.

$L_0$ revised

From Table 1 we can conclude that it is necessary a revision of $L_0$ values proposed in the French model. Only Estrella train has a negligible difference with the model. In the rest of the cases the model proposes sound levels that they are between 7 and 13 dB above the registered. We think that possible reasons of this fact, are speed dependence or the improvements in trains and railway networks. Thence the necessity of new measures in France to confirm this fact.

$k$ revised

Concerning the evaluation of the parameter $k$ that controls the distance attenuation, we should consider the attenuation due to geometric divergence and the attenuation due to all the real losses (divergence, absorption...). To calculate the attenuation due to geometric divergence, we can consider the value obtained in the adjustment for the band of 63 Hz. In the band of 63 Hz attenuation due to other aspects different to the own attenuation by geometric divergence should be minimal.

In Table 1, we can see $k^\text{exp}_{dB(A)}$ (attenuation due to all the real losses), and $k^\text{exp}_{63\text{Hz}}$ (an approximation to divergence attenuation). The French model uses a theoretic value for $k$, deduced from the values for a point source ($k = 20$) and a linear source ($k = 10$). For the results we could conclude that it is possible that the model was too much simple.

**CONCLUSIONS**

The evaluation of the experimental data through the French model offers as clear conclusion that the data used in this model should be updated for the Spanish case.

1. The values proposed to $L_0$ are between 7 dB and 13 dB greater to the measured.

2. The French model considers the attenuation with the distance due to geometric divergence. To evaluate this parameter we used the parameter $k^\text{exp}_{63\text{Hz}}$ since in the band of 63 Hz the sound losses due to any other factors should be the minimal possible. The values proposed by the model are something inferior to the obtained for the parameter $k^\text{exp}_{63\text{Hz}}$ too.

The French model is very simple and easy of use, but railway networks and train improvements could cause the necessity of a more complex model. Furthermore, statistical models always implies possible revisions because population change.

**REFERENCES**

Measurement of the Low-frequency Sound Radiated from the Train Using the Microphone Array

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When a train runs in an open section at high speed, various pressure fluctuations are generated. Some researches have been carried out until now about the pseudo-sound observed when the train nose, tail, and pantograph-shield sections pass. However, researches have not been performed so far about the low-frequency sound continuously radiated from the train. In this research, the low-frequency sound was measured with a microphone array to search the sound source. When the microphone array \cite{1} is applied to the low-frequency sound, it is required to assume that the incident wave is spherical. When the spherical wave enters the microphone array, however, its directivity will decrease. Then, a method to improve the directivity is proposed. Basic experiments were conducted to investigate the directivity of the microphone array and the effectiveness of this correction method. Next, the low-frequency sound radiated from high-speed trains was measured with the microphone array by applying the above-mentioned correction method. It has been clarified that the sound sources of the low-frequency sound are in the train nose section and the pantograph-shield section.

**SPHERICAL WAVE CORRECTION METHOD**

The directivity of a microphone array in case the incident wave is spherical is shown in Figure 1. The results of the experiment corresponding to the theory are also shown in the figure. It follows from the figure that the directivity decreases as the frequency becomes lower.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Directivity of microphone array.}
\end{figure}

The reason why the directivity decreases when the incident wave is spherical is shown in Figure 2. That is, even when the angle of incidence is 0 degrees, different amplitudes and phase angles of the sound pressure are observed by different microphones. Then, if the correction method to make these differences 0 is performed, it will be thought that the directivity is improved.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{Relative location of the sound source and microphones in case the angle of incidence is 0 degrees.}
\end{figure}

The correction method is as follows. To correct the amplitude, the sound pressure observed with the j-th microphone is multiplied by \( q_j \). The value of \( q_j \) is given by the following equation,

\[ q_j = \left( 1 + \frac{\lambda_c}{2s} \right)^2, \]

where \( \lambda_c \) is the wave length corresponding to the center-frequency of octave-band and \( s \) is the distance between the 0-th microphone and the sound source when the angle of incidence is 0 degrees. To correct
the phase angle, the observation time of the j-th microphone is delayed \((q_j - 1)/c_0\) where \(c_0\) is the speed of sound.

If the above-mentioned correction is performed, the directivity \(K^2(\theta, \Omega)\) is expressed by the following equation,

\[
K^2(\theta, \Omega) = \left[ \sum_{j=0}^{2n} w_j \cos\left(\kappa_s q_j \left(1 - \alpha_j(\theta)\right)\Omega\right) \right]^2 + \left[ \sum_{j=0}^{2n} w_j \sin\left(\kappa_s q_j \left(1 - \alpha_j(\theta)\right)\Omega\right) \right]^2, \tag{2}
\]

where \(2n + 1\) is a number of microphones, \(w_j\) is the weighting factor for each microphone. And \(\alpha_j\), \(\kappa_s\), and \(\Omega\) are given by the following equations,

\[
\alpha_j(\theta) = \frac{1}{q_j} \sqrt{1 + \left(\frac{\omega_j}{2\pi} - \tan\theta\right)^2}, \quad \kappa_s = \frac{2\pi}{\lambda}, \quad \Omega = \frac{\omega}{\omega_s},
\]

where \(\omega_s\) is the angular frequency corresponding to the center-frequency of octave-band, and \(\omega\) is an angular frequency in octave-band.

The calculation results of equation (2) and its corresponding experiment results are shown in Figure 3. The figure shows that the directivity has been improved by the correction.

![Figure 3](image)

**FIGURE 3.** Directivity of microphone array after spherical wave correction.

### MEASUREMENT RESULTS OF FIELD TEST

The microphone array and the correction method were applied to the low-frequency sound radiated from high-speed trains. The measured frequencies are 8, 16, and 31.5Hz in octave-band. A schematic measurement diagram of the field test is shown in Figure 4.

![Figure 4](image)

**FIGURE 4.** Schematic measurement diagram of field test.

The directive waveforms before and after correction are shown in Figure 5. It has been verified that the sound sources are precisely located by the correction in the field test results as well. It can also be read in the figure that sound sources are mainly in the train nose section and the pantograph-shield section.

![Figure 5](image)

**FIGURE 5.** Directive waveforms before and after correction.

### REFERENCES