Road noise characterization by Harmonoise procedures reviewed for the Italian case

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Several methods have been introduced to describe acoustical properties of road pavements in situ, such as the extended surface technique (Adrienne), the Statistical Pass-By and the Close Proximity methods. In general the aim of these techniques, normed in ISO standards, is to evaluate some indexes that may be representative of noise generation and propagation with respect to tyre-road interaction and surface absorption.
In this paper we use results obtained in the LEOPOLDO project, that involves measurements carried out on many sites all over Tuscany Region characterized by typical conditions of Italian roads, to review the state-of-the-art of acoustical parameters in the modeling of road vehicles showed in the HARMONOISE documents. This task has been accomplished by comparing the theoretical results obtained from the HARMONOISE prediction method with the energy levels measured at the microphone locations close to the road borders, in order to apply corrections to the parameters influencing sound generation and propagation.
As a consequence, we introduce a new parameter, related to transfer function between source and receiver sound energy levels, which involves ground reflection effects, obtaining a more suitable characterization of road surface acoustical behaviour.

1 Introduction

The objective of the HARMONOISE [1] project is to provide a detailed road vehicle source model, in order to describe both noise generation processes and propagation effects to the receivers; its results have been presented in the final document WP 1.1 [2]. According to that, sound level models involve corrections due to road surface characteristics and age, driving and atmospheric conditions, directivity, with a remarkable degree of accuracy.

Regarding sound sources, a distinction between rolling and propulsion noise generation has been reported, by introducing two different sources settled at different heights, each of them sharing both contribution of tyre/road interaction and engine noise, with different rates.

Nevertheless, while applying this model to real Italian study cases (light vehicle pass-bys on ordinary Italian roads) some difficulties may be found, here resumed:

1. Regarding source/receiver transfer functions, it is not in general possible to get suitable physical results from measured levels with a back-processing technique;
2. While comparing theoretical results to *in situ* measurements appreciable discrepancies have been encountered.

These difficulties were overcome by reviewing the analytical procedure to describe propagation processes, introducing the distinction between pavement reflection contribution and the generation one. As a consequence, it is also possible to get a more proper characterization of road surface acoustical behaviour in terms of absorption.

Moreover, this method implies a review in the linear and logarithmic regression coefficients relating sound power levels to vehicle speed [2], separately for the case of both sources located at different heights.

2 The HARMONOISE model

According to the HARMONOISE model, vehicle noise emissions are radiated from two passing point sources, each with a specific height and sound power, representing different contributions from rolling and propulsion noise. These contributions are given by the different rates Q, such that:

$$\begin{cases} W_1 = Q_{1R} W_R + Q_{1P} W_P \\ W_2 = (1 - Q_{1R}) W_R + (1 - Q_{1P}) W_P \end{cases} \tag{1}$$

where W represents the sound power, the index i refers to the two sources placed at different heights, R and P indicate respectively rolling and propulsion noise.

The model introduces normalized transfer functions between j-th SEL and i-th source power levels such as:

$$SEL_{N;i}^{[j]} = L_{W_i} - L'_{C_{ij}} \tag{2}$$

where j refers to two microphone positions, located at 1.2 meters and 3 meters at an horizontal distance d_0 of 7.5 meters from the axle of the investigated lane. In the previous formula, SEL_N is the sound exposure level and L'_{Cij} is the transfer function between source position i and receiver position j; both these quantities are normalized according to the HARMONOISE procedure [3].

As far as it regards power levels, two linear regressions are given respectively for engine and rolling noise:

$$L_{WP}(f) = a_P(f) + b_P(f) \cdot \left(\frac{V - V_{ref}}{V_{ref}} \right) \tag{3}$$

$$L_{WR}(f) = a_R(f) + b_R(f) \cdot \log\left(\frac{V}{V_{ref}} \right) \tag{4}$$

where a_R, a_P, b_R, b_P are coefficients tabled in the HARMONOISE report [2] and V_{ref} is set to 70 km/h. Some further corrections take into account vehicle speed, horizontal/vertical directivity, driving conditions, temperature, age of road surface.

3 Theoretical background

By applying the model equations to the experimental results, some physical constraints have to be respected in order to obtain positive power values, which lead to inequalities that involve SEL differences, energy rates and transfer functions:

$$\frac{Q_{1R} \cdot 10^{\frac{L_{C_{21}}}{10}} + 10^{\frac{L_{C_{22}}}{10}} \cdot (1 - Q_{1R})}{Q_{1R} \cdot 10^{\frac{L_{C_{11}}}{10}} + 10^{\frac{L_{C_{12}}}{10}} \cdot (1 - Q_{1R})} \leq 10^{\frac{SEL^{[2]} - SEL^{[1]}}{10}} \tag{5}$$

$$\frac{Q_{1P}\cdot 10^{\frac{L_{C21}}{10}} + 10^{\frac{L_{C22}}{10}}\cdot\left(1-Q_{1P}\right)}{Q_{1P}\cdot 10^{\frac{L_{C11}}{10}} + 10^{\frac{L_{C12}}{10}}\cdot(1-Q_{1P})} \geq 10^{\frac{SEL^{[2]}-SEL^{[1]}}{10}} \qquad (6)$$

While applying the HARMONOISE model to measurements carried out on Italian roads, such these constraints are not respected in several cases.

Moreover, some discrepancies with the experimental results may be found comparing predicted and measured SEL values.

The aim of this work is to show how to improve the parameters evaluation, obtaining corrections to the HARMONOISE source parameters and transfer functions which may be valid for the Italian case of study.

For this purpose, the instantaneous sound level at the *j*-th microphone location radiated form the *i*-th passing source can be modelled as follows [4]:

$$L_i^{[j]}(t) = 10\log\frac{\bar{k}_{ij}(f)\cdot W_i(f)}{4\pi r_{ij}(t)^2 I_0} \qquad (7)$$

where the time origin is taken when the vehicle is in front of the measurement set-up location.

In Eq.(7) $r_{ij}(t)$ is the time-dependent geometrical source-receiver distance, W_i and I_0 are respectively the sound power and the related intensity reference value (10 ^{12} W/m^2); the averaged $\bar{k}_{ij}$ value is the factor which represents the ground source image contribution.

By defining the tail of the event t_{tail} as the time when the level is getting lower than 10 dB from its peak, the integration over time gives:

$$L_{eq_i}^{[j]} = 10\log\left[\frac{\bar{k}_{ij}(f)\cdot W(f)}{4\pi\cdot I_0\left(d_0^2 + h_{ij}^{\ 2}\right)}\cdot\frac{\arctan 3q_{ij}}{3q_{ij}}\right] \qquad (8)$$

where q_{ij} is defined such that:

$$q_{ij} = \frac{1}{3}\sqrt{10\frac{\bar{k}_{ij}(t=t_{tail})}{\bar{k}_{ij}(t=0)} - 1} \qquad (9)$$

The global not normalized SEL is then computed by considering the contribution of both sources, with the approximations $h_{1j} \cong h_{2j} \cong h_j$ and $q_{1j} \cong q_{2j} \cong q_j$ ($\Delta\varphi_i$ is the angle of view for each event and d_j is the minimum source-receiver distance):

$$SEL^{[j]} = 10\log\left[\frac{1}{2\pi d_j}\cdot\frac{1}{v}\cdot\arctan(3q_j)\right] + 10\log\sum_i 10^{\frac{1}{10}\left[L_{W_i} + 10\log\bar{k}_{ij}\right]} \qquad (10)$$

where v is now expressed in *m/s.*
When the HARMONOISE normalization is introduced [3]:

$$SEL^{[j]}{}_N = SEL^{[j]} + 10\log\frac{d_j}{7.5} - 10\log\left[\frac{\Delta\varphi_j}{2\arctan(5)}\right] \qquad (11)$$

By combining Eq.(2), (10), (11), it can be obtained:

$$SEL^{[j]}{}_N = 10\log\frac{1}{v}\sum_i 10^{\frac{1}{10}\left[L_{W_i} - L_{Ci\to j} + 10\log\frac{50}{3.6}\right]} \qquad (12)$$

So the transfer functions may be calculated as:

$$L_{Ci\to j} = 26.7 - 10\log\bar{k}_{ij} = \Omega - \Delta L_{ij} \qquad (13)$$

where the introduced constant value Ω is fixed for all the experimental sites, and ΔL_{ij} is intended to describe the sound source image contribution, which summarizes the acoustical absorption properties of the road pavement under study. The goal of this work is then to isolate this term in order to get the characterization of the road absorption, and at the same time to find an evaluation of the a_R, a_P, b_R, b_P coefficients, as reported in Eqs. (3), (4), suitable for the case of Italian road pavements.

4 Measurement techniques

In the Tuscany Region the LEOPOLDO project [5] has been planned to develop innovative noise source mitigation techniques based on experimental low noise road pavement layers; in order to characterize their acoustical performances, several sites all over Tuscany Region have been studied, using different measurement techniques such as the Statistical Pass-By (SPB, [6], as modified in the HARMONOISE protocol [3]) and the Close Proximity method (CPX, normed in a draft ISO standard [7], and improved in [8]).

As the first step, a check about power rates Q_{1R} and Q_{1P} appeared to be necessary; in order to characterize the CPX reference vehicle (Citroen Xsara Picasso mounting Green Michelin Energy XH1 reference 185/65/R15 tyres with a mileage between 2000 and 4500 km) a special test site was chosen in Tirrenia (Pisa), with measurements carried out both in pass-by and in coast-by conditions (i.e. with the engine switched off).

The procedure followed and showed in Fig.1 allows the assessment of the all the remaining parameters valid for the reference vehicle.

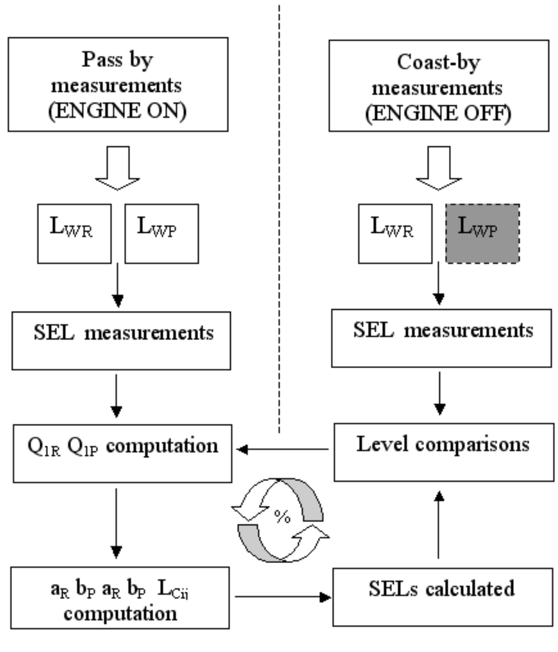


Fig. 1 Computation of power rates and regression parameters for the "Tirrenia" site with SPB+CPX technique.

The procedure consists of an iterative adjustment of the coefficients minimizing the weighted sums of squared residuals and using the statistical t-test between the data collected in the "Tirrenia" test site and model results.

A good agreement with Q_{1R} and Q_{1P} values suggested in literature [2] was found. Regarding source power levels and transfer function coefficients some adjustments have to be done in order to fit the cases of study.

Once all the coefficients had been determined for the test vehicle in the "Tirrenia" test site, it was possible to extend the analysis to the real traffic case, for which no coast-by transits are in general available. Ten sites were selected all over Tuscany Region, to get a complete characterization of typical Italian main regional roads, following the analysis pattern shown in Fig.2.

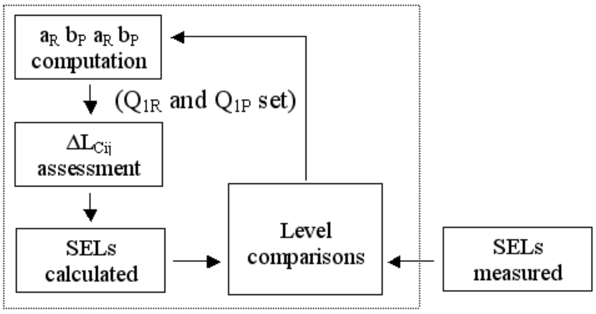


Fig. 2. The computational technique used to best estimate the source parameters

Once the power regression coefficients have been evaluated, the SEL values at the receivers depend uniquely on the assessment of the form factor k_{ij}.

The innovation in the reported technique consists in a determination of the parameter α_{eff}, which may be representative of the average absorbing properties of the pavement layers under study, solving some typical difficulties in computing the complex acoustical impedance with a high degree of accuracy.

The contribution in terms of sound pressure given by the source image can be described by an apparent reflection coefficient ρ (real). From the definition of $\bar{k}_{ij}$:

$$W_{ij;TOT} = \bar{k}_{ij} \cdot W_i \tag{14}$$

Thus the apparent coefficient can be written as:

$$\sqrt{\bar{k}_{ij}} \cdot \left| p_{ij\,dir} \right| = (1+\rho) \cdot \left| p_{ij\,dir} \right| \tag{15}$$

where the index *dir* refers to the direct out-coming wave. By solving Eq.(13) in terms of the not reflected energy rate:

$$\alpha_{ij\,eff} = 1 - \rho^2 = -\bar{k}_{ij} + 2 \cdot \sqrt{\bar{k}_{ij}} \tag{16}$$

In order to get the most representative estimation of the absorption properties of the surface layers close to the tyre contact, it has been considered the couple 1 cm source – 3 meters receiver.

5 Results

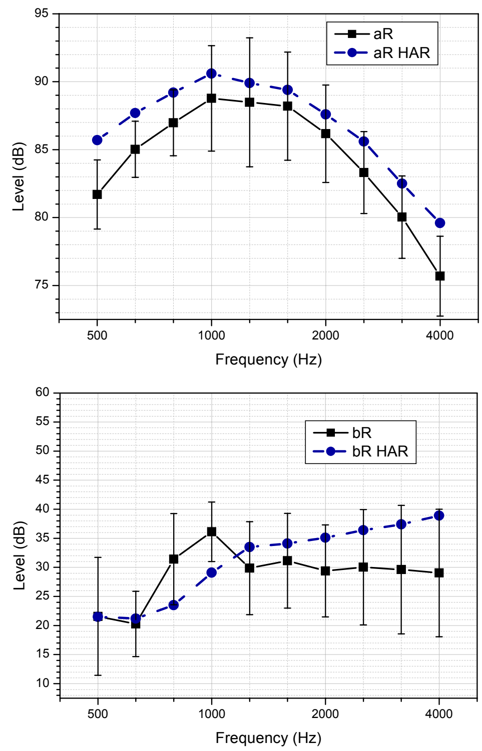
The proposed method has been applied to the data collected in the sites chosen by the LEOPOLDO project team all over Tuscany Region.

In Figs. 3, 4, 5, 6 the mean values over ten sites of the regression coefficients a_R, a_P, b_R, b_P are reported, as a function of the frequency, with their corresponding standard deviations. Greater fluctuations are found in the rolling noise source parameters (*R* indexed), which shows the great variability in level emissions involved in the generation process from tyre-road interaction.

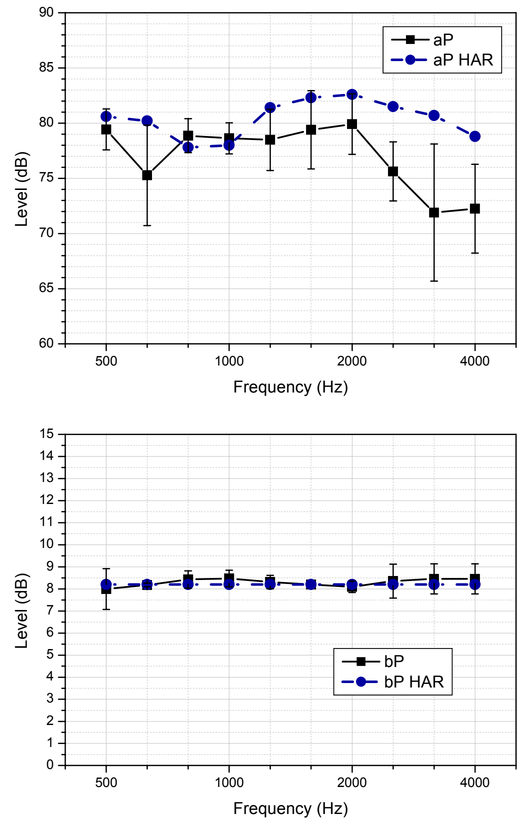
On the contrary, noise from the engine source (*P* indexed parameters) is affected by lower values of standard deviations, proving that the engine power is little influenced by the specific site characteristics (this is of course valid only for plane roads, with no slopes, as in this case).

In Figs. 7, 8, 9, 10 the mean values of the transfer functions L_{Cij} are reported, evaluated for the ten LEOPOLDO experimental sites, with the associated standard deviations, in comparison with values predicted by the HARMONOISE model using a highly reflective road surface with a flow resistivity of 200 MPa s/m^2, not far from typical values of a dense asphalt concrete (DAC) pavements. In this case remarkable differences in the comparisons can be observed for the 1.2 m microphone location.

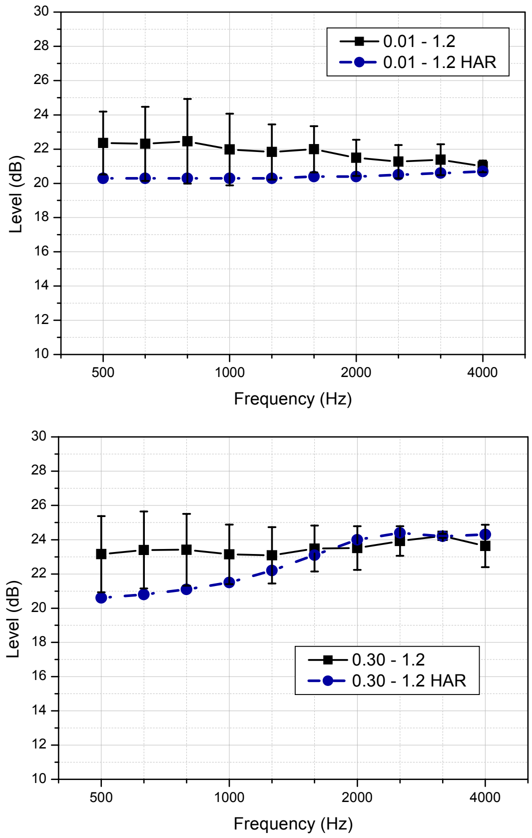
Since the engine acoustical power level computations are sufficiently close to the mean values for all investigated sites, particularly at medium-low frequencies, future developments may involve the CPX set up to obtain the noise mapping of existing Italian road infrastructures from measurements carried out directly close to the vehicle wheel source.



Figs. 3, 4. Comparisons between the mean value of a_R, b_R (regression sound power level-velocity for rolling noise) computed at each 1/3 octave band over the ten test sites of the LEOPOLDO project and the HARMONOISE model.



Figs. 5, 6. Comparisons between the mean value of a_P, b_P (regression sound power level-velocity for propulsion noise) computed at each 1/3 octave band over ten sites of LEOPOLDO and the HARMONOISE model.



Figs. 7, 8. Comparison between the mean value of transfer functions to the 1.2 microphone computed over the ten LEOPOLDO test sites at each 1/3 octave band, and the HARMONOISE model.

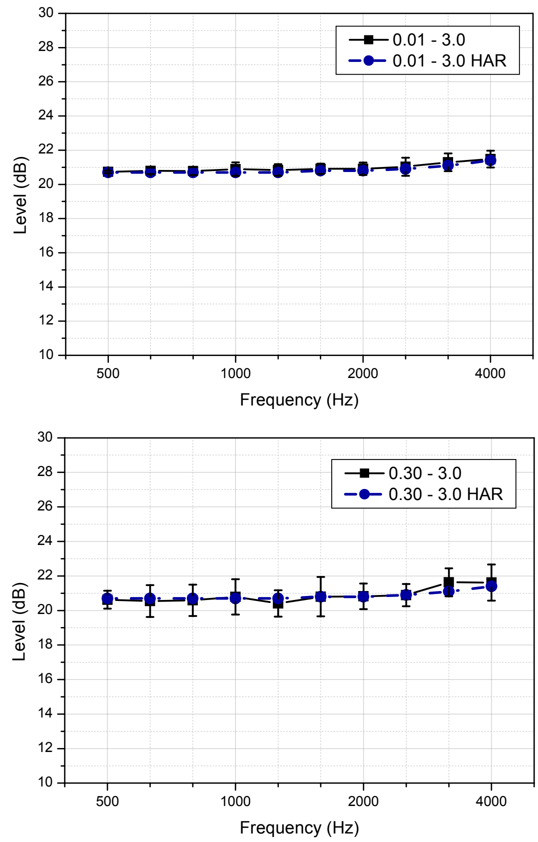


Fig. 9, 10. Comparison between the mean value of transfer functions to the 3.0 microphone computed over the ten LEOPOLDO test sites at each 1/3 octave band, and the HARMONOISE model.

As a further check of the showed method reliability, the estimated absorption properties computed for the couple 0.01 m source - 3 m receiver with the new technique have been compared to those evaluated with the "Adrienne" method, normed in the specific ISO standard [10].

The results of comparisons with Adrienne data are reported in Fig. 11, showing a very good agreement, in the limit of the experimental accuracy of the ISO standard. It must be pointed out that "Adrienne" method refers to absorption coefficient for normal incident waves.

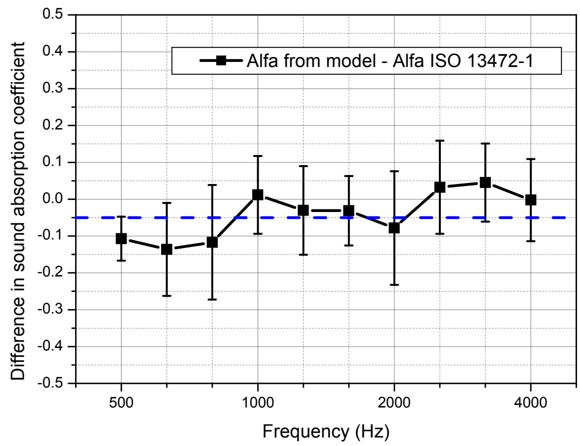


Fig. 11. Mean value of the differences between absorption coefficients computed for each 1/3 octave band and the one measured with "Adrienne" technique. The dotted line represents the mean value of the differences over frequency.

6 Conclusion

In order to test the effectiveness of action plans and particularly the reduction of noise emission at the source, it is important to assess the acoustical performance of road surfaces.

The method described, used to characterize the acoustical properties of the pavement layers by means of SPB and CPX measurements, allowed a finer computation, for the Italian roads, of all the coefficients involved in the regressions introduced by the HARMONOISE source model. Moreover it allows the assessment of the absorption performances which are specific of each road surface.

Tests carried out with other traditional techniques (Adrienne) show a very good agreement in results. SPB tests will then be used to characterize each site in terms of propagation.

Further measurements will be carried in sites with higher acoustical absorption performances within LEOPOLDO project, in order to verify both the efficiency of the test method when applied to experimental road pavement layers and, to the other side, the agreement with theoretical properties simulated in laboratory.

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