# Mesure in situ de la perte par insertion d'un prototype de protection antibruit de faible hauteur adaptée au tramway

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La performance acoustique d'un prototype d'écran antibruit de faible hauteur adaptée à la réduction du bruit de tramway pour les récepteurs proches (piétons et cyclistes) a été mesurée in situ. Le prototype est un assemblage de planches de bois aggloméré en forme de L inversé couvert de laine de verre sur le côté exposé aux sources de bruit. Il a été installé temporairement dans un quartier résidentiel à Saint-Martin-d'Hères, près de Grenoble, au travers duquel passe une ligne de tramway. Une série de mesures de niveaux au passage ont été effectuées à une position proche correspondant à une hauteur typique d'oreilles humaines (1.50m), ainsi que la vitesse du tramway grâce à un microphone auxiliaire placé très près de la voie, avec et sans le prototype. Malgré l'application d'une correction de vitesse sur le niveau moyen pendant le passage, on trouve une assez forte variabilité entre les différents tramways. La présence de l'écran cause cependant une réduction de plus de 10 dB(A) pendant le passage des trams les plus proches de la protection. La perte par insertion est aussi étudiée dans le domaine fréquentiel, ce qui permet notamment d'analyser les bandes de fréquences avec un bon rapport signal sur bruit.

# 1 Introduction

It is now well-documented that long-term exposure to noise can cause several negative health effects including the reduction of sleep quality, harm to cognitive abilities, as well as a feeling of annoyance and a decrease of performance [1, 2]. The issue of noise exposure is especially relevant in urban areas since more than half of the world population are urban dwellers, and many ground transportation noise sources coexist in such environments. Besides it seems necessary to tackle the issue of noise not only inside dwellings but also in outdoor urban areas, since according to the World Health Organization, 20% of the European population is exposed to noise levels exceeding 65 dB(A) during daytime [2], whereas the maximum recommended level in outdoor areas during daytime is 55 dB(A) [3].

A possibility to help achieve this goal is to implement compact noise barriers specifically designed for urban areas, which have received significant attention in the past decade [4–13]. This type of device should be easy to implement in a constrained environment, such as a city canyon or along an urban tramway track, which would typically require its height to be limited. This is why those devices have been referred to as *low-height noise barriers*, "low height" typically meaning less than one meter high.

Previous studies on low-height noise barriers mostly used numerical modeling and scale measurements to assess the efficiency of those devices. Baulac et al. considered a typical urban traffic noise situation and optimized the shape and the treatment (mostly absorbing) of a low-height barrier using boundary element method (BEM) simulations and genetic algorithms [4], and they showed that an insertion loss of 10 dB(A) is achievable. Simpler shapes have also been studied with scale modeling and it has been showed that numerical simulations were in good agreement with the measurements [5]. Koussa also studied numerically and experimentally a type of low height noise barrier made of gabions [7], as well as a so-called *sonic crystal* made of parallel cylinders [8], and the insertion loss ranged from 5 to more than 10 dB(A) in those cases. The European project HOSANNA [10] also studied numerically the effect of different types of low-height barriers in different configurations, and again found important noise reduction effects. These results suggest the applicability of low-height noise barriers in urban situations. This was also confirmed by a full scale experiment in Lyon [9], in which a vegetated low-height barrier was set-up close to an urban traffic lane, and which provided about 5 dB(A) of attenuation as well as an improvement of the subjective soundscape impression.

Many sources of noise coexist in urban environments, including road traffic (from light and heavy vehicles), but also tramways. There has been a renewed development of this means of transportation in the past decade, and tramways have hence become a significant urban noise source. Along with this development, researchers have characterized physical emission levels of tramway-induced noise and vibration [17–19] and annoyance [18, 20] : typically noise levels for close receivers can reach more than 80 dB(A). It has besides been shown that noise sources for modern tramway are mostly located close to the ground [19]. This suggests that a properly designed low-height noise barrier can be efficient against tramway noise, even for close receivers. A few types of tramway low height barriers have already been studied [8, 11–13], and it has been emphasized that, in this case, the multiple reflections between the barrier and tram body strongly influence the insertion loss, and therefore treating the barrier with absorptive material or an optimized shape seems critical in this context.

Nevertheless, the assessment of a noise barrier performance based on numerical calculations or scale model measurements is intrinsically biased, due to the idealization of the physical and geometrical features of a potential implementation site. For instance, in scale model measurements as well as numerical calculations, one or few omnidirectional sources are usually considered, whereas the actual noise sources of a tramway are a lot more complex due to their spatial distribution and directivity [19]. It is unclear how much those approximations matter for the actual performance of a low-height noise barrier. It seemed therefore necessary to actually build and set-up a full scale prototype in a real situation in order to assess what actual noise reduction can be obtained by such a barrier.

In this work, the performance of a full scale low-height barrier prototype meant to attenuate tramway noise for nearby pedestrians is measured in situ. The design of the prototype and the choice of the implementation site are first discussed. The performed measurements are then presented and analyzed in order to evaluate in a quantitative way the noise reduction.

# 2 Preliminary considerations

## 2.1 Choice of the implementation site

The city of Grenoble and its nearby towns have developed in the past few years several tramway lines. Based on background noise and practical considerations, it has been chosen to set up the low-height barrier prototype on an asphalt bicycle trail running along the B line of the Grenoble tramway system, between the stops Les Taillées

- Universités and Grand Sablon, opposite Antoine Polotti street in the town of Saint-Martin-d'Hères (France). A view of the site is shown in Fig. 1. The environment is relatively quiet since this site is next to a residential area, with few cars passing on Antoine Polotti street. However tram pass-bys are quite loud, as we will see later, due to the fact that trams roll at relativity high speeds in this area, and probably also to the type of track, as it has been shown that this has a major influence on tram noise power levels [19].

**Figure 1** – View of the implementation site, in Saint-Martin-d'Hères, France. The tramway tracks are those of the B line, between the stops Les Taillées - Universités and Grand Sablon.

## 2.2 Choice of the design

Due to time and feasibility constraints, a relatively simple design for the noise barrier prototype had to be utilized. Previous studies showed however that it is essential to cover the face of the barrier directly exposed to the noise sources radiation with absorptive materials in order to attenuate the multiple reflections happening between the tramway body and the barrier [11–13]. Therefore, an inverted L-shape covered on its interior part by fiberglass is proposed, since this shape is at the same time compact and since preliminary calculations suggest its efficiency in terms of acoustic performance.

The length of the barrier also had to be limited mainly for ease of transport and installation. The barrier therefore consists of 12 elements, each 1.85 m long, for a total length of a little more than 22 m. Trams running on the B line are Alstom Citadis 402 trams which are 43 m long, and therefore the barrier covers at most half of the tramway length, as shown in Fig. 2.

**Figure 2** – View of the noise barrier prototype with a Alstom Citadis 402 tramway of the Grenoble B line passing-by.

Each element is made of an assembly of two pressed wood boards - one 60 cm wide, the other 95 cm wide - bound together to form a right angle thanks to shelf brackets and a batten. The boards are 22 mm thick, which was chosen to ensure transmission across the board to be negligible. Each element is bound to the next via a simple joint system : a rectangular piece of dense foam is glued on the side of the pressed wood boards, and several tied plastic clamps ensure compression of the joint, thus preventing strong acoustic leaks. Similarly, an insulating foam sleeve is put at the bottom of the structure to prevent leaks at the ground level. The compression in this case naturally happens thanks to the weight of the structure. Views of the barrier cross section and joint system are shown in Fig. 3.

**Figure 3** – Views of the low-height barrier prototype. Left : cross section. Right : joint system between elements.

# 3 Performed measurements

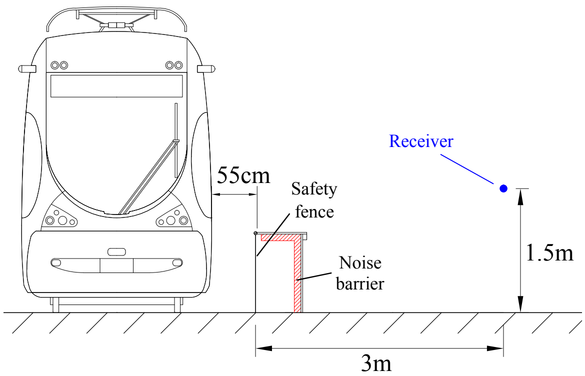


**Figure 4** – Cross sectional schematic showing relative positions of the tram, low-height noise barrier prototype and receiver location.

In this work, we are interested in assessing the benefit of the presence of a low-height barrier for a close receiver, typically a pedestrian or a cyclist, while a tramway is passing by. We therefore mostly need to measure the level at a receiver point located at the typical height of human ears, that is 1.5 m above the ground. The horizontal distance from the safety fence is 3 m, which corresponds to a distance of about 3.5 m to the tramway side (see in Fig. 4). Finally the receiver is located in the vertical plane cutting the barrier in the middle of its length, which is where the noise barrier has the most important effect.

Pressure signals and levels were recorded by a B&K sound level meter (SLM) model 2250 at the receiver location. The SLM was set up to record the pressure signal in a WAV file (sampled at 48 kHz) and the equivalent A-weighted levels $L_{\mathrm{Aeq,T}}$ over successive time periods of duration T = 100 ms. Besides, we used an auxiliary microphone (embedded in a cellphone) which was placed very close to the tracks, away from the shadow zone of the barrier, and meant to record the pass-by of the train without any influence of the barrier, which would allow us to determine the speed of the tram during the pass-by using the known distance between the bogies and the measured time interval between each bogie pass-by.

Finally, SLM measurements are performed over a constant time interval of 15 s, each measurement being started manually by an operator whenever a tram is approaching. Besides, measurements are done for *close* trams - running the closest to the barrier, going from Grand Sablon to Les Taillées - and *far* trams - running the opposite way and furthest from the barrier, towards the bridge over the Isère river (see in Fig. 5).

We therefore have four different configurations of measurements for which the analysis will be performed, depending on :

- Presence of the noise barrier (we will refer to each case as *with* or *without* barrier).
- Proximity of the tram : close or far.

**Figure 5 –** Views of two tram pass-bys. Left : close tram, rolling towards the foreground of the picture. Right : far tram, rolling towards the background of the picture (towards the bridge over the Isère river).

# 4 Measurement analysis and barrier effect

In this section different analyses of the measured data are proposed in order to evaluate the effect of the low-height noise barrier prototype in terms of noise reduction : first based on the equivalent pass-by level, then on the time histories of the $L_{\mathrm{Aeq,T}}$ during the pass-bys, and finally on the spectrum of the recorded signals.

## 4.1 Pass-by equivalent level and speed dependence

First the correlation between noise level and speed is studied, in each measurement configuration. The equivalent A-weighted sound pressure level is chosen to quantify the level during the pass-by, but one has to determine the time period of integration. Since the speed $v$ of the tram is known for each pass-by, we set the period over which the equivalent level is calculated as the duration of the whole tram pass-by in front of the SLM, given by $d_2/v$, with $d_2 = 43$ m the approximate total length of the tram. The result is referred

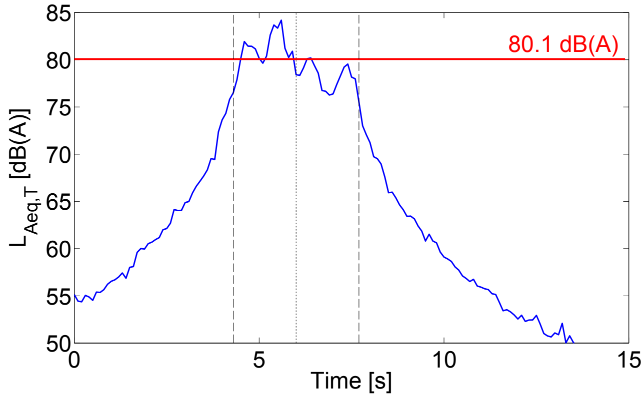


**Figure 6 –** Example of a time history of $L_{\mathrm{Aeq,T}}$ in dB(A) during a tram pass-by (close tram, without barrier). The dotted line corresponds to the center time, and the two dashed lines correspond to the initial and final instants of the pass-by. The equivalent pass-by level $L_{\mathrm{Aeq,pass}}$ is indicated on the plot as well.

to as the pass-by A-weighted equivalent level, written as $L_{\mathrm{Aeq,pass}}$, and calculated by logarithmic average of the $L_{\mathrm{Aeq,T}}$ in the corresponding time interval (see an example of this calculation in Fig. 6).

The pass-by levels can then be plotted as a function of speed, for all configurations (see in Fig. 7). The range of tram speeds does vary depending on the configuration, with far trams typically rolling faster (from 40 to 65 km/h) than close trams (from 35 to 50 km/h).

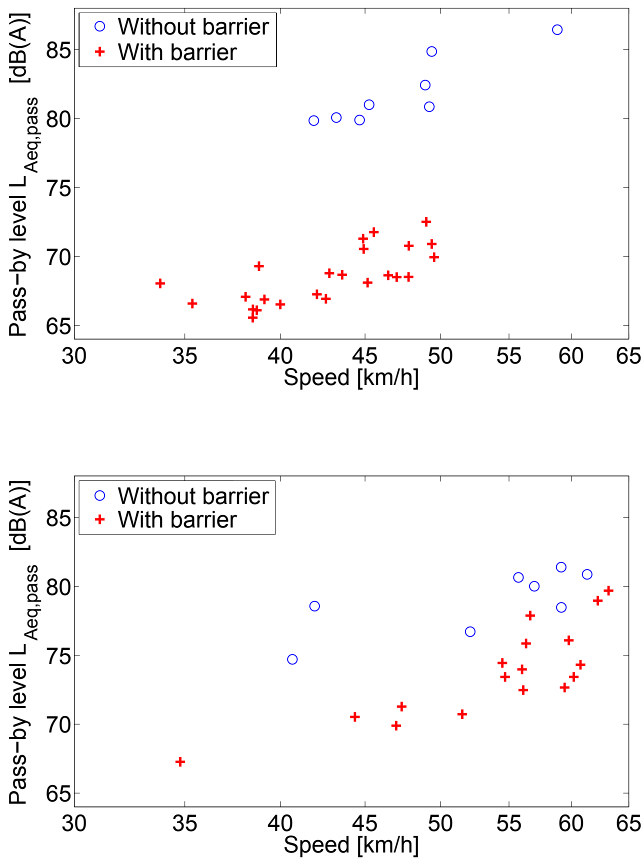


**Figure 7 –** Tram pass-by A-weighted equivalent levels $L_{\mathrm{Aeq,pass}}$ as a function of speed for all measurement configurations. Left - close trams ; right - far trams. Symbols : circles - without barrier ; crosses : with barrier.

Although there seems to be significant variability between the trams pass-bys, there is a positive correlation between levels and speeds in all cases. One can for instance

**Table 1** – Coefficients $L_{\text{Aeq,pass,ref}}$ and $\alpha$ and their uncertainty based on the regression of A-weighted pass-by levels with speed, assuming a dependence of the form $L_{\text{Aeq,pass}} = L_{\text{Aeq,pass,ref}} + \alpha \log(v/v_{\text{ref}})$ with $v_{\text{ref}} = 40$ km/h, in all configurations.

| Configuration | | $L_{\text{Aeq,pass,ref}}$ [dB(A)] | Speed-dependence coefficient $\alpha$ |
|---|---|---|---|
| Close tram | without barrier | 78.4 ± 0.7 | 48 ± 10 |
| | with barrier | 67.7 ± 0.3 | 29 ± 6 |
| Far tram | without barrier | 75.9 ± 1.1 | 25 ± 9 |
| | with barrier | 68.4 ± 1.0 | 40 ± 7 |

assume a power-law dependence of the received power on speed, which in terms of the pass-by level in dB can be written as $L_{\text{Aeq,pass}} = L_{\text{Aeq,pass,ref}} + \alpha \log(v/v_{\text{ref}})$ with $v_{\text{ref}} = 40$ km/h is the reference speed and $L_{\text{Aeq,pass,ref}}$ the reference level. The regression coefficients $L_{\text{Aeq,pass,ref}}$ and $\alpha$ and their uncertainties (approximately the 65% confidence interval) have been calculated using standard procedures (see for instance in [21]) and are tabulated in Table 1 for all configurations. One can notice the coefficients $\alpha$ vary a lot and have a large uncertainty, which suggests pass-by levels do not depend only on speed. Indeed defects in the tram can cause a great variability in levels between the different bogies. In addition, propagation effects (due to the ground and the barrier) may affect the coefficients as well.

However, we will assume that tramway noise source power levels depend only on speed, as done in [19]. Since our measurements have a large uncertainty, it has been chosen to use the value $\alpha_0 = 35$, which is close to the value measured by Pallas et al. for a modern tram in the case of soft pads and pavings [19]. From now on, we will define the speed-corrected value of any level $L$ at $v_{\text{ref}} = 40$ km/h as $L' = L - \alpha_0 \log(v/v_{\text{ref}})$. Finally, one can evaluate the speed-independent effect of the barrier in each configuration by comparing the $L_{\text{Aeq,pass,ref}}$ with and without the barrier, which is a reduction on average of more than 10 dB(A) for close trams, and 7.5 dB(A) for far trams. One can already state that the effect of the barrier prototype, although its length is only half of that of the tram, is significant.

## 4.2 Analysis of the $L_{\text{Aeq,T}}$ time histories

Another way of measuring the effect of the barrier is to analyze the measured $L_{\text{Aeq,T}}$ time histories (again here T = 100 ms). This will allow one to have a closer look at the noise reduction effect considering a time dependence. However, since the measurements were not synchronized, one first has to process the histories in order for them to have a similar center time (instant at which the center of the tram is the closest to the SLM). Besides, one needs to correct for the effect of speed, both on time and level. This will then allow one to make an elementary statistical analysis of the time histories, by considering the mean and the dispersion of the levels as a function of time.

The center time $t_c$ of each time history is evaluated as the center time of the tram pass-by. The *centered* time $\tau$ is then defined for each pass-by as $\tau = t - t_c$. The $L_{\text{Aeq,T}}$ levels and centered time $\tau$ are then corrected due to the speed dependence as :

$$L'_{\text{Aeq,T}} = L_{\text{Aeq,T}} - \alpha_0 \log\left(\frac{v}{v_{\text{ref}}}\right) \qquad \tau' = \frac{v}{v_{\text{ref}}}\tau$$

Since the corrected histories are no longer defined on the same instants, a linear interpolation in time is made.

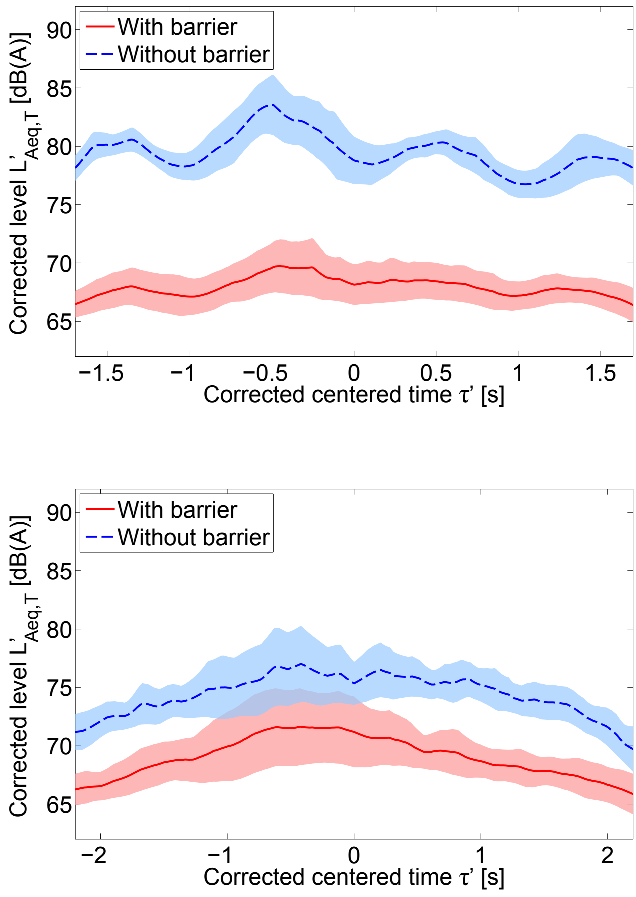


**Figure 8** – Mean and dispersion interval (plus and minus one standard deviation from the mean) of corrected levels $L'_{\text{Aeq,T}}$ time histories in dB(A) during tram pass-bys as a function of corrected centered time $\tau'$, with (solid line) and without (dashed line) the noise barrier. Left : close tram. Right : far tram.

Mean and dispersion calculations are then made at each instant on the corrected histories, based on the different pass-bys for all measurement configurations. Results are shown in Fig. 8. One can also notice that there is a strong variability of the levels, even after the speed correction is applied, which is certainly related to the different trams having different defects as pointed out earlier. Nevertheless, the main result from this approach is that, at the considered receiver location, the noise reduction effect of the barrier is effective during the whole pass-by (attenuation of 4-7 dB(A) for far trams, and of 9-15 dB(A) for close trams), despite the small length of the barrier compared to that of the tram. Indeed, when $\tau$ is large in absolute value, a smaller portion of the tram is “hidden” by the noise barrier, and therefore one might have observed a negligible noise reduction effect. This aspect also strongly depends on the directivity of the sources in the horizontal plane, which is difficult to evaluate directly with SLM measurements. However, based on the fact that the barrier does have an effect even at large values of $\tau$, it seems like the main noise sources of this type of tram - namely wheel radiation and rolling noise - have rather narrow horizontal directivity patterns.

## 4.3 Spectral analysis and third-octave insertion losses

Instead of comparing broadband levels such as the $L_{\text{Aeq,T}}$ or the $L_{\text{Aeq,pass}}$, one may wish to evaluate the insertion loss of the noise barrier for different third-octave bands. This can be achieved by performing spectral analysis of the recorded signals.

However, the presence of background noise in the surrounding environment can bias the evaluation of the low-height barrier insertion loss. Although the site was relatively quiet, which means that broadband levels such as the $L_{\mathrm{Aeq,T}}$ were sufficient above the background levels, this might not be true any more depending on which third-octave band is considered. We will therefore first analyze the data to find the frequency range in which the SNR was sufficiently good to evaluate the insertion loss accurately.

### 4.3.1 SNR evaluation and considered frequency range

The SNR over each third-octave has been evaluated by considering the *signal* portion of each recording as the tram pass-by (as defined in section 4.1) and the *noise* portion as the initial or last two seconds of the recording (depending on the pass-by center time). The third-octave levels of the signal are calculated by integration of the PSD of the signal portion over the corresponding band. Similar calculations are performed to evaluate the third-octave levels of the background noise. Applying this process for all the recordings, it has been found that for 90% of them the SNR was above 9 dB in the frequency range [200 Hz - 2500 Hz], which will be the range of study in the rest of this section. Indeed, it has been noticed that tramway noise emissions at low frequencies are usually comparable to typical background noise, and that at higher frequencies, birds singing significantly increase the background noise between 3 and 4 kHz.

### 4.3.2 Measured third-octave insertion losses

Now that the trusted frequency band has been determined, one can calculate for a given configuration the insertion loss of the low-height barrier from third octave levels without the barrier, averaged over all measurements, minus the averaged third octave levels with the barrier. Apart from the uncertainty due to the background noise, there is some variability in this evaluation which can be quantified by classical uncertainty calculations. Results are presented in Fig. 9. First of all, it is clear that the low-height barrier provides attenuation over the whole considered frequency range, both for close and far trams, although the attenuation is a lot higher for close trams.

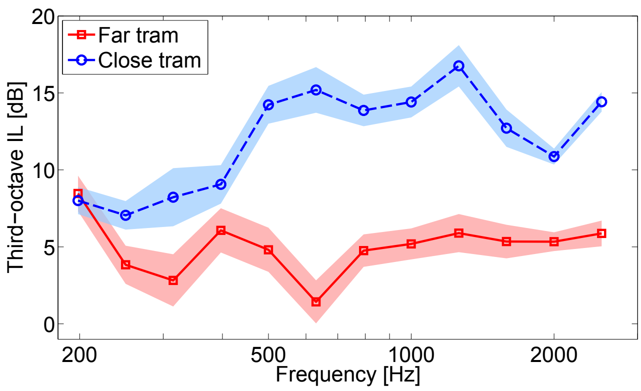


**Figure 9** – Mean values and uncertainty interval of measured third-octave insertion losses in dB in the frequency range 200-2500 Hz. Solid line : far tram - dashed line : close tram.

**Table 2** – Mean value and uncertainty of broadband insertion losses in the 200-2500 Hz range based on A-weighted third-octave levels with and without the barrier.

| Configuration | $\mathrm{IL_{bb}}$ [dB(A)] |
|---|---|
| Close tram | 13.8 ± 1.2 |
| Far tram | 4.3 ± 1.1 |

One can then consider a broadband insertion loss in dB(A) in the considered frequency range - 200 to 2500 Hz. Levels are first converted to dB(A) by applying the A-weighting correction to the third octave levels. The broadband insertion loss $\mathrm{IL_{bb}}$ is then evaluated as :

$$\mathrm{IL_{bb}} = 10\,\log\left[\sum_j 10^{(L^{\mathrm{wo}}_{A,j}/10)} \Big/ \sum_j 10^{(L^{\mathrm{w}}_{A,j}/10)}\right] \qquad (1)$$

in which $L^{\mathrm{wo}}_{A,j}$ (resp. $L^{\mathrm{w}}_{A,j}$) are the A-weighted third-octave levels in the band of index $j$ without the barrier (resp. with the barrier). The corresponding uncertainties are evaluated as well. Results for both configurations are shown in table 2.

Notice, these results are a little different than the first estimate of the broadband insertion loss shown in section 4.1, which might be due to the fact that no speed correction was applied on the third-octave levels, and also since the evaluation based directly on the measured pass-by levels was evaluated over a larger frequency band, but was also more subject to error due to the background noise implicitly present in the levels estimation. The choice not to apply a speed correction on the third-octave levels was based on the fact that such a correction should be dependent on the considered third-octave band (as done in [19]), but in our case it has been found that the uncertainty on the regression coefficients was very high for most frequency bands, and therefore the coefficients not meaningful.

## 5 Conclusion

A full scale prototype of a tram low height noise barrier has been built and implemented in a real environment, along the B line of the Grenoble tramway system, in the town of Saint-Martin-d'Hères, France. A 22 meters long L-shape barrier prototype made of pressed wood and fiberglass is proposed. The design of the noise barrier as well as its length were chosen essentially to cope with feasibility and time constraints. A series of pass-by measurements were performed at a close location from the tram track, with and without the noise barrier. The tram speed has been measured as well using an auxiliary microphone located very close to the track.

First, a positive correlation has been found between pass-by equivalent level and speed, in agreement with previous studies. This was used to approximately correct for the speed in pass-by equivalent levels and time histories. Although a significant variability is found between the different trams, it is shown that the barrier provides on average an attenuation of more than 10 dB(A) for close trams, and of more than 5 dB(A) for far trams, during the whole pass-by, and not only when the barrier covers most of the tram length.

The effect of the noise barrier in the frequency domain has been studied as well. It is found that the barrier provides attenuation in the whole frequency range 200-2500 Hz (which is the range in which the effect of the barrier could be evaluated accurately), which yields a broadband insertion loss in this range of 13 dB(A) for close trams and about 5 dB(A) for far trams.

Finally, based on the experimental data collected during this work, one can state that low height noise barriers can be efficient solutions to attenuate tramway noise for close receivers, namely pedestrians and cyclists. It is also likely that this type of noise protection could be efficient as well against any urban noise source located close to the ground, as long as it can be placed sufficiently close to the source. More efficient - using more complex shapes or more efficient sound absorbing materials - and more sustainable - for instance using natural or recycled materials - designs could certainly be achieved as well.

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