# Auralization of Urban Traffic Noise - Quantitative and Perceptual Validation

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This paper presents recent validation results of a new auralization approach for non-stationary urban traffic noise. The technique uses a real time granular synthesis algorithm to construct the source signals of engine and tire emission noise. Vehicles moving with arbitrary engine and speed variations can thereby be auralized dynamically. Acoustic propagation effects between sources and listener position are modeled based on standard engineering propagation methods with individual 3D rendering of perceptually important propagation paths and diffuse rendering of the summed remaining contributions. Perceptual validation tests of the granular synthesis approach are discussed. Results of the comparison of pass-by noise sequences obtained from on-site recordings and from the auralization approach modeling the same site are also discussed. The chosen site, an urban street, includes two types of road surface types. The auralized sequences based on equivalent traffic conditions also include additional road surfaces as well as a low noise barrier. Pass-by noise levels obtained on auralized sequences are compared to on-site measured levels.

# 1 Introduction

Traffic noise due to ground transportation in urban areas represents a serious annoyance and a threat to public health according to the World Health Organization [1]. Much research has been done to find ways to reduce the environmental noise due to traffic. In this area, prediction models are valuable tools to aid in assessing new abatement solutions, both for vehicle noise emission and noise propagation. However, noise level exposures can be difficult to translate into annoyance levels. In addition to the purely quantitative assessment of noise pollution provided by noise maps, it is therefore necessary to consider the subjective perception of soundscapes for an accurate evaluation of comfort or annoyance levels. Nevertheless, the qualitative aspects of sound environments are difficult to communicate to non-specialists with no special training.

In this context, the use of auralization for road traffic noise has gained much interest in the recent years by allowing the evaluation of noise annoyance based on perception. As described in an early paper by Kleiner *et al.* [2], auralization describes the process of rendering audible a 3D virtual sound environment based on a numerical model which is physically valid. As such, it may be used both as a research tool for the assessment of abatement solutions and as a decision tool to help action planning in the design of quieter cities.

This paper presents new results obtained on the evaluation of a recently developed auralization technique for non-stationary traffic noise. The approach is based on previous work on the auralization of construction site noise which implements the real time audio rendering of fixed and moving sources using multiple propagation paths and pre-recorded source audio signatures [3]. This work assumed constant source speed in order to obtain source signature from pass-by recordings. Most of the previous work on road noise auralization also assumes stationary traffic conditions with constant vehicle speeds. In these studies, the vehicle source signals are obtained from pass-by audio recordings of individual vehicles [4, 5, 6]. More recently, a new approach was proposed for the real time synthesis of engine noise with varying engine speed [7]. A similar approach was also applied to rolling noise [8]. The ability to synthesize in real time variable vehicle speeds allows the auralization of non-stationary traffic including accelerating and decelerating vehicles. Furthermore, the real time implementation enables dynamic listener motion and facilitates the comparison of various scenarios.

After a brief overview of the approach, results from listening tests performed on separate engine and rolling noise source signals will be presented. The use of the technique to auralize a non-stationary traffic in an urban street will then be discussed. The quantitative comparison of auralized and recorded sound pressure levels will be presented as well as auralized scenarios based on three different noise abatement solutions.

# 2 Auralization system

The auralization approach used in this paper is part of an integrated software for the evaluation of outdoor noise. The prediction of noise levels is based on a 2.5D beam tracer and a choice of standard acoustic propagation models including the recently proposed Harmonoise model [9]. The software implements data import and edition, as well as results analysis in a 3D view of the site including various types of noise level maps. Figure 1 shows the interface including the 3D view of the site used in the present study (see Section 4).

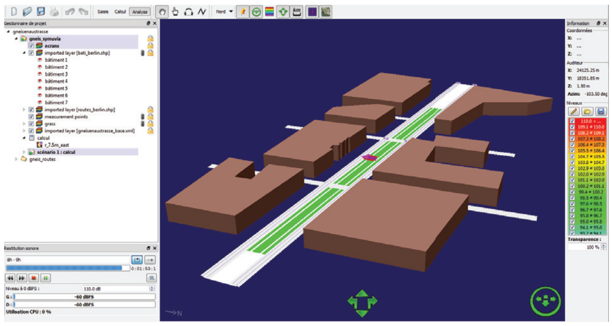

Figure 1: Interface of the prediction and auralization tool (road surface: light gray, road lane: light purple, specific impedance surface: green).

The auralization module is based on three main components: the traffic flow simulator, the vehicle source signal synthesis and the moving source renderer. The traffic flow simulator implements a macroscopic traffic model [10] which calculates traffic states at discrete times. A traffic state contains positions, speeds and accelerations for all vehicles found on the network. For each vehicle to be auralized, the noise synthesis module uses the vehicle type, road surface, speed and acceleration to adjust the generation of engine and rolling noise source signals.

The source signal synthesis implements a real time granular synthesis technique. Engine signals are constructed using a synchronous overlap-and-add algorithm which assembles sound samples (also referred to as grains) containing the noise emitted during a full engine cycle [7]. The extraction of individual sound samples associated with specific engine speed values is performed during the analysis stage on recorded signals of slowly accelerating engines. The synthesis of rolling noise signals uses an asynchronous overlap-and-add scheme in which samples of random length are added at random locations. The sound samples are extracted during the analysis stage from rolling noise audio recordings following the CPX standard of slowly decelerating vehicles. The above synthesis technique provides realistic source signals with a very low computational cost compared to other algorithms such as additive or model based synthesis.

Both engine noise and rolling noise signals are fed to the moving source renderer which implements the signal processing steps necessary to model acoustic propagation along a number of time varying acoustic paths [3]. The acoustic paths are obtained from the pre-computed transfer functions between short road lane segments at the appropriate source heights and receiver points. Each transfer function contains multiple paths. The $N$ perceptually most important paths plus one "diffuse" path summing the remaining contributions are saved. Finally, 3D audio rendering is applied to each individual contribution based on its direction of arrival at the listener position. Available restitution systems include binaural (headphones) and Ambisonic (multi-speaker) rendering. Figure 2 presents a schematic of the modules described above and their interactions.

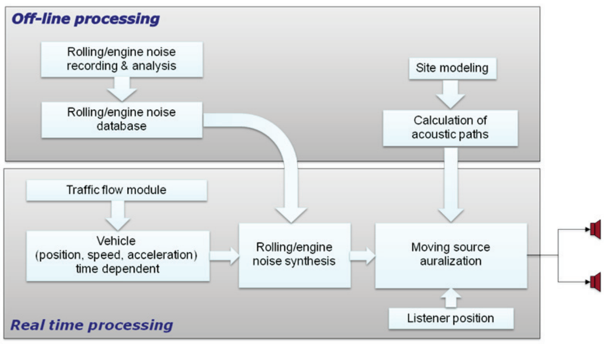


Figure 2: Schematic of the auralization system.

## 3 Qualitative validation of source signal synthesis

A perceptual validation of engine and rolling noise synthesized signals is now presented. Paired comparison listening tests using a panel of 40 subjects (23 men and 17 women aged between 21 and 62) were carried out based on the *individual test* procedure [11]. The aim of the tests is to determine whether there are perceptual differences between recorded and synthesized vehicle source signals. Three sets of 16 recorded/synthesized pairs of signals associated respectively with gas engine, diesel engine and rolling noise were created. For each set, there is an equal number of stationary versus varying and low versus high engine/vehicle speed. Stimuli can therefore be separated into 4 categories of stimuli for specific analysis. To reduce the duration of the test, 10 pairs were randomly chosen among the full set. The subjects were asked to separate the 20 signals in two groups of 10 recorded and 10 synthesized signals. Each signal could be listened to over headphones multiple times and placed in either categories. Half of the subjects benefited from a training procedure during which they could freely listen to correctly classified recorded and synthesized signals before taking the test. The statistical analysis of the results is based on the two-tailed Student test procedure. The tested hypothesis is $H_0 : \mu_0 = 50$ % where $\mu_0$ is the percentage average of correct answers for a given signal category. The acceptance of the above $H_0$ hypothesis corresponds to a random classification of stimuli which means recorded and synthesized signals are perceptually equivalent.

Table 1 presents the results for the $H_0$ hypothesis acceptance at a significance level of 0.10 in the case of trained (a) and untrained (b) subjects for the three sets of stimuli. The first four columns correspond to the four categories of stimuli presented above and the last column, to the test result including all stimuli together.

| | | High | Low | Const | Var | All |
|---|---|---|---|---|---|---|
| (a) | Gas | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Diesel | ✓ | ✓ | ✗ | ✓ | ✗ |
| | Tire | ✗ | ✗ | ✗ | ✗ | ✗ |
| | | High | Low | Const | Var | All |
| (b) | Gas | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Diesel | ✗ | ✓ | ✓ | ✓ | ✓ |
| | Tire | ✓ | ✓ | ✓ | ✓ | ✓ |

Table 1: Summary of the Student test results of the three types of vehicle noise. Trained (a) and untrained (b) subjects. Each column presents test acceptance (✓) or rejection (✗) for different sets of stimuli (High speed, Low speed, Constant speed, Varying speed, All stimuli)

For gas engine signals, the $H_0$ hypothesis cannot be rejected for any of the tested categories of stimuli. This holds for both trained and untrained subjects, suggesting that for gas engine noise the training process has no significant effect on the subject scores. Globally, the results demonstrate the effectiveness of the granular synthesis algorithm applied to gas engine noise.

The results for the diesel engine indicate that trained subjects can make the difference between recorded and synthesized signals when the engine speed is constant. This difference is sufficient to reject the null hypothesis on the whole set of stimuli. Without training, the subjects appear to be able to differentiate recorded and synthesized signals at high engine speed only. However, the mean value for this category (44%) indicates that synthesized high engine speed signals are judged more realistic than their recorded counterparts. Besides, over the complete set of stimuli, it appears that the $H_0$ hypothesis cannot be rejected. In other words, for untrained subjects, there is no significant difference between recorded and synthesized diesel engine noise signals.

For tire noise, the subjects with training are able to make the difference between recorded and synthesized signals whereas they are unable to do so without training. Trained subjects reported that the recorded signals contained measurement artifacts referred to as high frequency clicks. These artifacts are due to the presence of little stones or other particles on the road surface during the recordings. They are not reproduced in the synthesized signals as they represent transient phenomena that are not intended to be rendered by the asynchronous granular synthesis algorithm. On account of the results obtained by untrained subjects, the difference between recorded and synthesized tire noise signals reported by trained subjects does not affect the realism of synthesized sounds.

Overall, it can be concluded that the granular synthesis algorithms for both tire and engine noise signals achieve sufficient realism for the auralization of traffic noise.

# 4 Quantitative validation of pass-by vehicles

As detailed in previous work [8], the calibration procedure for the engine and tire noise sound samples ensures that the synthesized signals represent the sound pressure at 1 m in free field according to the Harmonoise emission model. In order to leave the spectral content of the sound samples unchanged, a single calibration gain is applied to a given engine or tire noise sample dataset. This gain is calculated such as to follow on average the acoustic power level in dB(A) of the Harmonoise emission model. As an illustration, Figure 3 compares the power levels of tire noise and engine noise versus vehicle speed obtained from synthesized engine and tire noise signals, to the Harmonoise emission levels. These results correspond to light vehicles

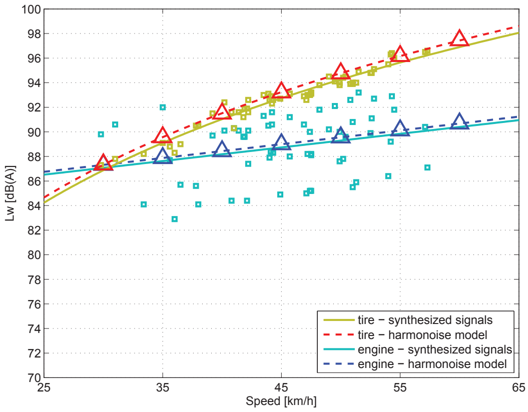


Figure 3: Comparison of emission power levels for synthesized tire (yellow) and engine signals (light blue) versus speed with the Harmonoise emission levels (tire: red, engine: dark blue).

and the reference road surface. Four distinct diesel engines and one gas engine are included in the analysis. It can be seen that both engine and tire noise components follow on average the Harmonoise curves. Note that in the case of engine noise, the spread of engine noise levels results from the varying gear indexes and gear ratios between vehicles, i.e., two vehicles driving at the same speed will possibly have different engine speed.

The comparison of sound pressure levels measured on recorded and auralized sequences of pass-by vehicles is now presented. Such comparison was performed previously on an open site with free field propagation [8]. In this paper, the chosen site is an urban area where the sound field from passing-by vehicles is more complex. The site is located in Berlin on Gneisenaustraße which is a two by two-lane avenue with a wide center vegetated area. Figure 4 shows a view of the site. Binaural recordings and Statistical Pass-By (SPB)

Figure 4: View of the urban site (the recording and measurement position is located on the edge of the center area).

measurements were performed on the eastbound direction at a distance of 7.5 m from the right lane and at a 1.5 m height. The measurements were carried out at night in order reduce the background noise level. Figure 5 shows a photo of the equipment positioned on the street side.


Figure 5: Measuring equipment installed on site (from right to left, Soundfield microphone, Neumann artificial head, radar station and B&K measurement microphone).

Rolling noise was recorded using the CPX technique on the same road section. The CPX data was then used to construct the rolling noise sample dataset as outlined previously. The sample dataset is calibrated such that the synthesized signal represents the free-field sound pressure at 1 m for the standard A-type tire (representative of light vehicles) on the site road surface. The calibration gain applied to the CPX recordings is obtained by matching levels from previous CPX recordings performed on a standard road surface, representing the Harmonoise standard surface, with the emission levels obtained for the standard surface of the Harmonoise model. Applying the calibration gain calculated for the dataset corresponding to the standard surface to all different tire/surface datasets ensures to properly render the noise level of different road surfaces.

The chosen site is modeled in the auralization software over a 600 by 600 m area around the listening point (see Figure 1). The model includes three variants: (1) reference road surface (SMA 0/11), (2) low noise road surface representing the real site (thin porous layer) and (3) low noise road surface with the addition of 1 m low barriers along each road and "green" building facades (A3 type absorption). The transfer function calculations use the Harmonoise propagation model including reflections up to order 3. Among the calculated propagation paths, the first 4 most important paths are kept for auralization in addition to the diffuse path containing the sum of all remaining paths. The road network includes the 2 eastbound and westbound lanes with two stop lights on each side. Traffic on crossing streets is not considered. Auralized sequences are obtained for traffic conditions equivalent to the one measured on site with speed of entering vehicles randomly distributed between 40 and 70 km/h.

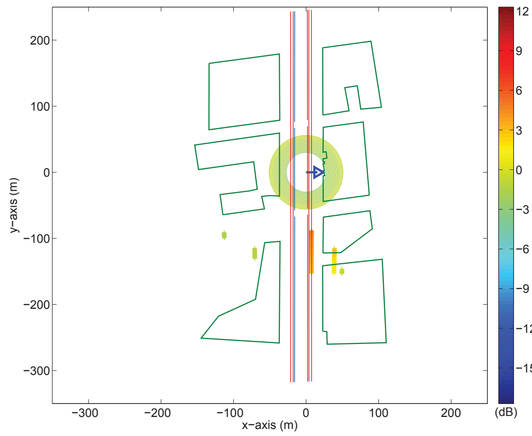


Figure 6: Site geometry including road lanes, low barriers, buildings and positions of image sources (crosses) associated with a single vehicle moving over an approximate 50 m distance. Colors represent relative importance level in dB. Circles around the listener (blue arrow) represent the "diffuse" path contributions.

Figure 6 shows a snapshot of the evolution of auralized image sources associated with a single vehicle moving on the eastbound right lane. Image source positions are shown for the current vehicle position as well as past positions over approximately 50 m. The diffuse path contributions are also depicted as circles centered on the listener. The figure shows the relative amplitude of each contribution. From these values, it is clear that reflected contributions (individual and diffuse) must be auralized separately in order to accurately reproduce the spatial properties of the sound field at the listening point.

Using the three variants described above, auralized sequences of 12 min each are generated. Pass-by time and speed of individual vehicles are also recorded. For each individual pass-by, $LAF_{max}$ levels are computed and used to perform SPB analysis of the auralized sequence. Figure 7 shows the auralized levels for the three variants along with the levels measured on site. The auralized sequence associated with the variant which simulates the real site yields pass-by levels (blue curve) that are in agreement with the measured levels (purple curve). Also, as expected, the standard road surface variant (red curve) gives levels that are approximately 3 dB above the low noise surface. Finally, the addition of a low noise barrier and absorption on the building facades, on the other hand, decreases the average pass-by levels by approximately 4 dB.

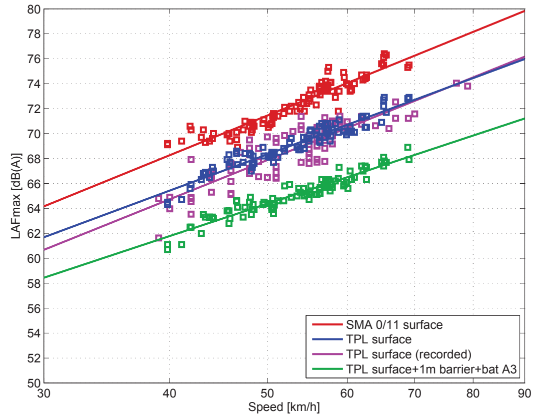


Figure 7: SPB analysis of auralized traffic in three cases (red: standard road surface, blue: low noise road surface, green: low noise road surface with low barrier and "green" facades). The auralized low noise surface case is also compared to the recorded case (purple). Pass-by levels of individual vehicles are represented by squares and the associated logarithmic regression by solid lines.

# 5 Conclusion

Results from the validation of a new auralization method for road traffic noise are presented. The proposed approach features granular synthesis algorithms allowing real time generation of engine and tire noise signals for varying vehicle speed. Listening tests performed on vehicle source signals show that the synthesized signals are perceptually very close to recorded signals for different types of engine types and speed evolutions. Similar results are obtained on tire noise synthesis. Next, the comparison between sound pressure levels of recorded and auralized sequences obtained for a real non-stationary traffic flow in an urban site shows good agreement. Additional configurations including different road surfaces and the addition of a low barrier were also auralized allowing a perceptual evaluation of their impact. Current work focuses on listening tests carried out on the recorded and auralized sequences in order to compare noise annoyance levels obtained in both cases.

# 6 Acknowledgments

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