Selection of a sound propagation model for noise annoyance prediction: A perceptual approach (L)

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Sound propagation effects need to be considered in studies dealing with the perception of annoying auditory sensations evoked by transportation noise. Thus, in a listening test requiring participants to make dissimilarity ratings, the effects of several feasible propagation models are compared to actual recordings of vehicle noises made at a given distance. As a result, a model taking into account first order reflections without any phase term is found to be the most appropriate model for simulating road traffic noise propagation in an urban environment from a perceptual point of view.
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I. INTRODUCTION

European directive 2002/2049/EC requires that every European city of more than 100 000 inhabitants produces strategic noise maps[1] to account for transportation noise exposure. Such noise maps, built using sound propagation software, traffic, and topographical data, specify exposure in terms of the energy-based index L_{DEN} (i.e., the A-weighted day–evening–night equivalent level) at any given geographical point. Miedema and Oudshoorn[2] proposed EU-approved annoyance models from this index. However, the prediction quality of these models is weak (e.g., Ref. 3) and mean energy-based indices are not sufficient to assess noise annoyance in an urban environment. Other acoustical factors influence annoyance, such as the frequency composition and temporal structure of the noise. These factors (e.g., amplitude modulation) often produce annoying sensations. Certain indices have proven to be relevant to assess annoying sensations evoked by transportation noise [e.g., the Total Energy of Tonal Components (TETC) at high frequencies[4]]. These indices have subsequently been used to construct noise annoyance models, which provide better predictions under laboratory conditions than mean-energy based models do.[4] Such models need to be tested using *in situ* data. However, determining these indices would require extensive *in situ* recordings and analysis on a city scale. A simpler approach would be to investigate the effect of sound propagation on the annoying auditory sensations, thereby permitting the estimation of these indices for any point on the map, using L_{DEN} values and topological information, both of which are part of available noise maps already.

State of the art of constructing noise maps is described in New Method of Noise Prediction.[5] This method computes L_{DEN} at any given point, taking meteorological and atmospheric propagation effects into account, along with building refraction and reflection, as these effects influence spectral content of an acoustic source at the reception point. To take this kind of modeling one step further, the present study investigates the influence of sound propagation on annoying auditory sensations, by selecting an appropriate sound propagation model on the basis of perceptual judgments.

For this purpose, recordings of vehicle pass-bys were made *in situ* at different distances from sound sources in order to assess relative perceived dissimilarities between sound recordings attenuated by actual sound propagation and the corresponding pass-by noises altered by simulated attenuations based on different models. The recordings were selected to give rise to various auditory sensations, relevant in the context of annoyance. Subsequently, attenuation due to sound propagation in an urban environment was simulated using suitable acoustics software for a given urban topography. The simulated attenuations were applied to the road pass-by noise excerpts recorded close to the source. Several propagation models were implemented in the software and compared to each other in a listening test, which provided dissimilarity ratings with respect to a reference, an *in situ* vehicle pass-by actually recorded at the far distance. The objective is to select the propagation model for which "far-distance" recorded and the corresponding simulated pass-by noises are judged to be similar for a sampling of different urban vehicles.

II. EXPERIMENTAL METHODOLOGY

In order to determine the most accurate propagation model from a perceptual point of view, an experiment was carried out. The question to be answered is as follows: Which of several competing sound propagation models rendering a simulated pass-by turns out to be most similar to an actual recording at the given distance, even when different kinds of vehicles or driving conditions are considered? To answer this question, a listening experiment based on dissimilarity ratings using a reference is proposed.

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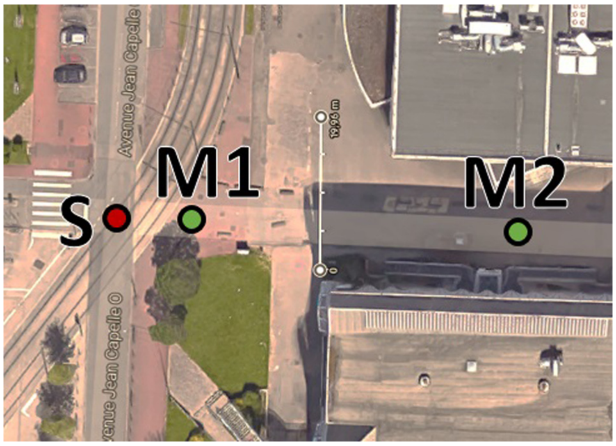

FIG. 1. (Color online) Location of the recordings. S: position of the point source. M1: position of the closest microphone, 10 m away from S. M2: position of the long-distance microphone, 50 m away from S.

A. Stimuli

1. *In situ recordings*

Acoustic recordings were conducted in Villeurbanne, a suburb of Lyon, France. Simultaneous recordings were carried out in a side street perpendicular to a main road, in order to account for pass-by noise emanating from that main road. The acoustic recordings were carried out at two receiver points in the side street with the vehicles passing by on the main road being considered the source S, as shown in Fig. 1. The first receiver point, denoted M1, was 10 m away from S. The building arrangement close to M1 defined its location as an "open" street in the sense of Ref. 6. The distance M1-S justifies a point source hypothesis valid for frequencies higher than 100 Hz.[7] The second receiver point, denoted M2, was 50 m away from S, where the building arrangement defined this location as a "U-shaped" street.[6]

M1 setup included an omnidirectional microphone in order to collect monophonic recordings. Urban background noise level was low at this point: 31 dB(A). M2 setup included an omnidirectional microphone as well with the background noise level corresponding to approximately 47 dB(A). The microphones were placed at a height of 1.2 m and at least 2 m away from any reflecting wall. Two sets of pass-by noises were recorded, one composed of road-traffic noise, and one of tramway noise (not considered in this paper).

Road traffic pass-by series consisted of five recordings (cf. Table I), encompassing three types of vehicles (powered-two-wheelers "d," light vehicles "v," and a heavy vehicle "p") and two driving conditions (acceleration "a" and constant speed "f"). These five stimuli were selected from categories of the perceptual typology of Morel *et al.* of urban road pass-by noises,[8] since they included various annoying acoustical features (e.g., amplitude modulation). Yet another road pass-by noise, an accelerating powered-two-wheeler recorded at M2, was chosen as the reference.

2. *Sound propagation models and filtering*

In order to model sound propagation in an urban environment, a computer software[9] was employed.[10] This software offers three distinct propagation models (cf. Table II). It was chosen since it covers a frequency range from 16 Hz to 16 kHz. This bandwidth is important when studying transportation noise, where high-pitched tonal components influence annoyance (e.g., Ref. 4). A simple level decrease was also considered. This model, named geometrical divergence, was based on the theoretical diminution of level with distance from a point source for a spherical wave.

TABLE I. Road traffic pass-by noises studied. Acc. = accelerating, const. = constant speed.

Pass-by noise	Vehicle Type	Vehicle Driving condition	Duration (s)	Sound pressure level at M2 [dB(A)]
da	Powered-two-wheeler	acc.	6	40.3
df	Powered-two-wheeler	const.	4	38.4
pf	Heavy vehicle	const.	11	51.1
va	Light vehicle	acc.	7	53.9
vf	Light vehicle	const.	5	52.5
Ref.	Powered-two-wheeler	acc.	6	52.8

Each of these four sound propagation models was applied to the M1 recordings in turn, to simulate pass-by noises heard at M2. The four simulated pass-by noises then formed a set of M′2 noises. Background noise recorded at M2 was mixed with these M′2 noises in order to account for the environmental conditions at M2. The four (simulated) M′2 sounds and the corresponding (actual) M2 recordings led to five variations per vehicle pass-by. Thus, 25 stimuli were studied in the road traffic series. High-pass filtering at 80 Hz and 1-s fade-in and fade-out were applied to each sound stimulus.

B. Apparatus

The experiment took place in a quiet laboratory room, with a background noise level measured at 20 dB(A). Pass-by noises were reproduced through a pair of active loudspeakers and an active subwoofer. The loudspeakers were positioned at a height of 1.20 m, and they formed an equilateral triangle (side length of 1.7 m) with the participant's interaural axis. Participants were facing a computer screen. The subwoofer was placed on the floor between the two loudspeakers.

C. Participants

Thirty-one listeners (13 male, 18 female) participated in the experiment. Their mean age was 33.7 years (range 20 to 58). Participants were paid for their participation, and they all declared to have normal hearing.

TABLE II. The sound propagation models employed and their abbreviations (Abbr.).

Model	Abbr.
DefaultSolver Energy (first order reflections without phase)	DSE
DefaultSolver Interference (first order reflections with phase)	DSI
Anime3D (first to third order reflections with phase)	A3D
Geometrical Divergence (level decrease due to distance)	Div

D. Procedure

Participants were asked to rate the perceived dissimilarity between each stimulus and the reference. Dissimilarity was evaluated on a continuous scale displayed on the screen, ranging from "very similar to the reference" (rating 0) to "very different from the reference" (rating 10). Participants were instructed to attentively listen to the stimuli, and then make their mark using the computer mouse.

Stimuli were organized in random order. Due to the number of stimuli, a simultaneous dissimilarity test relative to Ref. 11 was used. All stimuli making up a series of 25, plus the reference, were simultaneously visualized on the screen and could be played back at any time, with the option to reevaluate a given rating. This method allows participants to refine their rating of dissimilarity of a given stimulus compared to the reference, depending on their evaluation of the other stimuli. At the end of the experiment, short interviews were conducted to collect demographic information. On average, it took participants 28 min to complete the experiment, including tramway series not reported here.

III. RESULTS

Repeated-measures analyses of variance (RM-ANOVAs) were carried out to determine whether the perceptual evaluations based on four competing sound propagation models were significantly different from each other and from the actual recording at M2.

An one-way RM-ANOVA of the factor "STIMULUS" yielded a highly significant effect on dissimilarity ratings $[F(24,720) = 17.574,\ p < 0.001]$. Results are displayed in Fig. 2.

Furthermore, a two-way RM-ANOVA was carried out to inspect the factors "VEHICLE" [i.e., vehicle types and driving conditions (see Table I)] and "PROPAGATION" (i.e., simulated propagations, M′2 and real propagation, M2) separately. It showed a highly significant effect of the factor VEHICLE $[F(4,120) = 28.51,\ p < 0.001]$, explaining 49% of the total variance in mean ratings. It also showed a highly significant effect of the factor PROPAGATION $[F(4,120) = 10.17,\ p < 0.001]$, accounting for 25% of the total variance, which implies that participants were able to reliably detect differences between the M′2 stemming from different propagation models. It finally showed a significant interaction between the factors VEHICLE and PROPAGATION $[F(16,480) = 3.00,\ p < 0.001]$, explaining 9% of the total variance. This effect is due to the fact that PROPAGATION had similar effects across all vehicles except for all recordings filtered by Anime3D and for the M2-recorded pass-by of the constant-speed light vehicle (*vf*).

Tukey's HSD test was carried out in order to further investigate the influence of the factor PROPAGATION on the dissimilarity ratings. The test showed that stimuli based on Div, A3D and DSI processing were significantly different from M2-recorded stimuli when considering the dissimilarity ratings of all vehicles. By contrast, DSE-based stimuli were not significantly different from M2 stimuli. Thus, stimuli generated using the DSE propagation model were found to be perceptually indistinguishable from the stimuli recorded *in situ*. This is confirmed by a further Tukey (HSD) test carried out on all combinations of the factors VEHICLE and PROPAGATION showing that, for any vehicle, DSE-generated stimuli were judged not significantly different from the corresponding M2 stimuli.

Inspecting the attenuation in third-octave bands, it appears that the DSE model attenuates high frequencies more strongly than the other sound propagation models studied. To study the perceptual consequences, the Total Energy of Tonal Components (TETC) index, proposed by Klein *et al.*[4] to quantify the sensation of high-pitched tonal components, was calculated for each stimulus used. A t-test was conducted on the TETC values for DSE-based versus M2-recorded

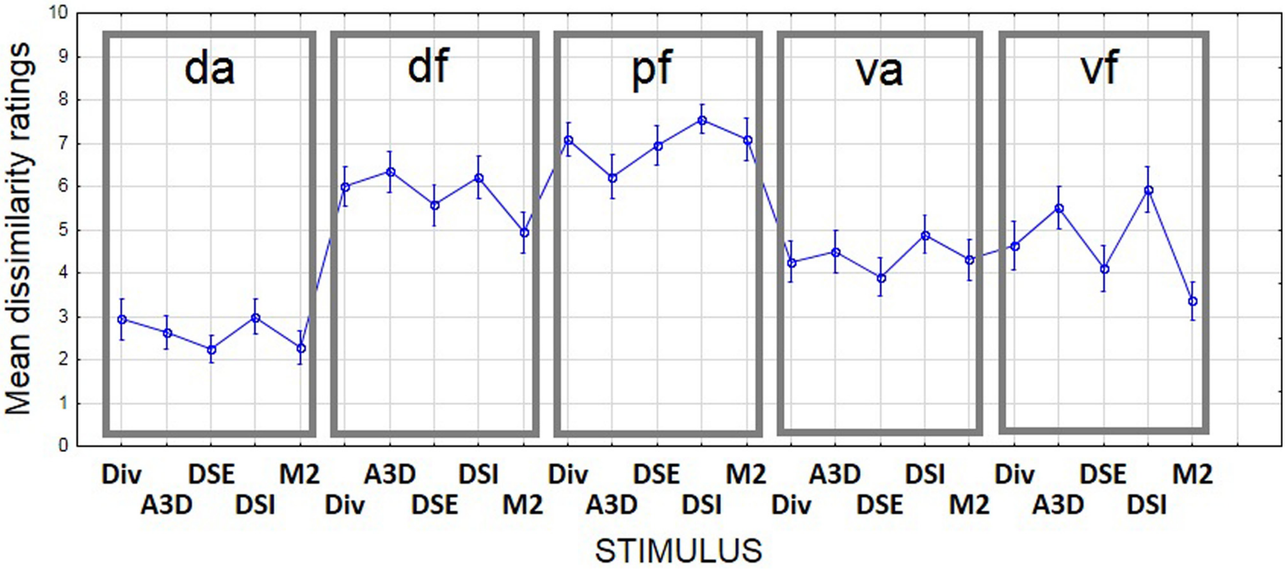

FIG. 2. (Color online) Mean dissimilarity ratings and standard errors for each vehicle and propagation model. Div = geometrical divergence, A3D = Anime3D, DSE = DefaultSolver Energy, DSI = DefaultSolver Interference, M2 = recorded, da = accelerating powered-two-wheeler, df = constant speed powered-two-wheeler, pf = constant speed heavy vehicle, va = accelerating light vehicle, vf = constant speed light vehicle.

stimuli. Results indicated no significant differences between DSE stimuli and M2 stimuli ($t = 0.86$, $p = 0.42$). Other t-tests were conducted on the TETC values for stimuli generated by the other models. The results indicate that TETC seems to account for a large portion of variance in participants' dissimilarity ratings depending on the models. Therefore, the attenuation of high frequencies might be an important feature indicating distance, and explaining the effect of sound propagation from a perceptual point of view.

IV. DISCUSSION

Data analysis showed a significant effect of the factor VEHICLE, which implies that the participants distinguished the different vehicles and driving conditions and judged dissimilarity accordingly. This is consistent with the findings of Morel *et al.*,[8] which stated that "vehicle type" and "driving conditions" are the most important factors when evaluating dissimilarities between urban road traffic pass-bys.

Post hoc comparisons showed that simulations of sound propagation based on the "DefaultSolver Energy" resulted in ratings more similar to the actual measurements at the "far" point M2. Furthermore, the analysis indicated that, for any vehicle, DSE-generated pass-by noises and corresponding M2 recordings were not judged significantly different.

The computation software used in this study was previously used in a perceptual study dealing with long-distance propagation (e.g., over several hundred meters) of stationary sound emitted by industrial sources (e.g., cooling tower noise) (cf. Ref. 12). It has therefore proven to be equally useful for faraway sources as for urban road traffic noise emitted by moving sources at shorter distances.

Thus, DSE-based simulations of sound propagation in an urban environment, ranging from 16 Hz to 16 kHz and based on first order reflections without any phase related term, have been shown to be valid from a perceptual point of view, and might be used in further studies investigating annoying auditory sensations.

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