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Modeling and prediction of vehicular traffic noise through direct, specular and diffuse paths at bus stops

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ABSTRACT

Bus stops for public transport systems are structures where users are exposed to intense levels of noise and are poorly evaluated in surveys. Therefore, the goal of this research is to develop a mathematical model of noise level prediction at bus stops, in order to contribute to the characterization of the traffic noise level. For this, a prediction model was developed based on direct waves and specular and diffuse reflections. A standard bus stop model was adopted on a three-lane roadway, simulating the user standing and sitting. The sound source was positioned on the axis of each strip, every five meters. In total, 126 source positions were evaluated. The descriptors, sound pressure level (SPL) and sound equivalent level (L_{Aeq}) were calculated. For the validation, the Anderson and Kurze model was applied, and later the Student t-test. The results presented better correspondence between the developed model and the reference model in the severe bands, whereas in the 8 kHz frequency there was a greater variance between the models. As a preliminary study, the research presented satisfactory results, which may contribute to future research.

Keywords: prediction model, road traffic noise, radiosidy

1. INTRODUCTION

Traffic noise is the main source of urban noise. With the cities growth this problem has been aggravated by the increase in demand for individual and collective transportation. Studies show that exposure to high levels can cause harmful effects to people's health (1-3). For this reason, studies related to urban noise have been extensively done (4-5).

In addition to studying and evaluating noise, studies are important tools in the planning and development of urban projects (6). Traffic noise prediction models are created from field measurements and analysis of different noise descriptors or traffic noise parameters. The development of noise prediction models allows the identification of critical points, the evaluation of population exposure and the simulation of mitigation measures in noise maps (7).

The simplest models are based on the relationships between the number of vehicles and the level of noise they emit (8-9). On the other hand, the more complex models calculate other parameters, such as the speed, percentage of heavy vehicles, road configurations such as width and inclination, building feedback, barriers, among others (9-11). Other studies have recently addressed the modeling of sound propagation through specular or diffuse reflection analysis (12-15). The researches which use this approach allow the prediction of the behavior of sound propagation in different urban configurations, as well as the path of reflected sound waves (specular and diffuse).

Based on this, the main goal of this research is to develop a mathematical model of prediction of the level of noise of road traffic, calculating the direct, specular and diffuse ways in bus stops, since these are spaces where the users are exposed to intense levels of and are poorly addressed in studies. This research seeks to contribute to the studies of traffic noise prediction models and to predict the sound levels in which users of the public transport system are exposed to at bus stops.

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2. METHODOLOGY

For the development of the research, a standard urban geometry model was elaborated. In the model, a standard bus stop was dimensioned, inserted in the middle of the block. The modeled street has three lanes with three-story buildings (9 meters high) on each side of the track. In each band, a sound source of 100 dB sound power level, measured every 5 meters of distance, was calculated and positioned 0.5 m above the street. In total, in each range, 21 source positions were calculated, totaling 63 positions in the three bands, as shown in Figure 1.

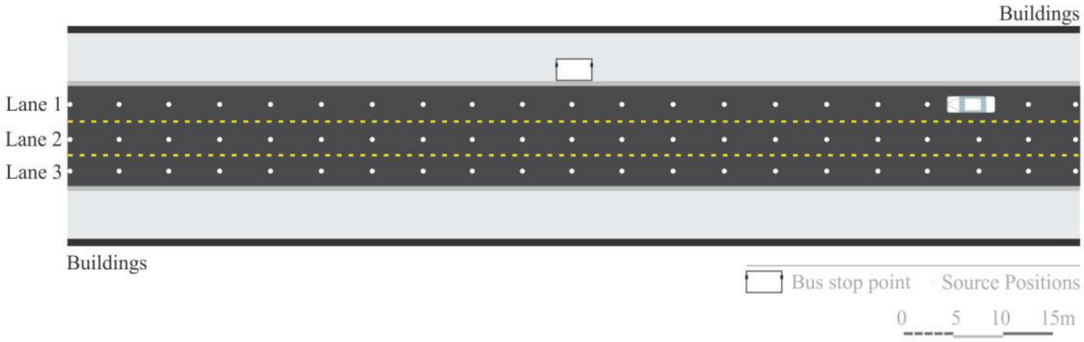

Figure 1 – Schematic model of the standard bus stop model and its insertion into the created geometry

Two scenarios were simulated separately, the first one simulating the user standing and the second one the user seated. At each point, the sound pressure level (SPL) and the sound equivalent level (L_{Aeq}) were calculated, in octaves of frequency. For the validation, the Anderson and Kurze model, and later the Student's t-test, were applied to verify the variance between the models.

2.1 Theoretical Model

The theoretical model calculates the direct paths and specular and diffuse reflections, these paths correspond to the pulses emitted from a sound source (Figure 2). The model simulates an urban street, limited by buildings up to three decks. Each plane, presents absorption and scattering coefficients, adopted later in the calculations of the sound reflections.

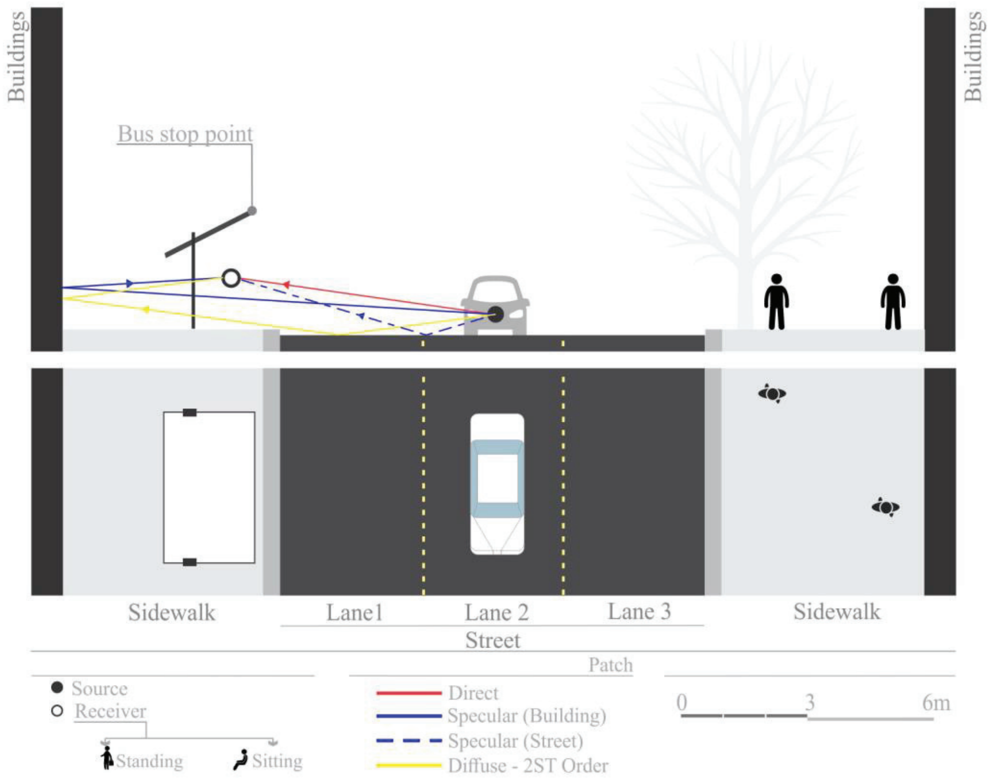

Figure 2 – Profile of the model with direct paths and specular and diffuse reflection

The direct path corresponds to the wave emitted by the source that arrives at the receiver directly without reflections. It is obtained by calculating the intensity (Id) given by the relation between the sound power of the source and the distance between the source and the receiver. In equation 01 the directivity factor (Ω) and the losses due to the absorption of the air (ψ) are adopted.

$$I_d = W_e + 10log\left(\frac{\Omega}{4\Pi d_T^2}\right) + e\left(\frac{4}{-\psi d_T}\right) \quad (1)$$

The attenuation due to air absorption is calculated using the methodology of ISO 9613-1: 1993. The losses (ψ) are calculated by the sum of the classical losses due to thermal effects, rotational relaxation, and vibrational relaxation of the oxygen and nitrogen molecules (16), as shown in Equation 2.

$$\psi = \psi_{cl} + \psi_{rot} + \psi_{O_2vib} + \psi_{N_2vib} \quad (2)$$

The intensity of the specular path is obtained by means of the relation between the sound power of the source and the distance between the source and the receiver. In addition to the Ω directivity factor and the losses due to the absorption of air ψ, the absorption and scattering coefficients of each plane in which the sound wave is incident and reflected are calculated (Equation 3). For the calculation of the specular path, the image source method is used, where the sound energy reflects at the same angle as it is on the plane. In this method the mirror image of the sound source will have the same distance on the opposite side of a reflecting plane (17).

$$I_e = W_e + 10log\left(\frac{\Omega}{4\Pi d_T^2}\right) + e\left(\frac{4}{-\psi d_T}\right)\sum_{\alpha=1}^{10}\left[\left(1-(\alpha_\alpha + \zeta_\alpha)\right)\right] \quad (3)$$

For the calculation of the specular and diffuse paths, absorption coefficients (α) and scattering (ζ) were adopted for each material adopted in the model, as shown in Table 1. The absorption coefficient (α) is the ratio between the sound energy is not reflected and the incident sound energy, is the sum of energy absorbed and transmitted (18). The scattering coefficient (ζ) is the ratio of the reflected sound energy in non-specific directions to the total reflected sound energy, the dispersion of the energy distributed unevenly according to the roughness of the material (18).

Table 1 – Absorption coefficients and scattering

MATERIALS	ABSORPTION COEFFICIENT (Hz)								SCATTERING COEFFICIENT AVERAGE (Hz)
	63	125	250	500	1000	2000	4000	8000	
Asphalt (street)	0.02	0.02	0.03	0.03	0.03	0.03	0.02	-	0.25
Concrete (sidewalk)	0.02	0.02	0.03	0,03	0.03	0.04	0.07	0.07	0.5
Smooth Concrete (external walls)	0.01	0.01	0.02	0.02	0.02	0.02	0.05	0.05	0.1
Bus stop (metal tile)	-	-	-	-	-	-	-	-	0.1

SOURCE: Adapted (19-21).

For the calculation of the diffuse path, the first and second order radiosity model was adopted. The radiosity model divides the space (model) into stretches and calculates path of noise from one stretch to the other (18). In the first-order radiosity, the path between the source and the receiver is only a diffuse reflection in one of the planes of the model. In the section where the reflection is calculated the sound power of the section of the plane is calculated as shown in Equation 4. In the calculation of the sound power reflected by the section, the sound power emitted by the source, the scattering coefficient and the area of the stretch. Subsequently, the diffuse path of the reflected segment is calculated to the receiver.

$$W_p = W_e + 10log\left(\frac{\Omega}{4\Pi d_{ep}^2}\right) + e\left(\frac{4}{-\psi d_{ep}}\right)\zeta_p A_P \tag{4}$$

The intensity of the first-order diffuse path is obtained by means of the relation between the sound power of the source of the "p" section and the distance between the first reflection section and the receiver. In equation 5, the directivity factor (Ω) and the losses due to the absorption of the air (ψ) are adopted for the calculation.

$$I_1 = W_p + 10log\left(\frac{\Omega}{4\Pi d_{pr}^2}\right) + e\left(\frac{4}{-\psi d_{pr}}\right) \tag{5}$$

On the second order, radiosity path a double diffuse reflection is calculated, that is, from the sound source, the stretch of the first reflection, the stretch of the second reflection, and then the receiver (r). In the second order of radiosity the path between the first reflection and the second reflection is calculated the diffuse energy radiated from the first stretch to the second, by means of the form factor (FF), as shown in Equation 6.

$$I_2 = W_p + 10log\left(\frac{\Omega FF_{ji} e^{-\psi d_{ij}}}{4\Pi d_{jr}^2}\right) + e\left(\frac{4}{-\psi d_{jr}}\right) \tag{6}$$

The form factor (Figure 3) calculates the fraction of energy that is radiated from one surface and reaches another surface (22), taking into account the distance, shape and relative orientation of the two planes. For the calculation of the FF used in Equation 6, the form factor was adopted from the Hemi-cube.

This way of calculating the FF, is similar to the geometric analogy of Nusselt in that it replaces the hemisphere with a hemicube and dividing the faces into small flaps (pixels) (23). For the calculation of the FF, the radius between the planes and the cosine of the angles i and j is calculated. (Eqs. 7, 8, 9 and 10).

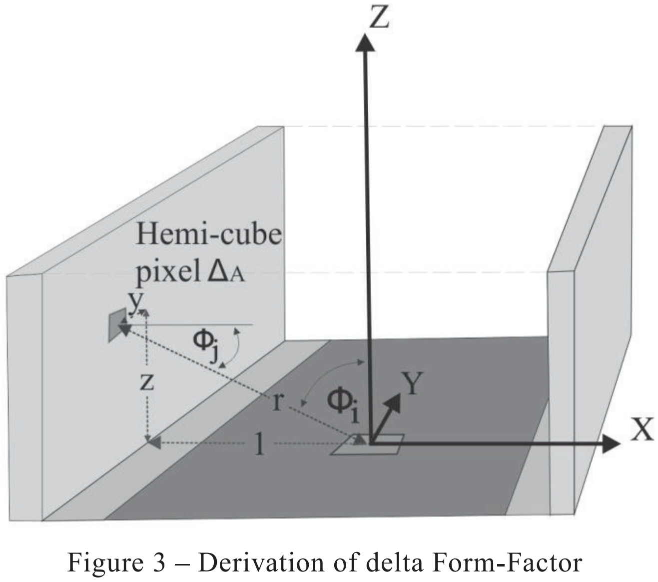

Figure 3 – Derivation of delta Form-Factor

$$r = \sqrt{y^2 + z^2 + 1} \tag{7}$$

$$cos\emptyset_i = \frac{Z}{\sqrt{y^2 + z^2 + 1}} \tag{8}$$

$$cos\emptyset_j = \frac{1}{\sqrt{y^2 + z^2 + 1}} \tag{9}$$

$$FF = \frac{cos\emptyset_i \times cos\emptyset_j}{\pi r^2} \Delta A \tag{10}$$

After calculating the paths, it is calculated the total intensity (It), which is the sum of all the pulses (paths) emitted by the source that arrive at the receiver, as shown in equation 11. The model was calculated in octave bands, in the bands from 63Hz to 8kHz.

$$I_t = I_d + \sum I_e + \sum I_1 + \sum I_2 \tag{11}$$

Subsequently, the comparison between the methods was calculated the descriptor Level equivalent sound (L_{Aeq}), as shown in Equation 12. For the validation the Anderson and Kurze model was applied. The Anderson and Kurze model describe a basic equation (Eq. 13) of outdoor sound propagation (24). In this model the solid angle (Ω) made available to the free propagation source is calculated. The directivity (DI_θ) and $A_{combined}$, corresponds to the attenuation between the source and the receiver.

$$L_{Aeq} = 10\log\left\{\frac{1}{n}\left[\sum\nolimits_{i=1}^{n}\left(10^{Li/10}\right)\right]\right\} \tag{12}$$

$$L_p(r,\theta) = L_W - 20\log r + DI_\theta - 10\log\frac{\Omega}{4\pi} - A_{combined} - 11dB \tag{13}$$

To verify the similarity between the models, the t-Student test was adopted. The test consists of a probabilistic model that calculates the variance between two samples. The sample size (n) is called degrees of freedom, which corresponds to the value of n - 1 (25). The t-critical is obtained according to the level of significance and degrees of freedom. If the t-critical is greater than or equal to the calculated, we accept Hypothesis H_0, that is, no significant variance between the samples (26). The value of t is obtained from equation 14 (26).

$$t = \frac{(\bar{X}_1 - \bar{X}_2)}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \tag{14}$$

Where $\bar{X}_1$ e $\bar{X}_2$ are the means of each group. S1 and S2. corresponds to the standard deviations of the respective groups and n1 and n2 are the point numbers.

3. RESULTS AND DISCUSSION

The calculated results of the 126 source positions, 63 of the model developed and 63 of the model of Anderson and Kurze, considered the users standing with height of 1.5 m and the users seated with height of 1.1 m. The overall value of the sound spectrum as shown in Figure 4 shows the L_{Aeq} values of the 126 source positions.

The results showed similarity between the models, in general the difference between the models was higher in the 03 range presenting values ranging from 0.7 dB to 0.9 dB between the developed model and the reference model. On the other hand, bands 1 and 2 presented values between 0.2 dB to 0.4 dB, for band 1 and 0.1 dB to 0.7 dB in band 02.

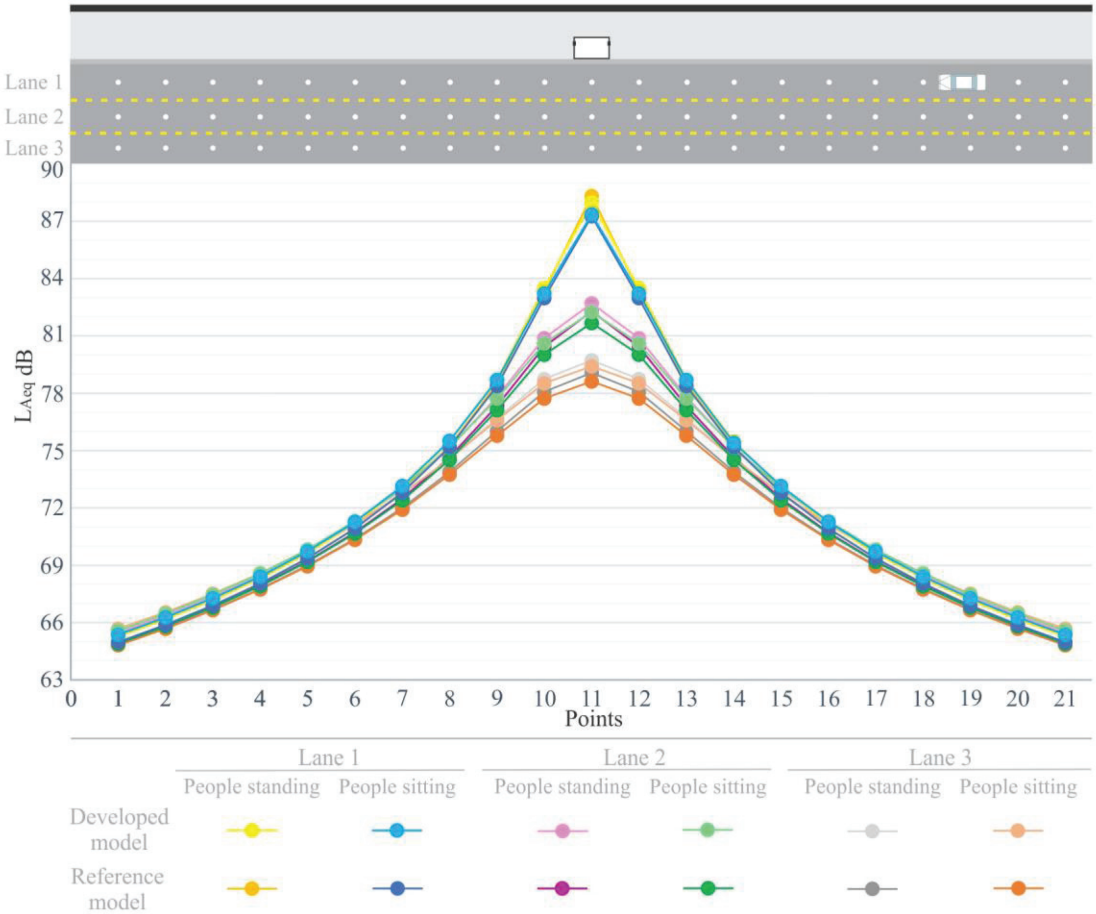

Figure 4 – L_{Aeq} of each point

The values obtained (Figure 4) were closer between the models at the points closest to the receiver, but were the ones that presented the most variation between the bands. This greater variation in points near the receiver occurred due to the distance between the source and the receiver being smaller, presenting a lower attenuation due to the atmospheric absorption and the absorption of the scattering of the materials. The comparison between the two scenarios (standing and sitting users) shows that standing users are more exposed to the noise emitted by the source.

The total value of the sound spectrum in the developed model presented Leq values of 78.3 dB, 75.5 dB and 73.9 dB, in lanes 1, 2 and 3 respectively, for the standing user, and 77.9 dB, 75.3 dB and 73.8 dB for the seated user. In the reference model of Anderson and Kurze, the values were 78.4 dB, 75 dB and 73.2 dB, in lanes 1, 2 and 3 for the standing user, for the seated user were 77.7 dB, 74.7 dB and 73 dB, respectively. The variance between methods was shown to be lower in the bass frequencies and in the bands closer to the receiver.

The values obtained show the level at which users using public transport systems are exposed at bus stops. The values (Figure 4) become more intense as they approach the bus stop. Exposure to levels above 70 dB can lead to cardiovascular problems and changes in the auditory system (27).

Student's t-test was used to determine the significance level of 5% ($\alpha = 0.05$). For the calculation, 21 samples corresponding to the 21 source positions in each range were adopted. In the similarity analysis, the developed model and the reference model were compared. Thus, the samples of each model were added, totaling 42 samples. It is observed that for each group analyzed we calculated (n-1). In this way the value of 40 degrees of freedom was obtained.

The first analysis of similarity of the two models, the global value of the sound spectrum of each band was calculated for the user sitting and standing. The test as shown in Table 2, presented values below the t-critical value. For the two-tailed test with 40 degrees of freedom the t-critical value corresponds to 2.021.

Table 2 – Bi-caudal t test of similarity of methods

SCENARIOS		MODEL	AVAREGE	VARIENCE	T	P(T<=T)	T CRITICAL
Lane 01	Standing person	Developed	72.62	43.68	0.105	0.917	2.021
Lane 01	Standing person	Reference	72.40	44.98	0.105	0.917	2.021
Lane 01	Sitting person	Developed	72.62	41.57	0.164	0.871	2.021
Lane 01	Sitting person	Reference	72.29	42.41	0.164	0.871	2.021
Lane 02	Standing person	Developed	72.07	29.52	0.300	0.766	2.021
Lane 02	Standing person	Reference	71.57	29.88	0.300	0.766	2.021
Lane 02	Sitting person	Developed	72.08	28.02	0.386	0.701	2.021
Lane 02	Sitting person	Reference	71.44	28.28	0.386	0.701	2.021
Lane 03	Standing person	Developed	71.55	28.38	0.496	0.623	2.021
Lane 03	Standing person	Reference	70.85	21.65	0.496	0.623	2.021
Lane 03	Sitting person	Developed	71.56	20.32	0.596	0.555	2.021
Lane 03	Sitting person	Reference	70.73	20.55	0.596	0.555	2.021

The "t" values (Table 2) show that there is no significant difference between the models. Thus presenting similarity between the developed model and the reference model.

The second analysis was calculated considering the users standing and seated in each bands in each frequency range. The calculated results (Figure 5) showed greater similarity between the models at low frequencies and in the band closest to the receiver.

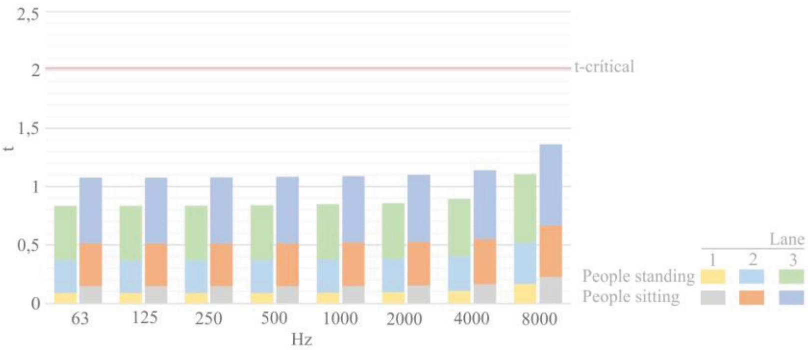

Figure 5 – Teste t-student by frequency lane

Analysis by frequency range, presented values of "t" inferior to the value t-critical, for 40 degrees of freedom. This means that the difference between the models is less than 5%, that is, the values are in the range of -2.021> t <2.021. In this way the hypothesis of Ho is accepted, in which it is assumed that there are no significant differences between the developed model and the Anderson and Kurze.

4. CONCLUSIONS

It is concluded that the prediction model based on the calculations of the paths (direct, specular and diffuse) allowed to predict the sound levels at the bus stop. The sound levels calculated in the model presented more intense values in the bands near the receiver, thus showing intensity that the users are exposed, and that can be harmful to health. The application of the t-Student test to evaluate the similarity, allowed to validate the developed model, comparing with the reference model of Anderson and Kurze. The difference presented between the models was less than 5%, that is, the model shows similarity higher than 95% with the reference model.

As a preliminary study, the research presented satisfactory results in the prediction of road noise levels reaching the receiver (standing or sitting user), emitted from a sound source. It is hoped that the study may contribute to evaluations of vehicle traffic noise characterization at bus stops and also to the application in other contexts.

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