Probabilistic model for urban traffic noise analyses using real sound signals

Modelo probabilístico para análises de ruído do tráfego urbano usando sinais sonoros reais

Italo César Montalvão Guedes
Stelamaris Rolla Bertoli
Jugurta Montalvão

Abstract

Vehicular traffic is pointed out as a major source of urban noise pollution today. In this paper, we evaluated the precision of a new probabilistic model for urban traffic noise analyses. The proposed model adopts real sound signals and the Monte Carlo method in simulations. Probability distributions of traffic variables were obtained *in-situ* on two urban roads. The acoustic signals and corresponding energies of single pass-by of vehicles were obtained using sound signal recordings on test tracks under free-field condition. The model simulates vehicular traffic noise on urban roads in free or in traffic light controlled flow and considers the influence of bus stops. The proposed model calculates different acoustic descriptors, such as Statistical sound levels (L_{A10} and L_{A90}), Equivalent continuous sound level (L_{Aeq}), Traffic noise index (TNI) and Noise pollution level (L_{NP}). Furthermore, it allows the listening of simulated noise. The experimental results indicate that the proposed model is reliable and accurate for vehicular traffic noise prediction.

Keywords: Urban noise pollution. Vehicular traffic noise. Probabilistic simulation. Real sound signals.

Resumo

O tráfego veicular é apontado como uma importante fonte de poluição sonora urbana nos dias de hoje. Neste artigo, foi avaliada a precisão de um novo modelo probabilístico para análises de ruído do tráfego urbano. O modelo proposto adota sinais sonoros reais e o método Monte Carlo nas simulações. As distribuições de probabilidade das variáveis de tráfego foram obtidas in-situ *em duas ruas urbanas. Os sinais acústicos e as energias correspondentes das passagens individuais de veículos foram obtidos usando gravações de sinais sonoros em pistas de teste sob condições de campo livre. O modelo simula o ruído do tráfego veicular em ruas urbanas com fluxo livre ou fluxo controlado por semáforos, e considera a influência das paradas de ônibus. O modelo proposto calcula diferentes descritores acústicos, tais como, Níveis sonoros estatísticos (L_{A10} e L_{A90}), Nível sonoro contínuo equivalente (L_{Aeq}), Índice de ruído de tráfego (TNI) e Nível de poluição sonora (L_{NP}). Além disso, o modelo permite a escuta de ruídos simulados. Os resultados experimentais indicam que o modelo proposto é confiável e preciso para a previsão de ruído do tráfego veicular.*

***Palavras-chave**: Poluição sonora urbana. Ruído do tráfego veicular. Simulação probabilística. Sinais sonoros reais.*

[1]**Italo César Montalvão Guedes**
[1]Universidade Federal de Sergipe
Laranjeiras - SE - Brasil

[2]**Stelamaris Rolla Bertoli**
[2]Universidade Estadual de Campinas
Campinas - SP - Brasil

[3]**Jugurta Montalvão**
[3]Universidade Federal de Sergipe
São Cristóvão - SE - Brasil

Recebido em 27/12/22
Aceito em 06/04/23

Introduction

Due to fast population growth, rapid urbanization and popularization of motor vehicles, vehicular traffic noise has been indicated as one of the main kinds of environmental noise in cities. According to the World Health Organization, "Environmental noise is an important public health issue, featuring among the top environmental risks to health." (WORLD…, 2018). Noise pollution is associated with various harms to people, from annoyance and discomfort at work, study, leisure or sleep, to socioeconomic impacts. But the main impact of noise is its deleterious effects on physical and mental human health, such as temporary or permanent hearing loss, high blood pressure, heart disease, hormonal changes, sleep disturbances and irritation (WORLD…, 2018; KASSOMENOS; VOGIATZIS; COELHO, 2014; HAMMER; SWINBURN; NEITZEL, 2014). These are relevant issues for the quality of life in urban areas.

The monitoring of noise exposure and its control should be among the main concerns of citizens, politicians, administrative bodies and the technical-scientific community. However, the assessment of environmental noise is difficult due to noise diversity, resulting from a myriad of different activities and devices that can generate noise in combinatorial manners, especially in cities (LICITRA, 2013). Moreover, in the urban environment, noise is modulated by uncountable sound propagation aspects, such as physical and geometrical urban shapes, including location of buildings and barriers and their absorption coefficients, atmospheric and meteorological factors (temperature, humidity and wind conditions) (GUEDES; BERTOLI; ZANNIN, 2011; AUMOND *et al*, 2021).

Vehicular traffic noise is further influenced by volume, composition (ratio of light, heavy vehicles and motorcycles) and vehicle flow speed, cross-sectional profile, slope and the type of road pavement (PREZELJ; MUROVEC, 2017). Other researches have shown that urban vehicular traffic noise is also influenced by traffic instabilities, caused by the relentless stopping and going of vehicles at intersections (with traffic lights or not), roundabouts, speed humps and bus stops (ABO-QUDAIS; ALHIARY, 2007; COVACIU; FLOREA; TIMAR, 2015; LI *et al.*, 2011; CAI; LI; LIU, 2011; WANG; CAI; ZOU, 2012; LU *et al*., 2019).

Thus, having proper tools for assessment and control of the urban noise (e.g., noise mapping and prediction model) is relevant for city managers. The development of prediction models was boosted by the creation of the European Directive 2002/49/EC (EUROPEAN…, 2002), when strategic noise maps became recommended tools for analysis of transport noise and urban agglomerations. By the year 2007, European Union (EU) member states have been required to develop strategic noise maps for all agglomerations with more than 250,000 inhabitants, highways with over six million vehicle passages and railroads with over 60,000 train passages per year and major airports within their territories, and until 2012, for all agglomerations and major roads and railways. These strategic noise maps must be made every 5 years (EUROPEAN…, 2002).

Over the years, these actions have spread to other countries in the world (ASENSIO *et al.*, 2009; ARANA *et al.*, 2010; WANG; KANG, 2011; DINTRANS; PRÉNDEZ, 2013; SUÁREZ; BARROS, 2014; CAI *et al.*, 2015; PASCHALIDOU; KASSOMENOS; CHONIANAKI, 2019; NASCIMENTO *et al.*, 2021, FAULKNER; MURPHY, 2022; FALLAH-SHORSHANI *et al.*, 2022). In parallel, there have been methodological improvements toward noise mapping and calculation methods for noise assessment (ALAM *et al.*, 2020), such as the HARMONOISE project, the CNOSSOS-EU Project and the HOSANNA project, which are project-based methods to calculate, assess and reduce traffic noise (YANG *et al*., 2020).

The first models of traffic noise prediction were created in the mid-1950s. Garg and Maji (2014) developed a critical review of some examples of prediction models, such as the Federal Highway Administration Traffic Noise model – FHWA model (BARRY; REAGAN, 1978), the Calculation of Road Traffic Noise model – CoRTN (DEPARTMENT…, 1988), the Richtlinien für den Lärmschutz an Straben (RLS 90), the project Harmonised Accurate and Reliable Methods for the EU Directive on the Assessment and Management of Environmental Noise - HARMONOISE project (JONASSON *et al.*, 2004), the NMPB-Routes-2008 model (DUTILLEUX *et al*., 2010), the Common Noise Assessment Methods in Europe - CNOSSOS-EU model (KEPHALOPOULOS; PAVIOTTI; ANFOSSO-LÉDÉE, 2012), among others. Garg and Maji (2014) point out that the first traffic noise models consider the characterization of traffic noise through sound power level, outdoor sound propagation, meteorological aspects, and acoustic phenomena (reflection, refraction, and absorption).

However, most models found in the technical literature are based on linear regression analysis. The main limitation of these types of prediction models is that they do not consider the randomness of vehicular traffic (NEDIC *et al.*, 2014). Indeed, linear regression analysis models look for average correlations between acoustic and non-acoustic parameters (i.e. traffic flow and composition, average speed, road width) of specific situations investigated (CIRIANNI; LEONARDI, 2011). To overcome some limitations of linear prediction models, traffic noise prediction models have been improved by applying nonlinear approaches, such as artificial neural networks (NEDIC *et al.*, 2014; GIVARGIS; KARIMI, 2010; KUMAR; NIGAM; KUMAR, 2014; BACCOLI *et al.*, 2022; DEBNATH; SINGH; BANERJEE, 2022) and multimodal optimization methods, such as genetic algorithms (GÜNDOĞDU; GÖKDAĞ; YÜKSEL, 2005; RAHMANI; MOUSAVI; KAMALI, 2011), providing more accurate forecasting results when compared to classical or statistical models.

Among the advances of prediction models, Guarnaccia (2013) highlights the dynamic modeling methods, where the interaction between vehicles is modeled to improve performance in cases under heavy traffic flow, congested and road intersections. According to Li, Liao and Cai (2016, p. 313), "A dynamic simulation model can be used to predict not only the L_{eq} over a period of time but also the second-by-second dynamic changes of the noise level […]". Several researches have used dynamic modeling for vehicular traffic noise prediction, for example, Can, Leclercq and Lelong (2008), Chevallier *et al.* (2009a, 2009b), Can *et al.* (2010), Li *et al.* (2011, 2017), Cai, Li and Liu (2011), Estévez-Mauriz and Forssén (2018). It is highlighted that most dynamic models use a complex traffic simulation model that combines a vehicle noise emission model and a sound propagation model (LI; LIAO; CAI, 2016).

In order to simplify the dynamic modeling of traffic flow in simulations, without impairing the accuracy of forecast parameters, Li, Liao and Cai (2016) adopted the Monte Carlo method to build a traffic noise prediction model based on probability distribution of vehicle noise emissions. More recently, Li *et al.* (2022) applied the model developed by Li, Liao and Cai (2016) for evaluating the expressways' noise under free traffic flow. We can also mention the research developed by Ramírez and Domínguez (2013) and Radwan and Oldham (1987). Ramírez and Domínguez (2013) applied the probabilistic and Monte Carlo method approach to traffic noise simulation based on speed distribution of vehicles. Radwan and Oldham (1987) developed a model for prediction of urban traffic noise under interrupted flow. The authors used the ray-tracing approach for modeling outdoor sound propagation and Monte Carlo method for vehicle traffic simulation.

As a matter of fact, the Monte Carlo method has been an effective solution for modeling the behavior of complex probability systems, being applied to a wide range of tasks in all areas of scientific knowledge (MAZHDRAKOV; BENOV; VALKANOV, 2018), including vehicular traffic noise (SINGH *et al*., 2022; RODRIGUES, 2022).

Furthermore, the state of the art has pointed to auralization technique as another approach to assess the road traffic noise (FORSSÉN *et al.*, 2009; LUNDÉN *et al.*, 2010; MAILLARD; JAGLA, 2012, 2013; PIEREN; BÜTLER; HEUTSCHI, 2015). Indeed, the auralization of road traffic noise has attracted the interest of urban planners as an appealing alternative for evaluating noise annoyance (MAILLARD; JAGLA, 2012, 2013). Within this context, Maillard and Jagla (2012) developed real time auralization of the sound field induced by non-stationary vehicular traffic in urban areas. They adopted a sample-based synthesis for the engine and tire noise, which allowed real-time variation of vehicle and engine speed. These signals were processed to model acoustic propagation and spatially rendered. Their validation process is based on the comparison between the pass-by recording of a single passenger car traveling at steady speed in free field and the auralized sequence of the same vehicle. The findings indicated a good agreement between the recorded sound pressure levels and the auralized sequences obtained for individual vehicles to a receiver point close to the test track. In a subsequent work, the same authors carried out the quantitative and perceptual validation of their real time auralization technique of non-stationary traffic noise in an urban street. The results of the listening tests demonstrated that the synthesized signals are perceptually very close to recorded signals, for different types of engines, speed and tires. They also concluded that granular synthesis algorithms achieved sufficient realism, whereas the comparison between the sound pressure levels of recorded and auralized sequences obtained for a real non-stationary traffic flow in an urban site also showed good adherence.

In this paper, we evaluated the precision of a new model for urban traffic noise analyses based on the probability distributions of vehicle traffic and bus arrivals at a bus stop, obtained by the Monte Carlo simulation. The proposed model allows the listening of simulated noise, coupled with the corresponding computation of common acoustic descriptors. Firstly, we applied an empirical method in order to get the probability distributions of traffic data on two urban roads. Secondly, we carried out experimental recordings of acoustic energy from single pass-by of light and heavy vehicles and motorcycles, as well as of bus arrivals at a hypothetical bus stop on test tracks. Based on that, we developed a probabilistic model for urban traffic noise analyses on roads either under free or under a traffic light controlled flow. Finally, the model is experimentally validated with measured data and survey listening test.

In Section 'Acoustic descriptors', we explain some of the acoustic descriptors used in this work, whereas in Section 'Proposed model', the conceptual aspects and details of the proposed model are presented. In Section 'Results and discussions', the findings of the model validation process are discussed. Afterwards, some conclusions are given.

Acoustic descriptors

The main acoustic descriptors used for evaluating vehicular traffic noise are: Statistical sound level (L_n), Equivalent continuous sound level (L_{eq}), Day night average sound level (L_{dn}), Traffic noise index (TNI) and Noise pollution level (L_{NP}) (KANG, 2007). Based on simulated vehicular traffic noise, the proposed model detailed here calculates instantaneous sound pressure levels (L_p) and the following acoustic descriptors, L_{10}, L_{90}, L_{eq}, TNI and L_{NP}, which are defined as follows.

Sound pressure level (L_p)

Sound pressure level (L_p) is the pressure level of a sound, in decibels (abbreviated dB). It is defined as shown in Equation 1.

$$L_p = 20 \times log \frac{p}{p_{ref}} \qquad \text{Eq. 1}$$

Where:

p corresponds to the sound pressure (Pa); and

p_{ref} is the reference sound pressure (20µPa) for propagation in air (TEMPLETON, 1997), which is the threshold of normal human hearing at 1000 Hz.

L_p is expressed as L_{Ap} when A-weighting is adopted.

Statistical sound level (L_n)

Statistical sound level (L_n) is "[...] the level of noise exceeded for *n* percent of a given measurement period." (KANG, 2007, p. 27). As such, L_{10} and L_{90} are widely adopted as rough descriptor of the maximum and background sound level, respectively (KANG, 2007). L_n is expressed as L_{An} when A-weighting is used.

Equivalent continuous sound level (Leq)

Equivalent continuous sound level (L_{eq}) can be defined as "[...] the sound level which if maintained for a given length of time would produce the same acoustic energy as a fluctuating noise over the same time period." (TEMPLETON, 1997, p. 139). Additionally, L_{eq} "[…] is widely used to measure any environmental noise which varies considerably with time." (TEMPLETON, 1997, p. 139). L_{eq} can be described mathematically by Equation 2.

$$L_{eq} = 10 \times \log\left[\frac{1}{T}\int_0^T \frac{p^2(t)}{p_{ref}^2}\, dt\right] \qquad \text{Eq. 2}$$

Where:

p(t) is the sound pressure (Pa) at time t (s);

T (s) is the measurement time interval; and

p_{ref} is the reference sound pressure (20µPa) (TEMPLETON, 1997).

If *p*(t) is weighted by the A-weighting curve, L_{eq} is denoted as L_{Aeq} (dB).

Traffic noise index (TNI)

Traffic noise index (TNI) "[…] is based on A-weighted sound levels statistically sampled over a 24h day. It depends on fluctuations in noise level over time and the background noise. It is assumed that the former is more important in traffic noise annoyance, […]." (KANG, 2007, p. 30). TNI can be calculated by means of Equation 3.

$$TNI = 4 \times (L_{A10} - L_{A90}) + L_{A90} - 30 \qquad \text{Eq. 3}$$

Whereas TNI is given in dB.

Noise pollution level (L_{NP})

Noise pollution level (L_{NP}) "[…] is another noise descriptor that has been found to correlate well with human responses to all types of noise sources." (KANG, 2007, p. 30). It is calculated as shown in Equation 4.

$$L_{NP} = L_{Aeq} + (L_{A10} - L_{A90}) \qquad \text{Eq. 4}$$

Where:

L_{Aeq} is the equivalent continuous sound level (dB);

L_{A10} and L_{A90} (both in dB) indicate the maximum and background sound level, respectively; and

L_{NP} is given in dB.

Proposed model

Conceptual model

The vehicular traffic noise prediction model is essentially a traffic simulator. The proposed computational model simulates vehicular traffic on free-flow roads and controlled-flow roads. In addition, it considers the influence of bus stop dynamics.

In computational terms, the occurrences of each random event, i.e. passage of a certain type of vehicle (light or heavy vehicle or motorcycle) and bus arrivals at a bus stop, are associated with their sound signals recorded on test tracks. To simplify, we restricted the simulation to a maximum of one event of each type per second. We assumed that vehicular traffic and bus arrivals at the bus stop obey a binomial model, which consists of a sequence of *n* independent Bernoulli events, with *n* very large and parameter $p \ll 1$, where $n \times p$ is the average value of occurrences of each type of event for *n* seconds of observation. A probability *p* of observing an event in a given interval of one second is empirically estimated for every kind of event, and independent binomial models are simulated simultaneously, one for each kind of event. It should be noted that by applying *n* large and parameter $p \ll 1$, a binomial model corresponds approximately a Poisson model, which has been adopted for modeling of vehicular traffic by other related works, such as Skarlatos (1993), Li, Liao and Cai (2016) and Li *et al.* (2022).

By using a pseudo-random number the proposed model defines which kind from a prerecorded database sequentially enters the simulation. Afterwards, it generates a new pseudo-random instance with equal probability of occurrence for all vehicles of same category (i.e. obeying the uniform distribution). After verifying the occurrence of a bus arrival at the simulated bus stop, the proposed model also defines which cycle of bus arrival, stopping and departure will enter the simulation. For this purpose, the model generates a new pseudo-random number with 25% probability of occurrence for cycles with total times of 24 and 35 s, and 50% probability, for a cycle with total time of 29 s. These probabilities are free model parameters that were defined based on the data acquired at two bus stops analyzed in this work.

The proposed model provides, as one of its outputs, the simulated sound signal of vehicular traffic added to an actual samples of prerecorded street residual noise. Based on the stochastically simulated sum of sampled sounds, the model determinates instantaneous sound pressure levels (L_{Ap}) and different acoustic descriptors (L_{A10}, L_{A90}, L_{Aeq}, TNI, L_{NP}).

The modeling and simulation approach adopted in this work offers to the user of this simulator system the possibility of hearing the simulated sound signal of vehicular traffic noise. That is, the user can listen to the dynamics of vehicular traffic in hypothetical scenarios. As far as we know from the literature, the proposed model brings a practical and simplified innovation of quantitative and qualitative analysis of urban vehicle traffic noise. Figure 1 summarizes the conceptual model flowchart.

Next, we will detail our procedures for sound signal recording from single pass-by of vehicles and from the process of stopping and going at a hypothetical bus stop, as well as our steps to acquire samples of residual noise. We will also describe how the model takes into account the influence of reflection on a street facade and of the green and red lights on urban roads with traffic light controlled.

This probabilistic model was developed in a Ph.D. thesis (GUEDES, 2018) of the Faculty of Civil Engineering, Architecture and Urbanism, State University of Campinas (UNICAMP). An initial version of this model was published in Guedes, Bertoli and Montalvão (2016). The main differences between the model detailed in this paper and its initial version are: inclusion in its database of new segments of real sound from individual passages of other vehicle types and cycles of bus arrivals, stopping and departure at a bus stop recorded on test tracks, the modeling approach of residual noise, and the influence of reflection on a street facade and traffic lights.

Acquisition of sound emission generated by a single vehicle

We used experimental methods to acquire the acoustic energy from the single pass-by of different vehicles (light and heavy vehicles and motorcycles) and from the cycles of bus arrivals, stopping and departure at a bus stop. For this purpose, we conducted sound recording and acoustic measurement experiments on test tracks under free field and favorable weather conditions. After concluding this stage, we set up a database with real sound signals from the abovementioned events. Notice that these sound signals are one of the main input data of the proposed model, since they are acoustic templates for simulated vehicles. To our knowledge, this is an innovative aspect of the computational modeling adopted. All vehicle types from the model database are shown in Table 1.

These sound recording experiments were conducted on Daniel Hogan and Walter August Hadler streets at the State University of Campinas (UNICAMP, São Paulo - Brazil), which will be referred to hereafter as test tracks in this paper. Both test tracks had asphalt pavement in good condition. These experiments were taken on three different days, during school vacation periods or on Sundays (when there were lower levels of residual noise). Figures 2 and 3 show sketches and photos of the experimental set-up used on the test tracks, based on BS EN ISO 11819-1 (BRITISH…, 2001) and Wang, Cai and Zou (2012).

First, we performed the sound signals recordings for the passage of each test vehicle (light vehicles and motorcycles traveling at steady speed) over a straight reference line (Figure 2(a)). The sound recording point was established at a distance $D_0 = 7.5$ m perpendicular to this reference line (BRITISH…, 2001; WANG; CAI; ZOU, 2012). We defined the 10 s time window for the passage of test vehicle to properly represent the acoustic influence during a vehicle pass-by at real traffic flow on urban roads. Furthermore, the choice of 10 s time window corresponds to the choice of other researches regarding traffic noise modeling based on acoustic measurements of single pass-by vehicle, which adopted 10 and 20 s for measurement times (ZHAO *et al.*, 2015; PAMANIKABUD; TANSATCHA; BROWN, 2008; TANSATCHA *et al.*, 2005).

The sound recording device was turned on and off just before and after a test vehicle pass-by, the limits set by points A and B, respectively. The distance between points A and B was adjusted depending on the constant speed adopted for each experiment (Figure 2(a)). Next, we carried out sound recording experiments of single pass-byes of heavy vehicles. After initial tests, we had to adjust the distance D_0 from 7.5 to 13 m in order to avoid signal saturation (clipping). Then, we applied the similar experimental procedure of sound signal recording above described.

Figure 1 – **Conceptual model flowchart of the stochastically simulated sum of sampled traffic flow sounds and residual noise by using the Monte Carlo method**

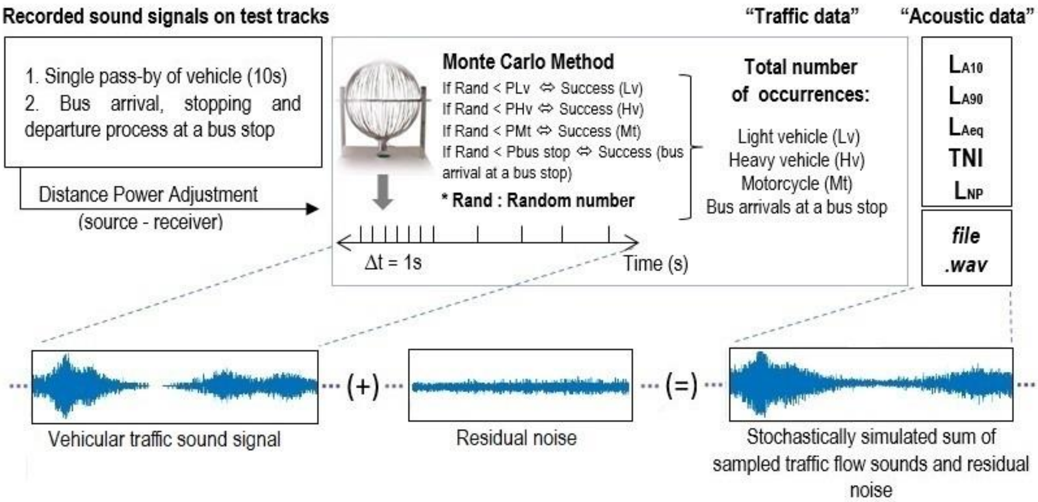
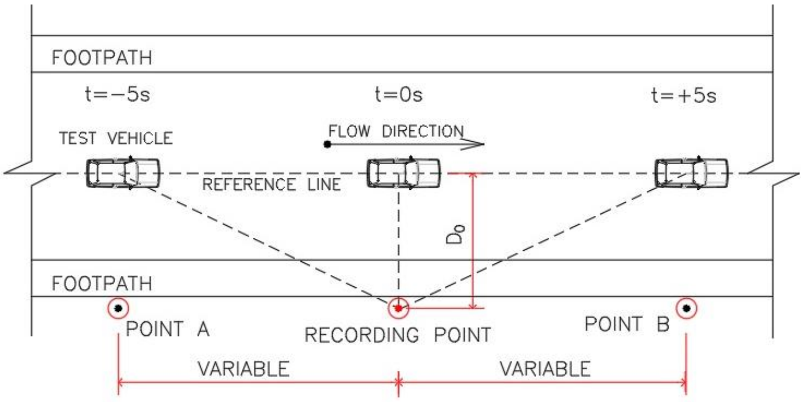


Table 1 – **Specific information regarding all test vehicles**

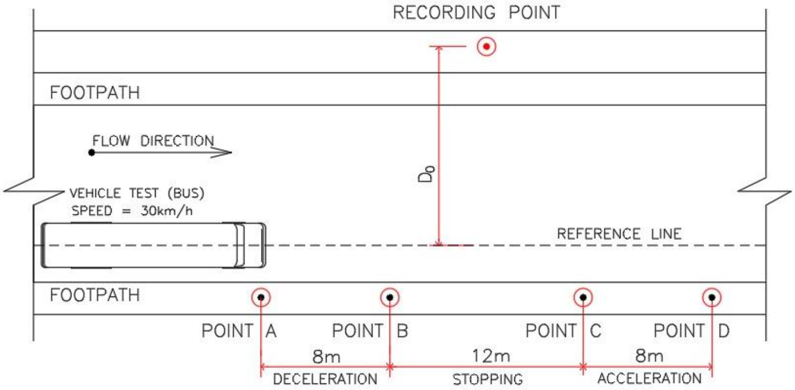
Category	Test vehicle
Light vehicle (Lv)	**Duster** Renault, engine 2.0. Automatic gear. Year/model: 2014/2014.
	March Nissan, engine 1.6. Manual transmission gear. Year/model: 2014/2014.
	Punto Fiat, engine 1.4. Manual transmission gear. Year/model: 2014/2014.
	Up Volkswagen, engine 1.0. Manual transmission gear. Year/model: 2014/2015.
Motorcycle (Mt)	**CB300R** Honda. Year/model: 2012/2012.
	Intruder 125 Suzuki. Year/model: 2014/2014.
Heavy vehicle (Hv)	**Pickup truck** Toyota, diesel. Manual transmission gear. Year/model: 1996/1996.
	Bus Mercedes Benz, engine: 204 HP, diesel. Manual transmission gear. Year/model: 1995/1996.

Source: adapted from Guedes (2018).

Figure 2 – **Experimental set-up on the test tracks used**



(a) Sound recording experiments of single pass-by of test vehicle



(b) Sound recording experiments of the deceleration, stopping, and acceleration of a single bus at a hypothetical bus stop

Source: adapted from Guedes (2018).

Figure 3 – **Photos of the experimental set-up used on the test tracks**

Source: first author's personal file.

Figure 2(b) shows the experimental set-up used in sound signal recordings and acoustic measurements of the deceleration, stopping, and acceleration of a single bus at a hypothetical bus stop. In this experimental procedure, the test vehicle (bus) approached over a straight reference line, traveling at constant speed of 30 km/h in 4th gear. In front of point A, the deceleration process began until the complete stop between points B and C. The bus remained stopped for different time windows (Stopping Times = ST). We adopted the following values of ST: 6, 11, and 17 s. Then, we established a time windows of 8 and 10 s for the deceleration and acceleration processes, respectively, which included all necessary gear changes. So, we obtained sound samples of the bus arrival, stopping and departure cycles with Total Time (TT) of 24, 29 and 35 s, as mentioned in Subsection 'Conceptual model'. Tables 2 and 3 summarize specific information regarding experiments of sound signal recording for single vehicle pass-by and decelerating, stopping and accelerating bus at a hypothetical bus stop.

The sound signal recordings were taken using a omnidirectional electret condenser microphone (DPA 4090 - 1/8" diameter, used only in the pre-test stage) and omnidirectional electret condenser microphone (ECM 8000, Behringer - 1/4" diameter), with windscreen and supported on a tripod (1.2 m height from the ground), B&K 4231 sound calibrator, external audio interface (Focusrite Scarlett 8i6) and notebook. Acoustic data were collected using a B&K 2270 Class 1 integrating sound level meter with windscreen and B&K 4231 sound calibrator. The instrument was set up on a tripod (1.2 m height from the ground). All acoustic measurements of L_{Aeq} were taken simultaneously with sound signal recordings. The results of these acoustic measurements were compared with sound emission levels calculated from recorded sound signals. Before starting the recordings, we always recorded a sound signal with noise level of 94 dB at 1000 Hz emitted by a sound calibrator.

Upon the conclusion of this sound signal recording stage, we selected the audio files with least wind effects or other anomalous events that may have been picked up by the recording device. This post-audio processing was carried out in laboratory, by using Audacity 2.1.2 (free, open source software, available on http://audacityteam.org/). First, we cut off the recorded audios from experiments of test vehicle pass-by within the 10 s time interval. For this, we used as reference the instant of highest energy observed at the envelope of recorded sound signal, that is, the instant that the test vehicle passes immediately in front of the recording point. Subsequently, we applied the fade in and fade out effects at a time window of 0.5 s to give more realism to the simulated noise (Figure 4). Finally, we applied the editing effect (i.e. fade in - fade out) of sound signals from bus arrivals at a hypothetical bus stop.

Table 2 – **Specific information regarding experiments of sound signal recording for single pass-by of vehicle, with D_0 in meters**

Test vehicle	Speed - Gear	D_0 (m)
Duster 2.0	45 km/h – 3rd 40 km/h – 3rd	7.5
March 1.6	45 km/h – 3rd 40 km/h – 3rd	
Punto 1.4	45 km/h – 3rd 40 km/h – 3rd	
Up 1.0	45 km/h – 3rd 40 km/h – 3rd	
CB300R	45 km/h – 3rd 40 km/h – 3rd 40 km/h – 3rd	
Intruder 125	45 km/h – 3rd 40 km/h – 3rd 45 km/h – 3rd 40 km/h – 3rd	
Pickup truck	40 km/h – 4th	
Bus	30 km/h – 4th 30 km/h – 3rd	13

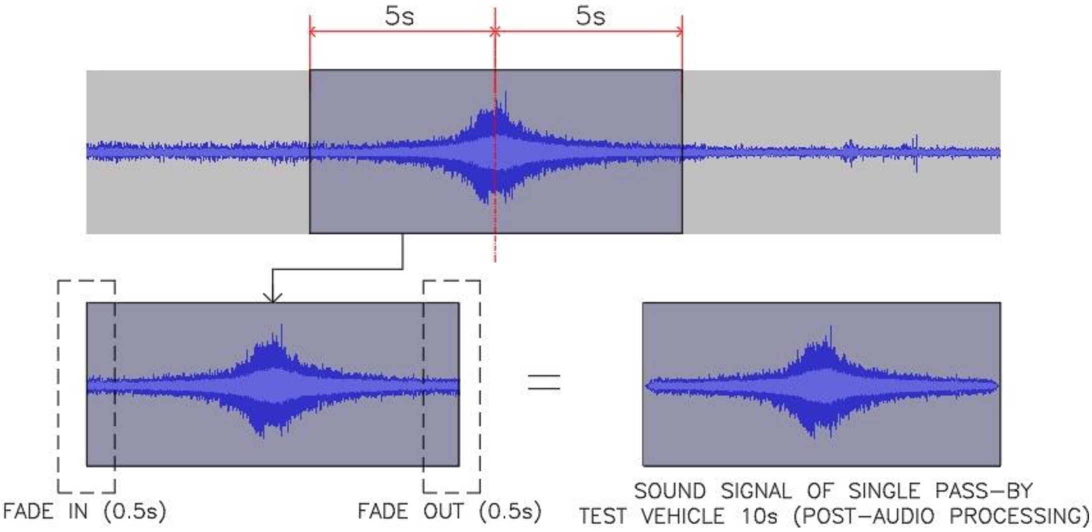
Source: adapted from Guedes (2018).

Table 3 – **Specific information regarding experiments of sound signal recording for decelerating, stopping and accelerating of bus at a hypothetical bus stop, being Stopping Times (ST) and Total Time (TT) in seconds and D_0 in meters**

Test vehicle	Speed - Gear	ST (s)	TT (s)	D_0 (m)
Bus	30 km/h - 4th	6	24	13
		11	29	
		17	35	

Source: adapted from Guedes (2018).

Figure 4 – **Post-audio processing of sound signal recording for single pass-by of the test vehicle**



Source: adapted from Guedes (2018).

Lastly, it should mentioned that the energy from recorded sound signals on test tracks can be adjusted (when necessary) due to the distance between source - receptor, having as reference the perpendicular distance of vehicular flow (lane axis) to the observation point. This adjustment is done based on Equation 5 (obtained by mathematical manipulations of Equation 6).

$$p = p_0 \times \sqrt{\frac{D_0}{D}} \qquad \text{Eq. 5}$$

$$L_p = L_{p_0} - 10 \times \log\left(\frac{D}{D_0}\right) \qquad \text{Eq. 6}$$

Whereas:

D_0 (m) is the perpendicular distance between the acoustic measuring point and the reference line of the test track (Figure 2);

D (m) is the perpendicular distance from the lane axis and the observation point on the investigated street; and

p (Pa) and L_p (dB) are the sound pressure and sound pressure level to distance D whereas p_o (Pa) and L_{p_0} (dB) are the sound pressure and sound pressure level to distance D_0, respectively.

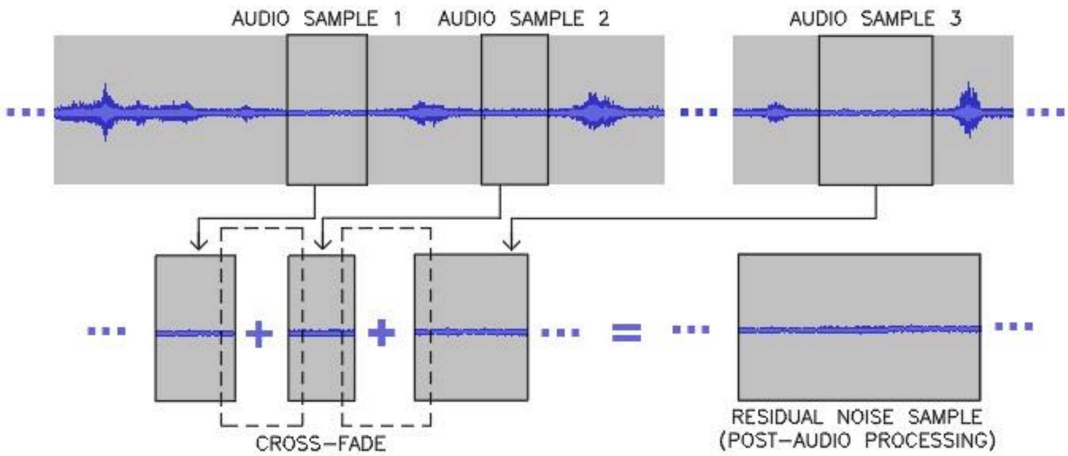
Thus, the power adjustment owing to distance source-receptor is carried out by considering the vehicular flow as the linear source.

Composition of residual noise

In order to provide more realism to the simulated noise, we chose to use a residual noise composed of real noise samples extracted from recordings made in urban roads analyzed in this work. Composite residual noise has different acoustic events typical of the street such as bird songs, people talking, and distant traffic noise.

To reduce the artificiality in listening at the junctions of different residual noise samples, we applied a cross-fade effect, as shown in Figure 5.

Figure 5 – **Post-audio processing for composition of residual noise from real samples of prerecorded street residual noise**



Source: adapted from Guedes (2018).

Influence of reflection on opposite street facades

The proposed model takes into account the influence of reflection on opposite street facades, whereas the adjustment of acoustic energy due to surface reflection is only made for sound signals from vehicle pass-by and bus arrivals at the bus stop, which were recorded on test tracks under free field condition. To simplify, we have used first order reflection. The adjustment of acoustic energy due to first order reflection on the facade surface was done as follows:

Step 1: definition of the reflection correction (C_{ref}) to be added at simulated noise based on Equation 7 or Equation 8, taken from the German standard RLS-90.

Step 2: determination of the discrete time delay (Δn) between the direct and reflected sound signal as in Equations 9 and 10.

Step 3: obtaining of the sound signal resulting from the sum of direct and reflected sound, as in Equation 11, considering the discrete time delay achieved in step 2, and the sound reflection coefficient determined by trial and error.

$$C_{ref} = 4 \times \frac{h}{d} \quad \text{Eq. 7}$$

Where C_{ref}< 3.2 dB for reflective surfaces.

$$C_{ref} = 2 \times \frac{h}{d} \quad \text{Eq. 8}$$

Where C_{ref} < 1.6 dB for absorbing surfaces.

In Equation 7 and Equation 8, C_{ref} is the reflection correction to be added at simulated noise (in dB); *h* is the height of reflecting surface and *d* is the distance between opposite facades.

$$\Delta X = (X_2 + X_3) - X_1 \quad \text{Eq. 9}$$

$$\Delta n = \frac{\Delta X}{c} \times f_s \quad \text{Eq. 10}$$

Accordingly, ΔX is the difference between paths traveled by the reflected and direct sound signals (see Equation 9 and Figure 6); Δn is the discrete time delay; *c* is the speed of sound in air (≈ 345m/s) and f_s is the sampling frequency of the sound signal (44100 Hz).

$$S_f[n] = S[n] + \alpha_r \times S[n - \Delta n] \quad \text{Eq. 11}$$

Whereas:

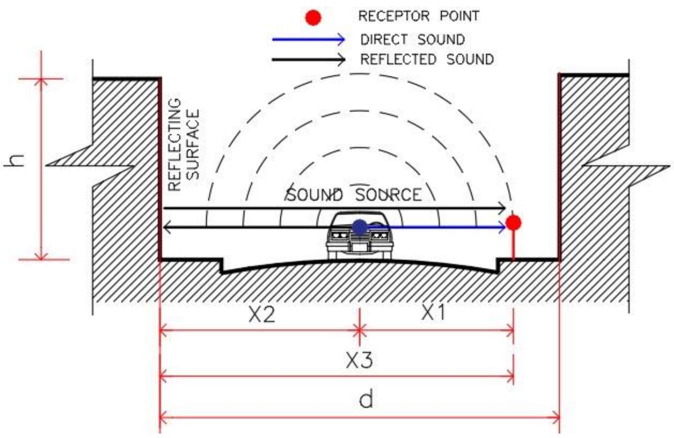
$S_f\,[n]$ is the resultant sound signal;

$S[n]$ is the direct sound signal;

$\alpha_r \times S[n - \Delta n]$ is the reflected sound signal (with discrete time delay (Δn)); and

α_r is sound reflection coefficient of the facade.

Figure 6 - **Visual representation of the first reflection on a street facade surface**



Source: adapted from Guedes (2018).

Influence of traffic lights

For roads controlled by traffic lights, vehicle traffic becomes cycle-stationary (see Antoni (2009)). In this case, the proposed model simulates the green and red traffic lights by the procedure represented in Figure 7. For this purpose, the proposed model performs a weighting of the parameters λ_{Lv}, λ_{Mt}, λ_{Hv}, $\lambda_{bus\ stop}$ (being the average occurrence rates of each vehicle type per second and the average number of bus arrivals at bus stop per second, respectively) with the factors f_{green} and f_{red}, obtained from observed vehicle flows at green and red traffic signals.

Model validation

To validate the proposed model, we used quantitative and qualitative approaches. The first corresponds to the comparison between measured and simulated results for traffic and acoustic data, whereas the subjective approach is based on jury testing.

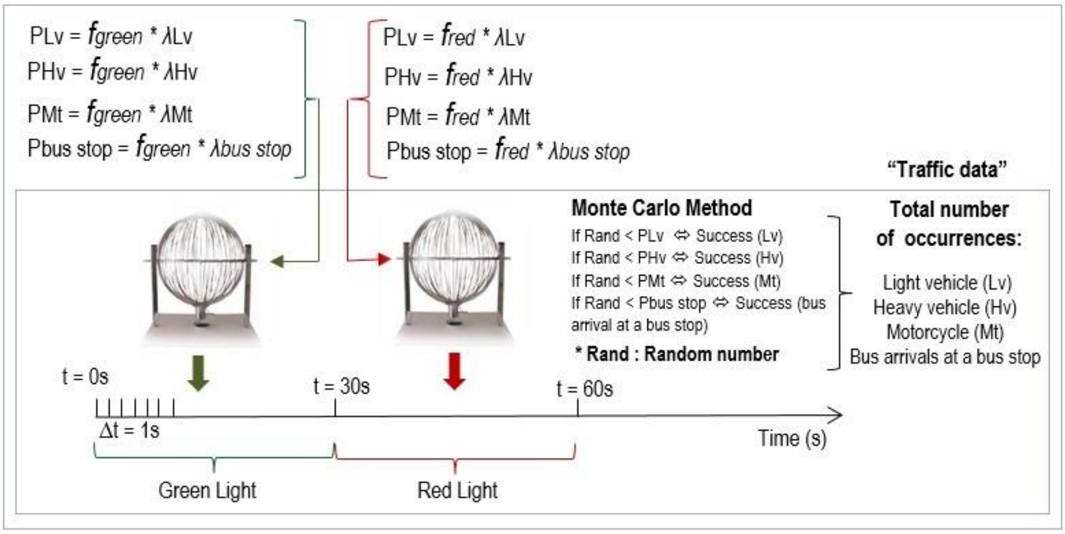
In the quantitative validation approach, we compared the simulated data with those measured *in-situ* on two urban streets in Campinas, São Paulo, Brazil: first, on Roxo Moreira (street A), in a section under approximate free traffic flow, and then on Dr. Buarque de Macedo (street B), in a traffic light controlled flow. The street A has two lanes separated by a central flowerbed and it is involved by one to three story buildings, some open spaces with parking lots, for example. On this street, the speed limit for vehicle flow is 40 km/h. While street B has a one-way lane, which is surrounded by one- to two-story buildings next to each other, being a U-shaped cross-sectional profile. The speed limit on street B is 30 km/h for buses and 50 km/h for other types of vehicles. Both streets had bus stops and lanes with flat surfaces and asphalt pavement similar to the test tracks (Figure 8).

The traffic variables collected for quantitative validation approach were: vehicle flow for each type (i.e. Light vehicle = Lv, Heavy vehicle = Hv, Motorcycle = Mt) and number of bus occurrences at a bus stop. While the acoustic variables were the following descriptors: L_{A10}, L_{A90}, L_{Aeq}. The acquisition of all variables was taken simultaneously at 3-minute time intervals.

We defined this time window based on in-situ observations, being specific to characterize the local acoustic conditions, and because it meets the ISO 1996-2 (INTERNATIONAL…, 2007), which was in effect at the time of data collection. According to ISO 1996-2 (INTERNATIONAL…, 2007), the minimum number of 30 pass-by of vehicles shall be considered over the reference time interval. Although this criterion was evidenced only for light vehicles, we considered that it was sufficient due to higher prevalence this vehicle type on the investigated streets. In addition, other researches have adopted the same measurement time interval, such as Zannin and Sant'ana (2011) and Zannin *et al* (2013).

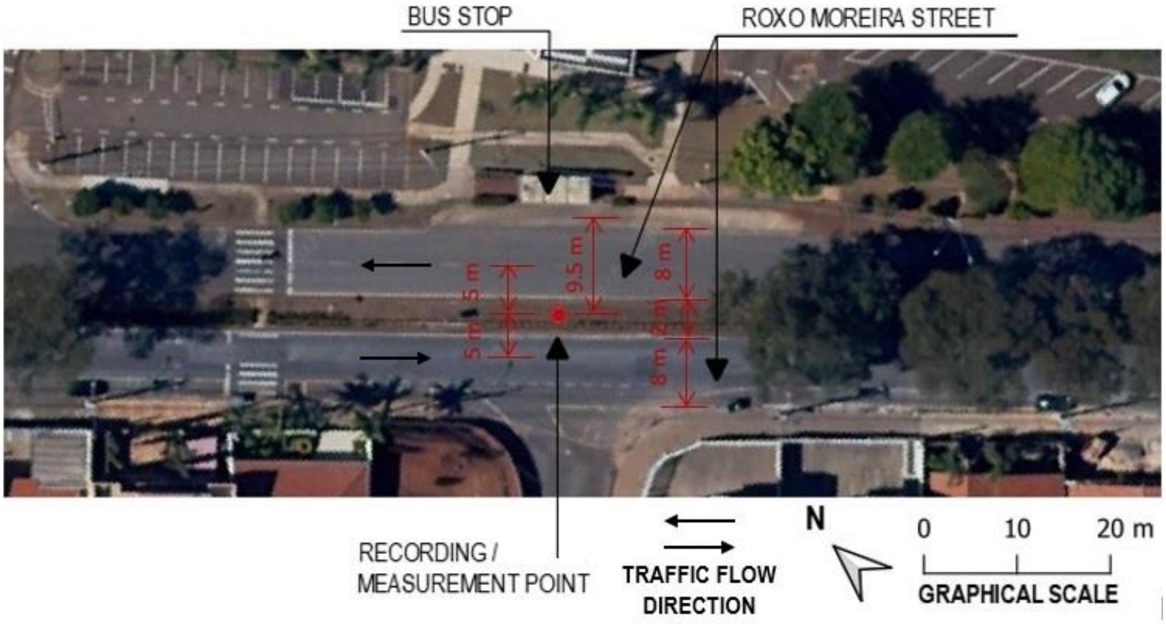
In street B, which had a traffic light at one end of the stretch analyzed, 3-minute represented three complete cycles of traffic light (red and green lights), similar to the criterion adopted by Skarlatos (1993).

Figure 7 – **Procedure for implementing a traffic light in the model**



Source: image created by the first author.

Figure 8 – **Position of acoustic recording/measurement points (a) and (b)**



(a) Street A

(b) Street B

Source: images created by the first author from Google Satellite (2022a, 2022b).

After the modeling and simulations of the real vehicle flow, scenarios based on the traffic parameters (λ, i.e., average vehicle occurrence rate of each vehicle type and bus arrivals at the bus stop per second) were obtained from the data samples used in this modeling step. It should be noted that the simulation results were compared only with the traffic and acoustic variables acquired in the validation step in order to ensure the cross-validation procedure.

We verified the goodness of fit between measured and estimated results by mean of the following statistical analyses: error, mean error (ME) and mean absolute error (MAE). For the acoustic variables, we also used the non-parametric statistical test of Kolmogorov - Smirnov (KS test), under a significance level of 5%. The null hypothesis (H_0) is that the cumulative distribution functions of the measured and simulated results are adherent. The cumulative distribution functions of the real acoustic data were obtained from recorded noise of vehicle flows on both urban streets studied.

In the qualitative validation approach, which aimed to verify the level of realism in listening to simulated vehicle traffic noise, we conducted jury testing. The H_0 of the listening test was: real and simulated vehicular traffic audios are indiscernible. That is, we expected that the jury participants would be unable to distinguish between real and simulated audios of vehicular flows, with probability $p = 0.5$ (50%) of success or not.

The real audio samples were taken from a recording on street A. The simulated audio samples were extracted from the vehicular traffic noise achieved by the proposed model, based on the input parameters (λ, i.e., average vehicle occurrence rates and average bus arrival rates at the analyzed street bus stop per second). The jury tests were conducted with 54 subjects (UNICAMP students and employees, with no restrictions regarding gender, ethnicity, or age). We considered the total number of sufficient volunteers based on related studies (MAILLARD; JAGLA, 2013; KLEIN *et al*., 2015). The rooms used for jury testing offered favorable background noise conditions and acoustic privacy for the tests. The jury test protocol has been approved by the Research Ethics Committee (by Plataforma Brasil, CAAE[1]: 71270117.2.00005404). The protocol adopted in the jury test involved the following procedures: the volunteer was invited to listen (with headphones) to 4 randomly chosen audio samples via a graphical computer interface (Figure 9).

The real and simulated vehicle flow audio samples could include part or all of the bus arrival process at a bus stop. In order to give the same testing conditions to all volunteers, 2 audios of each type (real and simulated) were presented (without the knowledge of participants), and were randomly resampled before each test. The volunteers listened to different audios, which were guaranteed through the drawing without replacement of real and simulated audios from a sample space of 30 audios of each type (real and simulated).

We adopted audios of short duration (1-minute), with adequate sound pressure levels so as to not impair the acoustic comfort and hearing health of the participant. As an audio reproduction system, we used a notebook, an external sound interface (Audiobox USB 2x2, PreSonus brand) and high definition headphones (Stereo Headphones, AKG, K.55) with frequency response between 20 Hz and 20 kHz. Finally, the exclusion criterion adopted in the jury tests was the volunteer's statement that he did not have normal hearing ability. In this case, his data were excluded from the research at the results' analysis stage.

Figure 9 – **Jury test audio assessment screen, originally in Portuguese**

Source: adapted from Guedes (2018).

[1]CAAE is the certificate of submission of ethical review number.

Results and discussions

In this section, the results of quantitative and qualitative validation approaches of the proposed model are presented. Simulation experiments in this step took into account both the real characteristics of the vehicular traffic on streets A and B, by considering the average occurrence rates of each vehicle type per second (λ_{Lv}, λ_{Mt}, λ_{Hv}) and the average number of bus arrivals at bus stop per second ($\lambda_{bus\ stop} = 1/\beta$). The parameters λ_{Lv}, λ_{Mt}, λ_{Hv}, $\lambda_{bus\ stop}$ play the role of estimated probabilities *p* of occurrences per second of light vehicle, motorcycle, heavy vehicle and bus arrival at the bus stop, respectively.

In street A, we observed the following average values of vehicle flows, Q_{Lv} = 996 vehicles/h, Q_{Mt} = 55 vehicles/h and Q_{Hv} = 47 vehicles/h, and the average time interval between bus arrivals at the bus stop (β) of 360 s, while in street B, we observed Q_{Lv} = 42 vehicles/3-min; Q_{Mt} = 4.6 vehicles/3-min, Q_{Hv} = 1.3 vehicles/3-min and β = 127 s. Table 4 highlights the parameters λ considered in the simulation model of vehicle traffic on streets A and B.

For the analyzed section of the street B, which has vehicular flow controlled by traffic light at one of its ends, the values of λ_{Lv}, λ_{Mt}, λ_{Hv}, $\lambda_{bus\ stop}$ shown in Table 4 were multiplied by weighting factors, f_{green} and f_{red}, obtained from the vehicle flow counts in 3-minute time windows on green and red lights. It should be emphasized that on the red light, the vehicles on this stretch of street B were coming from the Imperatriz Leopoldina avenue that is perpendicular to street B at the signalized intersection, as can be seen in Figure 8(b). The factors f_{green} and f_{red} multiplied by the input parameters (λ_{Lv}, λ_{Mt} and λ_{Hv}) were 1.725 and 0.275, respectively. Regarding the $\lambda_{bus\ stop}$, we adopted the value $f_{green} = 2$ and $f_{red} = 0$, since the buses that stopped at this bus stop came only from B street.

At the top of Figures 10(a) and 10(b), the simulated vehicular traffic sound signals in the 3-minute (180 s) time window are shown for streets A and B, respectively. These sound signals simulated by the model were used as an important listening resource in the verification of random entries of different types of vehicles in the simulation, including bus arrivals at the bus stop on the analyzed sections of the streets. Also for this task, we adopted the plots shown at the bottom of Figures 10(a) and 10(b), which indicate the instant of entry of each vehicle.

Further experiments of simulation were conducted for quantitative validation of the traffic and acoustic variables estimated by the model. Based on the λ parameters for A and B streets, shown in Table 4, we performed 5 simulation sets independent of each other. Each simulation set generated *m* samples for each traffic and acoustic variables, which were compared to the measured data. Table 5 presents the mean values of the Simulated (S) and Measured (M) traffic data (t = 3-minute intervals) for both streets. The *m* values of the samples for each simulation set were those corresponding to the quantities of samples collected on the investigated streets. Namely: *m* = 58 samples for street A and *m* = 26 samples for street B.

From Table 5, we can see that the mean absolute errors of all simulated traffic parameters were less than 1. These findings indicate that the proposed model simulates accurately the traffic variables. Regarding the acoustic variables, Table 6 shows the mean values of the measured and simulated data for the descriptors L_{A10}, L_{A90}, L_{Aeq}, TNI and L_{NP}, as well as the mean errors between the Simulated (S) and Measured (M) data for both A and B streets.

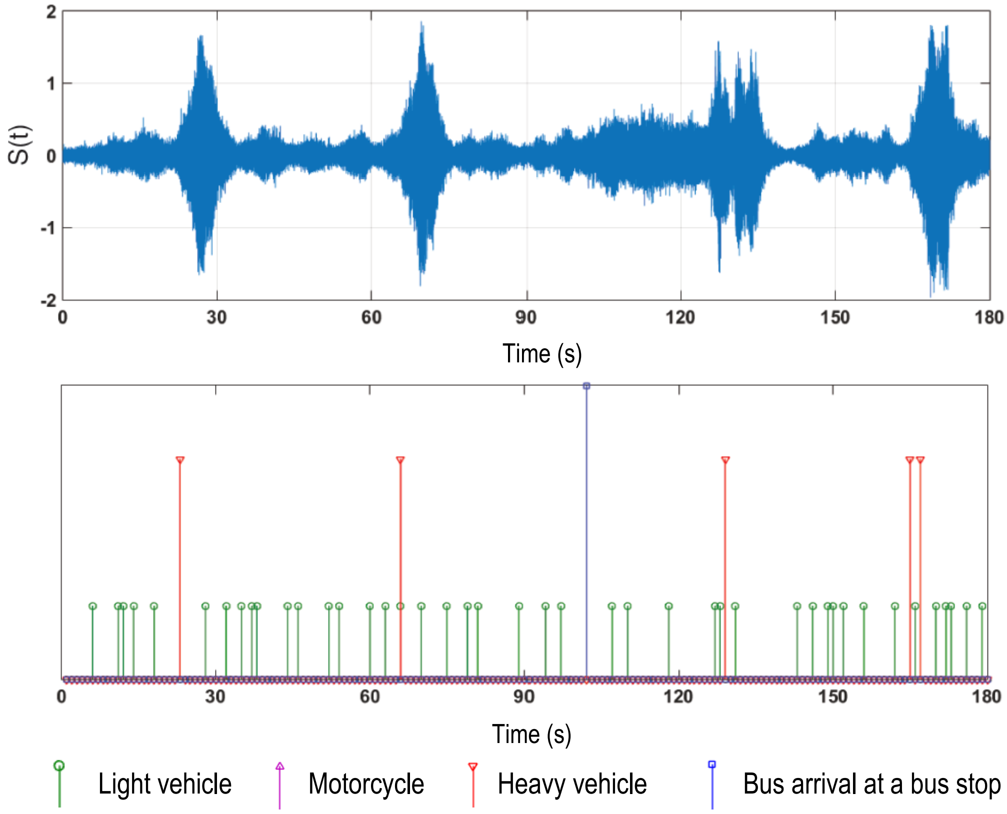
The findings from Table 6 indicate low mean errors between the simulated and measured data for most of the acoustic descriptors. Some of these values were close to the accuracy range of the sound level meter used in the acoustical measurements (± 0.5 dB). However, we can see higher mean errors for TNI (-1.9 dB and +4.5 dB for A and B streets, respectively), probably because this descriptor is highly influenced by noise variability (L_{A10} - L_{A90}).

Table 4 – **Parameters λ considered in the model for vehicular traffic simulation for streets A and B**

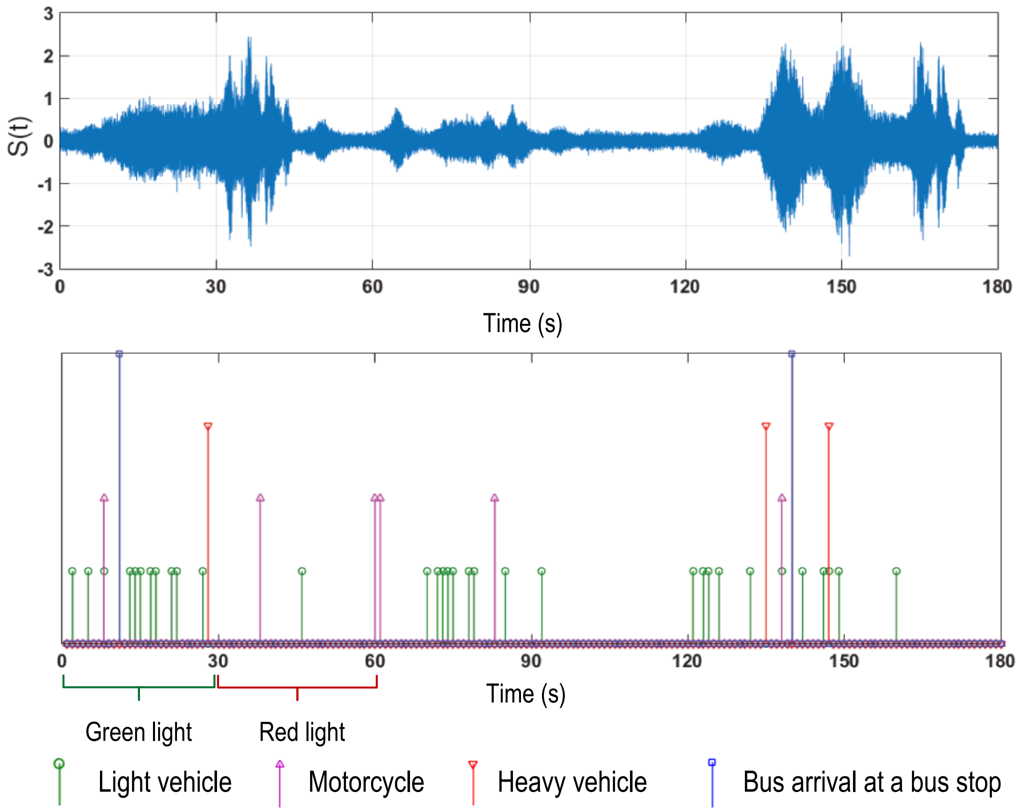
Street	λ_{Lv} (veh/s)	λ_{Mt} (veh/s)	λ_{Hv} (veh/s)	$\lambda_{bus\ stop}$ (veh/s)
Street A	0.2766	0.0153	0.0131	0.00278
Street B	0.2333	0.0256	0.0073	0.00790

Source: adapted from Guedes (2018).

Figure 10 - **Simulated noise plots from vehicular traffic for (a) street A and (b) street B**



(a) Street A



(b) Street B

Source: adapted from Guedes (2018).

Table 5 – **Comparison between Simulated (S) and Measured (M) traffic data for streets A and B, being Q in vehicles per 3-min**

Street A	Q_{Lv} (veh/3min)	Q_{Mt} (veh/3min)	Q_{Hv} (veh/3min)	Q_{sum} (veh/3min)	$Q_{bus\ stop}$ (veh/3min)
M	49	3	2	54	1
S_1	49	3	3	55	1
S_2	48	3	2	53	1
S_3	49	3	2	53	1
S_4	50	3	2	55	1
S_5	50	3	3	56	0
ME	**+0.2**	**0.0**	**+0.4**	**+0.4**	**-0.2**
Street B	**Q_{Lv} (veh/3min)**	**Q_{Mt} (veh/3min)**	**Q_{Hv} (veh/3min)**	**Q_{sum} (veh/3min)**	**$Q_{bus\ stop}$ (veh/3min)**
M	43	5	1	49	1
S_1	43	5	1	49	1
S_2	41	5	2	48	1
S_3	42	5	1	48	1
S_4	42	5	2	48	1
S_5	43	5	2	49	2
ME	**-0.8**	**0.0**	**+0.6**	**-0.6**	**+0.2**

Source: adapted from Guedes (2018).

Table 6 – **Comparison between Simulated (S) and Measured (M) acoustic data for streets A and B. Comparison acoustic descriptors (in dB) include L_{A10}, L_{A90}, L_{Aeq}, TNI and L_{NP}**

Street A	L_{A10} (dB)	L_{A90} (dB)	L_{Aeq} (dB)	TNI (dB)	L_{NP} (dB)
M	71.3	55.0	68.0	98.8	85.5
S_1	71.6	55.4	67.9	98.2	85.2
S_2	71.1	55.2	67.6	97.1	84.4
S_3	71.2	55.2	67.7	98.1	84.9
S_4	71.2	55.7	67.6	97.4	84.4
S_5	71.4	55.9	67.7	93.8	84.0
ME	**0.0**	**+0.5**	**-0.3**	**-1.9**	**-0.9**
Street B	**L_{A10} (dB)**	**L_{A90} (dB)**	**L_{Aeq} (dB)**	**TNI (dB)**	**L_{NP} (dB)**
M	74.1	55.3	71.4	106.0	91.4
S_1	74.8	54.8	71.0	108.1	91.4
S_2	74.8	54.7	70.9	108.9	91.7
S_3	74.5	54.7	70.7	110.4	91.3
S_4	75.1	54.7	71.2	111.1	92.2
S_5	75.4	54.8	71.5	114.1	92.8
ME	**+0.9**	**-0.6**	**-0.3**	**+4.5**	**+0.5**

Source: adapted from Guedes (2018).

Finally, we performed the analysis of adherence between real and simulated data of acoustic variables (L_{Ap}). For this purpose, we applied the KS test, under the significance level of 5%. Figure 11 shows the cumulative distribution curves of real and simulated data for the free-flow road (street A) and the controlled-flow road (street B). The cumulative distribution functions of the real data were obtained from recorded sound signals of vehicular flows on both streets analyzed. For this, we extracted 50-minute samples from the recordings made in both streets at the same acoustic measurement points adopted in this research (Figure 8). These recordings were made on typical weekdays (two Thursdays), in the afternoon.

In a simple visual analysis, we can see from the functions in Figure 11 that the cumulative probability distribution curve of L_{Ap} determined by the proposed model is in good accordance with the one taken from the real data. Even though, the KS test indicated that real and simulated data curves are not adherent for both

A and B streets. The plots in Figure 11 also indicate that the cumulative L_{Ap} distribution curves of the real and simulated data are more convergent on A street (with free-flow road) than on B street (with controlled-flow road), showing greater discrepancies between the values of 65 and 70 dB for A street, and 60 and 70 dB, for B street. These differences can be explained by anomalous events at the streets, which the proposed model does not simulate, such as, vehicle passages with speeds higher than those existing in the model database, car horns, etc.

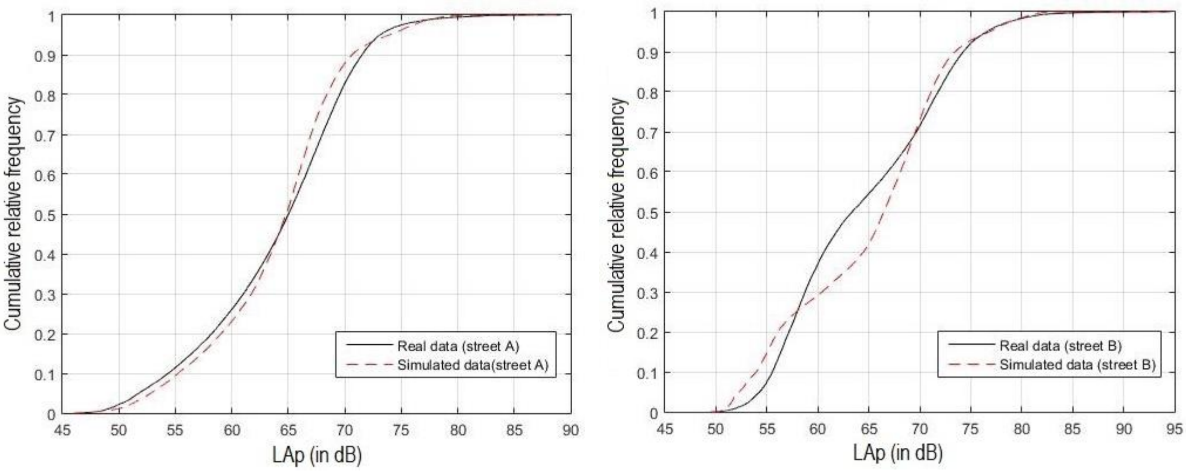
In addition, Table 7 presents the acoustic descriptors L_{A10}, L_{A90}, L_{Aeq}, TNI and L_{NP}, calculated from the sound signal recorded on the two streets (Real = R) and the sound signal simulated by the model (Simulated = S).

The errors (absolute values) evidenced between simulated and real values of L_{A10}, L_{A90} and L_{Aeq} (Tables 6 and 7) were less than those obtained by Li, Liao, Cai (2016). These authors adopted the expected uncertainty of 2 dB, when comparing real (or measured) and simulated values. These findings indicate that traffic noise can be accurately estimated using the probability model proposed in this study.

In the qualitative validation process, the jury tests involved 54 volunteers, 33 men and 21 women, between 19 and 58 years old. All of them had their identity preserved. The H_0 of the listening test was: real and simulated vehicular traffic audios are indiscernible. The analyses were done based on the binomial model and under a significance level of 5% (for convenience, the binomial model was approximated by a normal model). We rejected H_0 if the number of hits or misses is outside the region defined by the boundaries around the mean obtained from the total number of audio samples k. Here, k was 216 samples, since each participant listened to 4 different audio samples from each other (2 real and 2 simulated).

The mean and variance values in this statistical analysis were, respectively, 108 and 54, with defined the interval [94, 122] as the region of non-rejection of H_0. Since the number of hits (successes) was 146, H_0 could not be accepted.

Figure 11 – **Comparison between the cumulative distribution curves of L_{Ap} (Real *versus* Simulated) for (a) street A and (b) street B**



(a) Street A (b) Street B

Table 7 – **Comparison between the acoustic descriptor of Simulated (S) and Real (R) data for streets A and B – comparison acoustic descriptors (in dB) include L_{A10}, L_{A90}, L_{Aeq}, TNI and L_{NP}**

Street A	**L_{A10} (dB)**	**L_{A90} (dB)**	**L_{Aeq} (dB)**	**TNI (dB)**	**L_{NP} (dB)**
R	71.5	54.4	68.4	93.1	85.6
S	70.6	55.2	67.8	86.8	83.2
Error	**-0.9**	**+0.8**	**-0.6**	**-6.3**	**-2.4**
Street B	**L_{A10} (dB)**	**L_{A90} (dB)**	**L_{Aeq} (dB)**	**TNI (dB)**	**L_{NP} (dB)**
R	74.3	55.5	71.0	100.4	89.8
S	73.5	54.0	70.3	102.0	89.8
Error	**-0.8**	**-1.5**	**-0.7**	**+1.6**	**0.0**

Analyzing from another point of view, from the total simulated audios that were listened to by the volunteers, there were 63 hits (58%) and 45 errors (42%), while from the real audios, there were 83 hits (77%) and 25 errors (23%). This result indicates a strong trend toward *Real* responses, when in fact the audios were real. This trend was not as evident when people answered *Simulated* when the audios were simulated. Furthermore, by considering only the set of simulated audios, for all 108 corresponding samples, the defined interval as the region of non-rejection of H_0 is [44, 64], under a significance level of 5%. Since the number of errors was 45, H_0 can be accepted, even though the auralization of traffic noise not being the main goal of the proposed model.

It should be noted that the proposed model has some limitations. Unlike Maillard and Jagla (2013), in this work, vehicle signal synthesis is not performed. The listening tests performed by Maillard and Jagla (2013) indicated that synthesized signals were perceptually very close to the signals recorded for different types of engine, speed and tire. Here, we adopted a simpler computational modeling approach using real sound signal recordings of single pass-by vehicle on test tracks. With this approach, although it may be limited, the results achieved in this work have proven to be satisfactory with low computational cost. Furthermore, the acoustic interaction between simulated vehicles is not modeled, which may have relevant impact in the case of traffic jams and high traffic volumes according to technical literature. In traffic modeling adopted, we considered the steady speed restriction, except for bus arrival processes.

Regarding outdoor sound attenuation mechanisms, we adopted a simplified adjustment of acoustic energy of individual vehicles based on the perpendicular distance between the reference axis of vehicular flow and observation point, disregard variations of meteorological and atmospheric factors. Also, we considered a simplified approach for reflection surface modeling, unlike Radwan and Oldham (1987) that used the ray-tracing approach for modeling outdoor sound propagation.

Finally, it should be mentioned that this model has a limited number of actual sound signal templates of individual vehicle passages. Adding new audio templates to the proposed model database will provide more variety of types and speeds by vehicle category, and bus arrival patterns, thus offering better adherence to vehicular traffic scenarios.

Conclusions

This paper presents a novel probabilistic model for urban vehicular traffic noise analyses. The proposed model simulates vehicular traffic noise on urban roads either with free or traffic light controlled flow, and it considers the influence of bus stops.

One of main features of this model is the use of real sound signals from individual passages of different vehicles types and bus arrivals at a bus stop as a basis for the acquisition of sound emission from these events. As far as we know from the literature, this feature consists of an innovation compared to the vehicular traffic noise simulation approaches adopted, for example, by Li, Liao, Cai (2016). This new probabilistic modeling and simulation approach allows not only the computation common acoustic descriptors, such as L_{A10}, L_{A90}, L_{Aeq}, TNI and L_{NP}, but also the listening of simulated vehicular traffic noise.

It should be noted that the simple and intuitive modeling approach we adopted also contributed to the model implementation process itself, as we could be able to verify its proper performance by listening to and perceptually analyzing the simulated sound, the acoustic descriptors data, and the identification of random entry instants of different vehicle types in the simulation. Furthermore, we can also state that the use of sound signals recorded on a test track simplifies the modeling process, since it is not necessary to synthesize them as seen in related works cited in this paper. Applying the Monte Carlo method in simulations avoids complicated traffic flow modeling approaches, while yielding a satisfactory accuracy in predicting vehicular traffic noise.

The results from the quantitative validation approach indicated a good correspondence with the measured data of traffic and acoustic variables. The absolute mean errors of L_{A10}, L_{A90}, L_{Aeq} showed values below the 2 dB. The results of jury tests, especially in analysis between the number of hits and errors of the universe of simulated audios, suggests that there is room for improvement, but simulated sounds from the proposed model were able to convince more than 40% of the listeners of its realism. This result indicates that the model appears to be promising in the application of listening to simulated noise in acoustic evaluations of urban vehicular traffic, including the influence of bus stop dynamics.

Regarding the main limitations of the proposed model, they are:

(a) the strongly simplified adjustment of acoustic energy of individual vehicles recordings, which is solely based on the perpendicular distance between the reference axis of vehicular flow and observation point;

(b) the lack of simulated interaction between vehicles in our traffic simulations;

(c) the constant speed restriction in all simulations, except for bus arrival recorded samples;

(d) the disregard of meteorological and atmospheric variations;

(e) the limited number of actual sound signal templates of individual vehicle passages, i.e. low diversity of types and speeds per vehicle category, and bus arrival patterns; and

(f) the restriction of reflection simulations to vertical surface (facade) of first order, thus disregarding reflections on other surfaces or objects in the acoustic field.

Moreover, the proposed probabilistic model can be easily adapted to other scenaria, through the straightforward adjustment of its free parameters (e.g. event probabilities) and the inclusion of new real sound segments in its database. Indeed, the modularity of the proposed model allows for its adaptation to virtually an unlimited quantity of analogous scenaria.

References

ABO-QUDAIS, S.; ALHIARY, A. Statistical models for traffic noise at signalized intersections. **Building and Environment**, v. 42, n. 8, p. 2939-2948, 2007.

ALAM, P. *et al.* Noise monitoring, mapping, and modelling studies: a review. **Journal of Ecological Engineering**, v. 21, n. 4, 2020.

ANTONI, J. Cyclostationarity by examples. **Mechanical Systems and Signal Processing**, v. 23, n. 4, p. 987-1036, 2009.

ARANA, M. *et al.* Strategic noise map of a major road carried out with two environmental prediction software packages. **Environmental Monitoring and Assessment**, v. 163, n. 1, p. 503-513, 2010.

ASENSIO, C. *et al*. GPS-based speed collection method for road traffic noise mapping. **Transportation Research Part D: Transport and Environment**, v. 14, n. 5, p. 360-366, 2009.

AUMOND, P. *et al.* Global sensitivity analysis for road traffic noise modelling. **Applied Acoustics**, v. 176, p. 107899, 2021.

BACCOLI, R. *et al.* An adaptive nonlinear autoregressive ANN model for high time resolution traffic noise predictions. Experimental results for a port city waterfront. **Building and Environment**, v. 207, p. 108551, 2022.

BARRY, T. M.; REAGAN, J. A. **FHWA highway traffic noise prediction model**. Washington: U. S. Departament of Transportation, 1978. Available: https://rosap.ntl.bts.gov/view/dot/30259/dot_30259_DS1.pdf. Access: Mar. 8, 2023.

BRITISH STANDARD. **EN ISO 11819-1**: acoustics: measurement of the influence of road surfaces on traffic noise: part 1: statistical pass-by method. Brussels, 2001.

CAI, M. *et al.* Road traffic noise mapping in Guangzhou using GIS and GPS. **Applied Acoustics**, v. 87, p. 94-102, 2015.

CAI, M.; LI, F.; LIU, J. K. Dynamic simulation and characteristics analysis of traffic noise at signal-controlled pedestrian crossing junction. **Noise Control Engineering Journal**, v. 59, n. 5, p. 549-555, 2011.

CAN, A. *et al*. Traffic noise spectrum analysis: dynamic modeling vs. experimental observations. **Applied Acoustics**, v. 71, n. 8, p. 764-770, 2010.

CAN, A.; LECLERCQ, L.; LELONG, J. Dynamic estimation of urban traffic noise: influence of traffic and noise source representations. **Applied Acoustics**, v. 69, n. 10, p. 858-867, 2008.

CHEVALLIER, E. *et al*. Dynamic noise modeling at roundabouts. **Applied Acoustics**, v. 70, n. 5, p. 761-770, 2009b.

CHEVALLIER, E. *et al*. Improving noise assessment at intersections by modeling traffic dynamics. **Transportation Research Part D: Transport and Environment**, v. 14, n. 2, p. 100-110, 2009a.

CIRIANNI, F.; LEONARDI, G. Road traffic noise prediction models in the metropolitan area of the Strait of Messina. **Proceedings of the Institution of Civil Engineers –Transport**, v. 164, n. 4, p. 231-239, 2011.

COVACIU, D.; FLOREA, D.; TIMAR, J. Estimation of the noise level produced by road traffic in roundabouts. **Applied Acoustics**, v. 98, p. 43-51, 2015.

DEBNATH, A; SINGH, P. K; BANERJEE, S. Vehicular traffic noise modelling of urban area: a contouring and artificial neural network based approach. **Environmental Science and Pollution Research**, v. 29, n. 26, p. 39948-39972, 2022.

DEPARTMENT OF TRANSPORT. **Calculation of road traffic noise**. London: Department of Transport, Welsh Office, Her Majesty's Stationery Office (HMSO), 1988.

DINTRANS, A.; PRÉNDEZ, M. A method of assessing measures to reduce road traffic noise: A case study in Santiago, Chile. **Applied Acoustics**, v. 74, n. 12, p. 1486-1491, 2013.

DUTILLEUX, G. *et al.* NMPB-routes-2008: the revision of the French method for road traffic noise prediction. **Acta Acustica**, v. 96, n. 3, p. 452–462, 2010.

ESTÉVEZ-MAURIZ, L.; FORSSÉN, J. Dynamic traffic noise assessment tool: a comparative study between a roundabout and a signalized intersection. **Applied Acoustics**, v. 130, p. 71-86, 2018.

EUROPEAN UNION. **Directive 2002/49/EC of the European Parliament and the Council of 25 June 2002**. Relating to the assessment and management of environmental noise. European Union: Comission Directive (EU), 2002. Available: https://eur-lex.europa.eu/legal-content/PT/TXT/PDF/?uri=CELEX:32002L0049. Access: Aug. 12, 2022.

FALLAH-SHORSHANI, M. *et al*. Estimating traffic noise over a large urban area: an evaluation of methods. **Environment International**, v. 170, p. 107583, 2022.

FAULKNER, J.-P.; MURPHY, E. Road traffic noise modelling and population exposure estimation using CNOSSOS-EU: Insights from Ireland. **Applied Acoustics**, v. 192, p. 108692, 2022.

FORSSÉN, J. *et al*. Auralization of traffic noise within the LISTEN project: preliminary results for passenger car pass-by. In: EUROPEAN CONFERENCE ON NOISE CONTROL (EURONOISE), 8., Edinburgh, 2009. **Proceedings [...]** Edinburgh: Institute of Acoustics, 2009.

GARG, N.; MAJI, S. A critical review of principal traffic noise models: strategies and implications. **Environmental Impact Assessment Review**, v. 46, p. 68-81, 2014.

GIVARGIS, S.; KARIMI, H. A basic neural traffic noise prediction model for Tehran's roads. **Journal of Environmental Management**, v. 91, n. 12, p. 2529-2534, 2010.

GOOGLE SATELLITE. [Map]. Available: https://www.google.com.br/maps/@-22.8243831,-47.0672982,358m/data=!3m1!1e3?entry=ttu. Access: 09 Aug. 2022a.

GOOGLE SATELLITE. [Map]. Available: https://www.google.com.br/maps/@-22.882687,-47.0660469,126m/data=!3m1!1e3?entry=ttu. Access: 09 Aug. 2022b.

GUARNACCIA, C. Advanced tools for traffic noise modelling and prediction. **WSEAS Transactions on Systems**, v. 12, n. 2, p. 121-130, 2013.

GUEDES, I. C. M. **Modelo Probabilístico para investigação da influência de pontos de ônibus no ruído do tráfego veicular**. Campinas, 2018. 180 f. PhD Thesis - Faculty of Civil Engineering, Architecture and Urbanism, State University of Campinas, Campinas, 2018.

GUEDES, I. C. M.; BERTOLI, S. R.; ZANNIN, P.H.T. Influence of urban shapes on environmental noise: a case study in Aracaju - Brazil. **Science of the Total Environment**, v. 412, p. 66-76, 2011.

GUEDES, I. C. M.; BERTOLI, S. R; MONTALVÃO, J. Monte Carlo simulation of traffic noise dynamics at a bus stop based on real sound signals. **Proceedings of Meetings on Acoustics (POMA)**, v. 28, p. 040005, 2016.

GÜNDOĞDU, Ö.; GÖKDAĞ, M.; YÜKSEL, F. A traffic noise prediction method based on vehicle composition using genetic algorithms. **Applied Acoustics**, v. 66, n. 7, p. 799-809, 2005.

HAMMER, M. S; SWINBURN, T. K.; NEITZEL, R. L. Environmental noise pollution in the United States: developing an effective public health response. **Environmental Health Perspectives**, v. 122, n. 2, p. 115-119, 2014.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. **ISO 1996-2**: acoustics: description, assessment and measurement of environmental noise: part 2: determination of environmental noise levels. Geneva, 2007.

JONASSON, H. *et al*. **Work Package 1.1 Source modelling of road vehicles**. Technical Report of the Harmonoise Project. Borås: Statens Provningsanstalt, 2004. Available: https://www.diva-portal.org/smash/get/diva2:674007/FULLTEXT01.pdf. Access: Mar. 8, 2023.

KANG, J. **Urban sound environment.** Abingdon: Taylor and Francis. 2007.

KASSOMENOS, P.; VOGIATZIS, K.; COELHO, J. L. B. Critical issues on environmental noise: editorial. **Science of the Total Environment**, v. 482-483, p. 399, 2014.

KEPHALOPOULOS, S.; PAVIOTTI, M.; ANFOSSO-LÉDÉE, F. **Common noise assessment methods in Europe (CNOSSOS-EU).** EUR 25379 EN. Luxembourg: Publications Office of the European Union, 2012. Available: https://op.europa.eu/en/publication-detail/-/publication/80bca144-bd3a-46fb-8beb-47e16ab603db/language-en. Access: Mar. 8, 2023.

KLEIN, A. *et al*. Spectral and modulation indices for annoyance-relevant features of urban road single-vehicle pass-by noises. **The Journal of the Acoustical Society of America**, v. 137, n. 3, p. 1238-1250, 2015.

KUMAR, P.; NIGAM, S. P.; KUMAR, N. Vehicular traffic noise modeling using artificial neural network approach. **Transportation Research Part C: Emerging Technologies**, v. 40, p. 111-122, 2014.

LI, F. *et al*. A probability distribution prediction method for expressway traffic noise. **Transportation Research Part D: Transport and Environment**, v. 103, p. 103175, 2022.

LI, F. *et al.* Dynamic simulation and characteristics analysis of traffic noise at roundabout and signalized intersections. **Applied Acoustics**, v. 121, p. 14-24, 2017.

LI, F. *et al*. Dynamic traffic noise simulation at a signalized intersection among buildings. **Noise Control Engineering Journal**, v. 59, n. 2, p. 202-210, 2011.

LI, F.; LIAO, S. S.; CAI, M. A new probability statistical model for traffic noise prediction on free flow roads and control flow roads. **Transportation Research Part D: Transport and Environment**, v. 49, p. 313-322, 2016.

LICITRA, G. **Noise mapping in the EU models and procedures**. Boca Raton: CRC Press. 2013.

LU, X. *et al.* Influence of urban road characteristics on traffic noise. **Transportation Research Part D: Transport and Environment**, v. 75, p. 136-155, 2019.

LUNDÉN, P. *et al*. Psychoacoustic evaluation as a tool for optimization in the development of an urban soundscape simulator. In: AUDIO MOSTLY CONFERENCE: A CONFERENCE ON INTERACTION WITH SOUND, 5., Piteå, 2010. **Proceedings** [...]. New York: Association for Computing Machinery, 2010.

MAILLARD, J.; JAGLA, J. Auralization of non-stationary traffic noise using sample based synthesis-Comparison with pass-by recordings. In: INTERNATIONAL CONGRESS AND EXPOSITION ON NOISE CONTROL ENGINEERING (INTER-NOISE), 41., New York, 2012. **Proceedings [...]** New York: Institute of Noise Control Engineering (INCE-USA), 2012.

MAILLARD, J.; JAGLA, J. Real time auralization of non-stationary traffic noise-quantitative and perceptual validation in an urban street. In: AIA-DAGA CONFERENCE ON ACOUSTICS, Merano, 2013. **Proceedings [...]** Merano, 2013.

MAZHDRAKOV, M.; BENOV, D.; VALKANOV, N. **The Monte Carlo method**: engineering applications. Sofia: ACMO Academic Press, 2018.

NASCIMENTO, E. O. do *et al.* Noise prediction based on acoustic maps and vehicle fleet composition. **Applied Acoustics**, v. 174, p. 107803, 2021.

NEDIC, V. *et al.* Comparison of classical statistical methods and artificial neural network in traffic noise prediction. **Environmental Impact Assessment Review**, v. 49, p. 24-30, 2014.

PAMANIKABUD, P.; TANSATCHA, M.; BROWN, A. L. Development of a highway noise prediction model using a Leq20s measure of basic vehicular noise. **Journal of Sound and Vibration,** v. 316, n. 1-5, p. 317-330, 2008.

PASCHALIDOU, A. K.; KASSOMENOS, P.; CHONIANAKI, F. Strategic Noise Maps and Action Plans for the reduction of population exposure in a Mediterranean port city. **Science of the Total Environment**, v. 654, p. 144-153, 2019.

PIEREN, R.; BÜTLER, T; HEUTSCHI, K. Auralization of accelerating passenger cars using spectral modeling synthesis. **Applied Sciences**, v. 6, n. 1, p. 5, 2015.

PREZELJ, J.; MUROVEC, J. Traffic noise modelling and measurement: inter-laboratory comparison. **Applied Acoustics**, v. 127, p. 160-168, 2017.

RADWAN, M. M.; OLDHAM, D. J. The prediction of noise from urban traffic under interrupted flow conditions. **Applied Acoustics**, v. 21, n. 2, p. 163-185, 1987.

RAHMANI, S.; MOUSAVI, S. M.; KAMALI, M. J. Modeling of road-traffic noise with the use of genetic algorithm. **Applied Soft Computing**, v. 11, n. 1, p. 1008-1013, 2011.

RAMÍREZ, A.; DOMÍNGUEZ, E. Modeling urban traffic noise with stochastic and deterministic traffic models. **Applied Acoustics**, v. 74, n. 4, p. 614-621, 2013.

RODRIGUES, R. C. Modeling urban traffic noise dependence on energy, assisted with Monte Carlo simulation. **Energy Reports**, v. 8, p. 583-588, 2022.

SINGH, D. *et al*. Traffic noise prediction using machine learning and Monte Carlo data augmentation: a case study on the Patiala city in India. **Journal of Physics: Conference Series**, v. 2162, n. 1, p. 012021, 2022.

SKARLATOS, D. A numerical method for calculation of probability density function of equivalent level in the case of traffic noise. **Applied Acoustics**, v. 38, n. 1, p. 37-50, 1993.

SUÁREZ, E.; BARROS, J. L. Traffic noise mapping of the city of Santiago de Chile. **Science of the Total Environment**, v. 466, p. 539-546, 2014.

TANSATCHA, M. *et al*. Motorway noise modelling based on perpendicular propagation analysis of traffic noise. **Applied Acoustics**, v. 66, n. 10, p. 1135-1150, 2005.

TEMPLETON, D. (ed.). **Acoustics in the built environment**: advice for the design team. 2nd. ed. Woburn: Architectural Press, 1997.

WANG, B.; KANG, J. Effects of urban morphology on the traffic noise distribution through noise mapping: a comparative study between UK and China. **Applied Acoustics**, v. 72, n. 8, p. 556-568, 2011.

WANG, L.; CAI, M.; ZOU, J. Traffic noise prediction model for bus stop. In: INTERNATIONAL CONGRESS AND EXPOSITION ON NOISE CONTROL ENGINEERING (INTER-NOISE), 41., New York, 2012. **Proceedings [...]** New York: Institute of Noise Control Engineering (INCE-USA), 2012.

WORLD HEALTH ORGANIZATION. **WHO**: environmental noise guidelines for the european region. Copenhagen, 2018.

YANG, W. *et al.* Evaluation of urban traffic noise pollution based on noise maps. **Transportation Research Part D: Transport and Environment**, v. 87, p. 102516, 2020.

ZANNIN, P. H. T. *et al*. Characterization of environmental noise based on noise measurements, noise mapping and interviews: a case study at a university campus in Brazil. **Cities**, v. 31, p. 317-327, 2013.

ZANNIN, P. H. T.; SANT'ANA, D. Q. de. Noise mapping at different stages of a freeway redevelopment project: a case study in Brazil. **Applied Acoustics**, v. 72, p. 479-486, 2011.

ZHAO, J. *et al.* Assessment and improvement of a highway traffic noise prediction model with Leq (20 s) as the basic vehicular noise**. Applied Acoustics**, v. 97, p. 78-83, 2015.

Acknowledgments

We would like to thank all the volunteers who participated in the jury tests. We would also like to thank the Laboratory of Environmental Comfort and Applied Physics (LACAF) of the Faculty of Civil Engineering, Architecture and Urbanism of the State University of Campinas (UNICAMP), Brazil, and all colleagues who contributed in the data collection stage. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior − Brasil (CAPES) − Finance Code 001.

Italo César Montalvão Guedes
Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing - Original Draft, Writing – review & editing.

Department of Arquitecture and Urbanism | Universidade Federal de Sergipe | Praça Samuel de Oliveira, 1, Centro, *Campus* of Laranjeiras | Laranjeiras – SE – Brasil | CEP 04917-000 | Tel.: +55 (79) 99924-7266 | E-mail: italomontalvao@academico.ufs.br

Stelamaris Rolla Bertoli
Conceptualization, Methodology, Resources, Writing - review & editing, Supervision.

Faculty of Civil Engineering, Architecture and Urbanism | Universidade Estadual de Campinas | University City Zeferino Vaz, Saturnino de Brito Street, 224 | Campinas – SP – Brasil | CEP 13083-889 | Tel.: +55 (19) 3521-2446 | E-mail: rolla@fec.unicamp.br

Jugurta Montalvão
Conceptualization, Methodology, Software, Formal analysis, Writing - review & editing.

Department of Electrical Engineering Federal University of Sergipe | Universidade Federal de Sergipe | University City Prof. José Aloísio de Campos, Marechal Rondon Av., Jardim Rosa Elze | São Cristóvão – SE – Brasil | CEP 49100-000 | Tel.: +55 (79) 98876-1736 | E-mail: jmontalvao@academico.ufs.br

Editores do artigo: **Enedir Ghisi** e **Ercília Hitomi Hirota**

Ambiente Construído
Revista da Associação Nacional de Tecnologia do Ambiente Construído
Av. Osvaldo Aranha, 99 - 3º andar, Centro
Porto Alegre – RS - Brasil
CEP 90035-190
Telefone: +55 (51) 3308-4084
www.seer.ufrgs.br/ambienteconstruido
www.scielo.br/ac
E-mail: ambienteconstruido@ufrgs.br