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# REVERBERATION TIME AS AN INDICATOR FOR NOISE MAPS

Lucas D. Penteado[1*], Léa Cristina L. de Souza[1] and André Luis Christoforo[1]

[1]Department of Civil Engineering, Federal University of São Carlos, Brazil

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**Abstract:** Despite being an important acoustic parameter in urban canyons, reverberation time (RT) is little used to make noise maps. This paper focuses on urban RT and urban equivalent sound pressure level ($L_{Aeq}$) in order to construct noise maps. Therefore, these indicators were sampled in 31 points distributed in the central region of a medium-sized Brazilian city. In addition, constructive geometric characteristics and the vehicle flow were collected. These data were used as input for a reverberation time prediction equation and then used to develop a thematic map on a GIS platform by applying the inverse distance interpolation method. Furthermore, a $L_{Aeq}$ indicator noise map was made using the NMPB-Routes 2008 method in calculation commercial software. The results show a relationship between $L_{Aeq}$ and the urban RT map. Moreover, the results allowed the validation of a predictive RT model able to calculate future scenario acoustics based on geometric-constructive features and vehicular flow.

**Keywords:** Reverberation time; urban noise; noise map; GIS; CADNA-A



* Correspondence to: Lucas D. Penteado
E-mail: penteado.lucas@gmail.com

## INTRODUCTION

Noise pollution is one of the main urban environmental problems, especially because noise exposure may affect human health, causing serious medical conditions, such as cardiovascular diseases, sleep disorders, gestational diabetes, among others (Pedersen *et al.*, 2012; WHO, 2011; Babisch *et al.*, 2014). Thus, mitigating and controlling urban noise emissions are required planning actions, however not yet effective in the case of developing countries. In Brazil, for instance, noise control is almost entirely restricted to regulations of sound level limits stated by the Brazilian National Standards Organization, as it is suggested by land-use classes in the NBR 10151.

In contrast, some developed countries have already provided mechanisms to combat urban noise, as is the case in the European Union Directive. As part of this legal act, noise mapping has become a mandatory tool for the European environmental noise diagnosis, and in addition, Bastián-Monarca *et al.* (2016), Wei *et al.* (2016), Suárez & Barros (2014) indicate a variety of methods to support the development of these noise maps, either by computational simulations and software or in situ measurements.

While developing these maps, Zannin *et al.* (2013) comment that the traditional acoustical parameters of $L_{Aeq}$, $L_{den}$, $L_{90}$, $L_{80}$ are mostly used. Although reverberation time could also be taken into account, as in studies carried out by Thomas *et al.* (2011), the reverberation time parameters of Early Decay Time (EDT), $T_{30}$ e $T_{60}$ are rarely used. Reverberation may be expected to occur along and inside urban canyons, because urban sound waves travel in the direction of building façades, surfaces and obstacles in such a way that urban geometry may influence sound diffraction and reflection, as shown by Montes-Gonzales *et al.* (2018), Echevarria-Sanchez *et al.* (2016). Therefore, sound levels may even be intensified by multiple sound waves, enhancing the number of components and increasing the permanence of sound in the air, thus leading to urban reverberation and enlarging the receptor exposure to noise (Thomas *et al.*, 2013; Mijic & Pavlovic, 2012; and Fielitz *et al.*, 2010). The higher the sound wavelength, the larger the total amount of energy reaching the receptor, hence the sound pressure level at the receptor is higher.

On the other hand, the reverberation time determination for an open space is a difficult task. The traditional dodecahedral sound source usually used in indoor spaces is a high-cost element with low portable conditions for open areas. One alternative method for this purpose could be to use impulsive sources, as presented by Pätynen *et al.* (2011), for which air-balloons are insufflated and then blown up to simulate a noise source.

In order to propose a prediction model to develop open-space reverberation time maps based on the $T_{60}$ acoustical parameter; this research explores the use of an impulsive method with air-balloon sources and establishes some statistical analysis and use this indicator to elaborate a noise map.

## METHOD

The reverberation time study included developing a prevision model, as well as applying and generating thematic maps of a study area in a GIS software. The results of this reverberation time map were compared to the traditional sound pressure level map developed with a computational simulation model.

### Study Area

Located at the south-latitude 22.01 and west-longitude 47.89, the study area is an urban region of the city of São Carlos (**Fig. 1**), situated in the interior of the state of São Paulo. The city occupies an area of 1143.9 km$^2$ and has a population of 243 765 inhabitants (IBGE, 2018). The analyzed urban region is part of the downtown, which corresponds to a high density occupation, crossed by important avenues and streets, and presenting high vehicular traffic flow. The region has various facilities mainly including one or two-floor residential buildings and some higher multi-family buildings.

### Measurement Points

Selecting and distributing measurement points are important for developing the noise map. For this reason, this research adopted a grid spacing of 140 × 140 meters (**Fig. 2**), resulting in an almost homogeneous distribution of collection points. The measurement

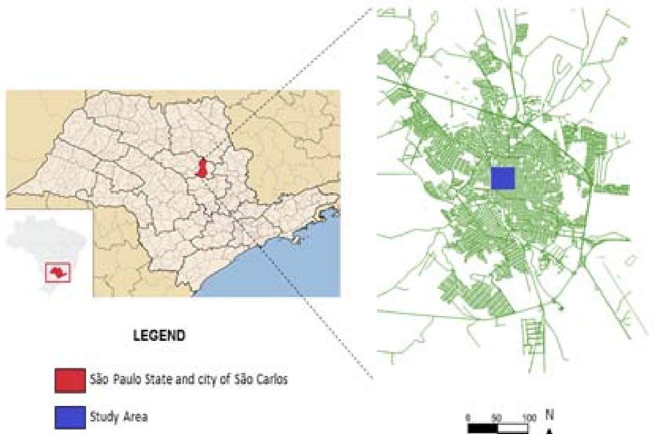


**Fig. 1** The Study area delimitation.

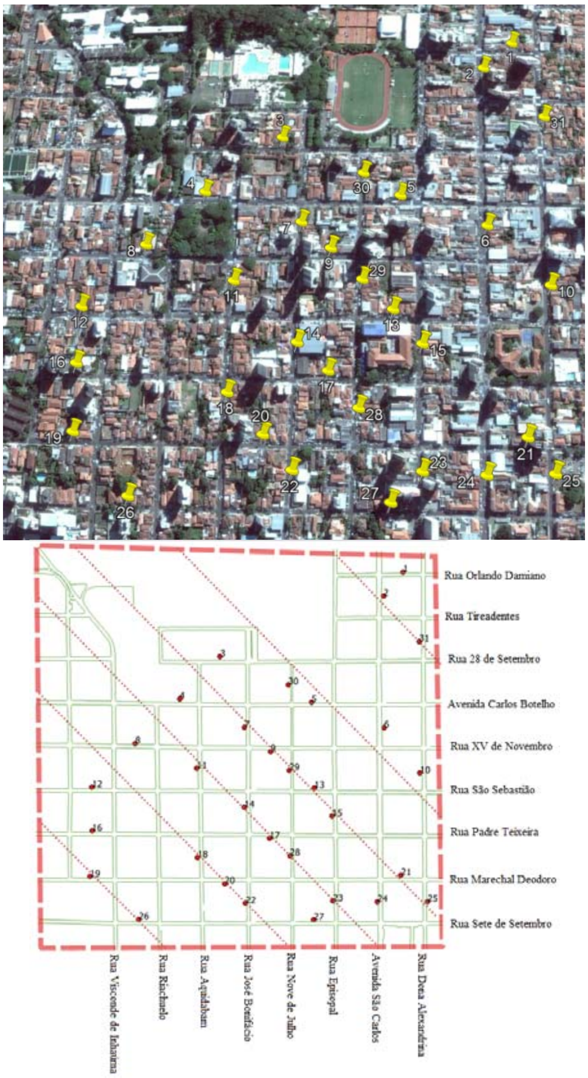


**Fig. 2** The 31 measurement points distribution around the study area.

points were positioned in the middle of the urban block (square), facing the streets in order to sample a continuous traffic flow and minimize the influence of noise generated by vehicular acceleration/deceleration at crossings, traffic lights and bus stops. For an area of 458.000 m$^2$, data was collected from 31 points to develop a reverberation time prediction model.

## Geometric-constructive data collection

Geometric-constructive data were collected on site and by consulting municipal cadastral maps and Google Earth. This data-collection includes the following features: street and pathway width; pavement type; building heights, shapes and location; and topography. The calculation of the H/W (buildings height/buildings width) was also determined, adopting the methodology proposed by Nakata-Osaki (2016). In the first step, this methodology considers, for each urban block, the average distance between each building façade and an imaginary axis along a street to calculate the average

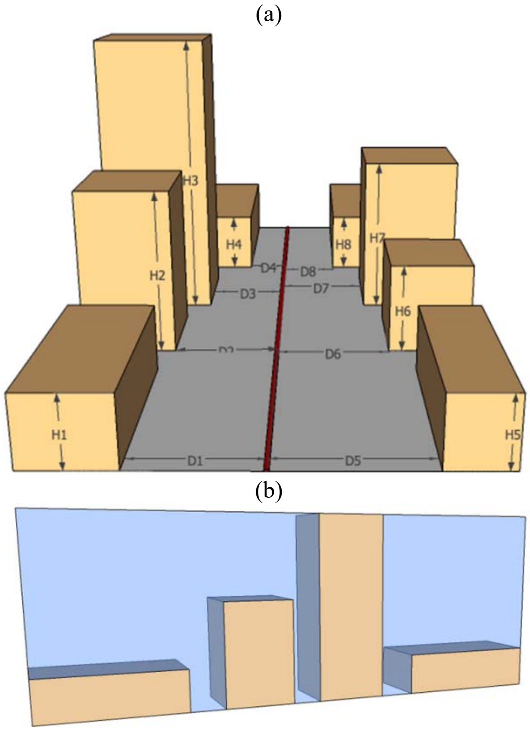


**Fig. 3** (a) Representation of Nakata-Osaki`s H/W calculation method. (b) Representation or empty space calculation method.

width of the street ($W_{average}$). The average building height of each side of the street is also calculated ($H_{right-average}$ and $H_{left-average}$). Then, the average height ($H_{average}$) between both sides is determined, so that the ratio between $H_{average}/W_{average}$ can be estimated. The method is shown in **Fig. 3a**.

In addition, the percentage of empty spaces (%Es) was also determined, considering the ratio between the building façade areas and an imaginary rectangular area around all these façades. The length of the imaginary rectangle is equal to the one from the urban block and the height is equal to the highest building of the whole study area. Then, the area occupied by the façades is calculated. The method is shown in **Fig. 3b**.

Moreover, the street declivity degree (%D) was obtained by its topographical profile. The level in each of the two corners of the urban block is measured and divided by the length between these corners. The vehicular speed limits at this block were also noted down.

## Acoustic and vehicular traffic data collection

The reverberation time was indicated by parameter $T_{60}$, which represents the decay of 60 dB after the extinction of the sound source. The impulsive method using insufflated air-balloons was adopted, based on the validation of Pätynen *et al.* (2011). The insufflated air-balloons were positioned at 1.50 m from ground level, at a distance of more than 2 meters from any reflecting vertical surfaces. A hand-held analyser 2270 Bruel & Kjaer was calibrated before each measurement period by a 4231 B&K calibrator. The sound pressure meter was placed one meter from the balloon and the balloon was blown up. Afterwards, the reverberation time values were registered. The measurements were carried out from 6:30 am to 7:00 am. In order to avoid the period of time with a higher interference of vehicular background noise.

To establish a relationship among reverberation time and noise level, sound pressure levels were also registered at the measurement points ($L_{Aeq}$). These campaigns were done on Tuesdays, Wednesdays and Thursdays, avoiding the atypical conditions of weekends and holidays. The $L_{Aeq}$ measurements were taken at the highest downtown peak hours of traffic flow, between 12 pm and 1 pm, from May to September, 2017. The same hand-held analyzer previously mentioned was used and the measurements were taken over 5 minutes, following the studies carried out by Mendonça *et al.* (2012), simultaneously to the vehicular flow counting.

### Mapping and relating urban reverberation time and noise

The measured values of reverberation time and $L_{Aeq}$ were cross-examined in order to verify the coincidences of high values points. This coincidence represents the potential of the reverberation time as a noise indicator.

A reverberation time prediction model was created based on the data collected at the 31 measurement points. The statistical multivariable method was able to construct an equation that associates reverberation time to urban geometry and vehicular traffic flow.

Thus, for the input of this model, the following variables were used: volume of vehicles (VV), average street width ($W_{average}$), average height of buildings ($H_{average}$), percentage of empty spaces (%Es) and street declivity degree (%D).

The multiple regression model was developed based on the variance analysis of ANOVA, with a significance level of 5%, considering the model and coefficients′ non-significance (P-value<0.05) as a null hypothesis and the significance as an alternative hypothesis. For the regression model validation, the Anderson-Darling residual normality test was also considered, with a 5% significance level and residual independence. The ANOVA is valid if residual distribution presents normality.

The model performance was then evaluated by analysis and visualization of the error magnitude. This analysis was made by comparing graphs and by spatialization of the reverberation time at the measurement points. To do this, the collected values were incorporated into QGIS and interpolated by the inverse distance interpolation (IDW) method to create a thematic map.

After the validation, the model was used to predict reverberation time values at other non-measured points of the study area, based on their traffic and geometric-constructive features. These other values were also inserted in the same GIS platform to complement the map information. Finally, the reverberation time map was also compared to the sound pressure level map by using the CADNA-A software. In the latter case, the French NMPB-Routes model was adopted, considering inputs such as the real geometric scenario of the study area and the real vehicular flow. For the façade absorption coefficient input, the "structured façade" default was adopted, thus resulting in a value of 0.37, which represents non-absorbent materials, such as brick, glass and mortar. The calculation protocol assumed the meteorological conditions default and the second order number of reflections. All the buildings were considered reflective surfaces.

## RESULTS AND DISCUSSIONS

### Geometric-constructive and acoustic data

**Table 1** presents the maximum and minimum values for the geometric-constructive variables and the traffic data at the measurement points. The maximum sound pressure level was 88.3 dB, while the minimum was 46.6 dB. Therefore, the minimum is lower than the 55 dB limited by NBR 10.152, but the maximum exceeded this value by about 33 dB, confirming the sound pollution in this city. Regarding the vehicular flow, there was a large variation from the minimum of 12 to the maximum of 101 vehicles. This large variation is due to the presence of important avenues within the limits of the study area, which form a two way system (binarium) of the streets and promote a high vehicular flow in the north-south direction. **Figure 4** shows the vehicular traffic flow and the speed limit allowed at the measurement points.

**Table 1.** Values for geometric constructive variables and traffic data

| Variable | Unit | Minimum | Maximum |
|---|---|---|---|
| RT | Seconds (s) | 0.58 | 1.87 |
| $L_{Aeq}$ | Decibels (dB) | 46.6 | 88.3 |
| VV | Units | 12 | 101 |
| Speed Limit | Speed (km/h) | 30 | 50 |
| Average height of buildings | Meters (m) | 1.94 | 21.10 |
| Average street width | Meters (m) | 7.00 | 11.00 |
| Percentage of empty spaces | % | 6 | 60 |
| Street Length | Meters (m) | 65.7 | 102.00 |
| Declivity | % | -9.8 | 11 |

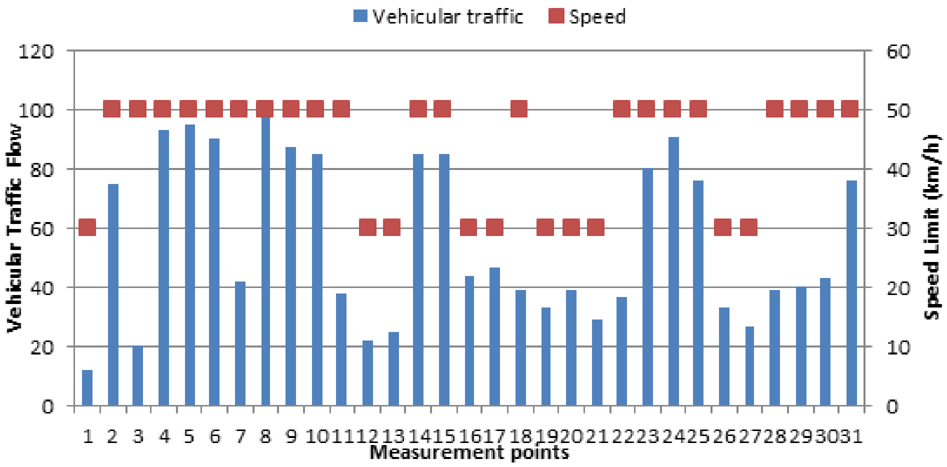


**Fig. 4** Vehicular traffic flow and speed limit at each measurement point.

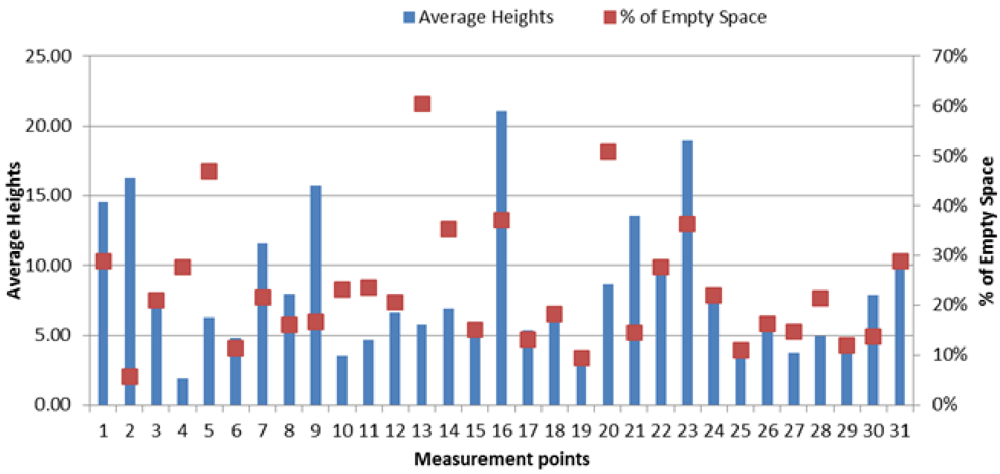


**Fig. 5** Average Heights and Percentage of Empty Space ate each measurement point.

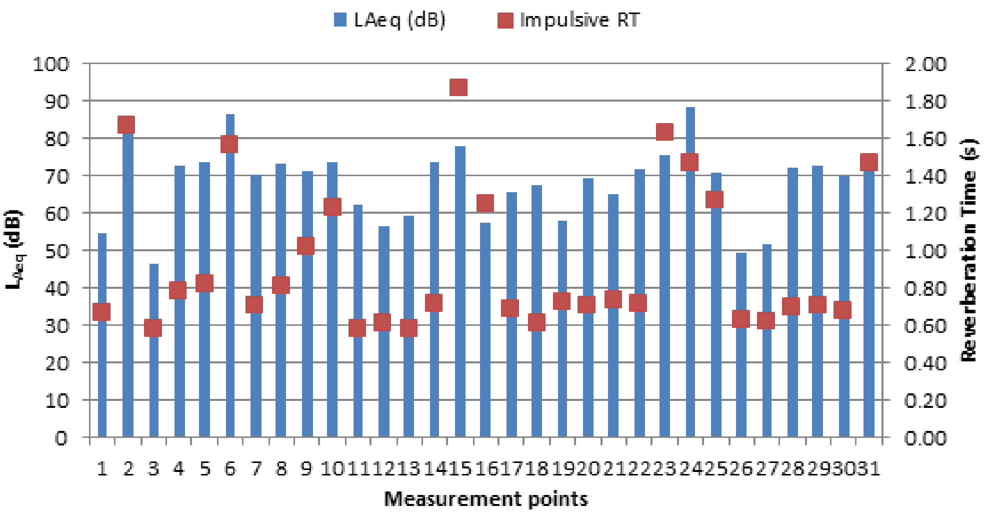


**Fig. 6** Sound Pressure Level and the Reverberation Time each point.

The highest vehicular flow in a decreasing order corresponds to points 8, 5, 4, 24, 6, 9, 10 and 15. Points 4, 5, 8 and 9 are located at two other important avenues (Av. Carlos Botelho and Av. XV de Novembro), which connect the city in the east-west direction and points 6, 10, 15 and 24 belong to the principal traffic axis of the city (Av. São Carlos), and two other traffic corridors that allow the displacement along the north-south axis

(Rua Alexandrina and Rua Episcopal). The maximum vehicular concentration corresponds to the street presenting the highest speed limits. For streets where the limit speed is 30 km/h, the vehicular flow is the lowest, usually less than 50 vehicles during 5 minutes.

**Figure 5** presents the average building heights and the percentage of empty space at the measurement points. The relationship between the mean heights of the points and the percentage of voids can be seen. It can be observed that the higher the mean height, the smaller the percentage of voids, as observed in points 2, 9, 16, 21 and 23. The smaller the average height around the point studied, the greater the percentage of voids in the point, thus showing the density of the studied region. **Figure 6** presents the sound pressure level and the reverberation time on each point.

**Figure 6** shows that there is a tendency for the highest reverberation times to occur in canyons with the highest sound pressure levels, as in points 1, 8, 17, 26 and 30. This shows the potential of the reverberation time as an indicator of the urban sound pressure level in the canyon.

### Mapping and reverberation time

The sound pressure level map and urban reverberation time map, which were developed by data interpolation on the Q-GIS platform, are shown in **Figs 7–8**. The comparison between the maps of **Figs 7–8** shows that the highest values of $L_{Aeq}$ and RT are located at points located to the east. These are points with high reverberation times and high traffic flow, as in points 2, 6, 10, 23, 24, 25 and 31 (which are points situated at Rua Episcopal, Avenida São Carlos and Rua Alexandrina).

### Modelling the urban reverberation time

The developed reverberation time prediction model is presented in **Eq. (1)**.

$$\begin{gathered} TR= A+B \\ A=0.5794+0.0141.(VV)-0.0683.(W_{average}) \\ B=0.0306.(H_{average})-9.10^{-6}.(\%Es)+0.0060.(\%D) \end{gathered} \quad (1)$$

where: VV is the volume of vehicles (in units); $W_{average}$ is the average distance between opposite façades along the street (in meters); $H_{average}$ is the average height of the buildings along the street (in meters); %Es is the percentage of empty space (%); %D is the street declivity degree (%).

### Comparing predictions

The model is valid with a P value higher than 5%, as shown in **Fig. 9**, presenting a determination coefficient of 0.92. The model was developed focusing on the geometric features of the canyons, mainly those of street width and building heights. As a result, VV and $H_{average}$ are variables presenting a positive contribution in the equation, while $W_{average}$ has a negative contribution.

**Figure 10** shows a $L_{Aeq}$ map and reverberation time map. The first one was generated by values predicted using the application of CADNA-A software, in dB. The second one was created in Q-GIS, by the association of measured values and Equation 1 predicted the values, in Points 11, 12 and 13 (at Rua São Sebastião) have low traffic flow when compared to other streets. Point 13 (at Rua Padre Teixeira) has a low average height of buildings and some empty lots, thus lowering the reverberation time.

## CONCLUSIONS

In conclusion, there is a correlation between geometric-constructive street characteristics and urban reverberation time, mainly for streets with a high average height of buildings and low value of empty spaces. Moreover, there is a correlation between sound pressure levels ($L_{Aeq}$) and the urban reverberation time, mainly for streets with a low percentage of empty spaces and high vehicular traffic flow.

Thematic maps, although made with different acoustic indicators, have a similarity between them. A range of sound pressure levels from 35 to 45 dB may be associated to a reverberation time between 0.7 and 0.8 s, while the range from 55 to 65 dB correspond to 0.8 and 0.9 s. For sound pressure values higher than 75 dB, the reverberation time may reach values above 1s.

The development of the reverberation time prediction model proposed here is able to calculate future scenarios based on the geometric-constructive features and vehicular flow, respecting the limits of values that generated the model. Nevertheless, the application of this equation should always be previously validated and applied only for medium-sized Brazilian cities which have approximately 250 000 inhabitants. Other sizes of cities were not taken into consideration in this research.

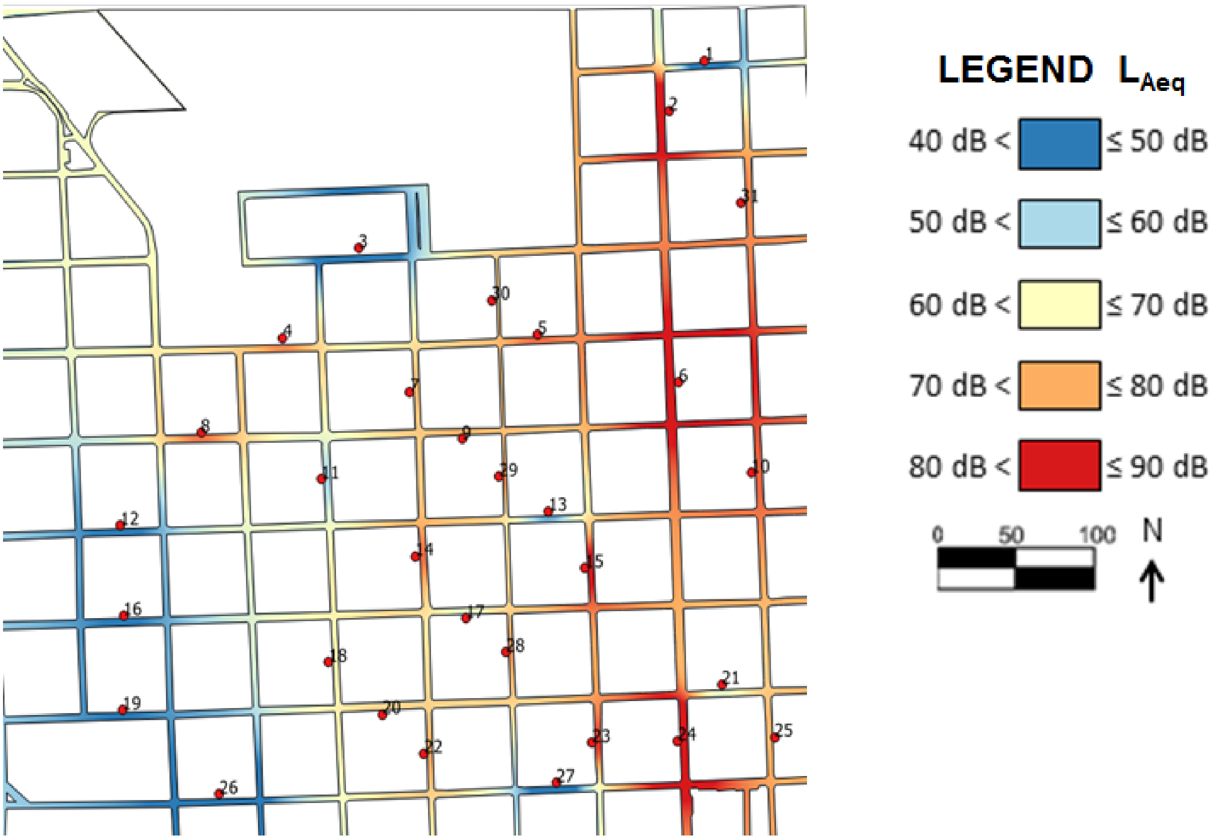


**Fig. 7** Sound Pressure Level Map.

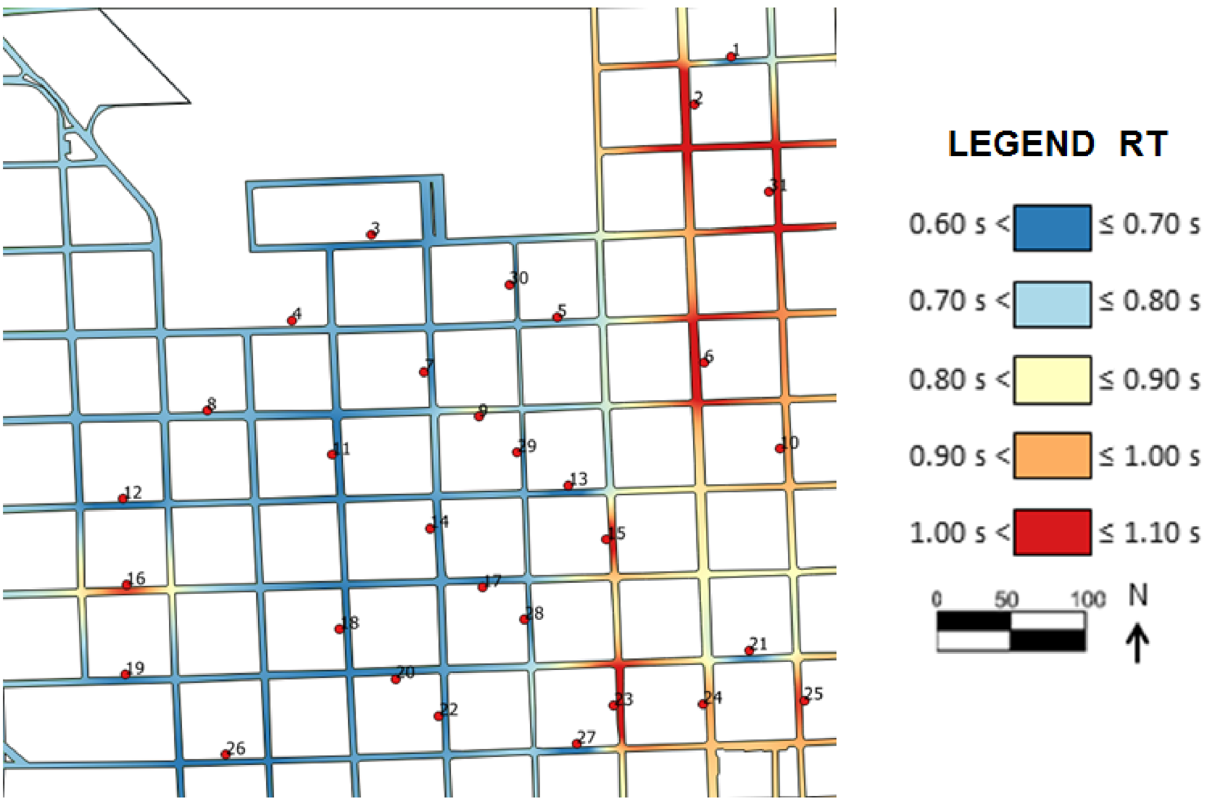


**Fig. 8** Reverberation Time Map.

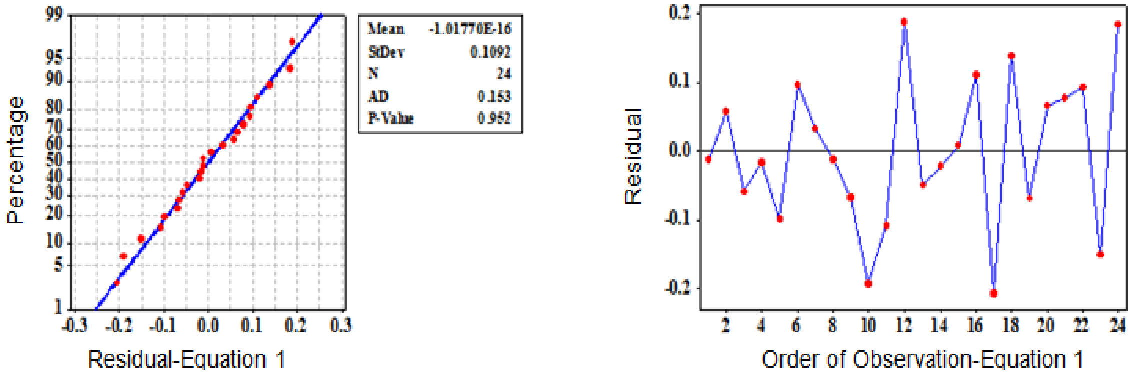


**Fig. 9** ANOVA validation test.

(a)


(b)

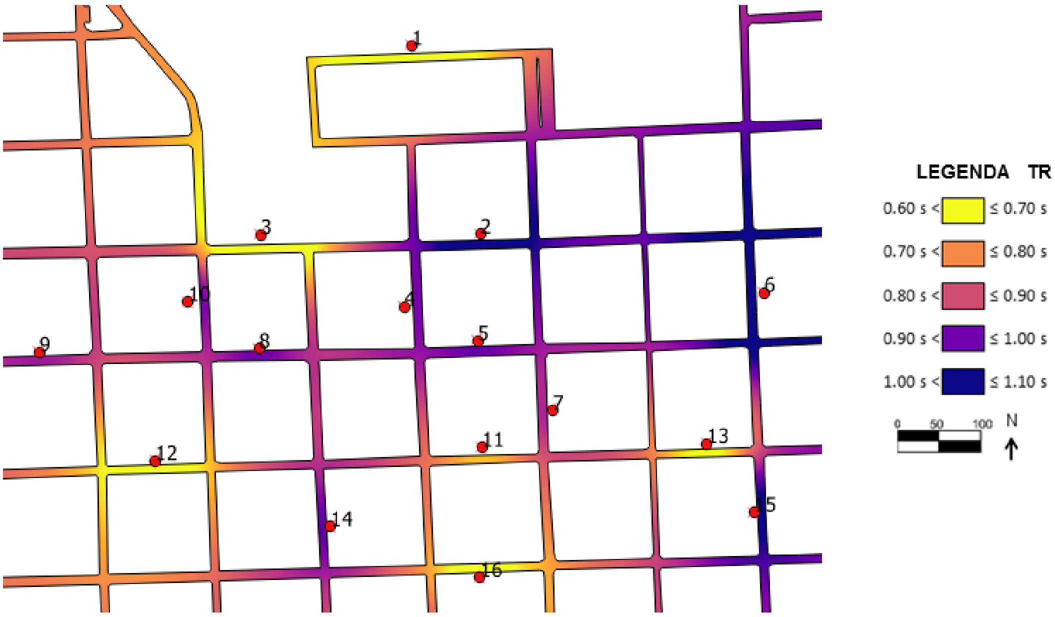


**Fig. 10** (a) Noise map developed with CADNA-A and Vehicular traffic flow. (b) Noise map developed with a SIG and values in **Eq. 1**.

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