ESTIMATING THE CONTRIBUTION OF PUBLIC TRANSPORT BUSES TO THE TOTAL TRAFFIC NOISE IN SANTIAGO DE CHILE

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An interesting research question is how much do public transport buses contribute to the total traffic noise in a city? In this article a cost-effective traffic noise source separation method is discussed to provide a statistical answer to this question. The method is applied in Santiago de Chile (SCL), a large city of more than six million inhabitants and a surface of almost 1,000 km^2. In this study, the sources contributing to the total motor vehicle traffic noise of SCL were light and heavy vehicles, motorbikes, and public transport (TS) buses. Roads were divided according to their use into express, arterial, collector, service, and local roads. In-situ individual sound exposure level (SEL) measurements of 186 buses and light vehicles were carried out. Based on their individual SEL values, it was concluded that a typical bus contains the sound energy of seven light vehicles. On the other hand, sidewalk noise measures were also obtained at 500 street sites located throughout SCL, along with data on time, location, classification, and traffic flows. The contribution of TS buses to the total traffic noise was estimated as the difference between A-weighted equivalent continuous sound pressure levels with and without TS. The relationship between traffic noise contribution of TS and density of traffic of buses was analyzed using regression models. Results showed that the contribution was significantly associated with the volume of TS traffic and street category. The contribution of TS buses to the total noise is highly associated to the street-type mean noise where the contribution is stronger in quiet streets. The estimated mean contribution of TS buses to the total traffic noise level in SCL is 1.3 dBA, contributing approximately 25% to the total mean traffic sound energy.
Keywords: traffic noise, transportation, SEL, urban noise

1. Introduction

Automobile, truck and bus traffic is the main source of environmental noise pollution in cities. It has been shown that street-level noise exposure is mainly associated with vehicular traffic. [1] In this sense, many cities worldwide have been developing strategic noise maps to be used as a tool to implement action plans for mitigating the environmental noise. During 2016, an update of the strategic noise map of Santiago of Chile (SCL) was performed. The project was commissioned by the Ministry of Environment to the Univ. Austral of Chile. Santiago is the capital and largest city of Chile. It has a population of over 6 million people and its surface of almost 1000 km^2 is divided into large suburbs, each with their own city council. The first results of traffic noise in SCL were reported in the first strategic noise map which was published in 2011. [2]

Traffic noise is composed by many individual sources, namely light vehicles, trucks, motorcycles, buses, etc. An interesting research question is how much do public transport buses contribute to the total traffic noise?

Within the objectives of the project it was considered to estimate the contribution of the noise of the public transport bus system of Santiago, known as TranSantiago (TS), to the total traffic noise of the city. In principle, this estimation could be made by disaggregating the buses within the traffic flows in the different roads that constitute the city. Subsequently, the noise could be modelled according to the classical methodology used by the modelling software, to obtain the corresponding day-, evening-, and night-levels (L_d, L_e and L_n). However, this presents the extreme difficulty of obtaining field measured values for the subsequent comparison and/or calibration of the model. It is unfeasible to make measurements of the noise contribution of the TS, since the other traffic sources will almost always be measured. An ideal scenario would be to "stop" the transit of vehicles other than buses and then carry out the measurements at a fixed point, which is not possible.

2. Methodology

For this project, a simplified procedure has been designed to estimate the contribution of public transport buses, which is based on the concept of the level of noise exposure. The sound exposure level (SEL) is defined as that constant A-weighted sound pressure level which has the same amount of energy in one second as the original noise event. Therefore, SEL is an A-weighted equivalent sound level, L_{eq}, with a reference duration of one second. [3] This level is numerically equivalent to the total sound energy of a single event. Several events with different individual SEL values can be added on an energy basis. This methodology has been previously used in estimating the noise levels produced by aircraft operations at airports (ISO 3891 [4] describes aircraft noise measurement based on the SEL as a simplified method for assessing discomfort in the affected areas), in transit-related environmental impact statements [5] and in the assessment of noise dose or sound exposure in the workplace. [6]

The convenience of this concept is best understood when dealing with an environment in which a variety of noise types are present, which in our case corresponds to the sources of the TS (comprising three types of buses). In this sense, the SEL has the advantage that the values obtained describe the individual sources of noise and the noisy environment in a compatible way, in A-weighting.

In the case of buses, it is known that at slow speeds (less than 40-45 km/h) mechanical noise (motor, gearboxes, brakes, etc.) tends to be predominant in total noise. At fast speeds (about 45-50 km/h) mechanical noise is no longer relevant and total noise is produced mainly by tire/pavement contact (tyre rolling noise) and aerodynamic noise. In this way, a methodology for measuring single events from several TS buses, which includes all the categories of buses in operation in the transport system of SCL, was established to obtain an average value of SEL for each class. These measurements were made at two speed conditions (slow and fast), in those cases where it is possible to measure a representative SEL of a bus without the effect of other sources of noise.

A set of measurements were conducted to experimentally obtain a SEL database for the different types of buses that are operating in the system. According to the standard TS buses classification, there are three types of buses according to their length: Class A (8-11 m), Class B (11-13 m), and Class C (larger than 14 m). Buses classified as C are articulated single-deck buses having two rigid sections linked by a pivoting joint enclosed by protective folding bellows. The following measuring procedure was followed:

- The SEL corresponding to a TS bus pass-by was measured at the same distance to the road and tripod height as the other traffic noise measurements were done to produce the noise map.
- To regulate the measurement time, the manual mode of the sound level meter was utilized. In this case, the measurement was started as the bus approached and it was stopped when the bus was far enough so the noise level returned approximately to the value of the background noise.
- The measurements were made in situations in which only the noise produced by a TS bus was the single source at that time.

- Measurements of each bus were made in two situations: a) bus at normal speed of circulation on the road, to quantify its rolling noise (greater than 50 km/h approximately). This situation was called “Fast.”; b) bus circulating at a speed lower than the normal traffic (less than 50 km/h approximately), where the sources of noise correspond to those associated with the acceleration and/or shifting gears. This situation was called “Slow.”
- For each class of bus (A, B and C), 45 buses were measured (30 in fast and 15 in slow conditions). Therefore, a total of 135 measures were registered, 90 in fast and 45 in slow conditions.
- The position of the measurement point was not considered relevant although caution was taken that no nearby buildings or other obstacles produced undesired reflections.

In addition, 51 SEL measures were performed for light vehicles in “Fast” condition, in order to compare the results obtained.

The Ministry official urban street categorization was used so that roads were divided according to their use into express, arterial, collector, service, and local roads. Data of L_{eq} and traffic flow were obtained from the field measurement campaign made for making the noise map of SCL. Noise levels were measured at 500 points, randomly distributed in the city and for different types of road classification. Vehicular flows were also measured at these points, separated by light and heavy vehicles, motorcycles and TS buses. Flow conditions were considered at fast speeds (approximately 50 km/h). Points that did not have buses flow and those that included cobblestones roads were discarded for the analysis. In this way, a total of 232 points out of 500 were considered.

3. Results and discussion

Figure 1 shows the histograms of the measurements made and the corresponding standard probability distributions for each type of bus, speed condition and for light vehicles in "Fast" condition. The statistical summary of the results is shown in Table 1.

Table 1: Results of measured sound exposure level (SEL) of TS buses and light vehicles.

Class	Speed	Statistical values, dBA			
		SEL max	SEL min	SEL average	STD
A	Slow	92.1	77.3	83.7	4.0
B	Slow	89.6	77.9	83.9	2.8
C	Slow	92.6	81.9	87.6	3.5
A	Fast	90.9	76.8	82.4	3.7
B	Fast	98.8	77.5	84.3	4.2
C	Fast	90.7	79.7	84.6	2.8
Light vehicles	Fast	81.3	67.7	76.0	2.9

From Fig. 1 it is observed that, in general, there is a better normal statistical distribution for buses in fast than slow condition, although the number of data measured in fast condition is higher. A bimodal distribution is noticed for class C buses in both slow and fast conditions. This may be due to the fact that, in this case, the noise levels are strongly dependent upon other variables, including the operation and maintenance conditions of the articulated buses. A statistically normal distribution of the measured data is observed for light vehicles at fast speeds, with a mean SEL = 76 dBA and a standard deviation of 2.9 dBA. This indicates that the prevalent source of noise at high speed in this type of vehicles is the tyre rolling noise, which does not depend on the engine characteristics of the vehicle.

We can see in Table 1 that in the case of Class A buses, the slow condition produces a level 1.3 dBA higher than in the fast condition. In the case of class B buses, the difference between idle and fast is not relevant, while for Class C buses, in the slow condition they produce an average of 3 dBA more than a fast one. This last result is reasonable since these are articulated buses, with a load of 30.5 tons and a 360 CV engine (9−12 litres) which is noisier than that of smaller buses of 150 to 290 HP engines. In addition, we can notice that buses of Class A, B and C, at slow speeds, are equivalent to 6, 6 and 15 light vehicles in fast speed, respectively. On the other hand, Class A, B and C are equivalent to 4, 7, and 7 light vehicles in fast speed condition, respectively. These results validate assumptions generally used in the vehicle traffic noise modelling process.

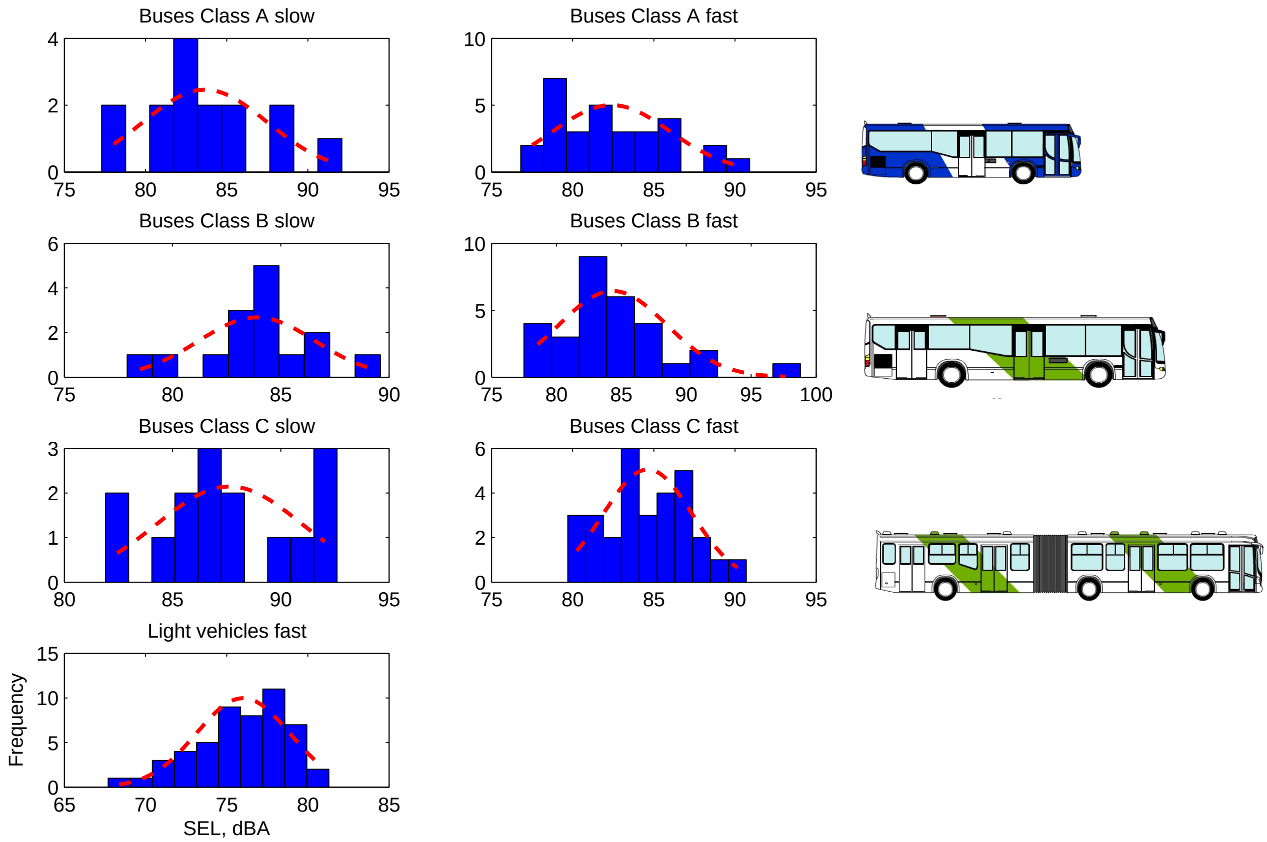

Figure 1: Probability distribution histograms for SEL measurements for the different types of TS buses in two speed conditions and for light vehicles in fast speed condition.

3.1 Determination of the contribution of TS buses to the total traffic noise

Since the estimated values of SEL for light vehicles proved to be statistically more reliable, equivalent flows may be used to separate the noise levels produced by the TS buses. We consider that most of the traffic flow is produced by buses of Class B and C (which are the noisiest), and which were shown to emit a noise level equivalent to seven light vehicles. From previous studies in SCL, [2] motorcycles and trucks have been considered equivalent to two and seven light vehicles, respectively.

Fig. 2 shows the measured $L_{eq,1\text{h}}$ as a function of total equivalent vehicle flow by weighing the heavy vehicles, motorcycles and TS buses. Performing simple linear regression on these data allows one to find the equation

$$L_{eq} = 9.67 \log(Q_E) + 41.8 \text{ dBA}, \tag{1}$$

where Q_E is the equivalent vehicle flow in one hour. In this case the Pearson correlation coefficient R = 0.84 indicates that, at each point, the equivalent vehicular flow explains 76% of the variation in the measured values of L_{eq}.

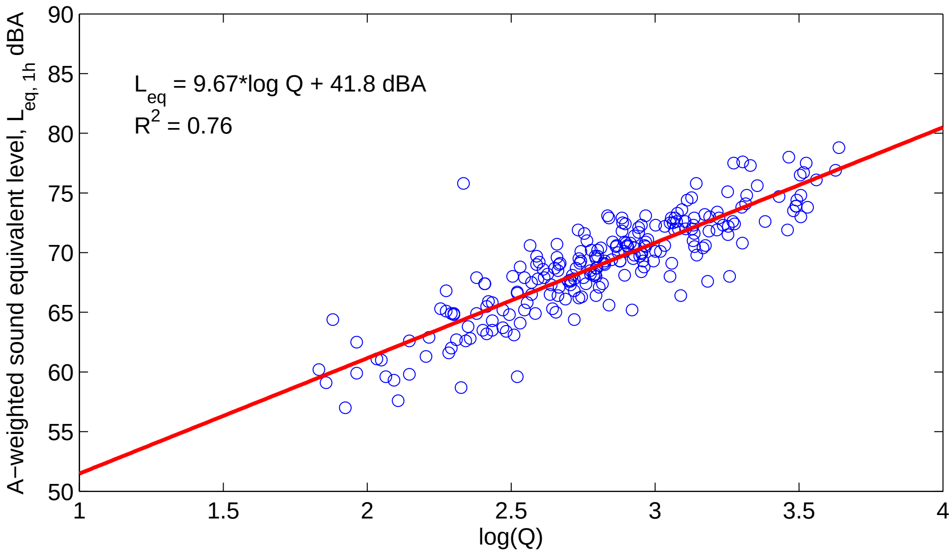

Figure 2: 1-hour A-weighted equivalent sound level as a function of the equivalent traffic flow.

Using Eq. (1), the equivalent noise levels were determined from the equivalent flow values in the cases with and without TS buses. Thus, the difference between both levels corresponds to the contribution of TS buses to the total traffic noise. The results are shown in Fig. 3. We observe that R = 0.99, which indicates that the percentage of TS buses flow in relation to the total traffic flow explains 97% of the contribution of TS buses to the total noise levels at each point. Simple linear regression gives the equation

$$\Delta L_{eq} = 0.18(\%TS) + 0.21 \text{ dBA}, \tag{2}$$

where $\%TS$ is the percentage of the TS buses flow in relation to the total flow of vehicles.

3.2 TS buses contribution to the noise levels according to the type of road

Since the traffic percentages of the TS buses are directly related to the total traffic noise levels and that the circulation of TS buses in different types of roads can produce more noticeable effects on the total noise, the same methodology used in Section 3.1 was applied, but now separating the results according to the road classification. Fig. 4 shows the average flow for each type of vehicle (light, heavy, motorcycles and TS buses) and according to the type of road (collector, express, local, service and arterial). We notice that the flow of light vehicles is predominant in all types of roads, always being greater than 88%. The lowest flow of light vehicles and the largest flow of TS buses are reported in the local-type roads. Table 2 shows the average A-weighted equivalent sound pressure level for each type of road. Table 3 shows the difference in A-weighted sound pressure level with and without the bus flow. It can be seen that the contribution of the TS buses to the traffic noise is 1.1 dBA in collector roads, 0.8 dBA in express roads, 2.3 dBA in local roads, 1.3 dBA in service roads and 1 dBA in arterial roads. These results make sense, since it is expected that the effect of the bus noise will be greater in quieter streets. On the other hand, in a noisier road, such as an express road, the effect of the bus noise should be less significant. The average value of the contribution of the TS buses to the A-weighted traffic noise level in SCL is determined as 1.3 dB.

It is interesting to plot the contribution of the TS buses to the traffic noise as the increase of the noise level according to the average levels of each type of road (indicated in Tables 2 and 3). The results are shown in Fig. 5. In this case, the data are best fitted to a third-degree polynomial, given by

$$\Delta L_{eq} = -0.006924L^3 + 1.474L^2 - 104.6L + 2474 \text{ dBA}, \tag{3}$$

where L is the equivalent sound level in the road.

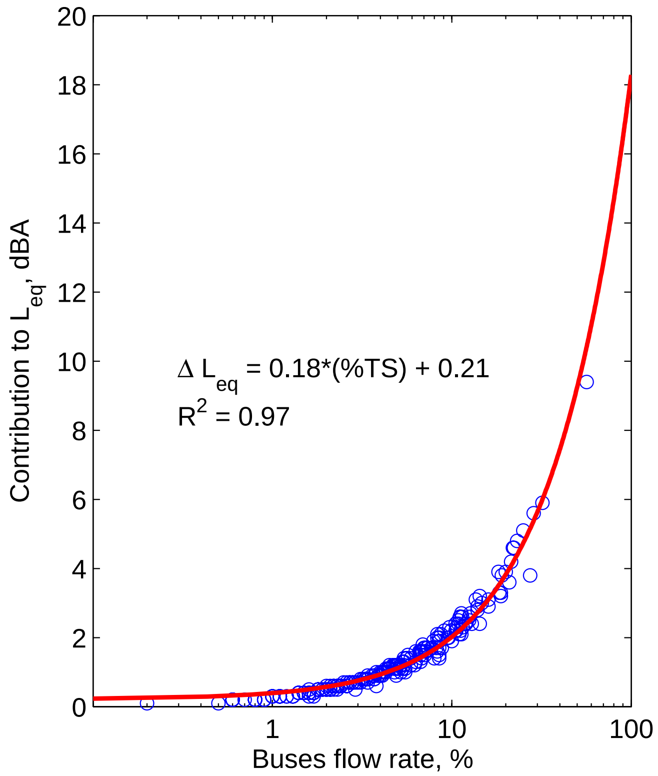

Figure 3: Contribution to the total A-weighted equivalent sound level as a function of the percentage of the TS buses flow in relation to the total flow of vehicles.

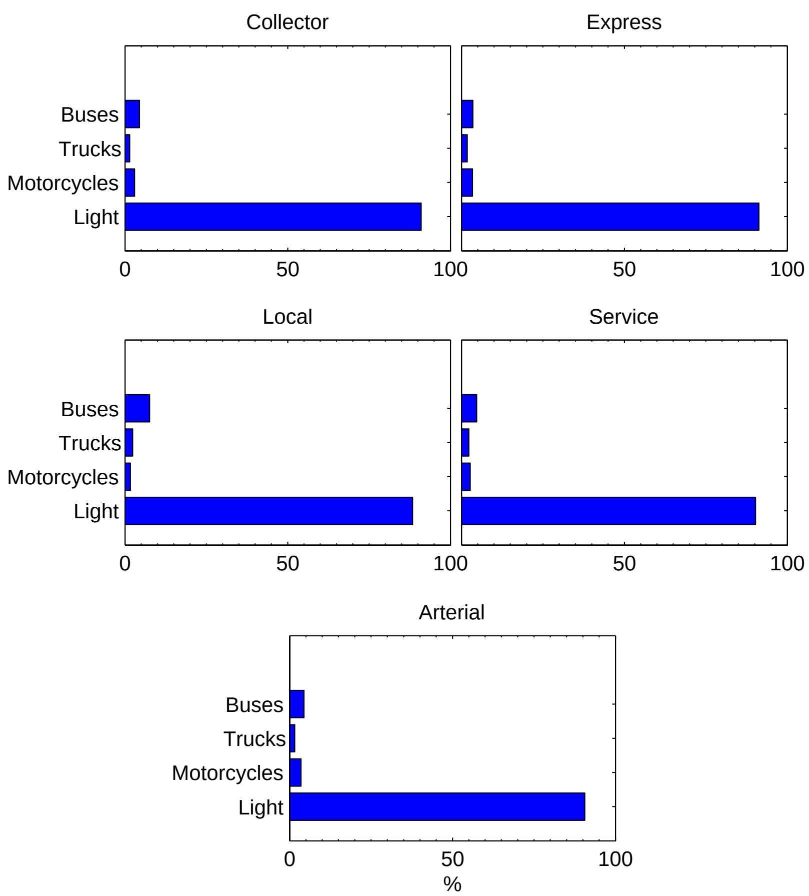

Figure 4: Flow percentages for the different types of vehicles and for the different types of roads.

Table 2: Average A-weighted equivalent sound pressure level for each type of road.

Type of road	L_{eq}, dBA
Collector	69,3
Express	74,2
Local	65,3
Service	67,5
Arterial	72,3

Table 3: Difference in A-weighted sound pressure levels with and without TS bus flow according to the type of road.

Type of road	Increase in L_{eq}, dBA
Collector	+ 1,1
Express	+ 0,8
Local	+ 2,3
Service	+ 1,3
Arterial	+ 1,0

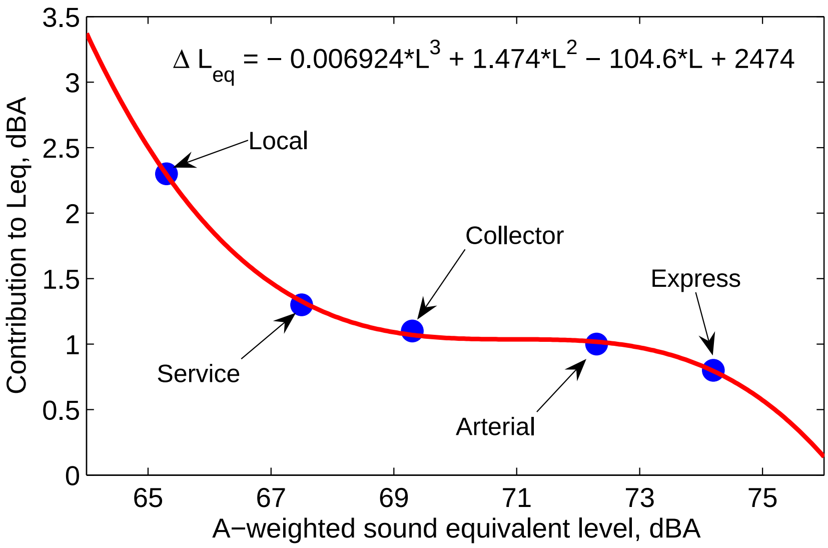

Figure 5: Contribution of the TS buses to the total traffic noise as a function of the A-weighted equivalent sound pressure level in the road.

4. Conclusions

The procedure for determining the SEL for TS buses delivers reasonable information about the behaviour of the TS buses as urban noise sources. It is found that articulated buses travelling at low speeds are those that exhibit the highest noise levels of all types of public transport buses in service in the city, reaching an average SEL of 87.6 dBA. In a fast condition, all bus classes emit similar levels of SEL ranging from 82.4 to 84.6 dBA, the latter being the average SEL of the articulated buses. It is verified that the noise emitted by the heaviest buses (with a length greater than 11 meters), travelling at fast speeds is equivalent to the noise emitted by approximately seven light vehicles in the same speed condition. Given the good normal statistical distribution of the SEL of light vehicles, this value can be used with enough confidence and precision to disaggregate the contribution of this type of vehicles to the total noise of urban traffic.

There is a linear relationship between the logarithm of the percentage of flow of the TS buses, in relation to the total vehicular flow, and the total noise levels in a road. The average contribution of TS buses to the global noise level is 1.3 dBA. Although this contribution may seem not statistically significant, it corresponds to a contribution of 25% of the total sound energy.

It was observed that the percentage of TS buses in total vehicular traffic explains 97% of the variation of the difference of noise levels with and without TS buses. Thus, it was also observed that the greatest contribution of TS to the total traffic noise level occurs in the local type of road, with a contribution of 2.3 dBA to the overall noise level (40% of the total sound energy). In this type of road, the percentage presence of TS is 7.6%, a percentage that is greater than all other types of roads. The lowest contributions of TS to traffic noise are in the express and arterial roads, where the overall noise levels are higher. Thus, it is concluded that TS buses have a significant effect on quiet roads whereas the effect is less important on noisy roads.

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