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Cyclists' noise exposure in a Brazilian medium-sized city

Thiago da Cunha Ramos (https://orcid.org/0000-0002-0413-1724) [1]
Antônio Nélson Rodrigues da Silva (https://orcid.org/0000-0003-0996-8600) [1]
Léa Cristina Lucas de Souza (https://orcid.org/0000-0002-5770-4370) [2]
Luc Dekoninck (https://orcid.org/0000-0001-6910-4316) [3]
Dick Botteldooren (https://orcid.org/0000-0002-7756-7238) [3]
Inaian Pignatti Teixeira (https://orcid.org/0000-0002-9723-4297) [1]

Abstract *This study aimed to assess cyclists' exposure to noise in a medium-sized Brazilian city. Mobile sensors were used to conduct noise measurements in streets with and without dedicated cycling infrastructures. The method can be summarized in the following procedures: i) characterization of the study area; ii) data collection and validation; iii) calculation of exposure indicators; and iv) comparison and representation of the results on maps. Two strategies were adopted for the analysis, namely, spatial data aggregation and temporal data aggregation. Thus, measurements were initially organized in 1,200 nodes distributed along the paths. The results indicate that bicycle riders in São Carlos may be exposed, in some routes, to a high proportion of high noise-level segments. In the two routes selected for this study, the cyclist was exposed to noise levels above the adopted threshold (> 75dBA) in 33.2% and 18.9% of the nodes. Also, the possibility of simultaneously working with two related indicators has broadened the classification criteria of the route segments regarding noise exposure.*

Key words *Noise, Noise transportation, Noise measurement*

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[1] Departamento de Engenharia de Transportes, Universidade de São Paulo. Av. Trabalhador Sãocarlense 400, Parque Arnold Schimidt. 13566-590 São Carlos SP Brasil. thiagramos88@gmail.com
[2] Centro de Ciências Exatas e de Tecnologia, Departamento de Engenharia Civil, Universidade Federal de São Carlos. São Carlos SP Brasil.
[3] Grupo de Pesquisa Waves, Departamento de Tecnologia da Informação, Universidade de Gante. Gante Bélgica.

Introduction

The city growth process is usually associated with increasing noise levels. Higher population densities and urban sprawl are among the common changes observed in growing urbanized areas in the last decades[1-3]. Therefore, additional trips were required and the demand for fast and efficient trips increased[3]. Motorized vehicles massively occupied the cities[4-8] with the popularization of transport technologies. Gradually, the movements of people and goods became noisy and harmful[9], and noise levels above a healthy threshold for human beings became usual[10].

An alternative to the high volumes of motorized vehicles and a tool for the improvement of well-being and health[11-13], cycling is currently promoted in various cities. However, the initiative seems to ignore that cyclists and pedestrians are increasingly exposed to air pollution and noise generated by vehicles operating with internal combustion engines[14-16] in the same street network.

Nevertheless, noise exposure-related problems are gaining importance in health studies. Associations with other health effects, mainly those derived from long-term exposure to traffic noise, replaced the isolated perspective of hearing loss. Noise produces stress[17], which is likely to interfere with sleep[18,19] and affects the neuroendocrinological systems[20]. This may result in various problems, such as difficulty in reproduction[21], cognition[22], blood pressure issues[23,24], myocardial infarction[25,26], and even type 2 diabetes[27] and premature mortality[28].

The effects of noise pollution have been compared to the effects of air pollution[29,30]. Various studies have analyzed noise alone or in combination with air pollution, such as those conducted in eleven Dutch cities[31], in Gent, Belgium[32], Bangalore, India[33] or in Montreal, Canada[34]. New noise measurement strategies were applied in some of these studies, such as the devices for mobile data collection campaigns conducted in Gent[35], and communication tools, such as mobile phones used in Cambridge, UK[36].

In Brazil, noise studies are usually conducted in large and medium-sized cities, based on noise maps of residential neighborhoods, city centers and commercial areas[2,37-40]. Other studies compared the efficiency of different measurement times in fixed points[41], focused on the noise resulting from the interaction between tires and pavement[42], or analyzed, in nearby neighborhoods, the impact of noise produced at airports and lumber facilities, and by road traffic[43-48]. On the other hand, studies focusing on the sound landscape, which can be understood as the acoustic environment perceived and experienced by an individual in a particular context[49], indicate that an intense noise level is not always a disturbance to the receptor. It depends on the relationship between the individual, the activity and the place, space and time.

In that context, this study aimed to assess cyclists' exposure to noise in a medium-sized Brazilian city. Mobile sensors were employed to conduct noise measurements in streets with and without dedicated cycling infrastructures. As the routes analyzed can be used by cyclists for commuting trips, the analysis considered the trip as part of the daily working journey.

Method

The method used to assess cyclists' exposure to noise can be summarized as follows: i) characterization of the study area; ii) data collection and validation; iii) calculation of exposure indicators; and iv) comparison of indicators' values and representation of the results on maps.

Characterization of the Study Area

São Carlos has an estimated population of 244,000 inhabitants[50] and is a medium-sized city (according to Brazilian standards) located in the state of São Paulo. The implementation of cycleways and cycle paths in the city started in 2012, but the proposed cycle network is still incomplete. Therefore, this study has considered two routes (hereafter referred as *Route 1* and *Route 2*) that contain parts of the existing cycling paths and parts of the road network that are regularly used by cyclists (Figure 1).

Route 1 includes four separated cycling infrastructures, all located in areas of environmental interest due to the presence of water bodies. This route also contains links of the street network that are potentially attractive for regular bicycle trips. These are mainly located in the central part of the city, which is an area with historical interest. The route contains 12 segments, all named with letters and numbers (from 1A to 12A, in which the numbers indicate sequential positions in the data collection trips and the letters indicate the locations of the segments, as shown in Figure 1).

The definition of *Route 2* was primarily based on the actual demand for cycling trips. It is also located in the central part of the city, but in an area without cycleways or cycle paths. It contains two segments, which were named as A and B, as shown in Figure 1.

In summary, the selected routes are located in a mixed land use zone served with good road infrastructure. They are located in a consolidated part of the city, according to the city master plan[51].

Other relevant information for this study is that more than half of *Route 1* is located in wide streets, close to green areas and rivers. In contrast, *Route 2* follows narrower streets, along which the buildings have relatively high façades.

Data Collection and Validation

The data collection campaigns used a mobile device developed by the *INTEC-Acoustics* research team at Gent University, in Belgium, to record noise data. The device automatically collects noise data at every 1 second, along with the geographic coordinates associated with the noise records obtained during the displacements.

A regular bicycle was adapted to carry the mobile sensor, in such a way that the sensor was positioned in front of the cyclist. With that arrangement, the noise captured by the sensor was essentially the surrounding traffic noise and not the noise generated by the bicycle itself. That was also the reason why the basket containing the sensor was internally protected with layers of soft material to reduce the empty spaces and the impacts of vibration (Figure 2).

A maximum speed of 18km/h was also observed during the campaigns in order to reduce the aerodynamic noise.

Campaigns were conducted in morning and evening traffic peak hours (between 7h30 and 8h30 and between 17h30 and 18h30, respectively) in typical weekdays (Tuesdays, Wednesdays, and Thursdays). After the trips, the dataset was carefully examined to confirm whether the geographic coordinates, the time stamps and the noise levels recorded were all within reasonable ranges. This validation process was performed to verify whether the calibration of the sensor was not strongly affected by the natural movement and vibration that occurred during the data collection trips. Another essential aspect observed was the evidence of problems in the GPS data, which could eventually misplace the actual geographic coordinates.

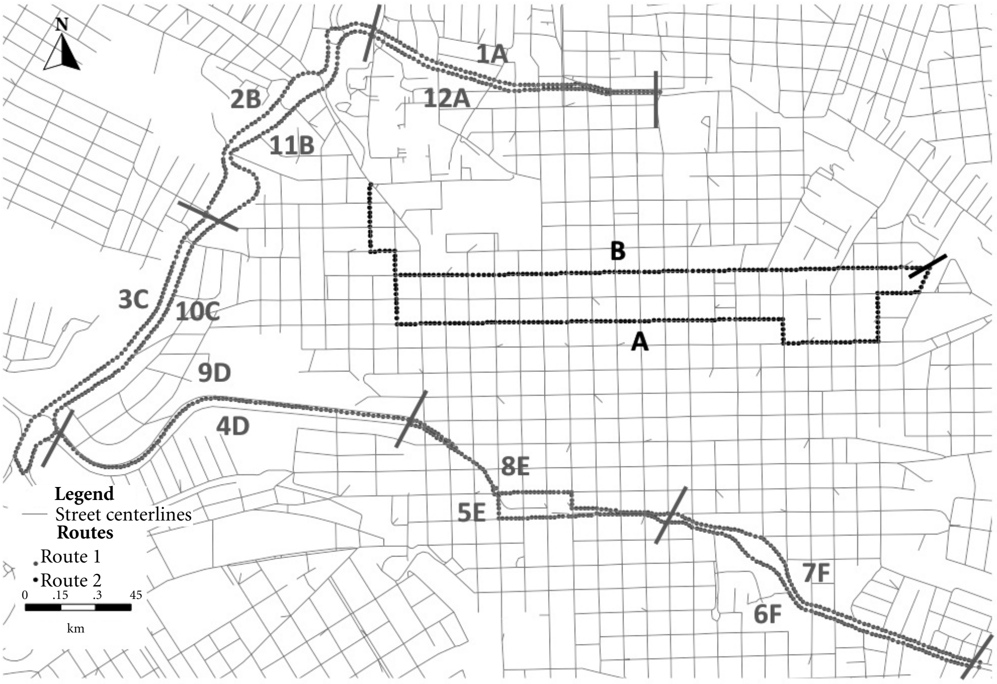

Figure 1. Cycling routes (with the identification of routes and segments) used for noise data collection campaigns in the city of São Carlos-SP.

Figure 2. Noise sensor (left) and its position in the bicycle (right) used for data collection campaigns in the city of São Carlos-SP.

We have conducted fifteen data collection campaigns, but only eight of them were considered valid for the study. In total, 26,914 valid registered records were obtained in *Route 1* (22,221 records in five trips) and *Route 2* (4,693 records in three trips). The Ethics Committee approved the research at the School of Arts, Sciences, and Humanities, University of São Paulo.

Calculation of Indicators

Two indicators were selected for data analysis: the Sound Exposure Level (SEL) and the equivalent continuous sound level (L_{Aeq}), which can be described by equations 1 and 2, respectively.

Equation 1:

$$SEL = 10 \log_{10} [10^{(\frac{l_1}{10})} + ... + 10^{(\frac{l_n}{10})}]$$

Where: *SEL* - Sound Exposure Level in dBA; l_1 - the first sound level measurement, in dBA; l_n - the last sound level measurement, in dBA.

Equation 2:

$$L_{Aeq} = SEL - 10 \log_{10} (\frac{T}{T_0})$$

Where: L_{Aeq} - the equivalent continuous sound level, in dBA; *SEL* - Sound Exposure Level in dBA; T - the moment when the exposure ends; T_0 - the moment when the exposure begins.

In the first part of the analysis, the calculation of the indicator L_{Aeq} was simply a spatial combination of reference points that worked as aggregation nodes. The aggregation process was based on the logarithmic mean of the L_{Aeq} values registered within a 20 meters' radius of each node. The process resulted in 1,200 nodes, 926 of which were along the 12 segments of *Route 1* and 274 along the two segments of *Route 2*. These aggregation nodes were sequentially numbered from 1 to 1,200.

In the second part of the analysis, the values of the indicators were calculated by the temporal aggregation of data continuously collected in three distinct time intervals: 5 seconds (SEL_{5s} and $L_{Aeq,5s}$), 3 seconds (SEL_{3s} and $L_{Aeq,3s}$) and 2 seconds (SEL_{2s} and $L_{Aeq,2s}$).

Comparison and Representation of Results on Maps

The analysis of spatially aggregated data made possible to identify the number of aggregation nodes with values above 75 and 85 dBA, which are thresholds of moderate and harmful noise levels, respectively, as suggested by the literature[52]. This can be performed individually for each trip and the results of all trips of each route combined to find the proportions of moderate and harmful noise per route segment.

In the analysis of temporally aggregated data, we verified the number of times the indicators were above the threshold of harmful noise (i.e., 85 dBA) in each segment. The results of both comparisons were subsequently plotted on a map with the mean percentages of the indicators values on both routes.

Results

The presentation of the results was organized according to the aggregation strategies adopted for analysis, namely, spatial and temporal aggregation.

Analysis of Spatially Aggregated Data

The results obtained with spatial aggregation of data (Table 1) show that the cyclist was exposed to moderate noise levels (> 75 dBA) in 33.2% of the nodes laid out along Route 1, whereas the same condition was observed in only 18.9% of Route 2 nodes. The exposure to harmful noise levels (85 dBA) occurred in 1.0 and 1.7% of the nodes of Route 1 and 2, respectively. In other words, the cyclist was exposed to acceptable noise levels (L_{Aeq} < 75 dBA) in 66.8% and 81.1% of the nodes of Route 1 and 2, respectively.

It is not difficult to find in Table 1 a repetition of nodes with moderate and harmful noise levels in different days. This suggests the existence of spots with specific and recurrent problems. In one of the crossings of Segment 1A, for example, relatively high speeds were observed in the ascending direction of the street. This often resulted in sudden braking and acceleration maneuvers of motorized vehicles, which increased the traffic noise levels to which cyclists were exposed. The first two nodes with issues in segment 3C were close to a crossing with traffic lights located right at the beginning of a long street with a speed limit of 60 km/h. In that case, the green light of the traffic signal also resulted in sudden and noisy acceleration maneuvers of motorized vehicles. The other two nodes of segment 3C were close to a roundabout with multiple entry points, which required frequent braking and acceleration maneuvers of the approaching motorized vehicles. The noise problems found in segment 8E were related to the street ascending gradient of approximately 12%, the proximity of a bus stop and a high concentration of motorized vehicles.

Table 1. List of nodes with noise levels above the moderate (75 dBA) and harmful (85 dBA, in bold) thresholds, by segment.

LAeq - equivalent continuous sound level

Route 1

Segment	Node number	Day 1 Evening	Day 2 Evening	Day 3 Morning	Dia 4 Evening	Dia 5 Morning	Events	
							> 75dBA	> 85dBA
1A	52	79.96	85.16	85.04	87.15	92.33	5	4
3C	2	88.95	82.93	86.66	87.97	85.30	5	4
	3	90.62	84.44	86.93	88.87	87.97	5	4
	78	85.26	85.63	83.13	87.99	85.71	5	4
	79	86.49	85.23	82.52	88.19	85.13	5	4
8E	30	87.17	87.17	88.75	80.85	86.46	5	4
	31	87.94	87.94	87.92	79.29	86.27	5	4
	32	86.38	86.38	88.55	77.00	86.37	5	4
10C	3	79.60	88.44	86.51	86.92	85.86	5	4
	36	87.43	83.11	85.15	95.31	87.33	5	4
	58	81.03	92.23	85.01	85.44	87.12	5	4

Route 2

Segment	Node number	Day 6 Evening	Day 7 Evening	Day 8 Evening	Events	
					> 75dBA	> 85dBA
A	102	86.88	81.10	88.14	3	2
	143	90.68	77.00	91.05	3	2
B	27	87.37	84.88	85.87	3	2
	28	86.50	85.66	83.91	3	2
	40	90.79	85.67	85.64	3	3
	41	88.56	85.49	85.41	3	3

In the case of segment 10C, the noise was mainly produced by motorized vehicles that sped up due to the considerable distance between the two successive crossings.

In Route 2, six nodes had a large number of records with moderate or harmful noise levels. Only two nodes of Segment B, which is an essential street for motorized traffic in the city of São Carlos, had three records with harmful noise levels. These two nodes with three records and two other with two records were all located in a block where the street is relatively narrow and bounded by a high factory wall. They were also close to a bus stop. The harmful noise levels observed in the two nodes of segment A were mostly caused by braking and acceleration maneuvers of motorized vehicles close to street crossings. Lastly, it is important to mention that the mean percentages of L_{Aeq} for the three time intervals considered remained practically stable in both segments of this route.

Analysis of Temporally Aggregated Data

Besides the spatial distribution of noise, we also attempted to analyze how long the cyclist was exposed to inadequate noise levels. The relationship between temporal indicators (SEL_{5s}, SEL_{3s}, SEL_{2s} - light grey lines) and spatial indicators ($L_{Aeq,5s}$, $L_{Aeq,3s}$, $L_{Aeq,2s}$ - dark grey lines) can be seen in the data displayed in Figure 3. The example shown in Figure 3 makes clear that the larger the time interval (in that case, 5 seconds), the higher the SEL values. All accumulated exposure levels ($SEL_{seconds}$) show, regardless of the time interval considered, that long time exposures were determinant in the identification of route segments with harmful noise levels. This is not so evident if the analysis is performed only with $L_{Aeq\ seconds}$.

For a better visualization of the results and comparison of the segments, Figure 4 contains a map in which the mean values of the indicators (μ%) are shown. Among the $SEL_{seconds}$ values, only those of SEL_{2s} are shown on the map, because these values are sufficient to highlight the segments with high noise exposure levels. However, in the case of $L_{Aeq\ seconds}$, we decided to show the mean percentages for all three time intervals considered.

Regarding Route 1, both indicators (SEL and $L_{Aeq\ seconds}$) highlighted the segments with the highest or lowest noise levels. Segments 4D and 9D were the segments in which the cyclist had the lowest noise exposure, whereas segments 3C and 10C were the segments with the highest noise exposure levels.

Concerning Route 2, the *SEL* indicator was very effective to highlight segment B as the segment in which the cyclist had the highest noise exposure in all time intervals considered. The local conditions, in which the narrow street was combined with a high wall and a nearby bus stop, may explain the duration of the noise and the 10 percentage points difference between the *SEL* values found in segments A and B.

Segment 3C had the largest number of nodes above the harmful noise level threshold, although the mean values of *SEL* and $L_{Aeq\ seconds}$ were lower than those found in segment 10C. The latter is the segment in which the cyclist was exposed to the highest noise exposure levels, with mean percentages of 51% for SEL_{2s} and 29% for $L_{Aeq,seconds}$.

In contrast, Route 1 segments 4D and 9D, which share the same nodes in both directions, were the least hostile segments. Served by a cycleway separated from vehicular traffic and surrounded by greenery and a lovely landscape, those were the segments with the lowest mean $L_{Aeq,seconds}$ and SEL_{2s} values. The slight variation between the values found in those segments can be explained by the different concentrations of motorized traffic during the data collection campaigns.

Discussion

Traffic noise is not only annoying, but it also affects the overall well-being of individuals. The results of this study indicate that cyclists riding a bicycle in some parts of the city of São Carlos may be exposed to high noise levels. We confirmed that the assessment of noise exposure over time is as essential as the instantaneous exposure, which can be characterized by $L_{Aeq,seconds}$, for the classification of noise exposure. The louder and more prolonged the noise, the more harmful it is to humans. It is important to mention that the problems associated with noise exposure transcend hearing problems[53]. Studies suggest an association of noise exposure with hypertension and other cardiovascular diseases[54,55], in addition to mental health issues, such as low concentration capacity, aggressive behavior, and high stress levels[56], among others.

It is important to mention that the adverse effects of noise on health do not occur only after prolonged exposure. Acute effects, such as high systolic and diastolic arterial pressure, heart rate

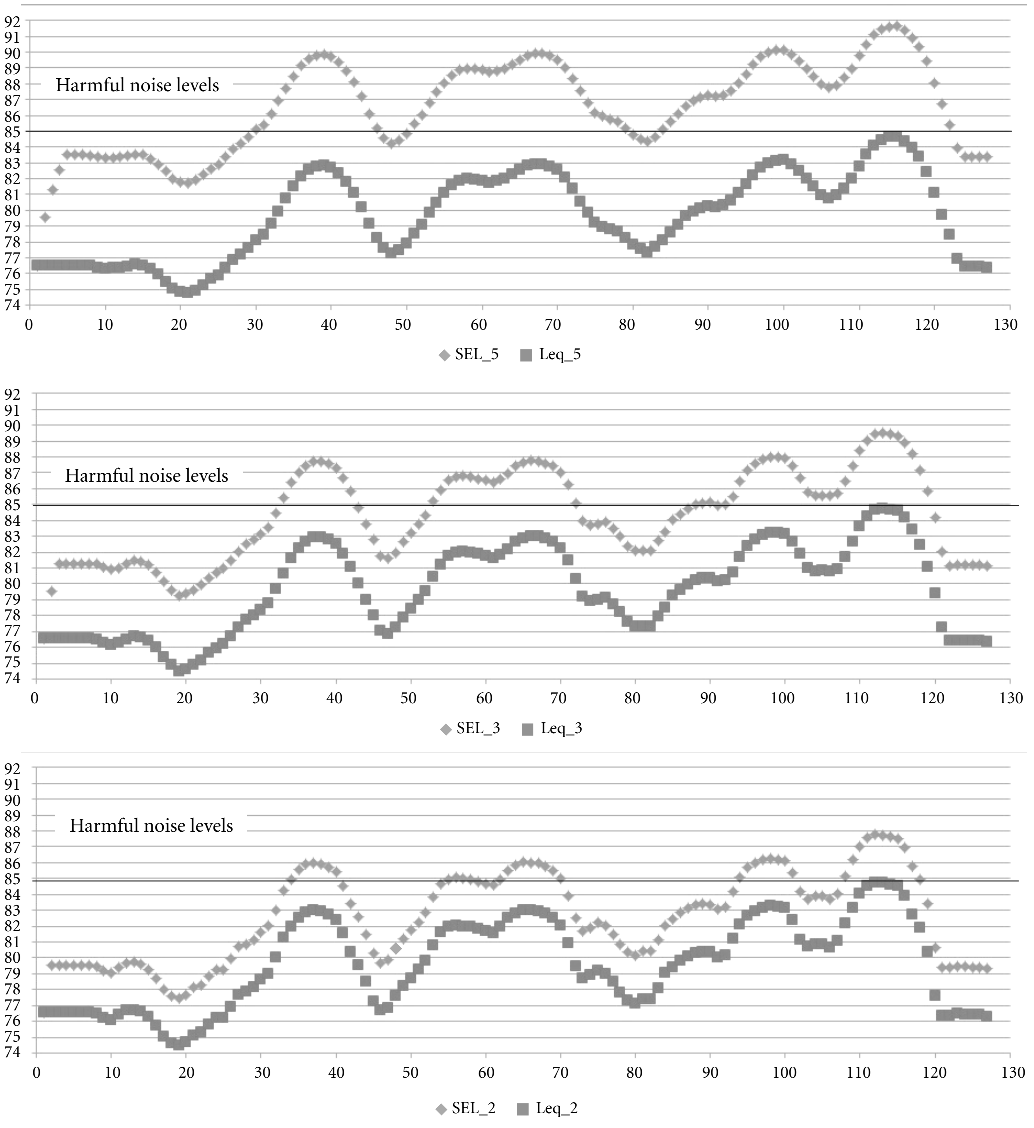

Figure 3. Distribution of SEL and LAeq values for different time intervals.

SEL, LAeq x Time.

changes, and stress hormones release can be observed even after a single event[57]. Nevertheless, chronic harm, such as increased risk factors for arterial hypertension, dyslipidemia, changes in the blood viscosity and glucose level[57,58] tend to be more systemic and complex.

Furthermore, it is worth mentioning that the source of this noise also influences the health outcome since, while prolonged exposure to noise is harmful to health, occupational noise risk estimates tend to be higher than those for urban sound pollution[59].

In large cities, a significant share of noise pollution is related to how people move around the city, such as an undesirable output of motorized vehicles (e.g., horns, braking, and acceleration). Thus, it seems reasonable to assume that the replacement of motorized trips by active modes trips would have a positive effect on noise emissions. However, right now, we observe that users of those modes are still vulnerable to air and noise pollution.

Rabl and De Nazelle[60] have estimated the impact of replacing cars with active transport

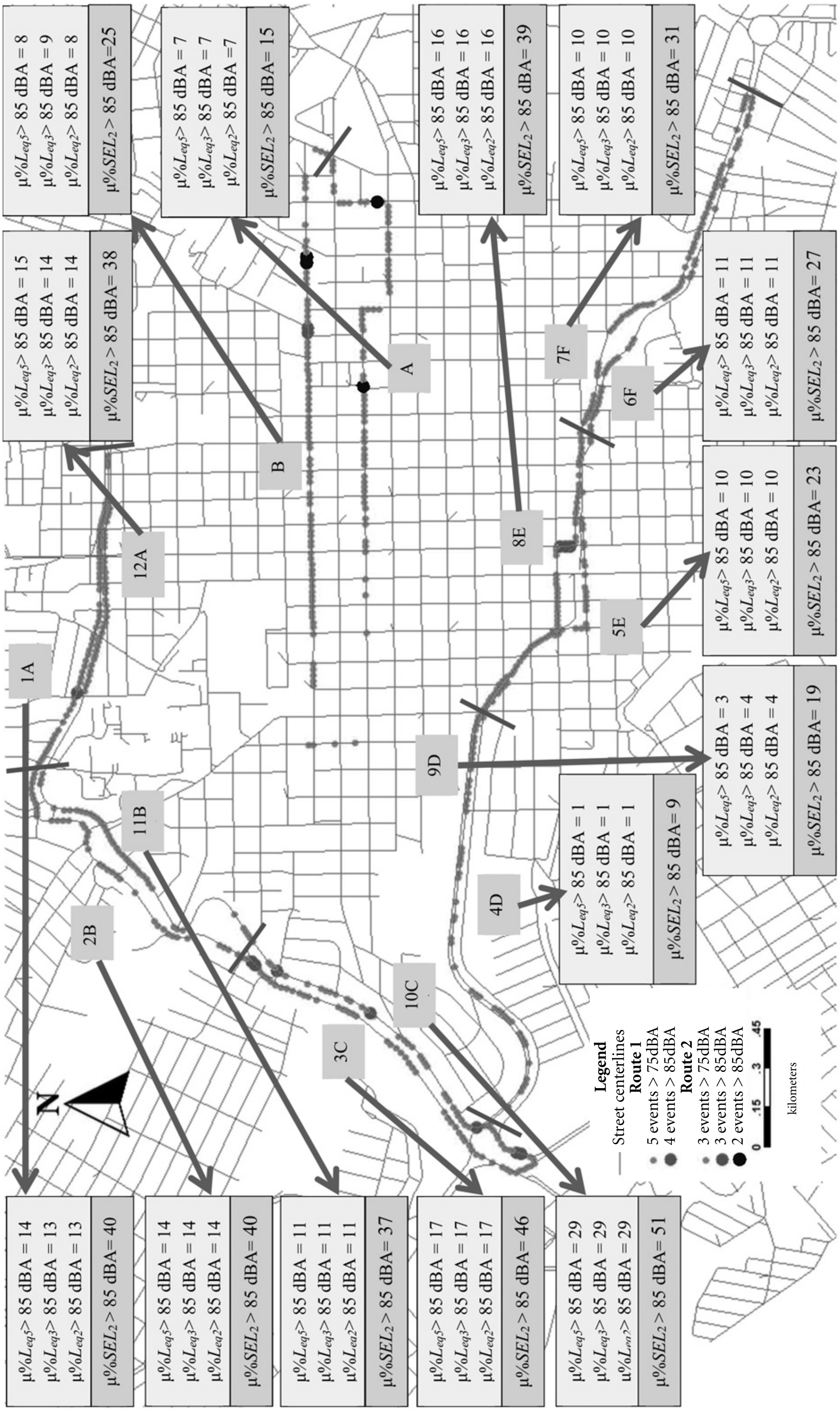

Figure 4. Nodes with harmful or moderate noise levels and mean percentages of the indicators obtained in both routes analyzed in São Carlos, SP, Brazil.

means. Assuming 5 km/day, five days per week and a relative cost to the health of 0.76 Euros per kilometer, the replacement would produce an annual benefit of 1,800 Euros per person as a consequence of lower noise pollution.

Strengths and Limitations of the Study

The main advantage of mobile data collection campaigns is their low cost, given that a single person riding a bicycle can instantaneously record sound pressure levels occurring during the trip. In general, as the equipment and the cyclists are exposed nearly to the same conditions along the way, mobile measurements can be an improvement in the assessment of the noise exposure of bicycle users. Also, the use of two related indicators increased the criteria for segments classification regarding noise. The mean percentages of $L_{Aeq,seconds}$ served as a simple and clear classification tool. However, the $SEL_{seconds}$ indicator was helpful to distinguish segments that only apparently had similar situations.

Mobile campaigns for data collection also have a negative aspect. One cannot separate the noise coming from the adjacent vehicular traffic from the noise produced by other sources, such as the aerodynamic noise and other noises produced by the cyclist or the bicycle itself.

Conclusions

The use of mobile sensors for noise measurements has been adequate and compatible with the context of dynamic exposure of cyclists, which vary in time and space. The collection of data at every one second has been a practical and feasible procedure for the following data aggregation in nodes or time intervals and further analysis of accumulated noise exposure levels or equivalent continuous sound levels.

Although we have found high noise levels in all segments, the application of the method in two distinct routes facilitated the identification of cyclist exposure in different parts of the urban street network. We also observed that the implementation of cycling infrastructures in streets with wide open spaces did not result in reduced noise exposure for the cyclist, contrary to what was initially expected. This was the condition of a segment of Route 1, which is located in a large avenue with a segregated cycleway along a river valley. In that case, the high-speed limit of motorized traffic resulted in high noise levels.

Collaborations

For this study, ANR Silva, TC Ramos, LCL Souza and D Botteldooren designed the experiments. TC Ramos collected the data. L Dekoninck and D Botteldooren provided the noise sensor and processed the noise sensor data, as well as the training and support for data collection and interpretation. TC Ramos, ANR Silva, LCL Souza and IP Teixeira analyzed the data, interpreted the results and wrote the paper.

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