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Noise Dosimetries during Active Transport in Montevideo, Uruguay: Evaluation of Potential Influencing Factors from Experimental Data

Alice Elizabeth González [1,*], Mauro D'Angelo [1], Valentina Colistro [2], Ignacio Franchi [1], Ana Clara Vera [3] and Alicia Alemán [4]

1 Instituto de Mecánica de los Fluidos e Ingeniería Ambiental, Facultad de Ingeniería, Universidad de la República, Montevideo 11300, Uruguay
2 Departamento de Métodos Cuantitativos, Facultad de Medicina, Universidad de la República, Montevideo 11800, Uruguay
3 Programa Unibici, Universidad de la República, Montevideo 11200, Uruguay
4 Departamento de Medicina Preventiva y Social, Facultad de Medicina, Universidad de la República, Montevideo 11800, Uruguay
* Correspondence: elizabet@fing.edu.uy

Abstract: This article presents a case study related to environmental noise exposure of cyclists in Montevideo (Uruguay), as a part of a wider interdisciplinary research project. The main objective of this study was to find the most important parameters related to cyclists' noise exposure in the city. Two monitoring routes were defined, and their traffic flows were characterized. After that, noise dosimetries were carried out along the monitoring routes, determining a set of relevant parameters for each measurement: L_{Aeq}, $L_{AF,10}$, $L_{AF,90}$, noise climate ($L_{AF,10}$–$L_{AF,90}$), kurtosis, occupational and environmental noise doses, exceedance time for each dose, and traffic flow by categories met during cycling. A total of 66 noise dosimetries were carried out: 34 on Route N°1 and 32 on Route N°2. L_{Aeq} was lower in Route N°1. With a basis in multivariate tests, the main variables related to noise exposure of cyclists were found to be the following: kurtosis; noise climate; total traffic; and number of trucks met during the trip. Noise doses were lower on Route N°1, as well as exceedance times, presenting this route with lower traffic flow and fewer trucks but narrower streets and higher street aspect ratio values. Better knowledge in terms of selecting healthier places for cycling routes was obtained: traffic flow—and not urban geometric characteristics—was found to be the main urban determinant of high noise doses.

Keywords: environmental noise exposure; noise dosimetries; active travel; public health; cycling routes

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1. Introduction

Dose is the main concept in determining the potential of an agent to cause adverse effects on the receiver. A dose is a quantity of "something" (e.g., a substance, a medicine, radiation, energy) that reaches a receiver during a specific time. From the environmental exposure point of view, the exposure dose is the amount of pollutant in the immediate vicinity of the receiver [1]. When speaking of noise, the exposure dose would refer to the sound pressure levels (SPLs) where the receiver is located, taking into account time exposure. The sound pressure levels measured at the location and the exposure time of the receiver are intended to be representative of the actual dose. However, the variability in sound pressure levels makes it not always easy to acquire a good approximation of the sound pressure levels to which a receiver is exposed by measuring environmental levels. In such cases, noise dosimetry should be carried out. In Malaysia, ambient sound pressure levels and personal dosimetry at 13 workstations were measured in two palm oil mills; in 3 cases, the environmental levels were lower than the dosimeter exposure levels by 1 dB, 5 dB and 9 dB; in 1 workplace, they were the same; and in the remaining 9 workplaces, the differences were between 1 dB and 33 dB higher in the dosimetry than in the environmental measurement [2].

In terms of occupational exposure, the noise dose is considered to be 100% when the receiver is exposed during the whole working day (usually 8 h a day, as stated in ILO Convention C0001 [3]) to the SPL allowed by the regulations (in Uruguay, Decree 143/012 [4] states that it is 80 dB, but it does not say which is the parameter to consider; actually, $L_{Aeq,8h}$ = 80 dB is used even though the decree does not establish it). For doses to be calculated for other SPLs and other exposure times, it is necessary to define the Exchange Rate (*ER*). The Uruguayan regulation does not define its value, but a value of *ER* = 3 dB is currently used; i.e., the 100% dose corresponds to 3 dB increments each time the exposure time is halved [5].

The adverse consequences of exposure to traffic noise are well described, and there is strong scientific evidence for adverse effects such as ischemic or cardiovascular disease, annoyance and sleep disturbance [6]. Brink et al. [7] stated that annoyance can be considered an early indicator of potentially more critical adverse health effects that could occur after longer exposure to high sound pressure levels. In other cases, the evidence is less compelling, such as for cognitive impairment, hearing impairment, well-being and mental health, among others [6]. For the Australian Government Department of Health [8], adverse health consequences may occur at sound pressure levels of $L_{Aeq,day}$ of 60 dB or $L_{Aeq,night}$ of 55 dB; for [6], the lower-risk figures for outdoor SPLs related to traffic noise are L_{den} of 53 dB and $L_{Aeq,night}$ of 45 dB.

Persson Waye and van Kempen [9], in their update on the extra-auditory effects of noise exposure, suggested that the link between noise exposure and mental health would start to increase at an L_{den} level of 55 dB. They proposed that annoyance would be more connected to mental health, while sleep disturbances would be more related to cardiovascular diseases.

Heinonen-Guzejev et al. [10] showed that noise sensitivity is genetically conditioned, indicating its physiological or organic root. When matching noise sensitivity with the chemical sensitivity factor, it was observed that they were not correlated; moreover, they were associated with different variables. Noise sensitivity was significantly correlated with hostility, self-control, neurosis, analgesic consumption, anger, depression and stress. The chemical sensitivity factor was significantly correlated with allergies and analgesic use. Differences were also found between men and women [11].

For Stansfeld and Clark [12], the relationship between mental health, annoyance and noise exposure is “active”: the receiver adopts attitudes depending on the noise exposure he or she suffers. Although there are not many conclusive studies yet, the relationships between mental health, neurotic predisposition and noise sensitivity, which were earlier anticipated by Stansfeld et al., 1992 (cited by [12]), are closer to being understood: an association between high noise sensitivity, phobic disorders and neurotic depression has been found. It would not be noise that causes a predisposition to psychiatric illness; just the opposite, those who are more predisposed to psychiatric illness are also more sensitive to noise.

Annoyance can generate stress responses in some people and could lead to the occurrence of disease. Noise annoyance activates stress responses in the hypothalamic–pituitary–adrenal (HPA) axis, which is involved in the pathophysiology of depression; hence, noise sensitivity can be considered a proxy indicator of anxiety. According to the most generally accepted conception, as described in [13], in order to counteract the stressful situation generated by high sound pressure levels, the body activates the secretion of adrenocorticotropic hormone (ACTH). Arriving in the adrenal glands via the bloodstream, ACTH promotes the release of stress hormones such as cortisol, adrenaline and noradrenaline from the adrenal glands. When exposure to high sound levels is rather acute (a very intense noise but of short duration), the release of cortisol is promoted; when it is not so high but more prolonged in time, the major release is of adrenaline and noradrenaline.

When noise disrupts active processes such as conversation or concentration, even if its L_{Aeq} level is below 60 dB, it can trigger adrenaline and noradrenaline secretion processes. During sleep, cortisol release can occur at traffic noise levels around 30 dB L_{Aeq}. If the augmented levels of these hormones become chronic, they will increase the risk of life-threatening diseases (such as cardiovascular diseases or weakened immune system diseases) [13].

Hahad et al. [14] presented a comprehensive review of noise exposure consequences for the brain. They studied both direct and indirect effects. The emotional and cognitive responses are linked to an activation of the endocrine system that alters the metabolic state; this is a well-known risk factor for cardiovascular and cerebrovascular disease, neurodegenerative disease, changes in glucose metabolism, lipid processing and hemodynamics.

Mental illness, depression and anxiety disorders are also related to noise exposure, as degenerative diseases and dementia are. Maybe one of the most concerning results was reported by Meng et al. [15]: there is enough evidence of a non-linear linkage between chronic noise exposure and dementia. A meta-analysis of published literature was conducted and different types of cognitive diseases were studied. Alzheimer's disease and dementia showed the highest risk increase with the least noise exposure level increase.

Picard et al. [16] highlighted the association between high noise levels in the workplace and the occurrence of occupational accidents. In particular, the hazard increases when daily exposure levels are 89 dBA or higher, even if workers have some (mild) degree of noise-induced hearing loss.

Wang et al. [17] conducted a cross-sectional study of 563 working adults with normal hearing, to whom they administered a set of cognitive tests simultaneously with exposure to different noise levels. Both bottom-up and top-down attention functions were impaired by the presence of noise, even in the absence of auditory threshold changes, as demonstrated by behavioral and brain responses.

Qiu et al. [18] stated that the consequences of exposure to non-Gaussian occupational noise are more severe than when the signal follows a normal distribution. This had already been anticipated by Goley et al. [19], who proposed adding a term related to the kurtosis of the noise sample to penalize the higher risk posed by a non-Gaussian noise sample. It should also be understood as a wake-up call for the present case study, since the statistical distribution of sound pressure levels associated with traffic has long been known, in the words of Don and Rees [20], as "anything but Gaussian".

The simultaneous exposure to traffic noise and nitrogen oxides (NO_x) can increase the risk of the so-called "metabolic syndrome", which includes insulin resistance, visceral obesity, atherogenic dyslipidemia and arterial hypertension [21]. In addition, the combined exposure to traffic noise and traffic-related air pollution could increase by three or four times the risk of preeclampsia [22]. On the other hand, Andersson et al. [23] presented a 5-year longitudinal study in Sweden. They found a significant increase in stroke risk for people exposed to an $L_{Aeq,24h}$ of 60 dB compared to those who were exposed to an $L_{Aeq,24h}$ of 50 dB; but NO_x concentrations only caused minor changes in the results.

Regarding the linkage between urban design and sound environment, sound design issues have been increasing in the literature, first from the perspective of urban sound design [24–27] and then from the restorative soundscape paradigm [28–30]. Jabłońska [24] studied the links between noise pollution and urban parameters in Wroclaw, Poland. She made recommendations for enhancing sound quality in residential zones, including the use of well-designed noise screens, buffer zones close to noise sources, such as recreational areas, avoiding narrow streets with tall buildings—i.e., avoiding high street aspect ratios—and promoting green infrastructure.

The Latin American experience of promoting active transport and city planning with this purpose is heterogeneous. First, handbooks for cyclists aimed to explain to bike riders how to go by bike in a city with plenty of cars [31,32]. There are also some guidelines for designing urban infrastructure for cyclists. This is the case with Mexico City, which aimed for a safer, healthier, more equitable and more profitable city, and with a more fluid circulation [33]. A recent guide was published in 2021 in Uruguay [34]. Barreto Aucapiña and González Reino [35] proposed an optimal design for cycling ways for the city of Cuenca, Ecuador, especially taking into account the economic parameters and mobility patterns of people. Bunn and Zannin [25] analyzed different measures to reduce SPLs related to a highway section in the city of Curitiba, Brazil. They studied four options via modeling with Predictor® software. The only one that allowed for the meeting of a significant SPL reduction (6 dB to 7 dB) was a drastic reduction (20%) in heavy vehicle flow.

Deloitte Insights for 2020 showed that the percentage of bicycle trips in Copenhagen and Amsterdam were greater than 40% and 30%, respectively, while the Latin American cities with the highest use of bicycles were Bogotá and Santiago, with 4% of the trips [36].

After the pandemic related to SARS-CoV-2 and in the current climate and energy crisis, the promotion of active transport is highly valued, as demonstrated by Liu in the case of China [37]; the same tendencies could be verified also in Uruguay, where the current average number of traffic tickets sold in a year is 80% of the pre-pandemic average value [38]. This case study is related to the environmental noise exposure of bicycle riders in the city of Montevideo. Montevideo is the capital city of Uruguay, a small South American country placed between Argentina and Brazil. In 1986, only 1% of the people living in the metropolitan area of Montevideo moved by bike; this figure was duplicated in 1996 and rose to 4% in 2007. The Municipality of Montevideo created in 2007 the Executive Unit for Urban Mobility Planning; it aimed to develop a rational and safe system, to reduce the environmental externalities and to promote transportation and traffic safety. In 2009, there were about 8.4 km of dedicated lanes for bikes in Montevideo (about 0.3% of the total roadway network length). The share of public transportation was one of the highest in Latin America (55%), which was considered a good figure, but new policies to make this figure grow were being studied [39].

The sound pressure levels of the main streets of Montevideo are close to 74–77 dB, expressed as L_{Aeq} during working days [40]. Although it is not a flat city, there are many people who opt for active transport, and not only for health reasons. Since 2008, the Municipality of Montevideo has promoted cycling in the city through different strategies. First, a dedicated cycling lane was demarcated in Ciudad Vieja (the "Old City") and a public bike system began to operate in 2013; then, more bike-only lanes and exclusive cycling infrastructure were built. The most ambitious project was announced in 2017: to convert the main avenue of the city into an avenue for only buses and active transport. Strong opposition from the commerce sector caused the project to abort.

Cycling infrastructure has been growing steadily in the city, but the design and location criteria are not clear. We intend with this study to contribute, with evidence, to the development of urban design in the city of Montevideo that allows for sensory sustainability and the limitation of the noxious impact of noise for active transport users.

This study is part of a wider interdisciplinary research project that has considered environmental exposure to some air pollutants (such as CO, nitrogen dioxide (NO_2) and particulate matter (PM_{10} and $PM_{2.5}$)) during active travel in the city. The research project aims to find statistically significant links between environmental pollutant exposure during active travel commuting and urban environmental parameters. If confirmed, these links will constitute a tool for public space design in Montevideo, aiming at reducing environmental exposure during active travel [41].

2. Methodology

2.1. Research Objectives

The main objective of this research was to find the most important parameters related to cyclists' noise exposure in the city. Another objective was to find a set of parameters that could easily help to anticipate if a high noise dose is to be expected or not, according to their values.

To achieve these objectives, a set of noise dosimetries was registered along two pre-selected routes in Montevideo city, taking into account their urban characteristics, including traffic flow density and composition. We considered not only the SPL results but also the block-by-block urban parameters, such as building height or street width, to investigate the relation between these parameters and cyclists' noise exposure. The experimental design was presented in a previously published paper [42].

2.2. Field Work

The experiment design considered the participation of volunteer cyclists in the measurements. The research team considered that citizen involvement in the study was desirable in order to enhance exchange with urban cyclists and research topic dissemination among the population. At first, a broad call for volunteers was carried out in social networks; more than one hundred responses were received. Based on such a large number of volunteers, it was decided that each cyclist should perform only one cyclist route, to allow for the involvement of more cyclists in the fieldwork. To meet the number of cyclist routes required to obtain representative results, the methodology of Van den Bossche et al. [43] was followed. The parameters for reaching the number of measurements were related to air pollution, since the main purpose of the research was focused on them. Through an iterative procedure, the minimum number of cyclist routes to be performed was found to be 30.

Two monitoring routes were selected for the exposure measurements. They were plotted together with some organized groups of bicycle riders linked to the research. The routes needed to be frequently used by cyclists, with differences in street width, construction density, building height and traffic flow, among other characteristics. Figure 1 shows the selected measurement routes: Route N°1 is a closed circuit 5.9 km in length close to downtown, while Route N°2 is a straight north–south section of a wide boulevard with high traffic flow and is 5.7 km in length. Both the "physiognomy" and "physiology" of the routes can be appreciated in Table 1, as shown by their characteristics. Route N°1 has a higher average building height and street aspect ratio; it is also composed of narrower streets than Route N°2. The average traffic flow met by the cyclists during their trips on Route N°1 is 21.6% of the same value for Route N°2; the maximum total traffic flow met on Route N°1 was 1122 vehicles, 37.8% of the maximum value registered for Route N°2 (2972).

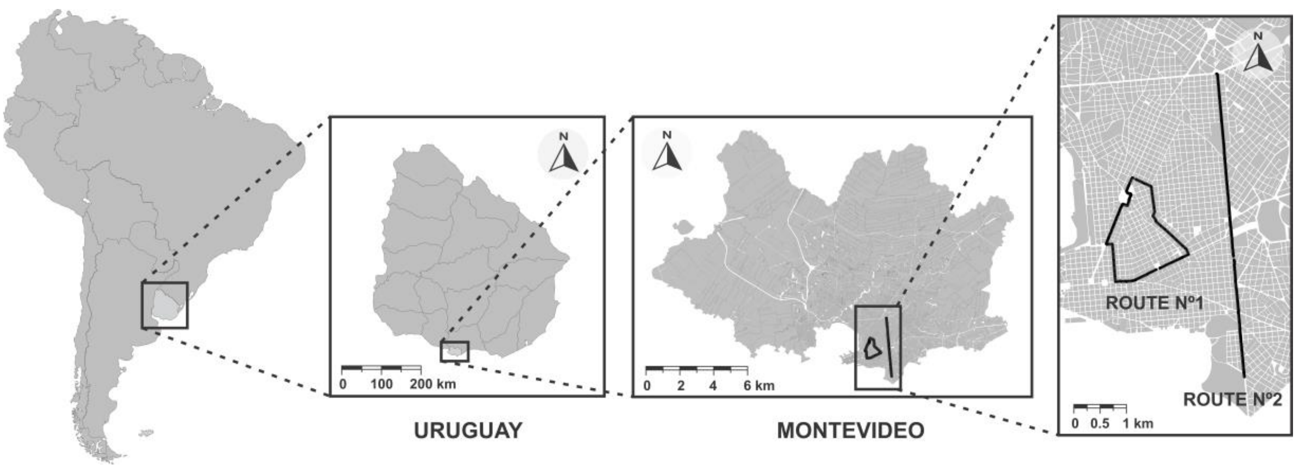


Figure 1. Monitoring routes.

Table 1. Urban environmental parameters of the study area (from [42]).

Parameter	Route N°1 *	Route N°2 *
Street width (m)	31.36 (27.71)	50.21 (20.86)
Building height (m)	12.84 (11.49)	10.38 (9.35)
Street aspect ratio	0.55 (0.33)	0.26 (0.16)
Construction density at the street level (%)	81.13 (21.67)	76.28 (26.45)
Cycling infrastructure at the street level (%)	8.45 (28.01)	16.42 (37.32)
Total vehicles met by trip	582 (133.25)	2700 (235.88)
Cars and vans (%)	73.37 (12.42)	84.21 (2.59)
Trucks (%)	5.03 (2.41)	3.52 (0.59)
Buses (%)	9.37 (11.87)	3.94 (0.87)
Motorcycles (%)	6.04 (2.95)	5.68 (1.33)
Active transportation (%)	6.18 (4.93)	2.64 (0.78)

* Mean (Standard Deviation).

"Cycling infrastructure at the street level" refers to the percentage of each route having this kind of infrastructure, and the standard deviation refers to the values block by block along each of the routes.

Traffic flows were obtained simultaneously with environmental exposure measurements from a set of cameras from the Municipality of Montevideo located in the study area (no cameras were available to install on the cyclists' helmets during riding). In addition, a previous set of manual counts at 15 sites (7 on Route N°1 and 8 on Route N°2) was carried out, counting 1 h $\times$ 3 times in each place. During each count period, 5 min count and rest periods were alternated. Traffic flow was divided into five categories: cars and vans, trucks, buses, motorcycles and active transportation (bicycles and skateboards). The traffic counts were made on working days without rain, during the morning rush hour (7:30 to 9:00 approx.), as most of the measurements on cyclists were carried out. The measurements were carried out from February 2021 to December 2021. The figures in Table 1 are averages of all the traffic flow values obtained for each route.

Since the purpose of the measurements was to determine the cyclists' exposure to some pollutants, they carried some sensors when travelling: GPS (Garmin Edge 1030 Bundle Plus), sensors for PM and NO_2 (Aeroqual Series 500), a heart rate sensor (an accessory of the Garmin Edge 1030 Bundle Plus sensor, placed under the sternum) and a dosimeter sensor (on the shoulder of the bike rider, approximately 10 cm from his/her ear; it recorded the values of L_{Aeq} and L_{Peak} each second). The dosimeter is a Personal Sound Exposure Meter "NoisePen Dosemeter", Class 2, from Pulsar Instruments, UK, that complies with IEC 61252:1993 and ANSI S1.25:1991 standards. The instrument measures A-weighted sound pressure levels between 65 dB and 140 dB. It has its own wind screen to avoid wind effects on the edge of the microphone. It was programmed under Uruguayan regulations. It was still under the manufacturing calibration and was checked before and after the monitoring campaigns.

Examples of the information registered along the trips are shown in Figure 2.

Wind data were measured along the trip with a specific device (Aeroqual AQM10), located on the roof of an educational building, which registered data from PM_{10}, $PM_{2.5}$, NO_2 and O_3 concentrations, wind speed and direction, ambient temperature and relative humidity every two minutes. Considering the series of average wind speeds registered simultaneously with noise exposure measurements for each cyclist route, the median values were 1.5 m/s and 2 m/s for Route N°1 and Route N°2, respectively. We did not process these data since the maximum value for the average wind speed registered during cyclist routes did not exceed the recommended value of 5 m/s. No rainy days were considered apt for measuring.

The two routes had asphalt pavement. The slopes were recorded along the routes; the extreme values were −5% and 5% on both routes. The speed of the vehicles was according to the speed allowed for the selected routes, with a maximum value of 45 km/h (with the exception of the initial section of Route N°2, where the maximum allowed speed was 60 km/h). There was no "green wave" synchronization of traffic lights along the routes.

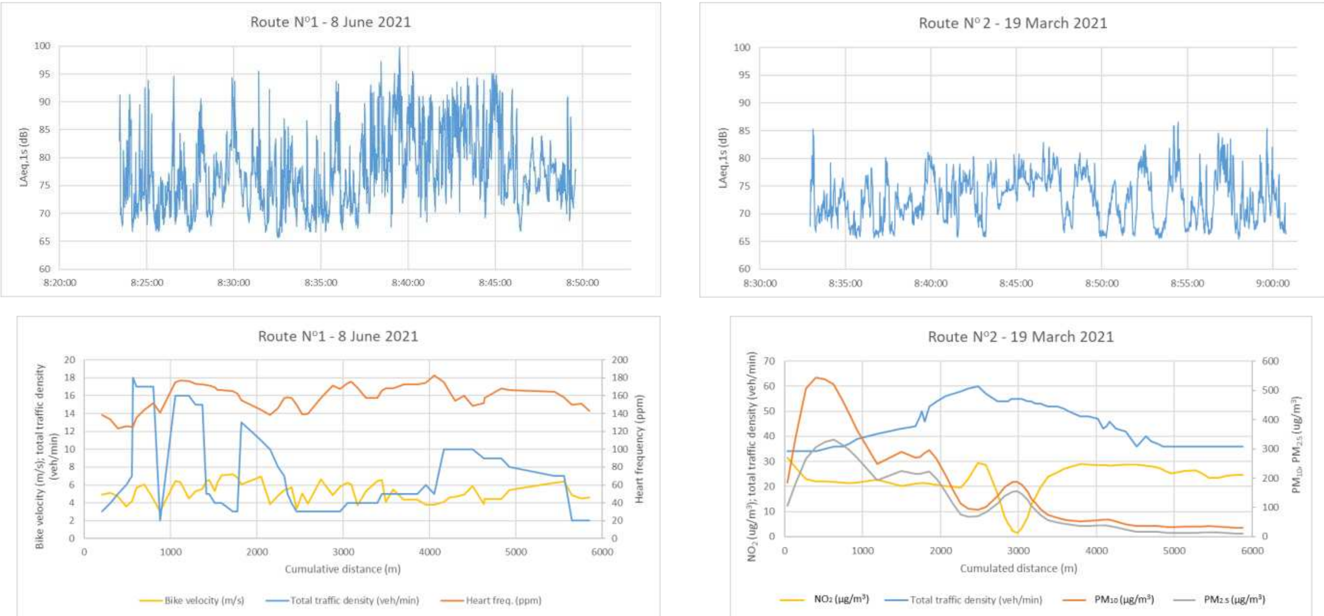


Figure 2. Examples of field information registered along the trips.

Before the beginning of the trip and after preparation of all sensors on the bike, an informed consent form to participate in the research was signed by one researcher and the volunteer cyclist. At the end of the trip, all the cyclists were asked about the occurrence of any special situation. Every trip with no special situations reported was intended to be a valid register and not an outlier; we avoided losing significant information this way. There were no special incidents reported during the measurements. The avoidance of bumping was especially recommended for the cyclists, even though it was not possible to know if rubbing of the cyclist's clothes had ever occurred while riding.

More details on the fieldwork can be found in [42].

2.3. Field Data

A total of 66 noise dosimetries were carried out: 34 on Route N°1 and 32 on Route N°2. On Route N°1, there were 21 male and 13 female bike riders; on Route N°2, there were 19 male and 13 female bike riders. Although the minimum detection limit of the dosimeter was 65 dB, we only found 3 registers where the $L_{A,min}$ was ≤65 dB. In all 3 cases, the values equal to or less than 65 dB were absolute minimum values that lasted only 1 s in each recording. The total recorded time for all cyclist routes performed was 27 h, 19 min and 50 s. Thus, considering all the measuring time, the dosimeter registered values equal to or below its detection limit for only 3 s (0.003% of the total measuring time).

Since the noise dosimeter had to be started before the beginning of the route and it was stopped a few minutes after arrival at the end of the route, the effective time riding the bike had to be identified. The clocks of all the instruments were synchronized at the beginning of the journey and the exact moment of the beginning and end of the trip was registered; thus, it was easy to cut the non-cycling minutes at the beginning and the end from each register. After this first step, the duration of the trips and their main parameters were obtained. Most of them lasted between 16 and 34 min approximately, except for one trip that lasted 59 min. The registered values of L_{Aeq}, $L_{AF,10}$ and $L_{AF,90}$ for each one of the measurements are presented in Tables 2 and 3. The values of noise climate ($L_{AF,10}$–$L_{AF,90}$)—to show variability of SPL—and kurtosis of each series—to show if they are normal or not—are also included in these tables.

Table 2. Sound pressure levels registered in Route N°1: main parameters.

Date	Start Time	Duration	Kurtosis	L_{Aeq} (dB)	$L_{AF,min}$ (dB)	$L_{AF,10}$ (dB)	$L_{AF,90}$ (dB)	$L_{AF,10}$–$L_{AF,90}$ (dB)
20/04/2021	9:10:24	0:24:42	0	78.3	65.7	81.4	68.5	13
21/04/2021	8:27:23	0:23:40	0	76.8	65.7	79.8	67.5	12
23/04/2021	8:22:56	0:22:07	0	74.8	65.6	78.2	67.1	11
27/04/2021	8:31:11	0:22:37	0	76.8	65.9	80.7	67.3	13
28/04/2021	8:19:07	0:21:19	0	75.0	65.4	78.5	66.6	12
30/04/2021	8:28:17	0:25:08	1	77.8	65.4	79.7	67.3	12
04/05/2021	9:10:00	0:24:37	1	74.7	65.3	77.8	66.9	11
05/05/2021	8:35:00	0:31:22	0	74.1	65.3	77.5	66.4	11
11/05/2021	9:05:27	0:29:40	0	74.6	65.2	78.0	66.5	11
14/05/2021	8:07:04	0:22:56	2	73.4	64.9	75.9	66.4	10
19/05/2021	8:34:28	0:21:25	0	77.7	66.2	81.3	69.0	12
21/05/2021	8:25:51	0:24:17	0	76.4	65.5	79.3	66.9	12
01/06/2021	8:16:14	0:33:54	2	78.5	65.7	79.0	67.3	12
02/06/2021	7:36:41	0:19:28	1	73.4	65.4	76.6	66.7	10
08/06/2021	8:23:26	0:26:10	0	84.0	67.4	88.9	69.4	20
27/07/2021	8:33:25	0:19:53	0	75.2	65.7	78.6	67.2	11
28/07/2021	8:30:06	0:23:11	0	75.2	65.3	78.1	67.8	10
03/08/2021	8:49:36	0:16:52	0	76.4	66.4	79.8	69.2	11
04/08/2021	7:57:43	0:26:21	0	78.4	66.0	81.4	68.6	13
12/08/2021	9:06:47	0:18:20	1	75.9	65.3	78.4	67.5	11
13/08/2021	8:51:06	0:29:12	0	74.4	65.1	78.1	66.5	12
20/08/2021	8:36:26	0:22:54	0	75.9	65.3	79.3	67.2	12
26/08/2021	8:43:47	0:28:31	0	74.6	65.2	78.1	66.6	11
27/08/2021	8:19:15	0:31:36	1	75.7	65.3	78.5	66.6	12
10/09/2021	8:29:16	0:24:38	1	75.6	65.3	78.2	67.4	11
16/09/2021	8:58:38	0:20:23	1	78.2	65.8	80.0	67.5	13
17/09/2021	8:53:49	0:27:17	1	75.1	65.1	77.9	66.8	11
30/09/2021	8:34:18	0:29:51	1	77.9	65.7	80.8	67.8	13
01/10/2021	8:27:26	0:24:46	0	75.2	65.6	78.7	67.1	12
07/10/2021	8:36:25	0:29:42	0	76.5	65.3	79.5	67.4	12
12/11/2021	8:58:18	0:32:58	2	77.5	65.8	79.1	66.9	12
19/11/2021	8:27:47	0:20:54	−1	78.8	65.6	82.1	68.2	14
24/11/2021	17:04:38	0:24:24	2	81.4	65.3	82.3	68.2	14
06/12/2021	8:36:59	0:26:28	0	76.7	65.6	79.9	67.6	12

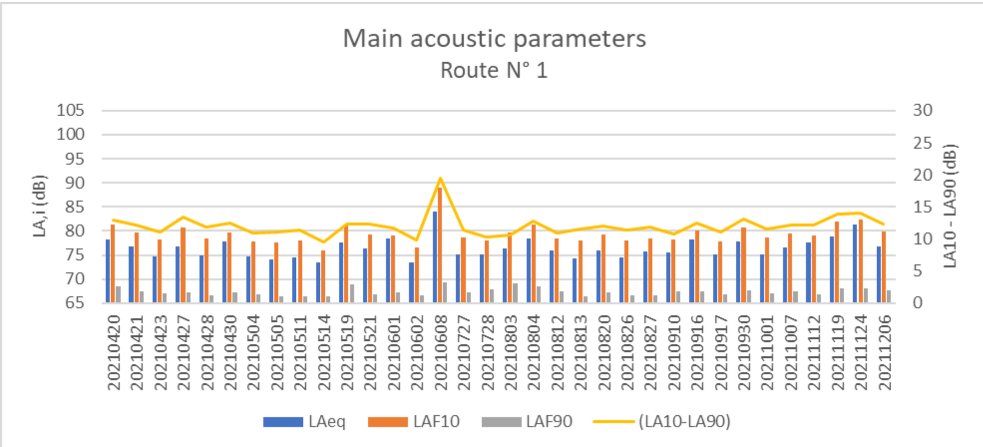
Table 3. Sound pressure levels registered in Route N°2: main parameters.

Date	Start Time	Duration	Kurtosis	L_{Aeq} (dB)	$L_{AF,min}$ (dB)	$L_{AF,10}$ (dB)	$L_{AF,90}$ (dB)	$L_{AF,10}$-$L_{AF,90}$ (dB)
10/02/2021	8:50:00	0:25:00	0	77.2	64.8	79.8	67.3	13
11/02/2021	8:41:03	0:16:09	0	79.6	66.2	82.5	68.7	14
18/02/2021	8:36:18	0:19:00	0	78.6	65.3	81.7	67.2	15
19/02/2021	8:37:50	0:59:04	1	77.4	65.4	79.7	67.0	13
24/02/2021	8:36:16	0:24:00	1	84.4	65.9	84.9	68.6	16
25/02/2021	8:27:36	0:17:06	0	74.1	65.3	77.8	66.4	11
26/02/2021	8:22:10	0:21:45	1	80.2	65.8	81.7	67.5	14
02/03/2021	8:27:17	0:28:08	0	81.8	65.7	84.1	67.9	16
03/03/2021	8:31:02	0:31:30	1	79.0	65.3	80.5	67.4	13
05/03/2021	8:36:27	0:30:46	0	78.0	65.2	80.9	68.1	13
10/03/2021	8:27:14	0:22:49	0	78.3	66.1	81.4	68.7	13
11/03/2021	8:34:51	0:22:00	1	79.2	65.7	81.6	68.9	13
12/03/2021	7:45:00	0:25:10	0	78.3	65.7	80.8	67.4	13
16/03/2021	8:27:16	0:23:58	0	79.2	65.2	83.0	69.0	14
19/03/2021	8:32:57	0:27:50	−1	74.9	65.4	78.5	67.0	12
23/03/2021	8:40:54	0:23:48	0	78.4	65.6	81.1	67.2	14
24/03/2021	7:58:17	0:20:15	1	77.5	65.3	80.1	68.1	12

Table 3. *Cont.*

Date	Start Time	Duration	Kurtosis	L_{Aeq} (dB)	$L_{AF,min}$ (dB)	$L_{AF,10}$ (dB)	$L_{AF,90}$ (dB)	$L_{AF,10}$-$L_{AF,90}$ (dB)
13/04/2021	8:26:51	0:23:43	0	78.9	65.5	81.3	67.4	14
14/04/2021	8:28:43	0:30:35	0	75.9	65.1	79.1	66.9	12
16/04/2021	8:20:00	0:23:53	0	79.5	65.3	84.0	67.3	17
08/10/2021	12:28:09	0:22:28	1	78.5	65.9	80.8	68.4	12
14/10/2021	8:57:11	0:24:08	1	79.8	65.2	81.4	67.0	14
15/10/2021	8:22:17	0:29:10	−1	87.6	67.4	91.9	69.8	22
21/10/2021	9:05:39	0:27:22	0	76.5	65.3	79.7	66.8	13
22/10/2021	8:20:06	0:23:04	0	80.7	65.9	83.0	68.8	14
28/10/2021	9:04:52	0:20:09	3	81.5	65.7	81.6	69.4	12
29/10/2021	8:00:09	0:28:45	−1	88.6	67.8	93.2	71.1	22
04/11/2021	8:47:13	0:26:14	−1	91.5	65.8	96.6	68.5	28
05/11/2021	8:24:32	0:33:24	−1	83.6	66.6	87.8	71.8	16
11/11/2021	8:50:41	0:22:49	0	77.9	65.0	80.6	68.6	12
26/11/2021	17:08:15	0:19:00	0	77.5	66.0	80.6	69.1	11
14/12/2021	8:02:26	0:28:33	0	79.3	65.5	82.1	68.3	14

The main acoustic parameters are shown by route in Figure 3. The values of $L_{AF,90}$ covered a range of 3 dB in Route N°1 and 6 dB in Route N°2. However, the values of $L_{AF,10}$ had great variability: they ranged from 76 dB to 89 dB (a range of 13 dB) in Route N°1 but from 78 dB to 97 dB (a range of 19 dB) in Route N°2. ($L_{AF,10}$–$L_{AF,90}$) varied from 10 to 20 dB in Route N°1 (a range of 10 dB) and from 11 to 28 dB in Route N°2 (a range of 17 dB).



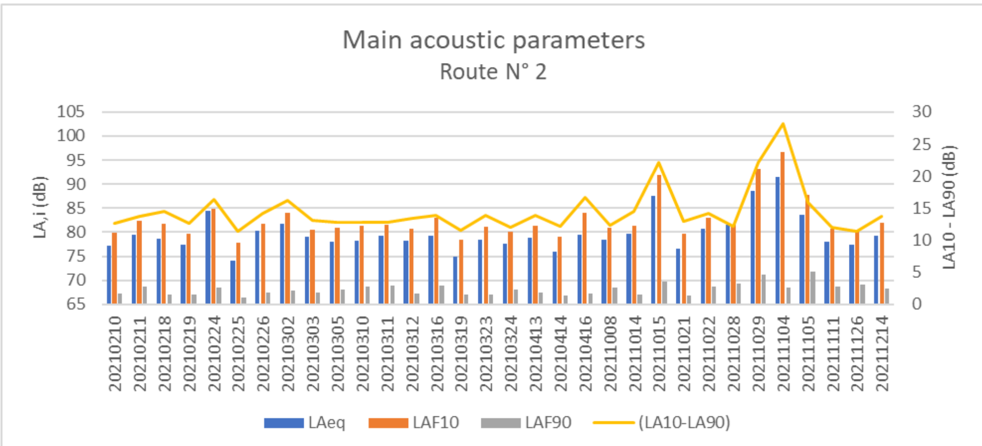


Figure 3. Measured values of L_{Aeq}, $L_{AF,10}$, $L_{AF,90}$ and ($L_{AF,10}$–$L_{AF,90}$): up = Route N°1; down = Route N°2.

Kurtosis was obtained by direct application of its definition [44].

It must be said that there were 5 cases for which the cameras' traffic data were not available; thus, it was not possible to get either the total number of vehicles along the cycling route or the classification by categories. Those days were 4 May 2021 and 5 May 2021 for Route N°1; and 28 October 2021, 29 October 2021 and 26 November 2021 for Route N°2. These days were excluded from the multivariate analysis described in Section 3.2.

2.4. Dose Calculation

Even though a noise dosimeter has been used, the doses had to be obtained manually because of the need to cut some minutes at the beginning and at the end of the register.

Thus, using only the section of the register corresponding to the effective bike trip, the exceedance time was determined; i.e., the number of seconds where the $L_{Aeq,1s}$ was greater than a pre-established threshold level. Once that value (and its time exposure) was selected, the noise dose was obtained by direct application of the definition of dose (see Equation (1)).

$$D = \frac{T_{exp_1}}{T_{adm_1}} + \frac{T_{exp_2}}{T_{adm_2}} + \ldots + \frac{T_{exp_n}}{T_{adm_n}} \quad (1)$$

where D is the noise dose, $T_{exp,i}$ is the total exposure time to sound pressure level *i* and $T_{adm,i}$ is the maximum exposure time to sound pressure level *i* allowed during a working journey. As stated in Section 1, the maximum permissible dose is 100%.

Two doses have been obtained: an occupational noise dose and an environmental noise dose. To obtain the occupational dose, as if the cyclist were working, e.g., on a delivery, an occupational sound pressure level $L_{Aeq,8h}$ of 80 dB was used (see Section 1).

To obtain the environmental dose, the recommended value of $L_{Aeq,24h}$ = 70 dB proposed by the WHO in 1999 [6] was considered; it is the same value proposed in 1982 by the US EPA [45]. It is a recommended threshold level to prevent hearing loss due to indoor and outdoor noise exposure (considering traffic noise, industrial noise, leisure noise, etc.). This value has not changed in the new WHO guidelines [6]. The new recommendations for traffic noise to avoid harm to human health (in general, not only auditory effects as hearing loss) were not considered because it can be easily understood that it is not possible to apply them to Uruguay in 2022. Thus, a value of $L_{Aeq,24h}$ = 70 dB was adopted for the calculation of the noise dose.

In both cases (occupational and environmental doses), the registered sound pressure levels $L_{Aeq,1s}$ were classified according to categories differing in steps of 1 dB (from 70 to 71 dB; from 71 to 72 dB, etc.), until reaching the maximum registered level $L_{AF,Max}$. The number of data for each category $T_{exp,i}$ was found by direct counting, and the maximum exposure time for each category was calculated as seen in Equation (2) (occupational dose) and Equation (3) (environmental dose). Note that the exposure time is 8 h for the occupational dose and 24 h for the environmental dose.

$$D_{occ} = \frac{8}{2^{\frac{L_i - L_{Aeq,8h}}{ER}}} \times 3600 = \frac{8}{2^{\frac{L_i - 80}{3}}} \times 3600 \quad (2)$$

where D_{occ} is the occupational noise dose; L_i is the sound pressure level in category *i*, in dB; $L_{Aeq,8h}$ is the allowed SPL during an 8 h working day, in dB; and *ER* is the exchange rate, in dB.

$$D_{env} = \frac{24}{2^{\frac{L_i - L_{Aeq,24h}}{ER}}} \times 3600 = \frac{24}{2^{\frac{L_i - 70}{3}}} \times 3600 \quad (3)$$

where D_{env} is the environmental noise dose; L_i is the sound pressure level in category *i*, in dB; $L_{Aeq,24h}$ is the recommended SPL for avoiding hearing loss, in dB [6]; and *ER* is the exchange rate, in dB.

The occupational and environmental doses values, and also the values of $L_{Aeq,8h}$ and $L_{Aeq,24h}$, are presented in Tables 4–7 for Routes N°1 (Tables 4 and 5) and N°2 (Tables 6 and 7), respectively.

Table 4. Noise dosimetries of Route N°1: main parameters.

	Environmental Exposure			Occupational Exposure		
Date	**D_{env} (%) (70/24)**	**Exceedance Time (s)**	**Exceedance Time (%)**	**D_{occ} (%) (80/8)**	**Exceedance Time (s)**	**Exceedance Time (%)**
20/04/2021	12	1263	85	2	278	19
21/04/2021	8	1087	77	1	152	11
23/04/2021	4	902	68	0	75	6
27/04/2021	7	881	65	1	186	14
28/04/2021	4	748	58	1	90	7
30/04/2021	10	1125	75	2	159	11
04/05/2021	5	924	63	1	91	6
05/05/2021	5	1005	53	1	86	5
11/05/2021	6	1013	57	1	102	6
14/05/2021	3	637	46	0	40	3
19/05/2021	9	1129	88	2	214	17
21/05/2021	7	1064	73	1	133	9
01/06/2021	8	1191	59	1	170	8
02/06/2021	3	639	55	0	38	3
08/06/2021	47	1405	89	13	530	34
27/07/2021	4	875	73	1	88	7
28/07/2021	5	972	70	1	85	6
03/08/2021	5	889	88	1	105	10
04/08/2021	13	1284	81	3	287	18
12/08/2021	5	810	74	1	79	7
13/08/2021	5	1039	59	1	91	5
20/08/2021	6	1053	77	1	121	9
26/08/2021	5	1008	59	1	95	6
27/08/2021	8	1162	61	1	144	8
10/09/2021	6	1100	74	1	83	6
16/09/2021	9	931	76	2	137	11
17/09/2021	6	1052	64	1	113	7
30/09/2021	6	1052	64	1	113	7
01/10/2021	5	1070	72	1	104	7
07/10/2021	9	1291	72	1	180	10
12/11/2021	13	1347	68	3	167	8
19/11/2021	11	1059	84	2	315	25
24/11/2021	23	1179	80	6	273	19
06/12/2021	8	1202	76	1	183	12

Table 5. Sound pressure levels L_{Aeq} measured and calculated in Route N°1 (different durations).

Date	Start Time	Real Duration	$L_{A,eq}$ (dB)	$L_{Aeq,8h}$ (dB)	$L_{Aeq,24h}$ (dB)
20/04/2021	9:10:24	0:24:42	78.3	65.4	60.6
21/04/2021	8:27:23	0:23:40	76.8	63.7	58.9
23/04/2021	8:22:56	0:22:07	74.8	61.4	56.6
27/04/2021	8:31:11	0:22:37	76.8	63.5	58.7
28/04/2021	8:19:07	0:21:19	75.0	61.5	56.7
30/04/2021	8:28:17	0:25:08	77.8	65.0	60.2
04/05/2021	9:10:00	0:24:37	74.7	61.8	57.0
05/05/2021	8:35:00	0:31:22	74.1	62.2	57.5
11/05/2021	9:05:27	0:29:40	74.6	62.5	57.7
14/05/2021	8:07:04	0:22:56	73.4	60.2	55.5
19/05/2021	8:34:28	0:21:25	77.7	64.2	59.4
21/05/2021	8:25:51	0:24:17	76.4	63.5	58.7
01/06/2021	8:16:14	0:33:54	78.5	67.0	62.2
02/06/2021	7:36:41	0:19:28	73.4	59.5	54.7
08/06/2021	8:23:26	0:26:10	84.0	71.4	66.6

Table 5. *Cont.*

Date	Start Time	Real Duration	$L_{A,eq}$ (dB)	$L_{Aeq,8h}$ (dB)	$L_{Aeq,24h}$ (dB)
27/07/2021	8:33:25	0:19:53	75.2	61.4	56.6
28/07/2021	8:30:06	0:23:11	75.2	62.3	57.6
03/08/2021	8:49:36	0:16:52	76.4	61.8	57.0
04/08/2021	7:57:43	0:26:21	78.4	65.8	61.0
12/08/2021	9:06:47	0:18:20	75.9	61.7	57.0
13/08/2021	8:51:06	0:29:12	74.4	62.2	57.5
20/08/2021	8:36:26	0:22:54	75.9	62.7	57.9
26/08/2021	8:43:47	0:28:31	74.6	62.3	57.5
27/08/2021	8:19:15	0:31:36	75.7	63.9	59.1
10/09/2021	8:29:16	0:24:38	75.6	62.7	57.9
16/09/2021	8:58:38	0:20:23	78.2	64.5	59.7
17/09/2021	8:53:49	0:27:17	75.1	62.7	57.9
30/09/2021	8:34:18	0:29:51	77.9	65.8	61.0
01/10/2021	8:27:26	0:24:46	75.2	62.3	57.5
07/10/2021	8:36:25	0:29:42	76.5	64.4	59.6
12/11/2021	8:58:18	0:32:58	77.5	65.9	61.1
19/11/2021	8:27:47	0:20:54	78.8	65.2	60.4
24/11/2021	17:04:38	0:24:24	81.4	68.4	63.7
06/12/2021	8:36:59	0:26:28	76.7	64.1	59.4

Table 6. Noise dosimetries of Route N°2: main parameters.

	Environmental Noise Exposure			Occupational Noise Exposure		
Date	D_{env} (%) (70/24)	Exceedance Time (s)	Exceedance Time (%)	D_{occ} (%) (80/8)	Exceedance Time (s)	Exceedance Time (%)
10/02/2021	9	1153	78	2	169	11
11/02/2021	10	838	86	2	225	23
18/02/2021	10	946	78	2	232	19
19/02/2021	9	978	70	2	151	11
24/02/2021	51	1351	85	14	425	27
25/02/2021	3	535	52	0	50	5
26/02/2021	16	1041	80	4	252	19
02/03/2021	30	1419	84	8	595	35
03/03/2021	17	1490	79	4	239	13
05/03/2021	14	1492	81	3	280	15
10/03/2021	11	1141	83	2	252	18
11/03/2021	13	1157	88	3	248	19
12/03/2021	11	1071	77	2	226	16
16/03/2021	14	1264	88	3	368	26
19/03/2021	6	1223	73	0	98	6
23/03/2021	11	1122	79	2	233	16
24/03/2021	8	1000	82	1	144	12
13/04/2021	13	1069	75	3	237	17
14/04/2021	8	1281	70	1	153	8
16/04/2021	15	1135	79	4	297	21
08/10/2021	11	1124	83	2	198	15
14/10/2021	16	1114	77	4	267	18
15/10/2021	118	1600	91	34	812	46
21/10/2021	8	1150	70	1	174	11
22/10/2021	19	1188	86	5	324	23
28/10/2021	20	1083	90	5	214	18
29/10/2021	147	1605	93	43	892	52
04/11/2021	264	1353	86	78	681	43
05/11/2021	54	1949	97	15	993	50
11/11/2021	10	1184	86	2	208	15
26/11/2021	7	997	87	1	171	15
14/12/2021	17	1448	84	4	386	23

Table 7. Sound pressure levels L_{Aeq} measured and calculated in Route N°2 (different durations).

Date	Start Time	Duration	$L_{A,eq}$ (dB)	$L_{Aeq,8h}$ (dB)	$L_{Aeq,24h}$ (dB)
10/02/2021	8:50:00	0:25:00	77.2	64.3	59.5
11/02/2021	8:41:03	0:16:09	79.6	64.8	60.1
18/02/2021	8:36:18	0:19:00	78.6	64.8	60.1
19/02/2021	8:37:50	0:59:04	77.4	64.2	59.5
24/02/2021	8:36:16	0:24:00	84.4	71.8	67.0
25/02/2021	8:27:36	0:17:06	74.1	59.6	54.9
26/02/2021	8:22:10	0:21:45	80.2	66.8	62.0
02/03/2021	8:27:17	0:28:08	81.8	69.5	64.8
03/03/2021	8:31:02	0:31:30	79.0	67.2	62.4
05/03/2021	8:36:27	0:30:46	78.0	66.1	61.3
10/03/2021	8:27:14	0:22:49	78.3	65.1	60.3
11/03/2021	8:34:51	0:22:00	79.2	65.8	61.0
12/03/2021	7:45:00	0:25:10	78.3	65.1	60.3
16/03/2021	8:27:16	0:23:58	79.2	66.2	61.4
19/03/2021	8:32:57	0:27:50	74.9	62.6	57.8
23/03/2021	8:40:54	0:23:48	78.4	65.3	60.6
24/03/2021	7:58:17	0:20:15	77.5	63.8	59.0
13/04/2021	8:26:51	0:23:43	78.9	65.8	61.0
14/04/2021	8:28:43	0:30:35	75.9	64.0	59.2
16/04/2021	8:20:00	0:23:53	79.5	66.5	61.7
08/10/2021	12:28:09	0:22:28	78.5	65.2	60.5
14/10/2021	8:57:11	0:24:08	79.8	66.8	62.0
15/10/2021	8:22:17	0:29:10	87.6	75.4	70.6
21/10/2021	9:05:39	0:27:22	76.5	64.1	59.3
22/10/2021	8:20:06	0:23:04	80.7	67.5	62.7
28/10/2021	9:04:52	0:20:09	81.5	67.7	62.9
29/10/2021	8:00:09	0:28:45	88.6	76.4	71.6
04/11/2021	8:47:13	0:26:14	91.5	78.9	74.1
05/11/2021	8:24:32	0:33:24	83.6	72.0	67.2
11/11/2021	8:50:41	0:22:49	77.9	64.7	59.9
26/11/2021	17:08:15	0:19:00	77.5	63.5	58.7
14/12/2021	8:02:26	0:28:33	79.3	67.1	62.3

2.5. Multivariate Statistical Tests

Some multivariate statistical tests were carried out to find the main variables to describe cyclists' noise exposure throughout their trips. If a smaller set of representative variables could be found, the processing of field data would be easier.

The selected tests were principal component analysis (PCA) and clustering. Iterative application of them helped reduce the initial set of variables to a more manageable one.

The use of PCA was selected because it was not predictable that the main variables were traffic ones. Other tests, such as multiple linear regression or simple linear regression, are useful when a well-known relation between variables is expected. Thus, math relations are well known for the link between noise and traffic flow when SPLs are taken from a fixed point but not when SPLs are measured from a mobile device like a dosimeter carried by a cyclist, who moves into traffic flow at a velocity that is different from the main average velocity of the traffic flow. In addition, there are no noise monitoring stations informing about SPLs in real time in Montevideo.

All multivariate statistical tests were performed with the free software Past 4.08 [46].

3. Results

3.1. Field Data Processing

The measured SPL values were higher than most of the recommended values for avoiding harm to human health, according to the references discussed in Section 1 [7–23].

The general results from field data processing are presented in this section. At first, the time-evolving graphs of four registers are presented in Figure 4; they have been selected because they have one of the lowest or highest L_{Aeq} values obtained for each route. All of them last between 20 and 30 min. It may be highlighted that no special situations were reported by the cyclists on any of these days, so the four registers are considered valid.

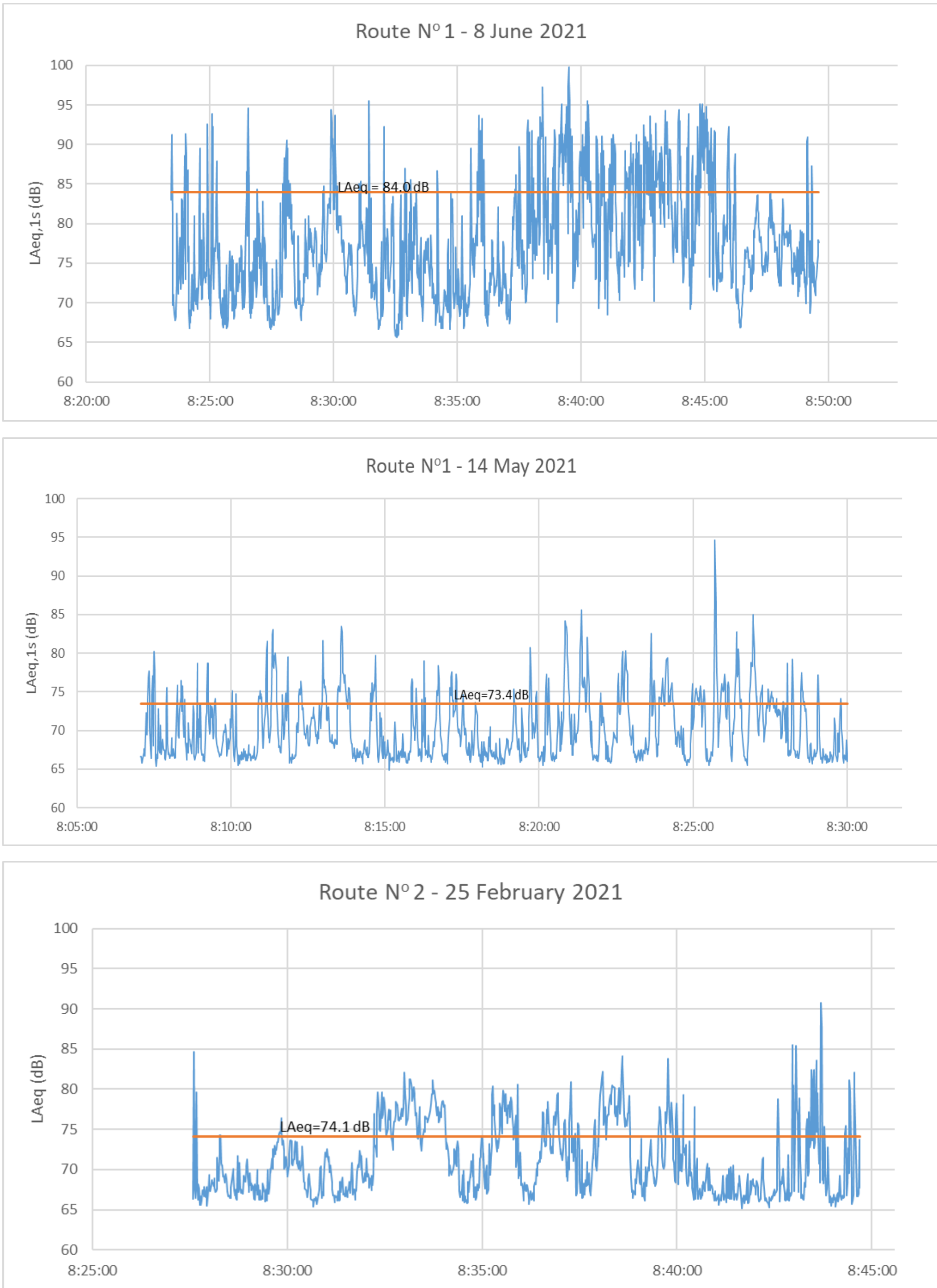


Figure 4. *Cont.*

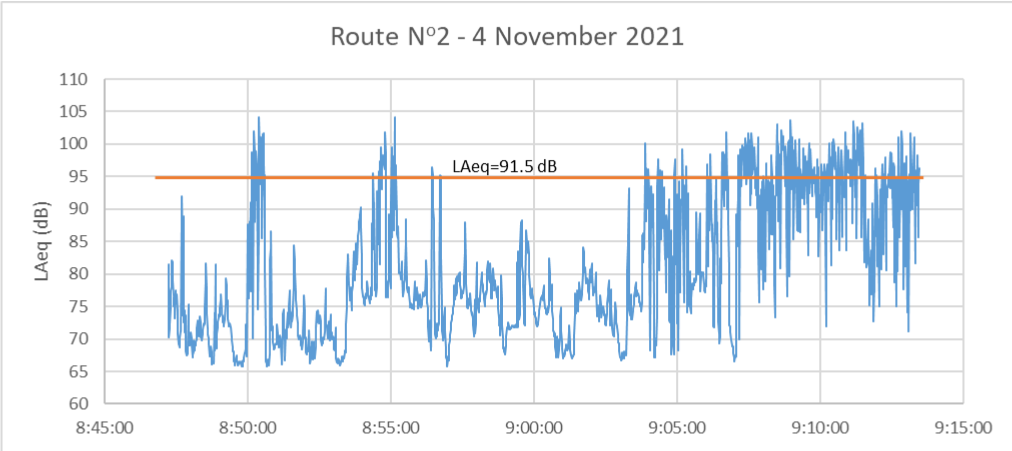


Figure 4. Time-evolving graphs of registers with extreme L_{Aeq} values in each monitoring route (up: Route N°1; down: Route N°2).

Figure 5 shows the permanence curves of the registered values of L_{Aeq}, $L_{AF,10}$, $L_{AF,90}$ and noise climate for each measurement, first in Route N°1 and then in Route N°2. Less variability in all acoustic parameters was verified in Route N°1 compared to Route N°2. The highest values for noise climate do not reproduce the shape of the permanence curve of $L_{AF,10}$ in Route N°2, as they do in Route N°1.

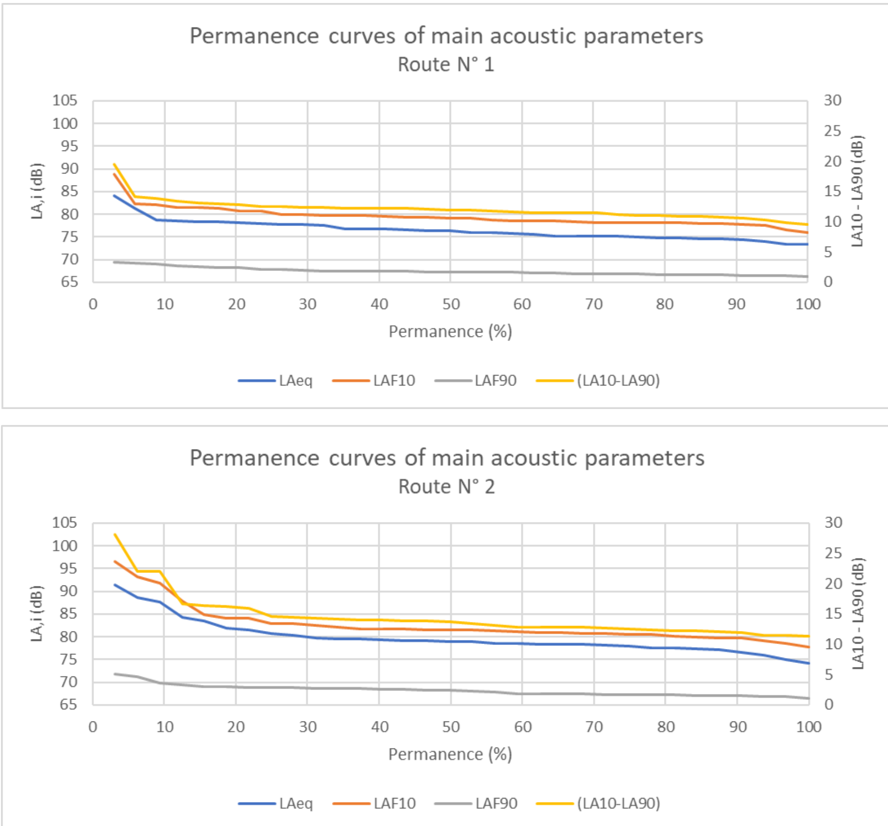


Figure 5. Main noise parameters, by route: permanence curves (up = Route N°1; down = Route N°2).

Figure 6 illustrates the permanence curves of the kurtosis of the measured data; the horizontal line represents the kurtosis of a Gaussian distribution. It is interesting to note that more than 40% of non-normal measurements were found in each route (14/34, or 41%, in Route N°1 and 14/32, or 44%, in Route N°2). When working with the $L_{Aeq,1min}$ series in

Montevideo, non-normal series are expected to occur [47]. Moreover, traffic noise levels do not fit a normal distribution, as verified in different cities [20,48–51].

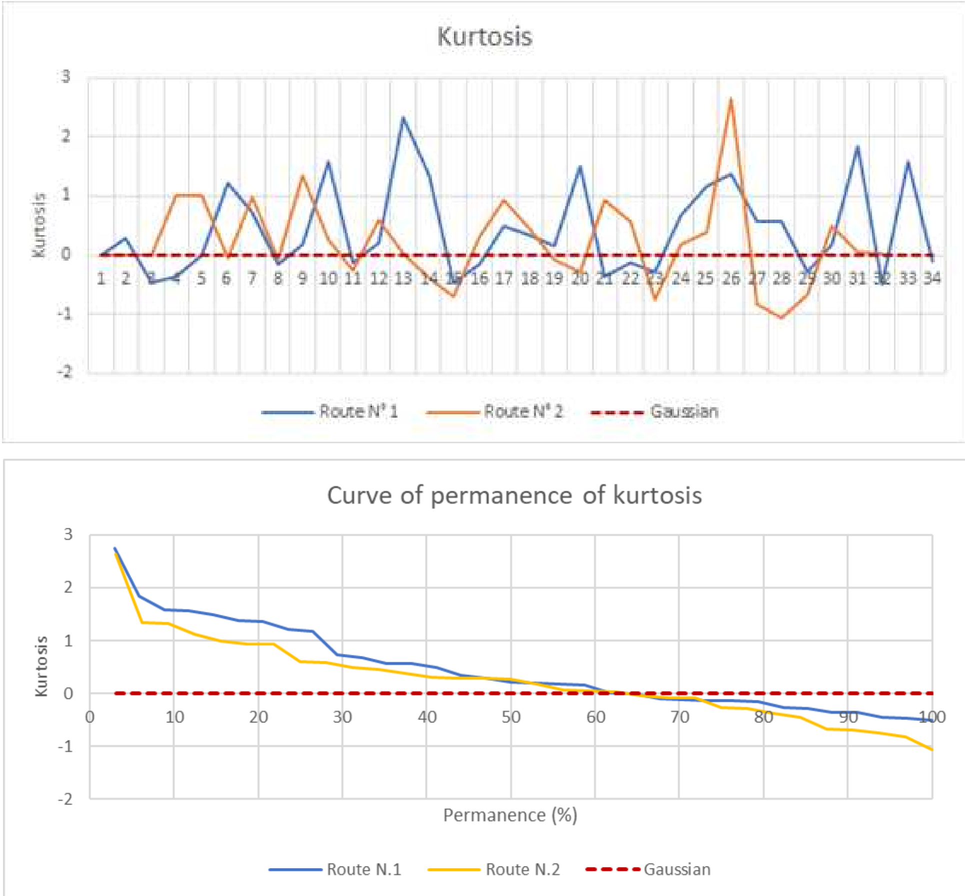


Figure 6. Kurtosis, by route: up = values of each measurement; down = permanence curves.

The permanence curves of traffic flows are presented in Figure 7, by route. As can be seen, Route N°2 has higher total traffic flow and more stable figures for all categories of vehicles (the upper 60–70% of the cases have lower fluctuation in total traffic, number of light vehicles and number of buses than the other ones; trucks are the less variable vehicle category). The registered maximum number was 13 trucks and 133 buses in Route N°1, while there were 68 trucks and 99 buses in Route N°2.

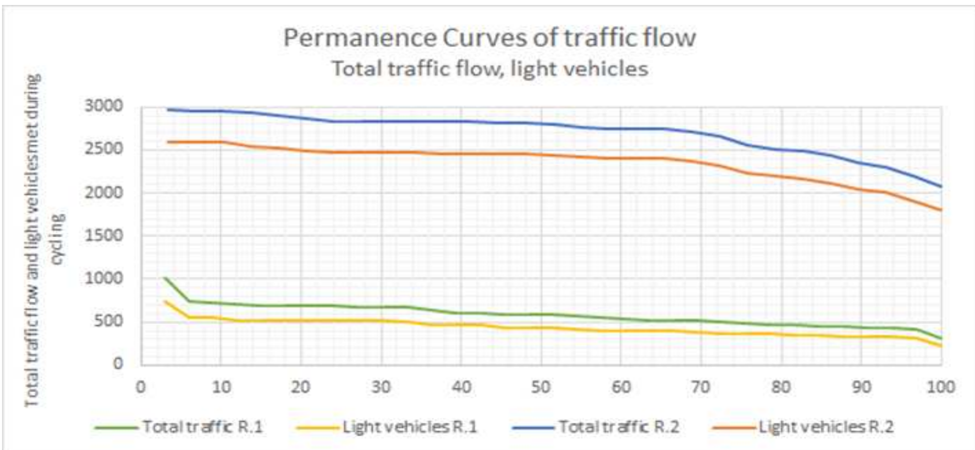


Figure 7. *Cont.*

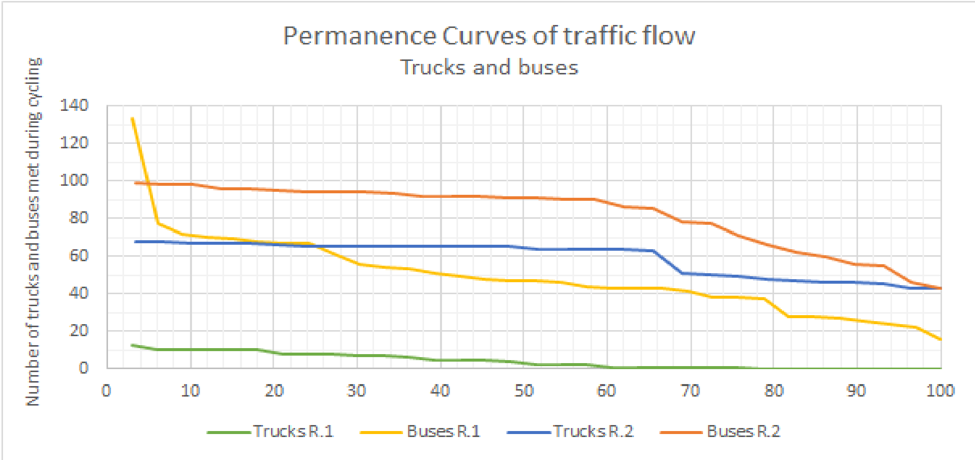


Figure 7. Permanence curves of traffic flow for categories, by route: up = total traffic and light vehicles; down = trucks and buses.

The noise map resulting from the field data is presented in Figure 8 (reproduced from [42]). Higher SPLs were found in Route N°2, with more than 50% of its length having values greater than 75 dB. On the other hand, more than 50% of Route N°1 exhibits values lower than 75 dB.

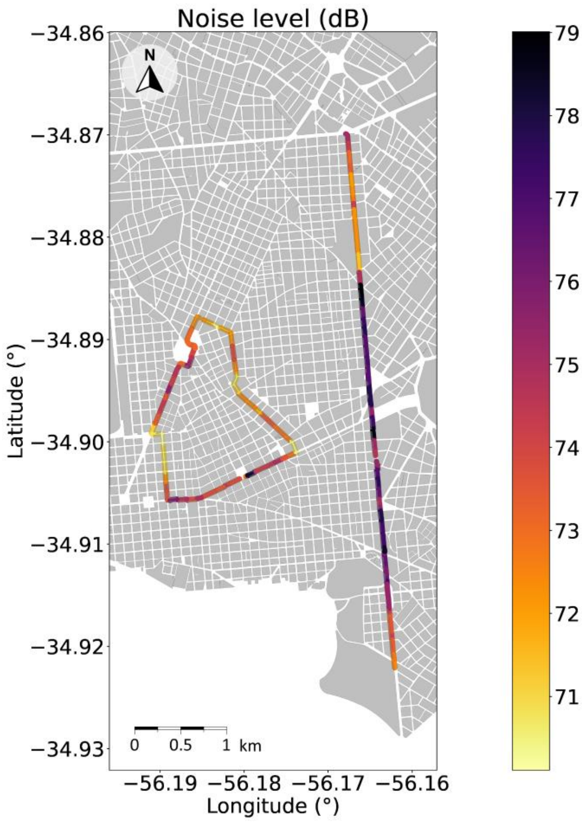


Figure 8. Noise maps of the two monitored routes (measured L_{Aeq} by block, in dB) (from [42]).

3.2. Noise Doses

Noise doses are presented in Tables 4 and 6 with their exceedance times, case by case. This allows for the real registered doses to be known. The values of registered L_{Aeq} and calculated $L_{Aeq,8h}$ and $L_{Aeq,24h}$ are presented in Tables 5 and 7; they help to compare the registered values over a short time period (L_{Aeq}) with the values of $L_{Aeq,8h}$ (daily allowed occupational noise exposure, e.g., for by-bike delivery services) and $L_{Aeq,24h}$. According to US EPA and WHO recommendations, the latter comparison value is 70 dB for hearing impairment avoidance in 96% of exposed people [45].

All the obtained values were coherent: there were no values of $L_{Aeq,8h}$ greater than 80 dB, according to no occupational noise doses greater than 100%. For the environmental values, only three exhibited noise doses greater than 100%. The three cases were from Route N°2.

Figures 9 and 10 present the environmental and occupational noise doses with their exceedance times by route.

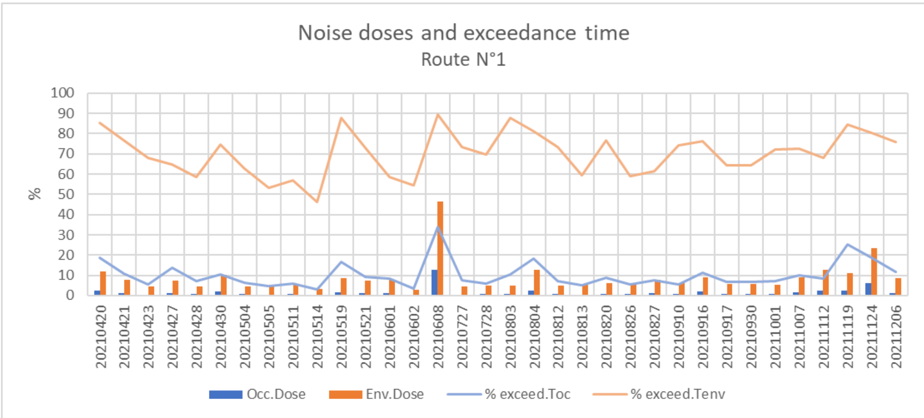


Figure 9. Noise doses and exceedance times in Route N°1.

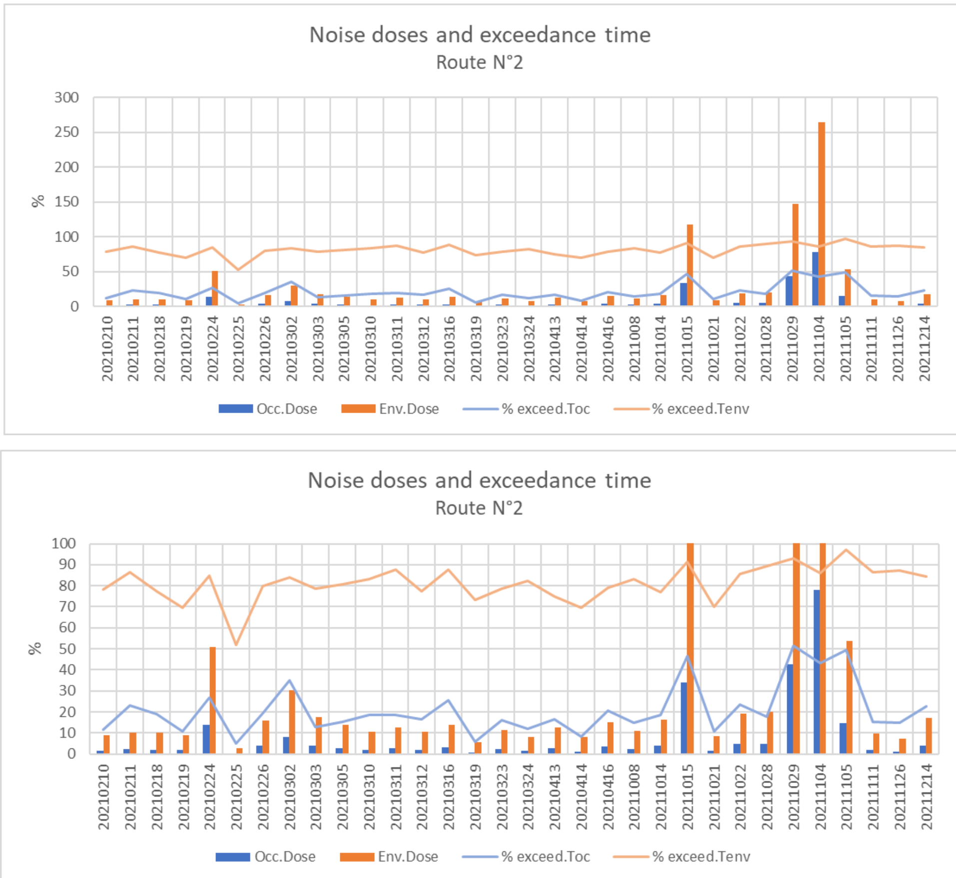


Figure 10. Noise doses and exceedance times in Route N°2 (up = all values; down = zoom for values less than 100%).

When the Mann-Whitney test for equal medians was performed both for environmental doses and for occupational doses between routes, the test was rejected with *p*-values of 1×10^{-5} and 5×10^{-5}, respectively. The tests were performed with Past 4.08 [46].

3.3. Multivariate Statistical Tests

For the multivariate analysis, 62 cases were considered, after excluding the 5 cases without traffic data. The process began with 17 variables. When clustering data by the classical method using a Euclidean distance, kurtosis and the number of trucks appeared to be weakly related to the other variables (Figure 11). Moreover, the doses, total traffic and light vehicles were linked at the lowest levels. L_{Aeq} and $L_{AF,10}$ were also related at a very low level, which is usual for urban noise. PCA ratified these results.

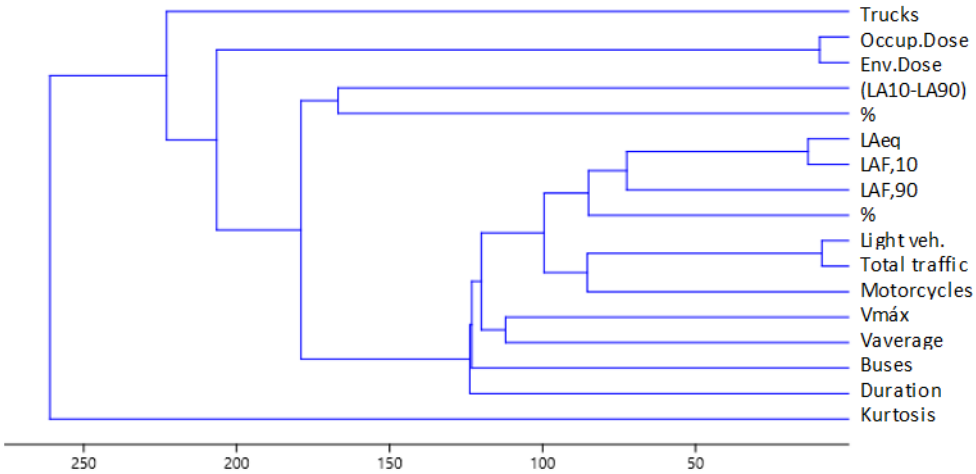


Figure 11. Clustering analysis, first step (single linkage).

In the next step, kurtosis appeared to be independent of traffic data (their vectors were just perpendicular to kurtosis), while the duration of the trip, the average velocity and the maximum velocity of the cyclist, $L_{AF,90}$ and L_{Aeq} appeared to have less interest (Figure 12). Iterating with clustering and PCA tests, we selected a final set of 4 variables that explained 94.6% of the variance of data: kurtosis, ($L_{AF,10}$–$L_{AF,90}$), total traffic and number of trucks met during the trip. The final scatter plot is presented in Figure 13. The 95% ellipse showed only one outlier: the register of 1 June 2021 (Route N°1). Traffic data from 1 June 2021 were rather low, but with a high proportion of motorcycles. It is also a long register, and L_{Aeq} and $L_{AF,10}$ had the same value.

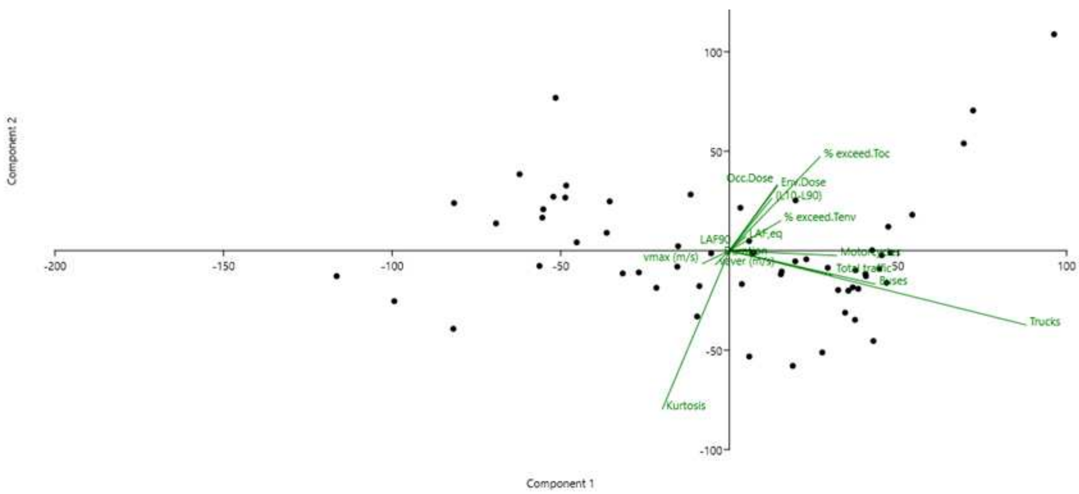


Figure 12. *Cont.*

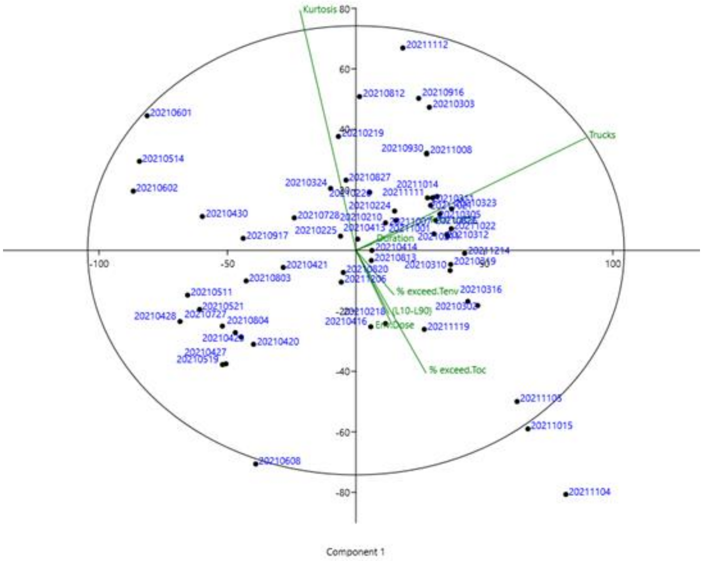


Figure 12. PCA scatter plots (intermediate steps).

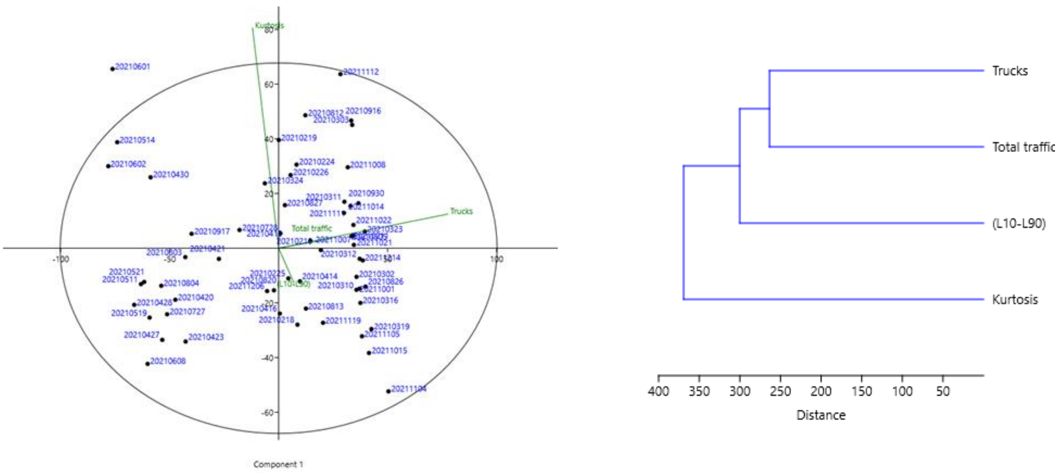


Figure 13. Final PCA scatter plot (**left**) and dendrogram (**right**).

4. Discussion

4.1. Comparison between Routes

As a first comment, both routes have similar numbers of bus stops and traffic lights, i.e., similar fluidity of traffic would be expected. A visual comparison of the results for the 2 routes are presented in Figures 3–6 for some of the parameters: L_{Aeq}, $L_{AF,10}$, $L_{AF,90}$, noise climate ($L_{AF,10}$–$L_{AF,90}$), kurtosis, classified traffic flow during the trip, and occupational and environmental noise doses. On the other hand, according to the Mann–Whitney test for equal medians, neither the series for environmental noise doses nor the series for occupational noise doses appeared to be equivalent for both routes.

Based on the results of the measurements and their processing, as presented in Sections 2 and 3, it can be said that:

- The durations of the bike trips were similar in both routes (Figure 14).
- L_{Aeq} were lower in Route N°1 than in Route N°2, as presented in Figure 15.
- Variability of SPL was less in Route N°1 than in Route N°2, as presented in Figure 15 (L_{Aeq}) and Figure 16 (noise climate).
- Noise doses were lower in Route N°1 than in Route N°2, as were the exceedance times (Figure 17).

- Occupational noise doses were always less than 100% in both routes. The highest value in Route N°1 was 13%, while in Route N°2 it was 78% (Figure 17).
- Environmental doses in Route N°1 were always below 100%, with a maximum value of 47% (Figure 17). This case corresponds to the register of 8 June 2021; its time-evolving graph is presented in Figure 4.
- Environmental doses in Route N°2 exhibited 3 cases of doses greater than 100%, with a maximum dose of 264% (Figure 17); this corresponds to the register of 4 November 2021, which is included in Figure 4. In these 3 cases, the exceedance time was between 86% and 91%.

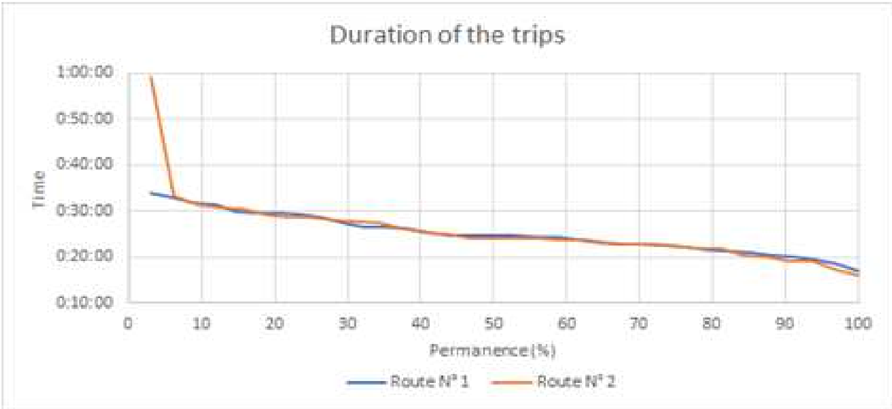


Figure 14. Permanence curves of duration of the trips.

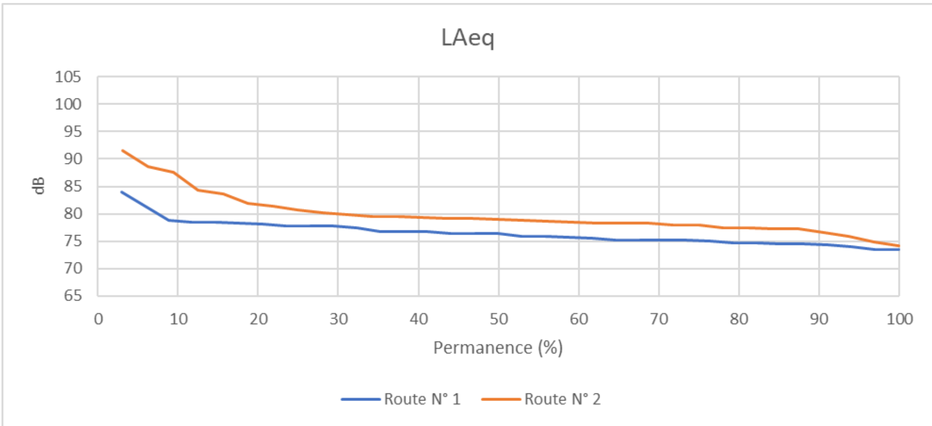


Figure 15. Permanence curves of L_{Aeq}.

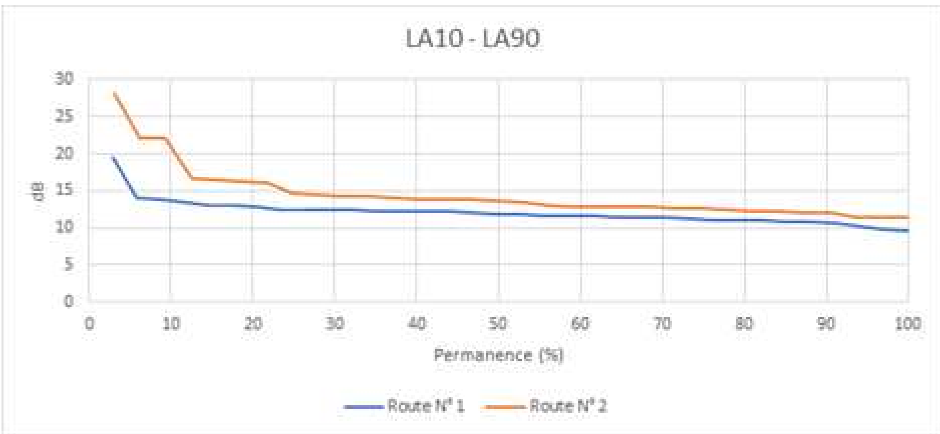


Figure 16. Permanence curves of noise climate.

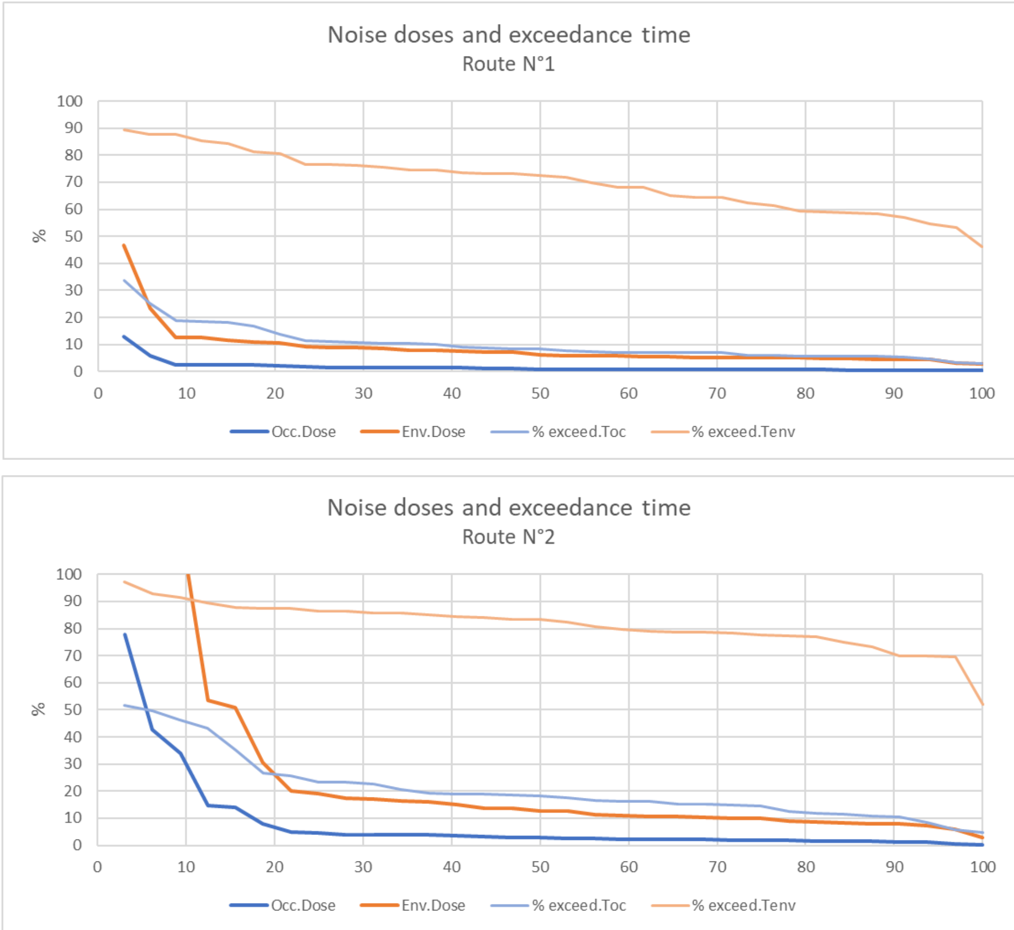


Figure 17. Noise doses and exceedance time: Route N°1 (up) and Route N°2 (down).

It must be highlighted that the morphology of the street (width, building height, street aspect ratio) has been found to be less of an influence on the noise doses than the traffic flow met during the trip. Since Route N°1 has higher buildings and a higher aspect ratio, and it comprises narrower streets, it would be expected to be related to higher noise doses for cyclists. However, just the opposite is true: both environmental and occupational noise doses are significantly lower in Route N°1.

The most remarkable difference between both routes is the total traffic flow, which is about 5 times higher in Route N°2 than in Route N°1. Even though the percentage of heavy vehicles is higher in Route N°1, the absolute figures for classified traffic flow are higher for Route N°2: the maximum number of trucks in Route N°1 was 13, while in Route N°2 it was 68. It may be also taken into account that both routes were selected in a participatory way, working with cyclists' communities to carry out the measurements on representative streets.

4.2. Main Parameters

In Section 3, a set of 4 parameters was selected to describe the noise exposure of cyclists during active transportation: total traffic flow met during the trip; number of trucks met during the trip; ($L_{AF,10}$–$L_{AF,90}$); and kurtosis.

A possible interpretation of this set of variables could be as follows:

- Total traffic flow met during the trip: The cyclists are integrated into the traffic flow; most vehicles in Montevideo are not silent ones. Therefore, the higher the total traffic flow met during the trip, the higher the possibility of being exposed to high SPLs.
- Number of trucks met during the trip: Trucks are some of the noisiest vehicles in urban traffic; Montevideo has not turned to electric trucks yet.

- Noise climate, $L_{AF,10}$–$L_{AF,90}$: this is an indicator of variability of SPLs. When noise climate is larger, the possibility of having higher SPL values increases, because the lowest SPLs (and, consequently, $L_{AF,90}$) do not change significantly along each of the selected routes.
- Kurtosis: this is a way to learn if SPL series of data are Gaussian (normal) or not. Although at least 1/3 of the urban SPL series should be expected to be no normal, the more frequent the occurrence of so-called "anomalous noise events"—such as horns, noisy exhausts on motorcycles and other vehicles, sirens, alarms and noisy brakes—the lower the probability of a data series being Gaussian. Anomalous noise events are those acoustic signals that are involved in the urban traffic soundscape, but they are not related to engines or tire noise. The "avoidable anomalous noise events" include horns, noisy brakes and exhausts on motorcycles or other vehicles [45,52]. The greater the number of anomalous noise events, the higher the noise climate value and stabilization time of the measurements.

5. Limitations of This Study

The main limitations of this study can be summarized as follows:

- The available resources allowed for the consideration of only two monitoring routes. This fact could restrict the spatial representativeness of the results. However, many streets in the city share similarities with the routes selected in this study and the results obtained may be useful inputs for the town hall authorities at the time to plan urban cycling routes.
- In addition, due to resource constraints, it was not possible to simultaneously monitor the noise exposure of other users of public space, i.e., pedestrians or public transport users.
- No SPL measurements were made at fixed points during dosimetry performance.
- The apparent wind velocity experienced by the cyclist was not measured, even though we recorded the driving speed. The average values were between 3 m/s and 6 m/s, but instantaneous maximum values of each trip were $\geq$5 m/s; in some cases, they were higher than 10 m/s. Hence, it is not possible to confirm that the apparent wind velocity did not affect the registered SPL values. However, PCA analysis showed that both velocities did not exhibit an important relative weight (Figure 12). Thus, the authors estimate that apparent wind effects on results would not be of paramount importance.
- The number of vehicular flow cameras made it necessary to interpolate the available information to have the information at the block level.

6. Final Remarks

The main remarks of this work are listed below:

- A total of 66 noise dosimetries have been carried out in Montevideo city on a group of volunteers that usually move by bike. A set of other personal and environmental parameters was simultaneously measured as well.
- Traffic flow was found to be the main urban determinant of high noise doses. Other urban environmental parameters, such as street aspect ratios, had less influence on noise levels.
- The processing of these data showed that noise exposure is mainly related to the variability of SPL (measured by noise climate), total traffic flow, number of trucks, and the normality or not of the series, measured by its kurtosis.
- The highest noise doses occurred when traffic was more intense and when heavy vehicle flow was higher.
- Both environmental and occupational noise doses were significantly lower in Route N°1 compared to Route N°2. Route N°1 has higher buildings and higher aspect ratios, and it comprises narrower streets. On the other hand, total traffic flow was about 5 times higher in Route N°2 than in Route N°1.

- The high variability in traffic noise (measured by $L_{AF,10}$–$L_{AF,90}$ values) and simultaneous exposure to other air pollutants exposed the cyclists to deleterious health conditions in the city, showing the need to consider cyclists' environmental exposures within the frame of public space design.
- According to the obtained results, to maintain urban cyclists' quality of life in Montevideo, traffic flow should be limited across streets equipped with cycling infrastructure (with emphasis on truck flow).
- The authors consider that the methodology followed in the present study could be replicated in other cities around the world, generating valuable data for the design of low-noise-exposure cycling routes and public spaces. In this sense, citizenship involvement in the research process is considered crucial in order to select realistic monitoring routes and to make people aware of environmental health risks and their possible mitigation strategies.
- Further research linking environmental noise doses with the acoustic parameters of L_{Aeq} or noise climate is needed to relate environmental noise parameters with exposure parameters.

Sensorial phenomena play an important role in the way citizens experience cities, beyond health problems that may be related to exposures, especially to noise. Even though most urban planning is dominated by reductions in visual contamination, it is critical to advance multisensory approaches that articulate other senses, like sound and smell. This study contributes to a better understanding of exposure to noise pollution in Montevideo and its potential effects, especially in the vulnerable population of active transport users. Although the scope of this study did not include a sensory representation of the city, we expect our findings will contribute to the promotion of this kind of view of the urban environment in Montevideo city and to the advancement of sensory sustainability in our city.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Facultad de Medicina (Universidad de la República, Uruguay) (EXP Nº 070153-000585-18, 1 November 2018).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Abbreviations

The following abbreviations are used in this manuscript:

SPL	Sound Pressure Levels
L_{Aeq}	Equivalent SPL weighted A, measured with time-weighting Fast
$L_{Aeq,t}$	Equivalent SPL weighted A, measured with time-weighting Fast during a period *t* (e.g., $L_{Aeq,1s}$, $L_{Aeq,1min}$, $L_{Aeq,24h}$, etc.)
$L_{Aeq,8h}$	Equivalent SPL weighted A, corresponding to 8 h. It represents the occupational L_{Aeq} during a working journey
$L_{AF,10}$	The SPL weighted A, measured with time-weighting Fast, which is exceeded during 10%) of the total measuring time
$L_{AF,90}$	The SPL weighted A, measured with time-weighting Fast, which is exceeded during 90% (and no more than 90%) of the total measuring time
$L_{AF,Max}$	The maximum SPL weighted A, measured with time-weighting Fast, which occurs during the total measuring time
L_{Peak}	The level which corresponds to the maximum sound pressure during a certain period. It does not consider either a frequency weighting or a time-weighting. It is not an RMS value. The value of L_{Peak} is used for occupational noise assessment
T_{exp}	Exposure time to a certain SPL
D_{occ}	Occupational noise dose. In this paper, we used 8 h exposure to 80 dB weighted A, according to Uruguayan occupational regulations
D_{env}	Environmental noise dose. In this paper, we used 24 h exposure to 70 dB weighted A
PM	Particulate matter
PM_{10}	Particles with an aerodynamic diameter less than or equal to 10 µm
$PM_{2.5}$	Particles with an aerodynamic diameter less than or equal to 2.5 µm
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides ($NO_x = NO + NO_2$)
CO	Carbon monoxide
PCA	Principal Component Analysis

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