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# Stabilization Time of Running Equivalent Level $L_{Aeq}$ for Urban Road Traffic Noise

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**Featured Application: The efficiency of temporal sampling of road traffic noise could be improved considering the stabilization time ST of the running equivalent level $L_{Aeq,ST}$, rather than referring to a fixed measurement time $t$, often used in common practice and chosen regardless of the amount of road traffic flow.**

**Abstract:** In urban areas, noise levels can largely vary in space and time due to the great complexity of these environments. The time required for the fluctuations of the running equivalent level $L_{Aeq}$ to be limited within a preset variability range is a key issue for determining a statistically representative sample of the urban acoustic environment. The goal of the present study is to evaluate the potential of the stabilization time, defined as the minimum time $ST$ after which the difference between the corresponding continuous equivalent sound pressure level $L_{Aeq,ST}$ and the continuous equivalent sound pressure level $L_{Aeq,T}$ referred a longer time $T$, including $ST$, is never greater than a preset uncertainty interval $\varepsilon$. For this purpose, a dataset of road traffic noise continuously monitored in 97 sites in the city of Milan, Italy, is considered, providing 268 time series of 1 s short $L_{Aeq,1s}$, each lasting 24 h. The stabilization time $ST$ referred the hourly $L_{Aeq,1h}$ was determined for three preset uncertainty intervals $\varepsilon$, namely $\pm 0.5$, $\pm 1.0$ and $\pm 1.5$ dB(A). The results are promising and provide useful hints to obtain short-time noise monitoring as a statistically representative sample of the urban acoustic environment and, therefore, can be a tool to increase the low spatial resolution usually achievable by unattended permanent monitoring units.

**Keywords:** urban road traffic noise; stabilization time; temporal sampling of environmental noise

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## 1. Introduction

In 1982, Utley published a critical review of the existing practice of temporal sampling techniques for the measurement of environmental noise [1]. He concluded that whilst sampling techniques provide savings in human resources and equipment, the techniques were inadequate to determine accuracy except in a number of specific situations. He also pointed out that continuous monitoring was impractical due to the resource requirement.

Meanwhile, the increases in urbanization and mobility have led road traffic to become a major noise source in urban areas, with a large impact on the health of the exposed population (e.g., annoyance [2], psychological distress [3] and psychotropic medication use [4]). This noise shows large and random sound pressure level (SPL) fluctuations over time and, therefore, it is a challenge to track its time variability by sampling it. This subject has attracted the attention of many researchers, and several studies and surveys are reported in the literature (e.g., [5–16]).

Until relatively recently, local authorities and researchers have largely used short-duration localized noise measurements and computer-generated noise maps to comply with the Directive 2002/49/EC requirements [17]. The predictions of noise by numerical models of outdoor sound propagation and "on the spot" short-duration measurements are useful tools, even though a network of permanent noise monitoring stations measuring continuously may be a preferable solution. The high cost of installing and maintaining such networks is often the main reason for not implementing them on a large scale and with adequate spatial resolution. These limitations are even more evident in urban areas, where the complexity of outdoor noise propagation, due to the spatial configuration of the built environment and the noise source distribution, leads to high variability of sound pressure levels in space and time [18,19] and, therefore, requires spatially "dense" noise monitoring units. Despite the facts that the technology has improved significantly and the costs have been reduced, short-time noise monitoring is still an appealing measurement technique, also because it is usually performed by an operator, unlike the unattended permanent noise monitoring units. Among the advantages of attended noise measurement, nonrelevant sounds can be excluded or tagged in order to not be considered in post-processing and adverse weather conditions unsuitable for measurements can be avoided. Furthermore, the operator can stop the measurement when the running equivalent level $L_{Aeq}$ shows time fluctuations within a preset range. This allows for saving time and moving to another location and, therefore, increases the spatial resolution of noise monitoring and saves resources. On the contrary, unattended continuous noise monitoring requires validation of the collected data that could be difficult, cumbersome and time consuming in the necessary post-processing phase.

In any noise time sampling, the value of the continuous equivalent sound pressure level $L_{Aeq,T}$ referred to medium- and long-time $T$ is estimated by the $L_{Aeq,t}$ level measured for a shorter time $t$, usually much shorter than $T$ ($t << T$). For instance, the Italian legislation on road traffic noise requires that $T = 1$ h, and it is common practice that the hourly $L_{Aeq,1h}$ value is estimated to be equal to the measured value $L_{Aeq,t}$ over time interval $t$ within the selected hour. The duration of $t$ and, therefore, the time sampling ratio $m = t/T$, which is always $m \leq 1$ being t << T, is variable and in common practice is very often fixed at 10–15 min in urban areas and road traffic noise, regardless of the amount of road traffic flow. This procedure leads to an uncertainty $\pm\varepsilon$ in the $L_{Aeq,T}$ estimate, which should be combined with other sources of uncertainty, such as that of instrumentation:

$$L_{Aeq,T} = L_{Aeq,t} \pm \varepsilon \quad [\text{dB(A)}], \tag{1}$$

A further important parameter in noise time sampling is the stabilization time $ST$ of the running equivalent level, defined as the minimum time after which the difference between the corresponding continuous equivalent sound pressure level $L_{Aeq,ST}$ and the continuous equivalent sound pressure level $L_{Aeq,T}$ at the reference time $T$, which includes $ST$, is never greater than a preset uncertainty interval $\varepsilon$ [20]. In other words, the stabilization time $ST$ is obtained by comparing the $L_{Aeq,T}$ level at the reference time $T$, usually equal to 1 h, with the running $L_{Aeq,t}$ computed from the beginning of $t$ onward, until the time $ST$, from the beginning of $t$, after which Equation (1) is always fulfilled for the preset $\varepsilon$. Naturally, when the time $t$ continues to run after $ST$ until reaching $T$, then the running $L_{Aeq,t}$ is equal to $L_{Aeq,T}$ and $\varepsilon = 0$ dB(A).

Figure 1 shows the concept of stabilization time $ST$ for two values of the uncertainty interval $\varepsilon$ set for the $L_{Aeq,T}$ estimate. The green band corresponds to $\varepsilon = \pm 0.5$ dB(A) and the orange one to $\varepsilon = \pm 1.0$ dB(A). The blue and red lines represent the sequence of SPL values and the running $L_{Aeq,t}$, respectively, whilst the horizontal dashed black line corresponds to the $L_{Aeq,T}$ level. In the example shown in Figure 1, the stabilization time is reached at $ST_{0.5} = 370$ s and $ST_{1.0} = 90$ s for the accuracies $\varepsilon = \pm 0.5$ and $\pm 1.0$ dB(A), respectively.

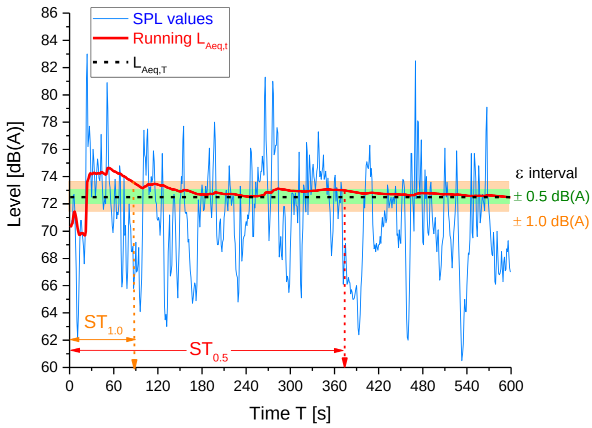



**Figure 1.** Concept of stabilization time *ST* of the continuous equivalent level $L_{Aeq,t}$ and two preset uncertainty intervals $\varepsilon$ set for the $L_{Aeq,T}$ estimate. The green band corresponds to $\varepsilon = \pm 0.5$ dB(A) and the orange one to $\varepsilon = \pm 1.0$ dB(A). The blue and red lines represent the sequence of SPL values and the running $L_{Aeq,t}$, respectively, whilst the horizontal dashed black line corresponds to the $L_{Aeq,T}$ level.

Some studies [20–22] showed that *ST* is useful for characterizing the temporal composition of urban soundscapes and for estimating the hourly $L_{Aeq,1h}$ level with a preset uncertainty $\pm\varepsilon$ from short-time $L_{Aeq,t}$ measurements. As observed in [21], the presence of sound events, such as those produced by vehicle pass-by, influences the duration of the stabilization time *ST* because it increases the SPL fluctuation over time. To evaluate the contribution of these events on the hourly $L_{Aeq,1h}$ level, the intermittency ratio *IR* can be used and computed as follows [23]:

$$IR = \frac{10^{0.1L_{Aeq,Tevents}}}{10^{0.1L_{Aeq,T}}} \cdot 100\ [\%], \tag{2}$$

where $L_{Aeq,Tevents}$ accounts for all sound energy contributions that exceed a given threshold, *K*, that is clearly standing out from background noise, and $L_{Aeq,T}$ is the continuous equivalent level referred to the measurement time T. The threshold *K* for sound event detection is computed as [23]:

$$K = L_{Aeq,T} + C\ [\text{dB}], \tag{3}$$

where $C = 3$, as stated in [23] as an outcome of the numerical simulations of different urban road traffic situations. The *IR* metric has been fruitfully used in a previous study to classify urban roads on the basis of their acoustic features, rather than their functional classification according to the Italian legislation [24–26].

The present paper describes the main results of an analysis on the stabilization time of running equivalent level $L_{Aeq,t}$, based on a large dataset of urban road traffic noise collected in the city of Milan, Italy. The results showed that in selecting the measurement time *t* to obtain an estimate of the hourly $L_{Aeq,1h}$ level within a preset uncertainty $\varepsilon$, referring to the stabilization time *ST* is much more suitable and efficient than using a fixed time sampling *t*, usually lasting 10–15 min, frequently applied in common practice regardless of the amount of road traffic flow. A step ahead of this crude approach has been introduced by the standard ISO 1996-2:2017 [27], which relates the standard uncertainty $\varepsilon$ with the total number *n* of vehicle pass-by in mixed road traffic:

$$\varepsilon \cong \frac{10}{\sqrt{n}}\ [\text{dB}], \tag{4}$$

For instance, to obtain a $\varepsilon = 0.5$ dB it is necessary that at least $n = 400$ vehicle pass-by in mixed road traffic are counted to end the measurement time *t*.

## 2. Materials and Methods

### 2.1. Experimental Data Set

Noise monitoring data collected in 97 sites in the city of Milan, Italy, were considered for the present study [28]. They consisted of 268 time series of 1 s short $L_{Aeq,1s}$ level, each lasting continuously for 24 h. Road traffic noise was the predominant source in each site and, therefore, the reference time $T$ for computing the stabilization time $ST$ was set to $T$ = 1 h, according to the current Italian legislation.

The selected sites were representative of the urban road network in Milan, which includes different types of roads according to the Italian road functional classification, namely motorways (class "A"), thoroughfare roads (class "D"), urban district roads (class "E") and urban local roads (class "F"). The distribution of the sites across the road types is given in Table 1, together with the number of 24 h time series of 1 s A-weighted short $L_{Aeq,1s}$ level, monitored continuously by a class 1 sound level meter, set to time weighting Fast with the microphone placed at 4 m above the road. The unattended monitoring was carried out on weekdays only (Monday to Friday), and data collected with rain and wind speed >5 m/s were excluded from the study. In 62 sites, the monitoring lasted continuously for a few days. More details on the noise survey (e.g., locations of monitoring sites in the urban area) are available in [28].

**Table 1.** Distribution of the 97 sites considered in the study according to the Italian road functional classification.

| Road Type | N. of Sites | N. of 24 h Time Series | N. of Sites with More than 1 Day Monitoring |
|---|---|---|---|
| A (motorways) | 2 | 15 | 2 |
| D (thoroughfare roads) | 6 | 16 | 3 |
| E (urban district roads) | 30 | 91 | 22 |
| F (urban local roads) | 59 | 146 | 35 |
| Total | 97 | 268 | 62 |

In addition, for each site the hourly traffic flow $Q_h$ was provided by the Municipal Agency of Mobility, Environment, and Land of Milan (AMAT). The road traffic flows were calculated by a model based on origin–destination matrices applied on the entire city road network, reported in Figure 2. It has to be addressed that the Italian functional classification of roads is mainly based on the geometry of the roads, and therefore does not always correspond to the roads' actual use by urban traffic. In other words, roads of the same geometry and functional class could show quite different amounts of road traffic flow, depending on their actual function in the mobility road network. Such discrepancy has been already observed in previous investigations carried out on Milan road network [24–26].

### 2.2. Data Processing and Analysis

A script running in "R" software [29] was developed to import each of the 24 h time series of the 1 s A-weighted $L_{Aeq,1s}$ as text files. Data were processed in order to compute for each $T = 1$ h the hourly $L_{Aeq,1h}$ level, the running $L_{Aeq,t}$ (red line in Figure 1), the difference $L_{Aeq,t}$—$L_{Aeq,1h}$ for every second, the intermittency ratio $IR$, the stabilization time $ST$ for three preset uncertainty intervals $\varepsilon$, namely ±0.5, ±1.0 and ±1.5 dB(A) and the standard deviation of the $L_{Aeq,1s}$ level within each hour $\sigma_h$. Moreover, statistical analyses were carried out on the data.

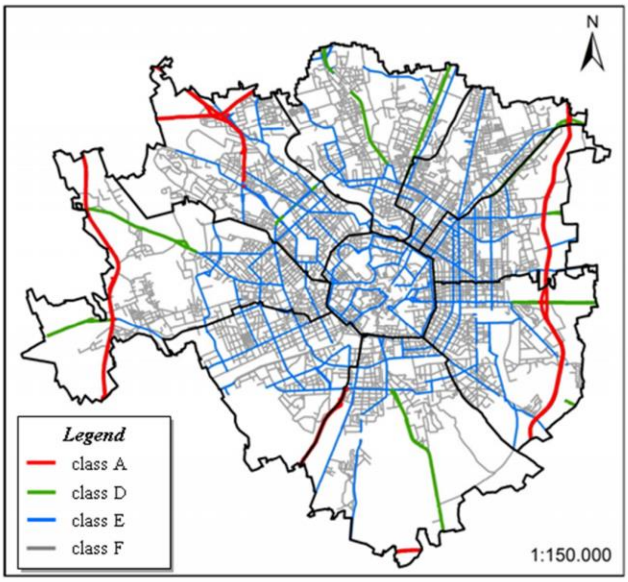
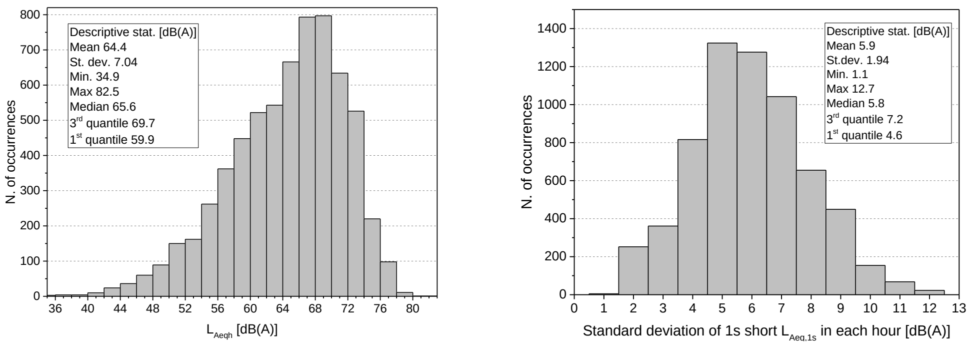



**Figure 2.** The spatial distribution of road types in the urban area of Milan, Italy.

## 3. Results and Discussion

Figure 3a reports the histogram of the 6426 hourly $L_{Aeq,1h}$ considered, together with some descriptive statistics. The range is rather wide (≅47 dB(A)), and the dataset is likely representative of the road traffic noise in the urban area. This is also reasonable for the standard deviation $\sigma_{1h}$ of the $L_{Aeq,1s}$ level within each hour, the distribution of which is given in Figure 3b, where the histogram varies from $\sigma_{1h}$ = 1 to 12 dB(A).




(**a**) (**b**)

**Figure 3.** The distribution of (**a**) the 6426 hourly $L_{Aeq,1h}$ considered in the study; (**b**) the standard deviation $\sigma_{1h}$ of 1 s short $L_{Aeq,1s}$ in each hour.

Figure 4 shows the median of $ST$ values for each hour and the three preset uncertainty intervals $\varepsilon$ of the $L_{Aeq,1h}$ estimate plotted versus the median hourly road traffic flow $Q_h$, as well as the regression lines according to the equation

$$ST = a \cdot (Q_h)^b \text{ [min]}, \quad (5)$$

where $a$ and $b$ are constants, the values of which are obtained by least squares data fitting. The $ST$ values decrease with increases in the uncertainty $\varepsilon$ and with increases in the road traffic flow $Q_h$. The trend is rather similar to that reported in [21]. The green dashed line corresponds to the measurement time $t$ = 15 min, often used in common practice for road traffic noise measurement. It is clear that this approach, which uses a measurement time selected regardless of the road traffic flow, can lead to low accuracy in the $L_{Aeq,1h}$ estimate, as reported in the first row in Table 2.

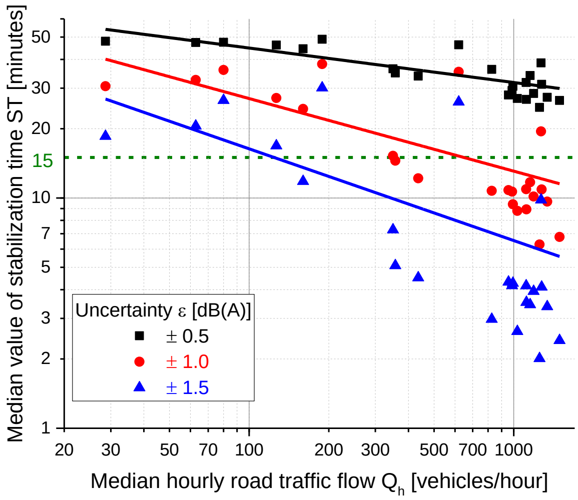



**Figure 4.** Median hourly *ST* values for the three preset uncertainty $\varepsilon$ of the $L_{Aeq,1h}$ estimate versus median hourly road traffic flow $Q_h$. The green dashed line corresponds to the measurement time $t$ = 15 min, often used in common practice for road traffic noise measurement.

**Table 2.** Percentage of *ST* values $\leq$ 15 min for each road type and uncertainty $\varepsilon$.

| Road Type | Uncertainty $\varepsilon$ of the $L_{Aeq,1h}$ Estimate [dB(A)] | | |
|---|---|---|---|
| | **±0.5** | **±1.0** | **±1.5** |
| All | 17 | 46 | 64 |
| A (motorways) | 46 | 77 | 93 |
| D (thoroughfare roads) | 26 | 60 | 74 |
| E (urban district roads) | 21 | 52 | 67 |
| F (urban local roads) | 10 | 38 | 58 |

The stratification of the dataset by road type leads to more meaningful outcomes of the statistical analysis, as pointed out in some studies [26,30]. Table 2 reports the percentage of the observed *ST* values $\leq$ 15 min for each road type and uncertainty interval $\varepsilon$. As expected, these percentages decrease from road types A to F and increase with increasing of the uncertainty $\varepsilon$. This outcome points out that the stabilization time *ST* could be an efficient tool to guide in selecting the measurement time $t$ adequate to the SPL time variability and, therefore, for increasing the accuracy of the $L_{Aeq,1h}$ estimate.

The Kruskal–Wallis test applied to the *ST* values obtained for each uncertainty $\varepsilon$ showed significant differences at 95% confidence levels for the road types and the Dunn test detected these significant differences for all six pairwise comparisons. This outcome confirms the importance of the dataset stratification by road type.

Moreover, the Kolmogorov–Smirnov test showed a non-normal distribution of the *ST* values for all the combinations road type, hours and uncertainty $\varepsilon$. This result is in agreement with that observed in [22], suggesting the use of the percentiles instead of the mean to summarize the *ST* values in each group. In the present study, adopting a precautionary approach, the third quartile of the *ST* values in each group was considered, corresponding to the 75th percentile; that is, 75% of the *ST* values were shorter than the third quartile. These values for each of the uncertainty intervals $\varepsilon$ are plotted in Figure 5 for each road type versus the median value of the hourly road traffic flow $Q_h$ together with regression lines according to Equation (5).

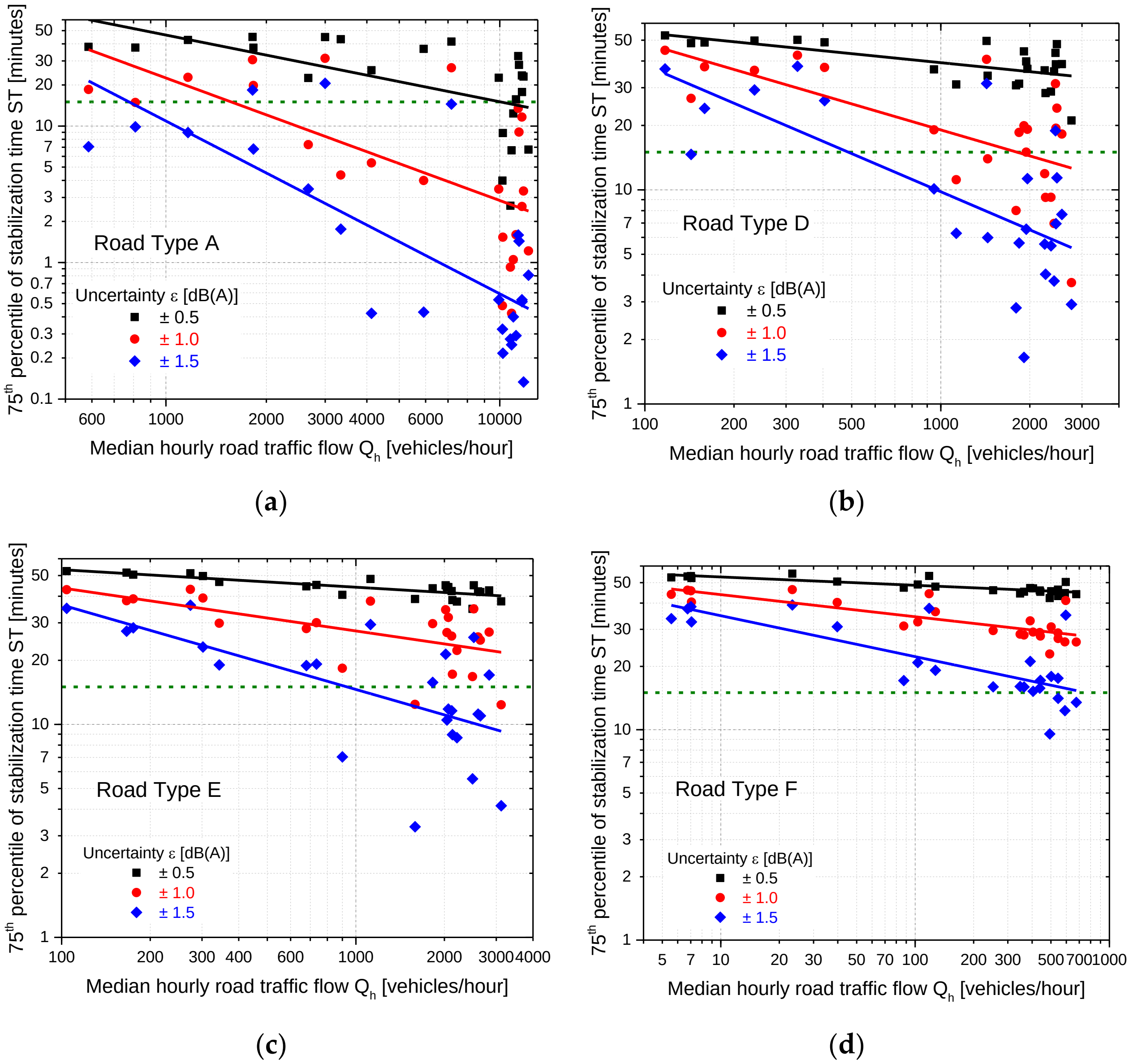



**Figure 5.** 75th percentile of *ST* values for the three preset uncertainties $\varepsilon$ of the hourly $L_{Aeq,1h}$ estimate, grouped by the four road types ((**a**–**d**)-letters refer to road types A, D, E, F) and hour, versus median hourly road traffic flow $Q_h$.

The *ST* values decrease with road traffic flow increasing and from F road type to A, as well as with increasing of the uncertainty $\varepsilon$. The horizontal dotted green line corresponds to the time $t$ = 15 min, often used in common practice for road traffic noise measurement. It is evident that this duration of the measurement time is acceptable only for road type A and low accuracy of the $L_{Aeq,1h}$ estimate (Figure 5a), barely acceptable for road types D and E for road traffic flow $Q_h$ > 700–1200 vehicles/h (Figure 5b,c), and never acceptable for road type F (Figure 5d), unfortunately the more diffuse in an urban area. Table 3 reports the values obtained for the constants $a$ and $b$ in the regression Equation (5), showing for A and D road types a stronger dependence of stabilization time on the traffic flow. This is essentially due to the more regular traffic dynamics observed for these types of roads.

**Table 3.** Values obtained for the constants $a$ and $b$ in the regression Equation (5).

| Road Type | Uncertainty $\varepsilon$ of the Hourly $L_{Aeq,1h}$ Estimate [dB(A)] | | | | | |
|---|---|---|---|---|---|---|
| | ±0.5 | | ±1.0 | | ±1.5 | |
| | $a$ | $b$ | $a$ | $b$ | $a$ | $b$ |
| All | 89.32 | −0.15 | 115.52 | −0.32 | 102.47 | −0.40 |
| A (motorways) | 324.46 | −0.30 | 443.14 | −0.45 | 360.25 | −0.53 |
| D (thoroughfare roads) | 97.59 | −0.13 | 195.21 | −0.32 | 277.03 | −0.45 |
| E (urban district roads) | 77.45 | −0.08 | 102.32 | −0.18 | 171.34 | −0.34 |
| F (urban local roads) | 58.14 | −0.04 | 54.87 | −0.10 | 51.58 | −0.17 |

Figure 5 shows the large influence of road traffic flow on the length of stabilization time and, therefore, the knowledge of this data is essential for an estimate of $ST$ values. Figure 6 shows the median hourly road traffic flow computed for the examined dataset and the four road types. The pattern is rather similar for all roads, with peaks at 8 and 18 h, more pronounced for local roads (F) than for the other types. The flows decrease from 18 to 4 h and increase again afterwards.

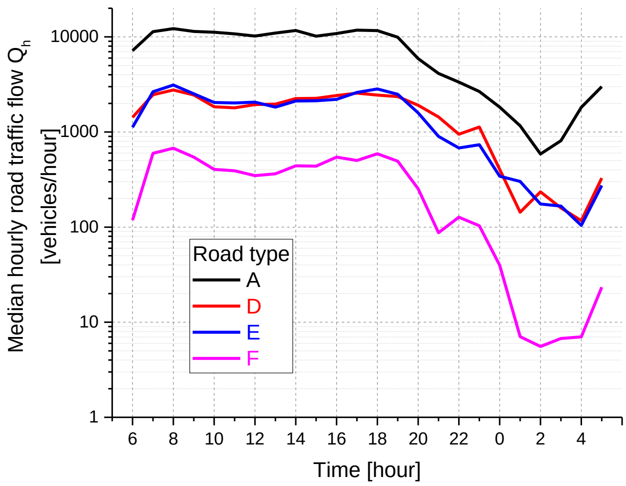



**Figure 6.** Median hourly road traffic flow $Q_h$ computed for the examined dataset and the four road types.

The flow data in Figure 6 can be input in the regression equations (Equation (5)) to obtain an estimate of the $ST_{75}$ value for each type of road and uncertainty $\varepsilon$. For instance, Figure 7 reports the estimated $ST_{75}$ values for each type of road at each hour for an uncertainty $\varepsilon = \pm 1.0$ dB(A). The values are rather stable in the daytime from 8 to 18 h; afterwards they increase until 2–4 h in the night, depending on the road type, and decrease again until 8 h. The horizontal green dotted line at $ST_{75} = 15$ min clearly shows that this measurement time is not appropriate for all roads at any hour, with the exception of motorways (type A), excluding the night period 0–4 h. The above pattern is rather similar for the other two accuracy intervals, and Table 4 gives the mean values in the day period 7–19 h of $ST_{75}$ values estimated by Equation (5) for each road type and uncertainty $\varepsilon$. It is clear that the measurement time $t = 15$ min is appropriate only for a large uncertainty, $\varepsilon \geq \pm 1.5$ dB(A), and acceptable for motorways (road type A) for uncertainty $\varepsilon = \pm 1.0$ dB(A).

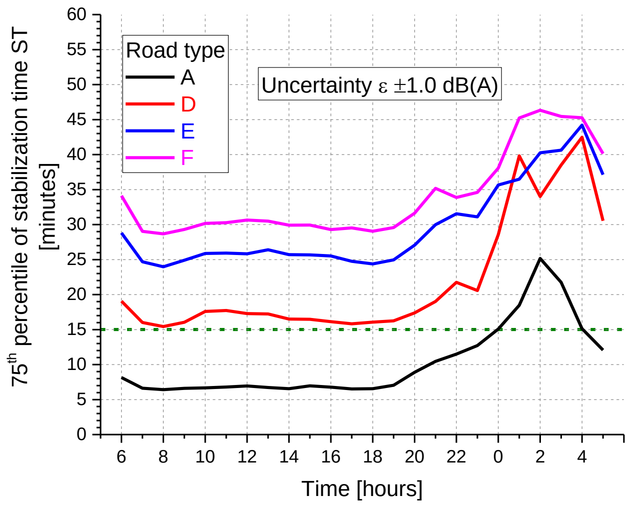



**Figure 7.** Estimate of 75th percentile of *ST* values for each type of road at each hour for uncertainty $\varepsilon = \pm 1.0$ dB(A).

**Table 4.** Mean values in the day period 7–19 h of 75th percentile of *ST* values [1] estimated by Equation (5) for each road type and uncertainty $\varepsilon$.

| Road Type | Uncertainty $\varepsilon$ of the $L_{Aeq,1h}$ Estimate [dB(A)] | | |
|---|---|---|---|
| | ±0.5 | ±1.0 | ±1.5 |
| A (motorways) | 20 | 7 | 3 |
| D (thoroughfare roads) | 36 | 17 | 9 |
| E (urban district roads) | 41 | 25 | 12 |
| F (urban local roads) | 45 | 30 | 18 |

[1] $ST_{75}$ [min].

From an applicative point of view, it is important to know the cumulative probability $P_{ST75,\varepsilon}$ that a preset $ST_{75}$ value provides a $L_{Aeq,1h}$ estimate within a fixed uncertainty $\varepsilon$ [14]. This probability was computed for all the road types and uncertainties $\varepsilon$ of the $L_{Aeq,1h}$ estimate and the results are shown in Figure 8 for some values of $ST_{75}$. Table 5 shows that for a measurement time $t$ = 10 min, the cumulative probability of $ST_5$ to obtain a $L_{Aeq,1h}$ estimate within $\varepsilon = \pm 0.5$ dB(A) is above 50% only for motorways (type A) and remains below 50%, even doubling the uncertainty up to $\varepsilon = \pm 1.0$ dB(A), for local roads (type F). Doubling the time $t$ up to 20 min increases the cumulative probability but does not change the pattern observed for the accuracy interval of ±0.5 dB(A) and road type, unless $t$ was at least tripled or even longer.

**Table 5.** Cumulative probability [%] of the $L_{Aeq,1h}$ estimate computed by Equation (5) for each road type and uncertainty $\varepsilon$ for some $ST_{75}$ values and daytime mean hourly road traffic flow $Q_h$.

| Road Type | A | | D | | E | | F | |
|---|---|---|---|---|---|---|---|---|
| Mean hourly road traffic flow $Q_h$ in the daytime (6–22 h) [vehicles/h] | 10,100 | | 2140 | | 2120 | | 420 | |
| Stabilization time $ST_{75}$ [min] | Uncertainty $\varepsilon$ of the $L_{Aeq,1h}$ Estimate [dB(A)] | | | | | | | |
| | ±0.5 | ±1.0 | ±0.5 | ±1.0 | ±0.5 | ±1.0 | ±0.5 | ±1.0 |
| 10 | 51 | 79 | 28 | 62 | 16 | 56 | 8 | 38 |
| 20 | 60 | 92 | 45 | 79 | 37 | 70 | 21 | 58 |
| 30 | 81 | 92 | 62 | 88 | 54 | 77 | 38 | 74 |
| 40 | 92 | 95 | 76 | 88 | 71 | 91 | 58 | 88 |

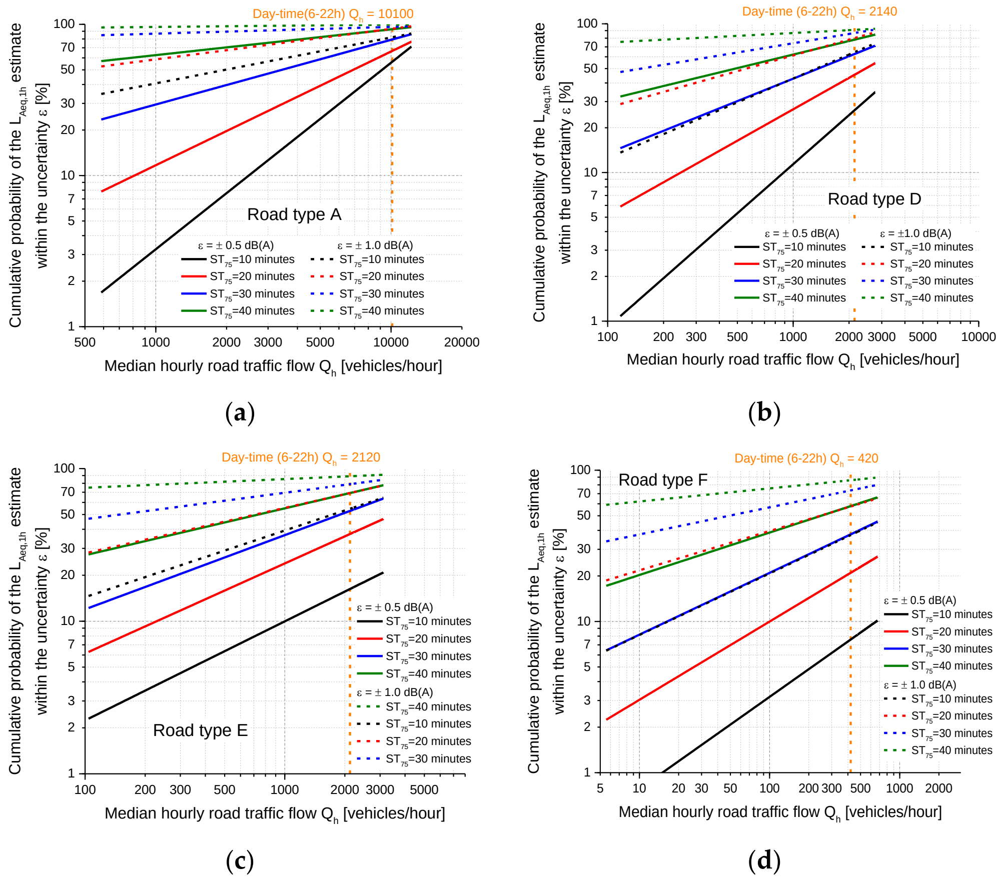



**Figure 8.** Cumulative probability $P_{ST75,\varepsilon}$ that a preset $ST_{75}$ value provides an estimate of $L_{Aeq,1h}$ within a fixed uncertainty $\varepsilon$ for each of the four road types ((**a**–**d**)-letters refer to road types A, D, E, F) versus the median hourly road traffic flow $Q_h$.

Regarding the presence of sound events and their contribution to the hourly $L_{Aeq,1h}$ level, Figure 9 shows the median values of the hourly *IR* for each hour and type of road. The *IR* time pattern is similar for the road types, with hourly values increasing from roads A to F. During the day, from 9 to 18 h, the *IR* time patterns show limited fluctuations (around 10%) and increase afterwards to reach the maximum value at 2–3 h in the night. Comparing these patterns with those reported in Figure 6, it is evident that *IR* is negatively correlated with the hourly values of road traffic flow $Q_h$, as shown in Table 6 reporting the Pearson's correlation coefficients for each road type for *IR* and $L_{Aeq,1h}$ versus $Q_h$.

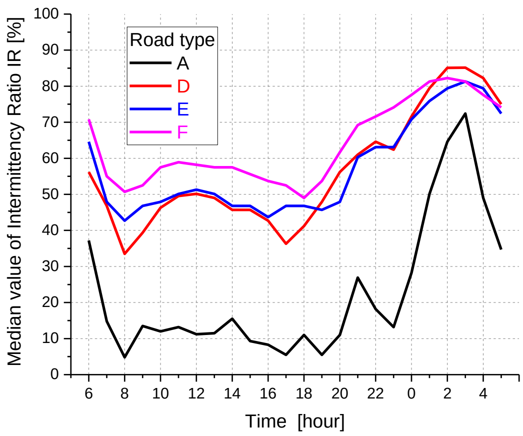



**Figure 9.** The median values of the hourly *IR* for each hour and type of road.

**Table 6.** Pearson's correlation coefficients for each road type for *IR* and $L_{Aeq,1h}$ versus $Q_h$.

| Road Type | Pearson's Correlation Coefficient r | |
|---|---|---|
| | ***IR* vs. $Q_h$** | **$L_{Aeq,1h}$ vs. $Q_h$** |
| A (motorways) | −0.83 | 0.82 |
| D (thoroughfare roads) | −0.50 | 0.27 |
| E (urban district roads) | −0.70 | 0.56 |
| F (urban local roads) | −0.28 | 0.50 |

The presence of sound events increases the SPL time variability and, therefore, rises the duration of the stabilization time *ST*. This influence is more evident at nighttime and low road traffic flows, when sound events clearly exceed the background noise. Figure 10 shows the 75th percentile of *ST* values for each hour and road type plotted versus the corresponding median values of the hourly *IR*. It is observed that the rise rate of $ST_{75}$ with *IR* does not significantly depend on the road type. The higher dispersion of data for roads of type A, especially at low values of *IR*, can be noted. Such dispersion can also be inferred by the time pattern of *IR* in Figure 9, where the day–night variation is much higher than for the other three types of roads. The regression equations used for data fitting are in the form of Equation (5) and Table 7 reports the values obtained for the constants *a* and *b* in the regression equation between $ST_{75}$ and *IR*.

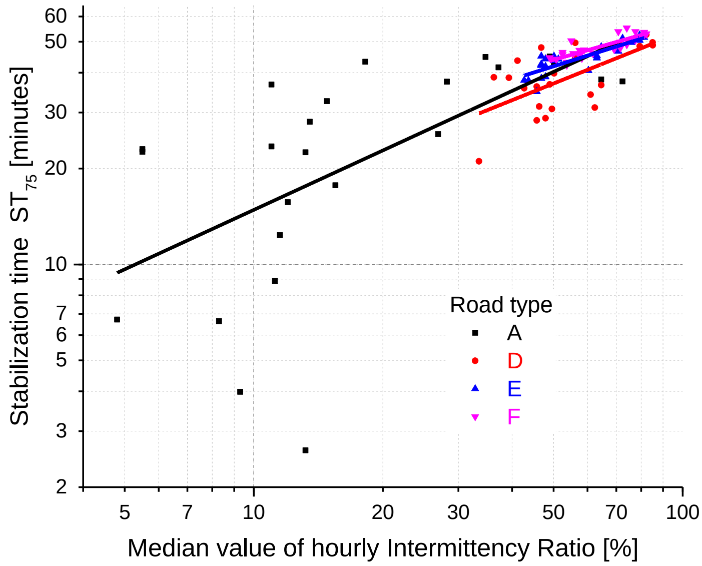



**Figure 10.** Regression of the median values of the hourly *IR* versus $ST_{75}$ values for each type of road.

**Table 7.** Values obtained for the constants *a* and *b* in the regression Equation (5) between $ST_{75}$ and *IR*.

| Road Type | $ST_{75} = a \cdot IR^b$ | |
|---|---|---|
| | ***a*** | ***b*** |
| A (motorways) | 9.67 | 0.39 |
| D (thoroughfare roads) | 8.12 | 0.42 |
| E (urban district roads) | 4.88 | 0.52 |
| F (urban local roads) | 6.81 | 0.45 |

## 4. Conclusions

The present study concerns the stabilization time *ST*, defined as the minimum time after which the difference between the corresponding continuous equivalent sound pressure level $L_{Aeq,ST}$ and the continuous equivalent sound pressure level $L_{Aeq,T}$ referred a longer time $T > ST$, including *ST*, is never greater than a preset accuracy interval $\varepsilon$. This parameter is very important for obtaining samples of urban road traffic noise representative of those over the longer time *T* taken as a reference, where $T = 1$ h normally. The observed non-normal distribution of the *ST* values for all the combinations of road type, hours and uncertainty $\varepsilon$ suggests summarizing the *ST* values in each of these combinations by means of the 75th percentile instead of either the mean or the median. This is a precautionary approach, being 75% of the *ST* values in each combination shorter than the considered $ST_{75}$.

The results obtained by the analysis on the large dataset collected on the roads in Milan clearly show that a fixed measurement time *t* of 10–15 min, frequently used in common practice regardless of the amount of road traffic flow, is very often not suitable for obtaining an estimate of the hourly $L_{Aeq,1h}$ level within a preset accuracy $\varepsilon$. On the contrary, the stabilization time *ST*, which is affected by the SPL time variability and the presence of sound events, is an efficient tool to choose the appropriate measurement time *t*. Furthermore, the intermittency ratio *IR* is an efficient metric to detect sound events, to determine their contribution to the continuous equivalent level $L_{Aeq}$ and their influence on the stabilization time.

An important parameter is the value chosen for the uncertainty $\varepsilon$ of the $\mathrm{L_{Aeq,1h}}$ estimate. As shown by the results, this value largely affects the duration of *ST*: the wider $\varepsilon$, the shorter *ST*. The SPL time variability of road traffic in urban environments is rather high, and setting an uncertainty $\varepsilon = \pm 0.5$ dB(A) leads to very long *ST* durations. At the same time, one must remember that the uncertainty $\varepsilon$ in the $L_{Aeq,1h}$ estimate must be combined with the other sources of uncertainty, such as that from instrumentation. As already reported in [21], setting $\varepsilon = \pm 1.0$ dB(A) seems to be a reasonable compromise, enabling good discrimination of different urban scenarios as well as SPL fluctuations throughout the measurement time *t*.

Moreover, the stratification of the dataset by road type was effective, as it showed that E and F roads, due to the low road traffic flow and the presence of noticeable sound events clearly exceeding the low background noise, are the most critical for noise measurement time *t* because the stabilization time *ST* has a long duration. In addition, these road types are the most numerous in urban areas and cannot be neglected, considering their potential noise impact on the health of the exposed population and the large number of people living close to these roads.

As a general conclusion, the stabilization time *ST* is much more suitable and efficient than using a preset fixed time sampling *t*, chosen regardless of the amount of road traffic flow. Thus, *ST* could be a very useful tool to guide in the selection of a more adequate time sampling *t*, also taking into account the cumulative probability to estimate the medium- and long-term $L_{Aeq,T}$ levels within a preset accuracy interval $\varepsilon$. A measurement time *t* shorter than *ST* would likely not be adequate to obtain the $L_{Aeq,1h}$ estimate within the preset accuracy $\varepsilon$.

Even though the results refer to data collected in Milan, the structure of this large city is similar to those of other cities, at least in Europe, and the analysis carried out could be interesting if its methodological approach was to be replicated in other urban contexts.

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## References


1. Utley, W.A. Temporal sampling techniques for the measurement of environmental noise. *Appl. Acoust.* **1982**, *15*, 191–203. [CrossRef]
2. Ouis, D. Annoyance from Road Traffic Noise: A Review. *J. Environ. Psychol.* **2001**, *21*, 101–120. [CrossRef]
3. Mucci, N.; Traversini, V.; Lorini, C.; De Sio, S.; Galea, R.P.; Bonaccorsi, G.; Arcangeli, G. Urban Noise and Psychological Distress: A Systematic Review. *Int. J. Environ. Res. Public Health* **2020**, *17*, 6621. [CrossRef] [PubMed]
4. Okokona, E.O.; Yli-Tuomia, T.; Turunena, A.W.; Tiittanena, P.; Juutilainenb, J.; Lankia, T. Traffic noise, noise annoyance and psychotropic medication use. *Environ. Int.* **2018**, *119*, 287–294. [CrossRef] [PubMed]
5. Bordone-Sacerdote, C.; Sacerdote, G.G. Sampling Problem and Traffic Noise. *Acustica* **1977**, *37*, 203–205.
6. Gaja, E.; Giménez, A.; Sancho, S.; Reig, A. Sampling techniques for the estimation of the annual equivalent noise level under urban traffic conditions. *Appl. Acoust.* **2003**, *64*, 43–53. [CrossRef]
7. Alberola, J.; Flindell, I.H.; Bullmore, A.J. Variability in road traffic noise levels. *Appl. Acoust.* **2005**, *66*, 1180–1195. [CrossRef]
8. Barrigón Morillas, J.M.; Prieto Gajardo, C. Uncertainty evaluation of continuous noise sampling. *Appl. Acoust.* **2014**, *75*, 27–36. [CrossRef]
9. Brambilla, G.; Lo Castro, F.; Cerniglia, A.; Verardi, P. Accuracy of temporal samplings of environmental noise to estimate the long-term $L_{den}$ value. In Proceedings of the Inter-Noise 2007, Istanbul, Turkey, 28–31 August 2007.
10. De Donato, S.R. Estimation of the minimum integration time for determining the equivalent continuous sound level with a given level of uncertainty considering some statistical hypotheses for road traffic. *Noise Control. Eng. J.* **2007**, *55*, 526–531. [CrossRef]
11. Can, A.; Van Renterghem, T.; Rademaker, M.; Dauwe, S.; Thomas, P.; De Baets, B.; Botteldooren, D. Sampling approaches to predict urban street noise levels using fixed and temporary microphones. *J. Environ. Monit.* **2011**, *13*, 2710–2719. [CrossRef]
12. Makarewicz, R.; Gałuszka, M. Nonlinear uncertainty of the long term average level calculated from short term average sound levels. *Noise Control Eng. J.* **2012**, *60*, 770–774. [CrossRef]
13. Brocolini, L.; Lavandier, C.; Quoy, M.; Ribeiro, C. Measurements of acoustic environments for urban soundscapes: Choice of homogeneous periods, optimization of durations, and selection of indicators. *J. Acoust. Soc. Am.* **2013**, *134*, 813–821. [CrossRef] [PubMed]
14. Brambilla, G.; Gallo, V.; Zambon, G. Prediction of Accuracy of Temporal Sampling Applied to Non-Urban Road Traffic Noise. *J. Pollut. Eff. Control* **2015**, *3*, 147. [CrossRef]
15. Jagniatinskisa, A.; Fiksa, B.; Zaporozhets, O. Annual Assessment of Transport Noise Using Representative Time Measurements. *Procedia Eng.* **2016**, *134*, 301–308. [CrossRef]
16. Hueso, M.C.; Giménez, A.; Sancho, S.; Gaja, E. Measurement techniques of noise level in various urban scenarios. Day selection and representative period. *Appl. Acoust.* **2017**, *116*, 216–228. [CrossRef]
17. European Union. Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise. *Off. J. Eur. Communities* **2002**, *L 189*, 12–25.
18. Zuo, F.; Li, Y.; Johnson, S.; Johnson, J.; Varughese, S.; Copes, R.; Liuc, F.; JiangWu, H.; Hou, R.; Chena, H. Temporal and spatial variability of traffic-related noise in the City of Toronto, Canada. *Sci. Total Environ.* **2014**, *472*, 1100–1107. [CrossRef]
19. Geraghty, D.; O'Mahony, M. Investigating the temporal variability of noise in an urban environment. *Int. J. Sustain. Built Environ.* **2016**, *5*, 34–45. [CrossRef]
20. Torija, A.J.; Ruiz, D.P.; Ramos, A. A method for prediction of the stabilization time in traffic noise measurements. In Proceedings of the 19th International Congress on Acoustics, Madrid, Spain, 2–7 September 2007.
21. Torija, A.J.; Ruiz, D.P.; Ramos-Ridao, A. Required stabilization time, short-term variability and impulsiveness of the sound pressure level to characterize the temporal composition of urban soundscapes. *Appl. Acoust.* **2011**, *72*, 89–99. [CrossRef]
22. Gajardo, C.P.; Barrigón Morillas, J.M. Stabilisation patterns of hourly urban sound levels. *Environ. Monit. Assess.* **2015**, *187*, 4072. [CrossRef]
23. Wunderli, J.M.; Pieren, R.; Habermacher, M.; Vienneau, D.; Cajochen, C.; Probst-Hensch, N.; Röösli, M.; Brink, M. Intermittency ratio: A metric reflecting short-term temporal variations of transportation noise exposure. *J. Expo. Sci. Environ. Epidemiol.* **2015**, *26*, 575–585. [CrossRef] [PubMed]
24. Brambilla, G.; Confalonieri, C.; Benocci, R. Application of the Intermittency Ratio Metric for the Classification of Urban Sites Based on Road Traffic Noise Events. *Sensors* **2019**, *19*, 5136. [CrossRef] [PubMed]
25. Brambilla, G.; Benocci, R.; Confalonieri, C.; Roman, H.E.; Zambon, G. Classification of Urban Road Traffic Noise based on Sound Energy and Eventfulness Indicators. *Appl. Sci.* **2020**, *10*, 2451. [CrossRef]
26. Zambon, G.; Benocci, R.; Brambilla, G. Statistical road classification applied to stratified spatial sampling of road traffic noise in urban areas. *Int. J. Environ. Res.* **2016**, *10*, 411–420.
27. *ISO 1996-2:2017*; Acoustics—Description, Measurement and Assessment of Environmental Noise—Part 2: Determination of Sound Pressure Levels. ISO: Geneva, Switzerland, 2017.
28. Zambon, G.; Benocci, R.; Bisceglie, A.; Eduardo Roman, H.; Bellucci, P. The LIFE DYNAMAP project: Towards a procedure for dynamic noise mapping in urban areas. *Appl. Acoust.* **2017**, *124*, 52–60. [CrossRef]

29. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2020.
30. Barrigón Morillas, J.M.; Gómez Escobar, V.; Méndez Sierra, J.A.; Vílchez-Gómez, R.; Vaquero, J.M.; Trujillo Carmona, J. A categorization method applied to the study of urban road traffic noise. *J. Acoust. Soc. Am.* **2005**, *117*, 2844–2852. [CrossRef]