

A STUDY OF RELATIONSHIPS BETWEEN TRAFFIC NOISE AND ANNOYANCE FOR DIFFERENT  
URBAN SITE TYPOLOGIES

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## A study of relationships between traffic noise and annoyance for different urban site typologies

Cristian Camusso, Cristina Pronello

### Abstract

The paper intends to analyse the different attitudes of residents in urban areas in regard to annoyance induced by traffic noise, account taken of the effects of the street configuration and of the presence of specific public transport modes in the definition of the dose-response curves.

People's annoyance was investigated through a campaign of noise and traffic measurements and an epidemiological survey, administered to a sample of 830 residents in the buildings close to the measurement points.

An ordinal regression model taking into account environmental and urban characteristics was used to identify a dose-response relationship. The cumulative probabilities allowed to define two cut points on the dose-response curves (60 and 75 dB(A)), grouping people in three classes and making the representation of the dose-response relationships different from those traditionally defined that use only the percentage of highly annoyed people.

The results show different people's attitudes towards the annoyance in the urban sites while the dose-response relationship shows that the correlation between annoyance and noise is low. For the same value of day equivalent level, 10% more people are annoyed in L sections (broad streets) than in U sections (narrow streets). Furthermore, all the dose-response curves show a higher sensitivity of people living in L sections; this difference can be measured as a shift of about 4 dB(A). Noise levels are, arguably, a useful indicator, but they are not reliable enough to define the discomfort of the residents, while the site characteristics could shed light on annoyance variability.

### Introduction

Studying noise emissions and related annoyance is important from different points of view because noise affects the quality of the environment, the resident's satisfaction (Kroesen et al., 2009), as well as their well-being and health (Camusso et al., 2010; Ohrstrom, 2004).

Noise brings on social and behavioural effects, notably annoyance and sleep disturbance. From a medical point of view, effects of noise on human health are well documented: hearing impairment, speech intelligibility, physiological disfunctions, mental illness, performance reduction, cardiovascular diseases (WHO, 1999, 2011; Pearsons, 1998; Pearsons et al., 1995; Passchier-Vermeer, 1993; Ohrstrom, 1993). Many of these effects are assumed to result from the interaction of a number of auditory and non-auditory variables.

For this reason, several research projects (SILENCE, Qcity, Harmonoise) have been undertaken to define mitigation techniques as well as a common European approach to reduce the noise emitted in the residential areas (Kephelopoulos et al., 2014; Salomons et al., 2011). However, the need to safeguard the quality of life and the health of the population calls for further efforts for transport noise abatement in regard to the increasing mobility demands. To reconcile these conflicting needs, the EU 6th Action Programme "Environment 2010: Our Future, Our Choice" stipulated that the number of people regularly effected by long-term high levels of noise, estimated as 100 million people in the year 2000, should decrease by around 10% by 2010 and by 20% by 2020. The difficulty to attain those targets is that 54% of people live in urban areas (WHO, 2014), where transport infrastructures represent the most important source of noise. In fact, today 115 million people are exposed to noise levels  $L_{den}$  (day-evening-night noise indicator) higher than 55 dB(A) and 80 million people are exposed to  $L_{night}$  (night-time noise indicator)

higher than 50 dB(A) (EEA, 2011). All over the world, a total of 2 billion citizens are subjected to road traffic  $L_{den}$  of over 55 dB (De Vos and Van Beek, 2011). Thence, policy makers are increasingly demanding the use of reliable and homogeneous instruments for monitoring and evaluating transport noise emissions. In some cases, national norms establish rules to preserve the acoustic quality in specific areas (e.g. parks, hospitals, schools) and to reduce people's noise exposure, recommending the adoption of noise indicators and setting thresholds to comply with.

To this extent, in the literature different noise indicators are proposed (Pronello and Camusso, 2012; Folkesson et al., 2010) according to the type of transport system and to the purpose of the evaluation.

In Europe, the need to define guidelines to set common noise legislation led to the Environmental Noise Directive 2002/49/EC, also known as the "END" (EC, 2002). This Directive requires to monitor noise levels in European cities over one million inhabitants and along the main transport infrastructures. To this end noise maps, showing the  $L_{den}$  and  $L_{night}$  to which people are exposed, are mandatory and dose-response relationships should be defined.

This task is quite challenging because the relationship between annoyance and noise exposure does not depend only on the noise sources, but also on the environmental context in which people live. Furthermore, the diversity of the effect on annoyance caused by the different transport modes suggests that different dose-response relationships can be defined (Miedema and Oudshoorn, 2001; Kryter, 1982; Schultz, 1978). However, while the evaluation of the noise impact of individual transport modes is well established, the assessment of the annoyance due to the noise emissions coming from different sources is more difficult (WHO, 2002; Miedema, 1986, 1996; Vos, 1992; Rice, 1986; Taylor, 1982).

In urban areas, noise is influenced by pavement and traffic typologies (Freitas et al., 2012), by street dimension (Tang and Wang, 2007; Nicol and Wilson, 2004), by urban shape (Montalvão Guedes et al., 2011) and by the presence of public transport (Paunovic' et al., 2014). Some researchers suggest to take into account the unpleasant noise events (Foertsch and Davies, 2013; WHO, 2009) or the awaking percentage and rattle (Eagan, 2007) to better explain annoyance. Also the typology of the area can influence people's disturbance; the access to a quiet area or a green area could decrease the annoyance of the residents (Li et al., 2010; Gidlöf-Gunnarsson and Ohrstrom, 2007; Ohrstrom et al., 2006; WHO, 2003). Moreover, the same noise source could produce a different annoyance, depending on the area – urban or rural (Knall and Schuemer, 1983) – but both areas, if people show high noise sensitivity, are mainly associated with high annoyance (Schreckenberget al., 2010; Fyhri and Klæboe, 2009; Miedema and Vos, 1999).

While the physical variables influencing noise and annoyance are easy to measure, the psycho-physical variables are more subjective, depending on the context and the characteristics of the residents, and they are not easy to interpret (Miedema and Vos, 1999; Fields, 1993).

The dose-response curves have been used to measure annoyance, but the most frequently used ones are based on average values and do not take into account the effect of the different urban contexts.

The paper aims at analysing the annoyance, induced by traffic flows passing along transport infrastructures, on the residents in urban areas and proposing alternative dose-response curves, taking into account the effect of the street configuration and of the presence of specific public transport modes, both on the noise propagation and on the definition of the dose-response curve.

The next section explains the methodology adopted to design the survey and the data analysis. Section 'Results' reports the results of the traffic and the noise measurements, showing the correlation with the annoyance for each of the three periods surveyed: day, evening and night. Finally, the dose-response relationships built on the epidemiological survey are presented. Section 'Discussion and conclusion' discusses those results and matches them with the relevant literature.

## Methodology: the survey and data analysis design

The noise produced by transport in urban areas as well as the disturbance perceived by people subjected to traffic noise is influenced by several variables. Restricting the analysis to the traffic characteristics allows the identification of source typology and its acoustic power, but it does not take into account the context where the infrastructure is located. This could seriously hamper the understanding of people's annoyance, as attitudes of exposed subjects towards noise and their perception are quite significant.

To define the relationships between noise levels and disturbance under a wider perspective, the methodology is based on a four steps approach: (a) the definition of the variables to be measured; (b) the selection of the urban sites where the survey should be conducted; (c) the implementation of the survey (noise levels, traffic flows and people annoyance); and (d) the data analysis design.

### *Variables definition and sites selection*

The first step allowed to define the physical variables (noise levels:  $L_{eq}$ ,  $L_{min}$ ,  $L_{max}$ , statistical levels  $L_{xx}$ , spectrum; traffic conditions, geometric characteristics of the roads) and the psychophysical variables (people's features and levels of annoyance) for the characterisation of the measurement sites and of the exposed people.

The second step addressed the site selection where the survey should be carried out through the definition of a few variables likely to influence the traffic and the noise emission. The variables used for the site selection were those easily measurable in a city: the number of road lanes – used as a proxy for traffic volumes (Nicol and Wilson, 2004) – the site configuration and the presence of tramways. The Design of Experiment (DOE) (Fowlkes and Creveling, 1995) was used to set up an experimentation plan identifying eight sets of locations – the standard sites – where both the noise and traffic measurements and the epidemiological survey should be carried out (Pronello and Camusso, 2007; Pronello, 2003). The “standard sites” are clusters of site typologies frequent in urban areas and where no physical or natural barrier between the street and the receivers is placed.

### *The survey*

The third step consisted on an integrated survey conducted in the city of Torino (north-west of Italy) according to three phases: (1) measurement of the noise emissions, (2) traffic counts and (3) investigation of people disturbance through a questionnaire, aimed to understand the relationships between traffic noise and annoyance of people living in the selected sites.

The campaign of noise measurements has been carried out using the integrating phonometer Larson Davis 824 and the 01 dB Symphonie system. Both instruments comply with the Italian technical specifications (D.M. 16/03/1998) and the European Directive (EC, 2002). Noise data were collected using “Fast” constant sampling, measuring  $L_{eq}$ ,  $L_{min}$ ,  $L_{max}$ , statistical levels  $L_{xx}$  and the spectrum in third octave bands. Each selected site was monitored once, during a continuous period from 8 h to three days. The noise was measured in the façade, 3 m from the axis of the outside lane and 4 m above the ground level, and the phonometer was placed on the balcony (first floor) of private homes. This is the reason of the variability of the measurement duration, constrained by the presence of the apartment owner.

At the same time traffic measurements were carried out, recording the number and typologies of vehicles as well as their speed, using the traffic counter HI-STAR NC-97 and a video camera.

Alongside the physical measures of noise and traffic, an epidemiological survey was carried out to record people's disturbance and noise perception in the selected sites. To offset the influence of the distance between noise source (traffic) and receiver (dweller) on annoyance perception, distance has been kept constant including in the epidemiological survey only people living close to the measurement point (see location of those points at the methodological description), in order to replicate exposure conditions.

Measurements and the survey were conducted in four different periods carrying out the noise and traffic measurements and administering the survey in the same time intervals to a total sample of 830 residents of the buildings close to the measurement points in the selected standard sites. Each person was surveyed only once through a questionnaire. A letter containing the paper questionnaire was sent to the selected sample, explaining the scope of the survey and announcing a phone call for respondents to opt for their preferred survey type. The questionnaire was administered according to a mixed technique: via web, e-mail, telephone and face to face interviews, according to respondents' preferences; it consisted of five sections:

1. the socioeconomic characteristics of the respondents: age, gender, occupation, income, etc.;
2. the characteristics of the dwelling: the floor at which the flat is located, the number of rooms, the typology of the windows, the layout of the different rooms specifying, for each room, whether they have a view on the street;
3. the perception of annoyance;
4. the attitude and sensitivity to noise;
5. the information about their personal health conditions.

The questionnaire was designed according to previous experience in similar studies (Pronello, 2001, 2006) and the state-of-the-art literature (ISO/TS 15666, 2003; Schultz, 1978).

Annoyance was evaluated through questions using five and seven points Likert scales (Likert, 1932) where respondents were asked to score their level of annoyance (from "not annoyed" to "very much annoyed") during different time slots, to find out potential changes along the day:

- day: 06:00–08:00; 08:00–09:00; 09:00–13:00; 13:00–17:00; 17:00–18:00; 18:00–19:00;
- evening: from 19:00 to 22:00;
- night: from 22:00 to 24:00 and from midnight to 06:00.

Besides the perception of annoyance in specific periods, a personal assessment of the street acoustic quality (named "street score") throughout the whole day was requested, measured on a five points Likert scale (from "quiet" to "not tolerable"): "How do you qualify your street under the acoustic point of view?"

### *The data analysis design*

The data analysis aimed at the following:

- illustrating the sample characteristics;
- analysing the relationships among the variables through an inferential analysis.

Data collected in the standard sites were as follows:

- qualitative: they come from the questionnaire and are classified into:
  - categorical data, as gender, occupation, etc., and dichotomous variables ("yes-no" answers);
  - ordinal data: level of education, level of annoyance and, in general, all data that can be ordered;
- quantitative: socioeconomic characteristics, noise and traffic data; they are numeric values expressed on "ratio scales", such as age, income, number and speed of vehicles,  $L_{eq}$ .

To properly describe the measured data and to find the relationship among them, some elaborations on traffic and disturbance data have been carried out.

The variable “number of lanes” allowed segmenting the sites according to the traffic volumes. For the “day period”, the traffic measurements allowed building a new variable, named “TRAFFIC”, divided into three classes:

- Class 1: volume  $\leq 500$  veh/h;
- Class 2:  $500 < \text{volume} \leq 1500$  veh/h;
- Class 3:  $>1500$  veh/h;

that was used in the ANOVA test to evaluate the effect on the hourly noise indicators  $L_{eq,h}$ ,  $L_{min,h}$  and  $L_{max,h}$  of the:

- traffic volume (variable called TRAFFIC);
- site configuration (vertical section) with L or U profile depending on the presence of the building on one or both sides of the street (variable called TYPE\_COD);
- the presence of tramway (variable called TRA\_COD). For each L or U section, the standard site with tramway line on the side close to receiver has been chosen in order to make negligible the effect of distance on noise exposure.

For the night period the same approach was used. In that case, due to the fact that traffic volume is lower than during the day and to have enough data for the statistical analysis, the traffic volume was divided into two groups:

- Class 1: volume  $\leq 150$  veh/h;
- Class 2: volume  $> 150$  veh/h.

The analysis of variance (ANOVA) was used for traffic and noise data to compare the site characteristics and confirm the classification made through the DOE.

The ANOVA is a statistical method requiring normally distributed and homoskedastic quantitative data, but it is a robust technique also if that hypothesis is violated (Hair et al., 1998).

The analyses of qualitative figures, and ordinal or quantitative data were conducted through contingency tables in order to evaluate their relationships, notably the ANOVA, the Spearman rho correlation coefficient for ordinal data and the ordinal regression.

To investigate the differences in annoyance during the different periods of the day (day, evening and night), the median of the scores given to annoyance in the different time intervals was used. The median was considered an appropriate indicator as, notwithstanding the normalisation of the scores, the annoyance is expressed through discrete values and, for this typology of data, statisticians do not suggest using the mean to measure the central tendency (Gravetter and Wallnau, 2010).

For each respondent, three values of annoyance for each time period and one variable for the perceived acoustic quality of the street were defined:

- Day\_Ann\_All = median of the annoyance score during the day period;
- Night\_Ann\_All = median of the annoyance score during the night period;
- Eve\_Ann\_All = value of annoyance in the evening period. Since the evening period is a two hours interval, the score is a unique value;
- Street score: value obtained from a specific question as explained in Section ‘The survey’.

When the measurement period does not cover the whole 24 h (day, evening and night), the noise value is calculated using the energetic mean of the available hourly noise values ( $L_{eq,h}$ ,  $L_{min,h}$ ,  $L_{max,h}$ ,  $L_{90}$ ,  $L_{95}$ ), recorded in the three periods (day, evening, and night). Brambilla and Piromalli (2001) have shown that weekly noise may be evaluated by sample measurements during some hours of the day rather than with seven continuous days of measurements. They state that a noise sample measured between 1 p.m. and 5

p.m. could be used to represent the noise in the day period because its value is statistically representative of the same noise value measured over the whole day.

Thence, the noise variables used for the calculation are as follows:

- $L_{day} (L_{eq6\_20})$  = equivalent level or energetic mean in the “day” period;
- $L_{evening} (L_{eq20\_22})$  = equivalent level or energetic mean in the “evening” period;
- $L_{night} (L_{eq22\_6})$  = equivalent level or energetic mean in the “night” period;
- $L_{min\_DAY}$  = minimum level or energetic mean of minimum levels in the “day” period;
- $L_{max\_DAY}$  = maximum level or energetic mean of maximum levels in the “day” period;
- $L_{bg\_DAY}$  = background noise in the “day” period; for this index  $L_{90}$ ,  $L_{95}$  or their average values during the period, depending on the availability of the data, are used;
- $L_{min\_NIGHT}$  = minimum level or energetic mean of minimum levels in the “night” period;
- $L_{max\_NIGHT}$  = maximum level or energetic mean of maximum levels in the “night” period;
- $L_{bg\_NIGHT}$  = background noise in the “night” period; for this index  $L_{90}$ ,  $L_{95}$  or their average value during the period, depending on the availability of the data, are used.

To investigate possible correlations among the noise variables, the annoyance and the standard sites, an explorative analysis over the whole sample was made, using the Spearman “rho” coefficient (Gravetter and Wallnau, 2010).

The evaluation of the dose–response relationship was carried out using the ordinal regression model to predict the probability that a respondent would belong to a defined category of annoyance, taking into account the explanatory variables (Wirth, 2004; Hosmer and Lemeshow, 2000; Agresti, 1984). Having adopted scales with different lengths, the scores were normalised according to Miedema and Vos (1998), where all the scores are referred to a 0–100 scale.

The kind of variables to be included in the model as the dependent variable was defined: the global level of annoyance and the “street\_score”, grouped into three classes:

- Little Annoyed, LA (coded 0) if the “street\_score”  $\leq 30$ ;
- Annoyed, A (coded 1) if  $30 < \text{“street\_score”} \leq 60$ ;
- Highly Annoyed, HA (coded 2) if “street\_score”  $> 60$ .

The central (A) interval was kept wider than the other two and cut points other than those suggested by Miedema and Oudshoorn (2001) were used to evaluate the probability that a respondent belongs to one of the above classes. The reason is that Miedema and Oudshoorn (2001) considered little annoyed (LA) those who expressed an annoyance level higher than 28, annoyed (A) those who gave a score higher than 50 and highly annoyed (HA) those who quoted more than 72. According to their approach, the people citing a score lower than 28 were disregarded while those quoting scores higher than 72 were considered in both levels LA and A.

The other variables used in the model are as follows:

- the equivalent level during the day period, “ $L_{eq\_6\_20}$ ”, because it shows the highest correlation with the annoyance. Unfortunately, as already mentioned, it was not possible to carry out weekly noise measurements, useful for the calculation of the  $L_{den}$ . For this reason it was decided to investigate the relationship between annoyance and noise using measured data on the day period, avoiding using a simulated value for  $L_{den}$ . The “ $L_{eq\_6\_20}$ ” is used as a continuous variable, covariate;
- the site typology, “Type”. This factor allows taking into account the different characteristics of the narrow and broad streets, as shown in the results. This variable is used as a two-levels factor: Type1 (section with L-shaped configuration) and Type2 (section with U-shaped configuration).

The model is built using the “complementary log-log” link function, that is the most appropriate for our data (SPSS, 2007), and it is run using all the respondents of the considered sites (350 cases) and only the variables without missing data.

The socioeconomic characteristics of the sample are not taken into account at this stage; some authors suggest that they are not correlated with the annoyance (Miedema and Vos, 1999; Fields, 1993). A specific study on this issue can be the subject of a future research.

## Results

This section presents the results of the analysis carried out in the standard sites according to the three phases of the survey. Firstly, results of the traffic and noise measurements in relation to the street configuration are displayed, to check the accuracy of the site selection made through the DOE. Secondly, the results of the correlation between annoyance during the three periods – day, evening and night – and the corresponding noise values expressed by different noise indicators are presented. Finally, the dose–response relationships built according to the epidemiological survey are reported.

### *The influence of site configuration on noise levels*

To understand the influence on noise levels of the variables characterising the standard site, traffic flows were grouped in three classes and the ANOVA test was used to evaluate the effect on the hourly noise indicators  $L_{eq,h}$ ,  $L_{min,h}$  and  $L_{max,h}$ .

In Fig. 1 the ANOVA results for “day period” show the statistical significance of the traffic-related variables ( $p < 0.05$ ) while the “presence of tramway” and the interaction “presence of tramway-site configuration” are not significant (respectively  $p = 0.281 > 0.05$  and  $p = 0.226 > 0.05$ ). Furthermore, it is possible to observe that the U-shaped configurations appear noisier than L-shaped ones.

It is possible to observe that in the standard sites, when the traffic flow is low (in our case  $< 500$  veh/h), the sections with tramway are noisier than the sections without it, independently of the L- or U-shaped configurations; when the traffic flow increases, this difference disappears and the presence of tramway is not useful to identify a noisy section (Fig. 1). In urban areas, the traffic speed interval is narrower than in suburban areas (Pronello, 2001); furthermore, the definition of standard site – requiring that the distance between receiver and traffic source is kept constant and that no obstacle between noise source and receiver is present – allows to highlight what causes the difference in noise levels. This is the reason why the results of ANOVA mainly refer to the interaction of the two traffic sources, tram and cars; when the traffic volume is high and speed has a negligible influence, traffic flow becomes the main noise source and masks the other ones (e.g. the tramway).

The ANOVA test was carried out also for the noise indicators  $L_{max,h}$  and  $L_{min,h}$ , important to understand the acoustical climate. The results in Fig. 2 (Part “a” and “b”) show that:

- the interaction “section typology-traffic” does not influence the  $L_{min,h}$  ( $p = 0.445 > 0.05$ ). The U and L sections present the same  $L_{min,h}$  in both groups of narrow and broad streets;
- the  $L_{max,h}$  is not affected by the “presence of tramway” and by the interaction of all three factors (tram, site typology and traffic), showing, respectively,  $p = 0.367 > 0.05$  and  $p = 0.062 > 0.05$ .



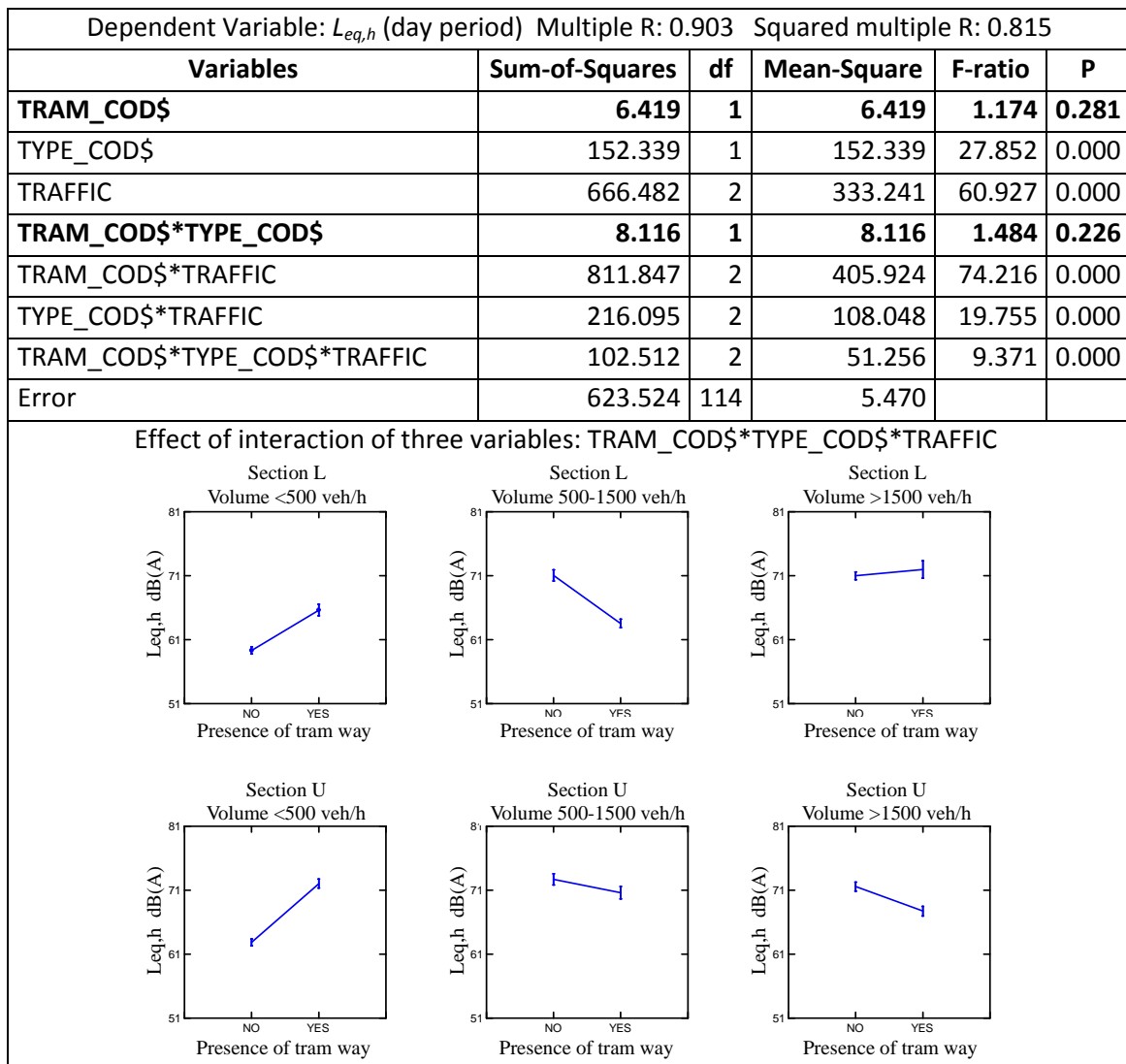


Figure 1 – Anova results about the interaction between hourly  $L_{eq}$  in day period and site variables

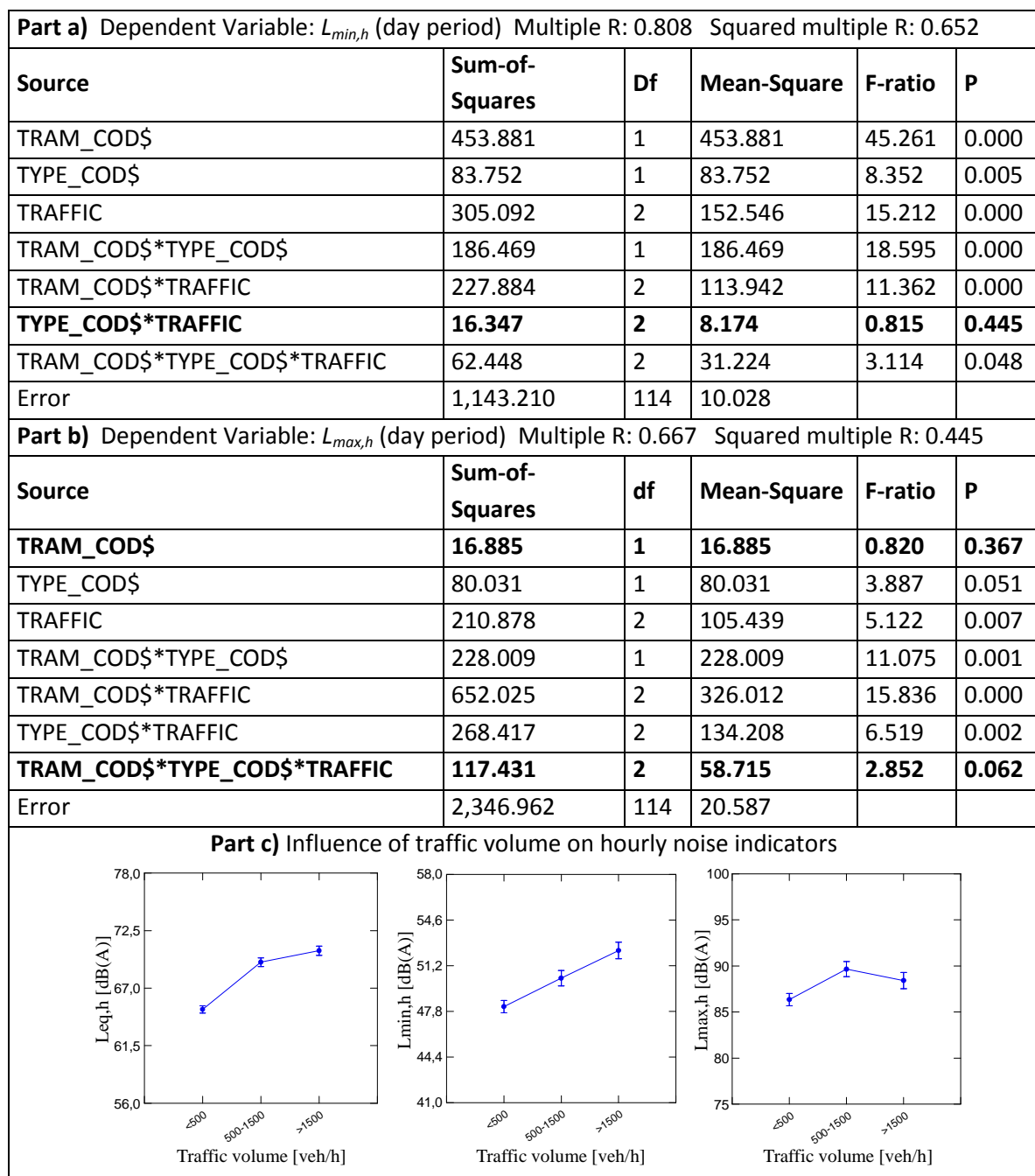


Figure 2 – Anova results: effect of the traffic on hourly noise indicators, during the day period

Both analyses show that the presence of the tramway and the interaction “presence tramway-site typology” are not enough to define noisier sections if traffic volumes are not considered too.

An increase in traffic does generate a corresponding increase of  $L_{eq,h}$  and  $L_{min,h}$ , but this does not apply for  $L_{max,h}$  (Fig. 2, Part “c”).

The reason is that the  $L_{max,h}$  could be influenced by events such as car acoustic systems, vehicle acceleration or other typical noise sources, difficult to ascribe to particular events once the measurements over, and not directly related to the traffic flow.

The analysis for the night period highlights that:

- the value of  $L_{min,h}$  and  $L_{max,h}$  is not influenced by the site typology (the presence of tramway, section configuration, traffic) used to define the standard sites, as shown by ANOVA ( $p < 0.05$ ), and it is not possible to discriminate the sections according to noise levels. As in the day period, the  $L_{max,h}$  due to traffic could be influenced from several events, hard to ascertain from the survey. In general, higher noise values are not correlated with traffic flows;

- further on the night period,  $L_{eq,h}$  is not influenced by the “presence of tramway” and by the interaction of the three above selected factors (the presence of tramway, section configuration, traffic). The “U” profile sections record 6–7 dB(A) more than the “L” ones. When considering the presence of tramway, differences between the “U” and “L” sections are noticed, but only in the “U” sections an increase in noise is recorded (Fig. 3), due, most likely, to the reflective properties at the site.

#### *The annoyance perception in reference to the noise indicators*

The results show that the annoyance during the day and the night period is similar and the scores given to the annoyance during the day period are correlated with those assigned to the night period (Spearman  $\rho = 0.64$ ) and with the global street score (Spearman  $\rho = 0.67$ ).

However, correlations between the annoyance levels during the different periods and the corresponding noise levels appear low: the equivalent level could be not sufficient to describe the perceived annoyance.

To understand whether respondent’s attitude towards annoyance is related to the site typology, the same analyses were conducted on the data grouped according to the geometric characteristics, already used for the site classification.

A different behaviour has been observed between broad and the narrow streets. The streets with less than two lanes, the tramway and a U-shaped configuration are typically narrow streets; for them the correlation coefficient between noise levels and annoyance is very low for all the combinations of the variables.

The streets with more than two lanes, no tramway and L-shaped configuration are typically broad urban streets; for them the correlation coefficients range from low to high values, showing quite high positive correlations ( $\rho$  from 0.6 to 0.8) between:

- the annoyance during the day period and the following indicators: the annoyance during the night period, the  $L_{min}$  during the night period, the background noise during the day and the global street score;
- the annoyance during the night period and the background noise during the day;

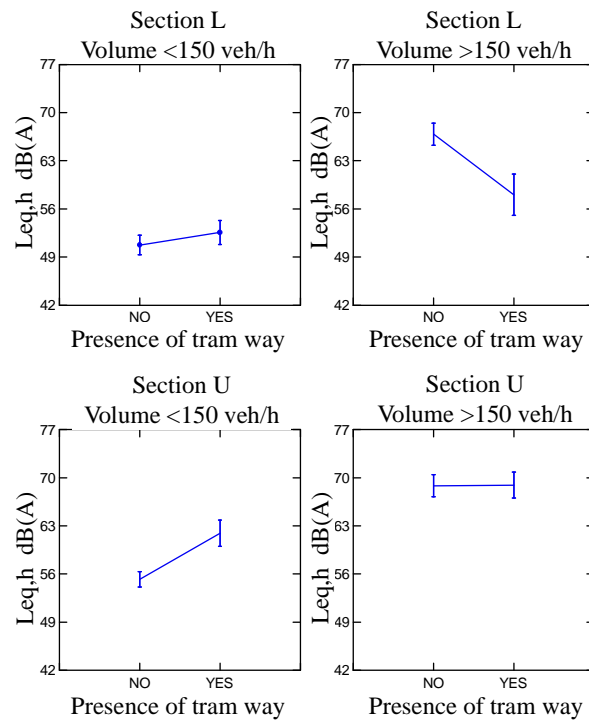


Figure 3 – Effect of variables interaction on  $L_{eq,h}$  during the night period

and lower negative correlations ( $\rho$  from 0.5 to 0.7) between:

- the annoyance during the day period and both the  $L_{max}$  during the day and the night period;
- the annoyance during the night period and both the  $L_{max}$  during the day and the night period;
- the annoyance between the global street score and the  $L_{max}$  during the day period.

The above correlations between the day annoyance and the noise level during the night – and vice versa – in different site configurations, call for further research in future studies to assess whether the noise stimulus can cause a stress influencing the perception of the disturbance also in other periods of the day.

#### *The dose–response relationship*

The results show that all the explanatory variables used are significant (Wald test with  $p < 0.05$  for all the variables), even though the variance explained by the model is partial (Nagelkerke  $R^2 = 0.144$ ).

Eqs. (1) and (2) give the cumulative probabilities for the two categories LA and A defined by the model.

$$\text{Prob}_{LA} = 1 - \exp^{-\exp[6,158 - (0,103Leq6_{20} + 0,306Type1 + 0Type2)]} \quad (1)$$

$$\text{Prob}_A = 1 - \exp^{-\exp[7,908 - (0,103Leq6_{20} + 0,306Type1 + 0Type2)]} \quad (2)$$

where:

- $Leq6_{20}$  = equivalent level during day period;
- Type1 = dummy variable for L shape; it is equal to “1” if the model is used for data in L sections and to 0 otherwise;
- Type2 = dummy variable for U shape; it is equal to “1” if the model is used for data in U sections and to 0 otherwise.

The probability that a respondent belongs to categories LA, A or HA, is given by the difference in the cumulative probabilities and it is reported in Eqs. (3)–(5):

$$\%LA = \text{Prob}_{LA} = 1 - \exp^{-\exp[6,158 - (0,103Leq6_{20} + 0,306Type1 + 0Type2)]} \quad (3)$$

$$\%A = \text{Prob}_A - \text{Prob}_{LA} = \exp^{-\exp[6,158 - (0,103Leq6_{20} + 0,306Type1 + 0Type2)]} - \exp^{-\exp[7,908 - (0,103Leq6_{20} + 0,306Type1 + 0Type2)]} \quad (4)$$

$$\%HA = 1 - \text{Prob}_A = \exp^{-\exp[7,908 - (0,103Leq6_{20} + 0,306Type1 + 0Type2)]} \quad (5)$$

In Fig. 4, the curves represented by Eqs. (3)–(5) are depicted, showing the influence of the variable “Type”.

The curves, for the streets with L-shaped configuration (Type1), are represented by continuous lines while dashed lines are used for the streets with U-shaped configuration (Type2).

The results show that, for the same value of day equivalent level ( $Leq6_{20}$ ), different reactions are registered. In L sections, at 55 dB(A), 30% of respondents are annoyed (A) and 70% lightly annoyed (LA). At the same level, for U sections, 20% of annoyed people (A) and 80% of lightly annoyed (LA) are recorded. If higher noise levels are considered, for example, 85 dB(A), a similar phenomenon can be observed: in L sections, 5% are lightly annoyed (LA), 22% are annoyed (A) and 73% are highly annoyed (HA). Instead, in U sections, figures are, respectively, 6% (LA), 28% (A) and 66% (HA). Thus, the curves show that, for the same noise level, in the L sections the probability that people are more annoyed is higher. Such difference is about 10% for each class of annoyance. Furthermore, all the dose–response curves show a higher sensitivity of people living in L sections (broad streets) who are similarly annoyed to those living in U

sections (narrow streets) for noise level less than 4 dB(A). For example, in LA curve, the 70% probability of being lightly annoyed (LA) occurs at 55 dB(A) in case of L sections while, at 59 dB(A), in case of U sections.

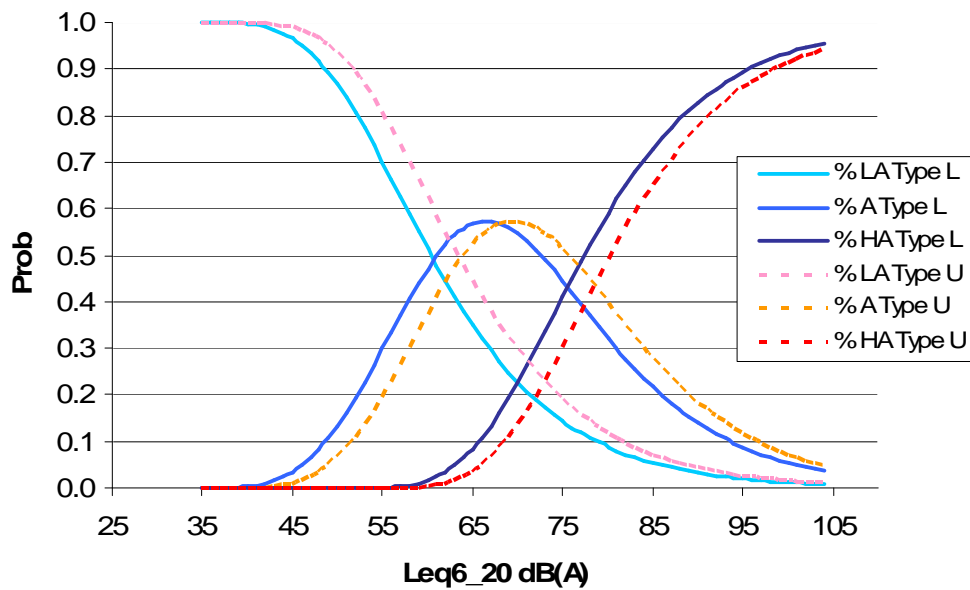


Figure 4 – Dose-response relationship expressed by the Eqs. (3)-(5).

This difference is not constant; notably, for LA and HA curves, differences decrease at the ends (lower and higher values of noise level); for A curve the same pattern applies except in the mid part of the curve (around 67 dB(A)).

Such result highlights that, at very low and very high noise levels, the annoyance perception is the same in each standard site; instead, from 45 to 95 dB(A) the annoyance could be influenced by the site configuration. This fact means that standard configuration always affects annoyance as the extreme values are quite difficult to register in a city. The reason could refer to people's sensitivity and to their expectation of being relaxed at home. Actually, buildings in the standard sites with L section are close to parks or green areas, having high property values and people living in those buildings are probably less willing to be exposed to certain noise levels. This aspect should be further investigated in future research.

Moreover, it is possible to define two cut points (the intersection of HA curves with the other two curves) related to the change in the annoyance level with higher probability of occurrence (Fig. 4), defining three intervals: up to 60 dB(A) the highest probability is that people are little annoyed (LA), from 60 dB(A) to 75 dB(A) the highest probability is to being annoyed (A) and over 75 dB(A) it is most probably to be highly annoyed (HA).

## Discussion and conclusion

This research has tackled the issue of the noise impact produced by the transport infrastructures pointing out the factors influencing the annoyance of the residents in the urban areas. The study of the phenomenon is complex because it puts in relationship the environmental and urban and transport planning issues with health and well-being.

This paper tries to investigate some of the possible relationships between noise emissions and annoyance perception taking into account the urban context.

The application of the Design of Experiment (DOE) to choose the measurement sites has proved a good way to design the data analysis and to find the factors influencing the noise through the definition of the "standard sites". Such approach allowed finding out that, during the day period, the noise produced by

road traffic (notably the traffic volumes) masks the noise produced by the tramway. An increase in traffic flows generates a corresponding increase of  $L_{eq,h}$  and  $L_{min,h}$ , but with different magnitude, while this does not apply for  $L_{max,h}$  (Fig. 2, Part “c”) as, in some cases, the  $L_{max,h}$  decreases. The reason is that the  $L_{max}$  could be influenced by some street events such as use of car acoustic system, vehicle acceleration or other typical road noises difficult to recognise from the measurements, like scooters passing by (Paviotti and Vogiatzis, 2012). For low traffic flows (in our case <500 veh/h) sections containing a tramway line are noisier than sections without it, whatever the site typology (L or U shape). Instead, when the traffic flow increases, this difference disappears (Fig. 1) due to the interaction of the two sources; when traffic flows are higher they become the main noise source and mask the other ones (e.g. tramway).

Furthermore, sections with U-shaped configuration appear to be noisier than L-shaped ones, under the same traffic conditions.

This result could help technicians and decision makers in selecting the sample points where monitoring the environmental noise produced by the infrastructures, notably in urban areas. In particular, if the aim is monitoring the noisiest sections, for narrow streets it is better choosing those with tramway lines while, in case of broad streets, any typology (with or without tramway) is good. This aspect supports the consideration of noise issues in transport planning, suggesting the location of tramway lines in streets with high traffic volumes because they are masked by traffic flows and do not worsen the acoustical climate any further, unlike the narrow streets where tramways are the predominant noise source, increasing people’s annoyance. For noise monitoring it is common to set up a grid on the built-up area in order to identify a spatial sample zone, close to transport infrastructures, where noise measurements should be taken. The proposed approach aims at changing this procedure and selecting specific site typologies (standard sites) with preferential attention to the streets with U-shaped configurations, as they appear critical in terms of noise levels and annoyance.

The inferential analysis points out the effect of the different site typologies on the dose response relationship, focusing on the following:

- the narrow sections: streets having less than two lanes and U-shaped configuration;
- the broad sections: streets having more than two lanes and L-shaped configuration.

In this first analysis, the narrow streets with U-shaped configuration were selected because they showed the highest sensitivity to the traffic changes and the traffic flow could mask the noise produced by the tram transit.

The evaluation of the relationship between annoyance and noise levels showed a significant, even if weak, correlation between them (from  $q = 0.25$  to  $q = 0.30$ ) in both sections (narrow and broad), showing values coherent with those obtained by other authors (Griefahn et al., 2008; Brambilla and Piromalli, 2001; Guski, 2001). A few exceptions regard annoyance versus the  $L_{min}$  during the night period, the background noise during the day and the global street score. Effectively, the annoyance perceived during the day period influences the perception of the acoustic quality of the street.

Using the noise recorded in the day period and the site characteristics it is possible to argue that, for the same value of day equivalent level ( $L_{eq6,20}$ ), 10% of more people are annoyed in L sections (broad streets) than in U sections (narrow streets). Furthermore all the dose–response curves show a higher sensitivity of people living in L sections; this difference can be measured as a shift of about 4 dB(A).

The two cut points identified on the dose–response curves (60 and 75 dB(A)) make the representation of our dose–response relationships different from that defined by Miedema where a third level polynomial approximation is used to fit the curves (Miedema and Oudshoorn, 2001). The use of an ordinal regression model and the calculation of the cumulative probabilities allowed evaluating, for each level of noise, the likely classification of annoyed people in the three categories. This representation could be useful to explain data to the public and decision makers alike, and differ from that of Miedema and Oudshoorn

where each curve is calculated evaluating the probability to pass a specific annoyance threshold (Miedema and Oudshoorn, 2001).

The results show different people's attitudes when they express their annoyance in urban sites. Noise levels are useful, but not conclusive enough to define the discomfort of the residents, while the site characteristics and people's sensitivity to noise, could shed light on the annoyance variance. In particular, it will be useful to investigate also noise indicators to describe the variability of noise during the day and the interaction of this variability with urban site configuration. Arguably, the annoyance perceived by residents could be influenced, for example, by the variability during the day of the traffic noise, not measurable with a single value of  $L_{eq}$ , or by the noise reflection effect due to the buildings in the different site configurations. This aspect should be researched in forthcoming works.

The paper gives some initial clues and highlights the need to investigate in depth the relationships between noise level and annoyance not only to obtain a better evaluation of the perception of disturbance, but also to allow a global evaluation of the urban soundscape, taking into account the city configuration thus supporting urban planners and developers. In addition, an interesting outcome is related to the approach used to measure the noise and traffic data, alternative to the current technical indications and overcoming the difficulty of the continuous seven days noise measurement.

A further development of the research could be the annoyance assessment in the selected urban sites as a function of the long-term indicator  $L_{den}$  as well as an in depth investigation on possible correlations with socioeconomical characteristics of exposed people. Furthermore, more data are required to analyse in depth the night period, using different noise indicators, such as the number of events or other indicators proposed in the literature (Pronello and Camusso, 2012), that in the current research could not be taken into account for noise recording limitations.

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