A new procedure to carry out noise and vibration measurements oriented to support an annoyance evaluation in the framework of the Life SNEAK project

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ABSTRACT

The LIFE SNEAK project, started in September 2021, aims at the reduction of noise from road traffic that mainly affects densely populated urban areas where the noise and vibrations produced by the tram overlap with noise produced by road traffic.
Applicative measures will be designed and tested in a pilot case of the city of Florence, such as low-noise and vibration surfaces with life cycle costs comparable to those of traditional surfaces, and measures to reduce tram noise aiming to obtain substantial reductions in noise and annoyance.
In the first phase, specific attention was dedicated to the state-of-the-art analysis concerning prediction and monitoring of the level of noise and ground-borne vibrations in urban environments. Moreover, the impacts of road traffic and tramway in terms of noise and vibrations on people annoyance in urban context have been investigated to design appropriate questionnaires for citizens. In fact, the exploration of any combined effect of vibration and noise on annoyance is also suggested by recent guidelines for designing dedicated social surveys.
In this paper the procedure to design a noise and vibration measurements and survey campaign oriented to support an evaluation of effective reductions in terms of both levels and annoyance is presented.

1. INTRODUCTION

As reported by the European Environment Agency, noise generated by road traffic is a major environmental problem in Europe. At least 20% of the EU population lives in areas where traffic noise levels are harmful to human health, causing annoyance, sleep disturbance, anxiety, hearing damage and stress-related cardiovascular problems. It is estimated that 113 million people are affected by long-term day-evening-night traffic noise levels of at least 55 dB(A). Thus, the goal of the EU is to cut by half the use of conventionally fueled cars in urban transport by 2030, phase them out in these areas by 2050, and achieve essentially CO_2-free city logistics in major cities by 2030.

The LIFE SNEAK project, co-funded by the EC, perfectly fits into this framework.

The project started in September 2021 and will last 3 years. The project is coordinated by the Municipality of Florence, and the partnership is composed by ASSTRA (Italian Transport

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The main challenge of the LIFE SNEAK project is the reduction of noise from road traffic that mainly affects densely populated urban areas where the noise and vibrations produced by the tram overlap with noise produced by road traffic. This will be achieved by means of low noise/vibration surfaces and retrofitting solutions with life cycle costs comparable to those of traditional surfaces, obtaining a substantial reduction in noise and vibrations.

In the first months of LIFE SNEAK project implementation two main activities have been carried out:

1) an in-depth literature review on the use of recycled materials, binders, mixtures, annoyance due to noise and vibrations induced by road traffic and the passage of trams, considered both as separate and joint contributions, and the types of questionnaires already used to assess public perception, indoor and outdoor noise and vibration measurement techniques and instrumentation
2) ante-operam measurements of noise and vibrations in the pilot area consisting in the performance of ante-operam measurements of noise by means of the CPX method, texture and mechanical impedance, road traffic noise and tram emission noise/vibrations. The roadside noise measurements were carried out in two separate locations at a sensitive receiver (high school) and a residential one. In addition, noise and vibration measurements were also carried out indoors to assess, together with the perception questionnaire, the annoyance perceived inside the building.

In the current paper, an overview about main results achieved until now from these two activities are reported and described, focusing on indoor and outdoor noise and vibrations measurements and survey designing. The paper is structured as follows: Paragraph 2 deals with the design and delivering of perceptive questionnaires; Paragraph 3 concerns noise and vibration measurements carried out indoor and outdoor, together with traffic volumes acquisition; finally in Paragraph 4 conclusions and next steps are described.

2. THE SOCIO-ACOUSTICAL SURVEY

2.1. Inputs from the literature analysis

According to the proposed annoyance evaluation method, beside the measurement campaign designed to evaluate the level of noise and ground-borne vibrations in the pilot case (Paragraph 3), a socio-acoustical survey addressed to exposed people living, working or carrying out their main activities in the proximity of the pilot street is planned.

The main aim of the socio-acoustical survey is to assess the annoyance caused by combined sources of noise and vibration, namely by noise and vibrations produced by road traffic in an urban context. In the case of the pilot street these will overlap with those produced by tramway.

In order to design questionnaires suited to the abovementioned research objective, a literature review focusing on i) recent studies that explores combined effects of vibration and noise on people annoyance and ii) recent guidelines for designing dedicated social surveys has been conducted.

Even though tramway is often seen as an environmentally friendly means of transport, it provides a supplementary noise and vibration source in urban contexts. In recent years, this aspect has started to receive scholar attention because of the repercussions that may have on residents, transport users and tram drivers' wellbeing [1][2]. In particular, complaints from residents living close to the tramway lines prove that tramways in operation may lead to annoyance due to generated noise and vibrations.

Noise annoyance is one of the multiple and intertwined non-auditory effects of noise on humans. It has not a consensual definition; nevertheless, the effect of noise exposure on people wellbeing and health commonly referred to as annoyance is often associated with irritation, depression, anger, and headache caused by continuous noise exposure [3][4]. For this reason, annoyance is considered an essential mediator between noise and well-being [5].
Annoyance due to tramway noise is usually assessed considering single noise exposure, and few studies has so far investigated the impacts of the interactions between road traffic and tramway noise [6]. In addition, the literature on railway suggests the importance of taking into account the combination between noise and vibration when assessing the environmental impacts of trams and their impacts on people annoyance in urban context [7]. Indeed, recent studies have confirmed the role of vibration as enhancing factor for disturbance: in particular, vibration has been reported to influence noise annoyance [8].

Considering that the research on the combination of road traffic and tramway induced annoyance, due to noise and vibration, is still in its early stages, the questionnaire employed for the annoyance evaluation and structured according to the most advanced social research techniques has been designed also according to:

- The Italian standard UNI 9614:2017 [9] that defines the methods to measure the vibrations introduced into buildings by sources inside or outside the buildings and the criteria for assessing vibration annoyance perceived inside the buildings.
- The ISO/TS 15666:2021 [10] which recently revised the ISO/TS 15666:2003 “Acoustics — Assessment of noise annoyance by means of social and socio-acoustic surveys” and provides guidance for socio-acoustic surveys aiming to obtain information about noise annoyance in a residential environment. It offers a noise reaction measure that is considered a valid international comparison of survey results and provides transparent results that could be easily interpreted.
- the questionnaire developed by Howarth and Griffin (2008) [11] that focuses on human responses to vibration in residential building but also encompasses question on noise annoyance.

2.2. Questionnaire design and distribution

During the process of questionnaire’s design, particular emphasis was given to define clear and comprehensible questions for the respondents and provide questions that allow an exploration of combined effect of vibration and noise on annoyance aiming to evaluate noise annoyance, vibration annoyance and total annoyance. In addition, specific questions were included to collect social data, namely the respondents’ socio-demographic characteristics, and personal noise and vibration sensitivity. These are crucial to highlight factors that affect different communities' perceptions and personal responses to noise and vibration.
As shown in Table 1, the structure of the questionnaire consists of eight sections on: i) personal data; ii) information on dwellings or rooms where the respondent lives/works/studies; iii) perception of soundscape; iv) noise annoyance; v) vibration phenomena and related annoyance; vi) total annoyance; vii) expected effects of the tramway passage on noise and vibration perceived indoor; viii) sensitivity to noise and vibration.

Table 1: Main sections of the questionnaire

Section n.	**Section description**	**Focus of the questions**
i	Personal data	Age, gender, education, occupation, city of residence, nationality
ii	Information on dwellings	Windows orientation in relation to the pilot street
iii	Soundscape perception	Perceptions of different type of sounds

		(e.g. traffic noise, natural sounds) and soundscape appropriateness to the urban context
iv	Noise annoyance	Perceived noise annoyance and disturbance during daily activities
v	Vibration annoyance	Perceived vibration annoyance and disturbance during daily activities
vi	Total annoyance	Total annoyance due to the combination of noise and vibration
vii	Expected effects of the tramway	Expected impacts of the tramway passage on perceived traffic noise and vibrations
viii	Noise and vibration sensitivity	Personal sensitivity to noise, personal sensitivity to vibrations

Four slightly different versions of the questionnaires have been prepared, so as to be more adapted to the specific target group (students and teachers of the Castelnuovo high school, residents, shopkeepers and traders), in particular as regards the language used to formulate the questions.

The questions included in the questionnaire are closed-ended questions. In particular, most of them are multiple-choice questions where only one answer can be selected. Questions with a five-point Likert scale, ranging from “not at all” to “extremely”, are employed.
In order to ensure the highest number of completions, two different methods of distribution were selected. Questionnaires were delivered by email to the students of the Castelnuovo high school, which is located within the pilot area. The door-to-door method was employed to distribute the questionnaire to exposed workers and residents in the proximity of the pilot area.
All the participants were informed about the objective of the LIFE SNEAK project and the aim of the socio-acoustical survey.
In addition to the questionnaire submission, the hearing of the participants to the survey was evaluated by means of an audiogram test using smartphone-based hearing test.
The comparative analysis between this ante-operam survey and the planned post-operam survey (after the realization of the interventions foreseen by the project) will allow to evaluate the effects of the new asphalt structure and noise-reduction prototypal system on tram, on citizens perception of noise and vibration.

3. NOISE AND VIBRATIONS MEASUREMENTS

3.1. The pilot street

The pilot interventions foreseen in the LIFE SNEAK project will be located in La Marmora street in Florence (Figure 1).
At present, La Marmora street is a two-way urban street with a width of about 10 meters. The road has sidewalk on both sides and on the right side (northbound) a section dedicated to parking is present. The entire stretch of the street, which runs from Pier Antonio Micheli street to Giacomo Matteotti street, is located within the Restricted Traffic Area of the municipality of Florence.
The northbound lane is mainly used by residents (mainly with light vehicles such as cars and motorcycles), service vehicles with temporary permits, taxis, bicycles, motorcycles and public transport buses.
The other lane is a preferential one and it is used by heavy vehicles (buses), taxis and bicycles.

Figure 1– La Marmora street

In particular, the planned interventions are the implementation of a new experimental low-noise and low-vibration emissions pavement (in the first section) and the installation of a traditional road surface (in the second section).

Figure 2– The two sections of La Marmora street involved in the project interventions

Figures 3 and 4 show the current state of the two sections of the street, namely the one where station P01 (Castelnuovo High School) and station P02 (Residential Building at street number 30) are respectively located.


Figure 3– Current state of site 1 (close to the Castelnuovo High School)

Figure 4– Current status of site 2 (La Marmora street number 30)

Regarding the current state of the road pavement, both Site 1 (Close to the measurement station P01 Castelnuovo High School) and Site 2 (at measurement station P02 corresponding to Via la Marmora 30) present traditional road pavements although with different ages.

3.2 Noise and vibrations measurements

The measurement campaigns carried out from February to April 2022 included the installation of two long-term (weekly) sound level monitoring station at the P01 (Castelnuovo High School) and P02 (Residential Building at street number 30) measuring stations. The two measurement stations were selected to represent the ante-operam situation of the two sections where the interventions envisaged in the project will be carried out.
Concurrently, weekly road traffic flows were registered by means of a radar system station.
The performed monitoring campaign has also included - at the same spots used for the phonometric measurements - the measurement of vibrations performed indoor to assess vibration annoyance based on the UNI 9614 standard. Concurrently, outdoor measurements have been performed.

Figure 5 shows a map with the location of the two measurement spots P01 (Castelnuovo High School) and P02 (Residential Building at street number 30).

In each location the following measurements were performed:

- A weekly measurement of environmental noise using a monitoring station (PR_XX), with an analysis of daily levels and average week levels.
- A weekly measurement of traffic volumes in Via A. La Marmora (CT_XX) by radar detection system with an analysis of vehicle classes, speed and direction.
- Measurement of vibrations performed indoor (VI_XX) by triaxial accelerometer with the analysis of vibration levels according to the UNI 9614-2017 standard. This short-term measurement was carried out at the same time of the aforementioned weekly measurements defined in the vibration measurement campaign. The analysis has focused, as defined by the technical standards, on the situations of greater annoyance that correspond to the passage of heavy vehicles (TPL bus).
- At spot P01 (Castelnuovo High School), in conjunction with vibration measurements, an indoor noise measurement campaign was also carried out. The measurement will allow to carry out a comparative analysis between distinct data (noise outside the buildings, direction and speed of vehicles, vibrations outside the building and vibrations inside the building).

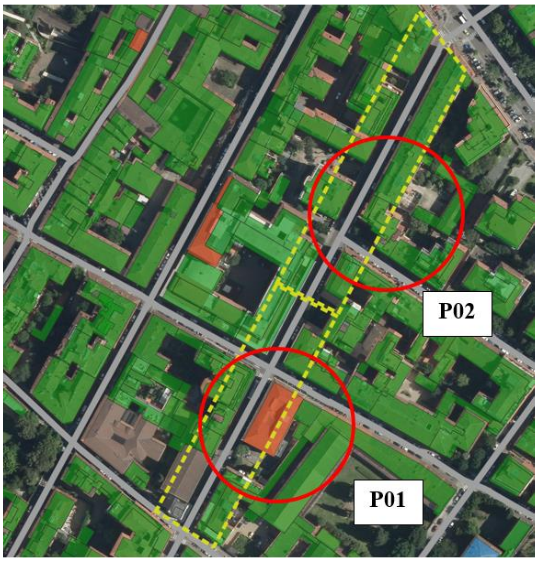

Figure 5– Location of the two buildings where measurements took place

Figures 6 and 7 show the locations of the spots where the measurements were carried out, in addition Table 2 and 3 presents the main information on measurement locations and photographs.

In Table 2 and 3 the following aspects are reported:

- ID: location identifier (px_xx).
- Duration: duration of measurements
- Type of measurement spot: noise, vibration, traffic.
- Description: General data of the measurement station (building category, description, height from the measurement spot, location, measurement system used, limits (acoustic class according to the Acoustical Territorial Zoning of the Municipality of Florence and the limit values of immission defined according to D.P.C.M. 14/11/1997 in dB (A), maximum reference limit values (in mm / s2) of the vibration source defined by the UNI 9614 standard based on the building use destination.
- Pictures: photos taken at the location.

Figure 6– Location of monitoring spots at P01

Table 2: Summary of measurements performed at P01

ID	Type	Description	Pictures
PR_01	Outdoor noise	**Location:** external area pertaining **Duration:** 1 week **Height from the measurement spot:** 4.00 m **Measurement system used**: n. 2 **Acoustical territorial zoning:** school building in IV class. Limit values of noise immission: 65 dB(A) – Class II (only Day period for schools)	
PM_01	Indoor noise	**Location:** In the centre of the room on the ground floor **Durata:** 4 hours **Height from the measurement spot:** 1.50 m **Measurement system used**: n. 3	
CM_01	Traffic	**Location:** Sidewalk in front of school building **Duration:** 1 week **Height from the measurement spot:** 1.00 m **Measurement system used**: n. 5	
VI_01	Indoor vibration	**Location:** In the centre of the room on the ground floor **Duration:** 4 hours **Height from the measurement spot:** on the ground **Measurement system used**: n. 4 **Maximum reference limit values UNI 9614:2017 –** Schools 5,4 mm/s^2	
VO_01	Outdoor Vibration	**Location:** Sidewalk in front of school building **Duration:** 4 hours	

Figure 7– Location of monitoring spots at P02

Table 3: Summary of measurements performed at P02

ID	Type	Description	Pictures
PR_02	Outside Noise	**Location:** external area pertaining **Duration:** 1 week **Height from the measurement spot:** 4.00 m **Measurement system used**: n. 1 **Acoustical territorial zoning:** Residential Building in IV Class. Limit values of noise immission: 65 dB(A): 65 dB(A) day period and 55 dB(A) night period.	
CM_02	Traffic	**Location:** Sidewalk in front of school building **Duration:** 1 week **Height from the measurement spot:** 1.00 m **Measurement system used**: n. 5	
VI_01	Inside Vibration	**Location:** In the centre of the room on the ground floor **Duration:** 4 hours **Height from the measurement spot:** On the floor **Measurement system used**: n. 4 **Maximum reference limit values UNI 9614:2017** - workplaces and residential environments 7.2 mm/s^2	

ID	Type	Description	Pictures
VO_02	Outside vibration	**Location:** Sidewalk in front of school building **Duration:** 4 hours	

3.3. Traffic measurements

Traffic measurements were carried out concurrently with long-term noise measurements by means of a radar system station located in correspondence with the Castelnuovo High School.
Once the ante-operam noise measurements are completed, obtained results in terms of noise levels will be weighted according to the number of vehicles occurred in the measurements period of time.

The analysis of the collected data shows that a great number of vehicles are two-wheeled vehicles (bicycles and motorcycles) which can access via La Marmora with no restrictions and buses.
The southbound lane is a preferential one and it is used by TPL vehicles, taxis and bicycles.
The following figures report the data elaboration regarding the sample collected by the radar system during the monitoring week.

The scatter chart (reporting for each transit the length of the vehicle and the speed) in Figure 8 shows the differences between the different categories of vehicles.
Indeed, from the performed analysis of the sample of vehicles in north direction –where a greater number of transits has been registered- we can clearly observe that:

- the 100-250 cm length range includes two-wheeled vehicles, those below 30 km/h are mostly velocipedes.
- the range of 350-600 cm lengths includes cars, whose average speed is included in the range of 30-50 km /h.
- buses are included in the 750-1100 cm length range, and their average speed is between 30-40 km/h.
- over 1100 cm in length there are unrepresentative samples including vehicles in a column or transiting simultaneously on the two directions, in this case the radar system has detected the total length.

The south direction generally has the same characteristics as the north one, however the number of registered transits is lower, and the category of cars is scantly represented (due to the restricted direction).

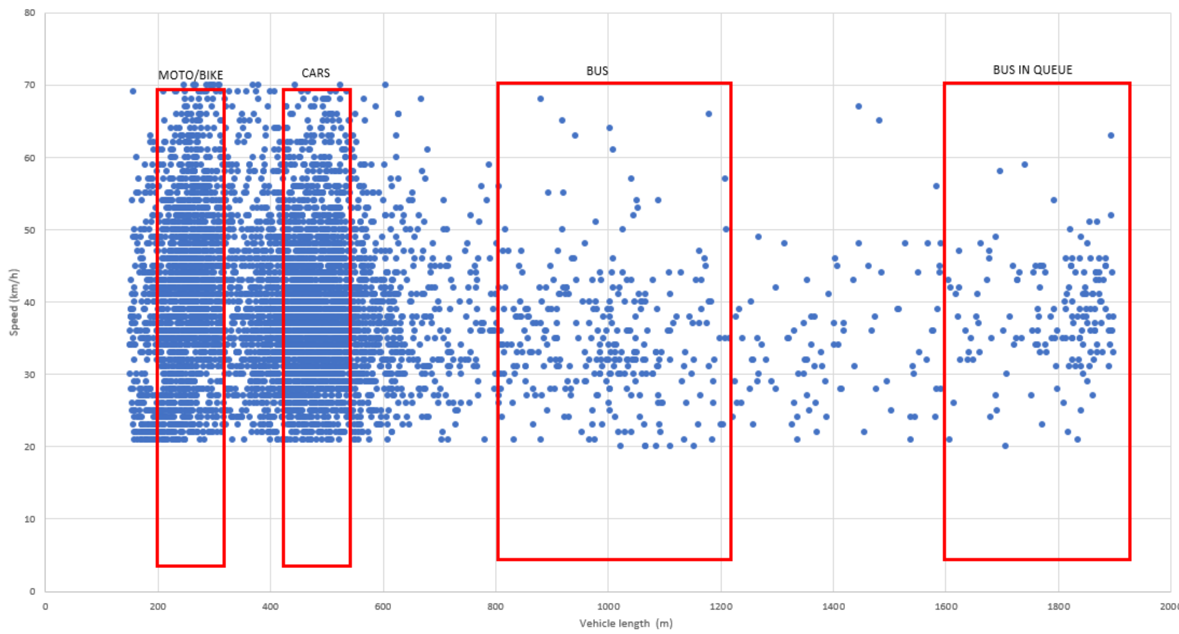

Figure 8– Scatter analysis – Vehicles (North direction)

3.4. Possible interconnection between objective and subjective data

Once the ante-operam noise and vibration measurements and the completion of the questionnaires are complete, the acquired data will be analyzed both separately and jointly.
In particular, as shown in Table 4, it is planned to combine the results of the questionnaires filled in by each target group with specific parameters relating to noise and vibration measurements, also on the basis of the period in which they are specifically carried out (daytime, evening, night-time).

Table 4: Summary of measurements performed at P02

Questionnaire's target group	**Period of activity**	**Noise parameters**	**Vibration parameters**
Students and teachers of the Castelnuovo high school	Daytime	L_{day} and SEL	Weighted acceleration measured in indoor position
Residents	Daytime, evening time and night-time	L_{day}, $L_{evening}$, L_{night} and L_{den}	Weighted acceleration measured in indoor and outdoor positions
Shopkeepers and traders	Daytime	L_{day}, $L_{evening}$	Weighted acceleration measured in indoor and outdoor positions

4. CONCLUSIONS

In European cities, scenarios in which noise from road traffic and noise and vibration caused by the tram system are present are increasingly common. The further exploration of any combined effect of vibration and noise on annoyance is suggested by recent guidelines for the design of social surveys and questionnaires to assess annoyance. This is particularly relevant to the study of tram-induced annoyance, which provides an additional source of noise and vibration in urban contexts, despite the fact that it is often seen as an environmentally friendly mode of transport due to its low emissions. The LIFE SNEAK project is perfectly suited to this scenario, having as its objective the reduction of road traffic noise that mainly affects densely populated urban areas, such as the one in Florence selected as a pilot case, where the noise and vibrations produced by the tram overlap with the noise produced by road traffic. In the first period of project's implementation, after a deep

literature analysis, the design of a perceptive survey aimed at understanding how residents, shopkeepers, traders, students and workers of the Castelnuovo high school perceive noise due to road traffic in the ante-operam scenario has been completed. The questionnaire's submission started, by using different administration modalities: digital ones for students and teachers of the Castelnuovo high school, direct in person ones for the other categories. Moreover, noise and vibrations measurements have been carried out both at roadside positions and at stations inside buildings and traffic volumes concurrently occurred have been collected.
Once the pilot interventions are completed, consisting in the designing and laying of a low emission asphalt to mitigate air-born noise and the reduction of tram noise due to contact between the rail and the wheel through a system of sound-absorbing panels to be applied on the tram (bogie skirts), post-operam measurements and perceptive survey will be carried out within the beginning of 2024 following the same procedure applied for the ante-operam scenario.
This will allow not only a direct comparison of the results obtained in each phase between the same types of measures in order to verify the effectiveness of the interventions implemented, but also to prove the possible existence of correlations between objective and subjective measurements.

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