Improving Urban Noise Monitoring Opportunities via Mobile Crowd-Sensing

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Abstract. In the recent years, mobile devices pervasivity has boosted the diffusion of a novel sensing paradigm known as Mobile Crowd Sensing (MCS). In this paper, we propose a MCS-based system exploiting FIWARE middleware platform and allowing users to gather noise measurements (both opportunistically and participatory) in order to perform large-scale, low-cost and sufficiently accurate urban noise monitoring campaigns. Collected measurements are then aggregated, filtered and interpolated in order to provide city managers with an overview of the actual noise pollution levels in their cities. Specific noise abatement measures are suggested to city managers (in terms of both estimated noise reduction and average installation costs). The already performed field tests demonstrated the feasibility of the proposed approach.

Keywords: Mobile Crowd Sensing · Urban noise monitoring · Urban traffic noise abatement measures · Data Warehouse · FIWARE

1 Introduction

In the last decade, wireless communications have shown an unrivalled growth, in both networks and devices, thanks to a series of key technological enablers [1]. Smartphones and tablets are quickly replacing PDAs and laptops as they can offer an unprecedented combination of computational power and embedded sensors (e.g., 3D accelerometers, hygrometers, gyroscopes, magnetometers, etc.). Moreover, novel broadband 4G wireless standards promise up to 1 GB/s transfer speed and high-quality coverage.

The more the users familiarize with mobiles in their everyday activities, the higher grows the possibility to leverage them effectively in order to improve life quality conditions. As described by the Mobile Crowd Sensing (MCS) paradigm [2], mobiles along with their embedded sensors represent very powerful sensing nodes that overcome the limitations of Wireless Sensor Networks (WSNs), since they provide wider coverage areas, greater number of deployable nodes (without requiring any network reconfiguration procedure when new nodes have to be added), more reliable communication and connectivity. Therefore, mobiles can be dynamically scattered across huge

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areas with heterogeneous sensing purposes and they can acquire contextual awareness opportunistically from the surrounding environment [3]. Similarly, they may improve users' knowledge about specific scientific phenomena and research challenges by engaging them in collaborative, large-scale monitoring experiences that widen the scope of traditional monitoring campaigns [4].

MCS can be applied profitably also in urban scenarios, where citizens can provide information about specific situations occurring around them thanks to their mobiles. Firstly, MCS allows defining innovative services capable of managing contextual information and interacting with user's social and physical situations. Secondly, it makes possible to harvest large and heterogeneous amounts of information from citizens, regarding their continuously evolving urban environments, thus representing a very promising way for city managers to acquire a better awareness of their municipalities without relevant additional costs.

In this research activity, we opted for the urban noise-monitoring scenario, which is gaining relevance in modern cities: several reports from the European Commission address public concerns about how noise can affect the quality of life and encourage local administrators to cope with urban monitoring and planning accordingly.

We propose a system with the following features: (1) users' direct involvement in sensing activities; (2) suggestion of noise abatement interventions to city managers; (3) inclusion of educational aspects; (4) users' opinion collection in order to obtain psychoacoustic measurements (i.e., how sound is perceived by humans [5]). These elements contribute to improve the overall quality of currently available MCS solutions in the noise-monitoring domain (see Sect. 3), which are typically tailored to single user's needs and do not provide any kind of valuable suggestions to city managers.

We designed, developed and tested (in a city from Southern Italy) a prototype of our system that gathers data from mobiles and sends them to a context broker application, which forwards them to a Hadoop-based server farm. These functionalities have been achieved by merging a set of components from the FIWARE middleware [6] to our ad-hoc developed platform. Then, a complete ETL (Extract-Transform-Load) pipeline elaborates and manages collected measurements in a Data Warehouse (DWH) system, for aggregating them w.r.t. sensing location, device type, timestamp, etc. Only freeware and open-source IT solutions have been used to promote knowledge sharing and reuse.

The proposed system is capable of behaving as: (1) a sensing platform; (2) a noise-abatement suggestion system for city authorities; (3) a learning platform for single users (e.g., citizens, students, etc.); (4) a preliminary, low-cost, large-scale and sufficiently accurate monitoring tool suitable to locate areas with potential noise pollution risks where more accurate measurement campaigns can be performed.

The paper is organized as in the following: Sect. 2 describes the actual scenario in terms of noise pollution concerns and Italian noise monitoring regulations. Mobile device pervasivity, MCS paradigm and its application in urban contexts are presented in Sect. 3. The proposed system is detailed in Sect. 4. Section 5 presents the actual outcomes of our research. Section 6 describes conclusions and further developments.

2 Urban Noise: Public Concerns, Health Effects and Regulations

Historically, noise pollution has not been considered similar to other urban pollutants (e.g., chemical or radiological) and still a low number of cities consider noise-related health risks in their policies despite several technical reports by the EU Commission ascertained citizens' concerns about noise pollution issues. According to the 2013 urban mobility report [7], 72 % of Europeans believes that noise represents the fifth most significant problem within cities. This concern reaches even higher values in Italy (83 %), Bulgaria (85 %), Greece (87 %) and Malta (92 %).

As for the Italian situation: only 0.98 % of the cities carried out noise monitoring campaigns in 2013, mainly required directly by citizens (91 %). In 63.2 % of the cases, at least one regulatory threshold was trespassed [8]. In 2014, 52 % of the noise emission controls performed in administrative centers exceeded thresholds, mainly due to high vehicular traffic volumes [9]. Moreover, only 63 % of the Italian administrative centers already complies with acoustic classification plans, as requested by national laws [10].

The necessity of proper noise monitoring activities is enforced also by the outcomes of several scientific research works thoroughly analyzing possible correlations between health effects and noise [11]. The outcomes of a primary exposure to a constant environmental noise source can be classified into acute effects, chronic effects and long-term risks [12] but exposure levels vary depending on multiple causes and on individual basis (i.e., some subjects are more noise-sensitive than other ones). Amongst the acute effects, we can enlist: decrease sleep quality and fragmentation; stress and distraction; noise-induced hearing loss (NIHL). Especially in urban scenarios, *noise annoyance* [13] is experienced. It stands for a series of socio-behavioral changes and overall discontent in citizens residing in noisy areas that may determine additional effects (e.g., increased drug consumption, increased number of accidents). Chronic effects entail hypertension, reduced learning and productivity, disruption of endocrine system and diabetes [14]. The long-term risks concern possible heart disease due to cardiovascular system and permanent NIHL [15].

Noise emissions also heavily affect specific categories of subjects or people exhibiting additional health risks: for instance, children living in noisy contexts or attending schools located in dense urban areas show poor performances, stress, decreased learning rates, misbehavior, concentration deficits and scarce reading comprehension [16]. However, despite the documented correlations between health effects and noise, local authorities do not yet implement stable noise monitoring policies due to several factors, such as high equipment costs, scarcity of skilled personnel and lack of environmental awareness, thus determining an overall relevant requests of novel and proper monitoring solutions to tackle these issues.

In order to assess quantitatively and qualitatively the noise exposure, proper measurement scales are needed. One of the widely adopted scale is the A-weighting: it measures the Sound Pressure Level (*SPL*) in units of *dB(A)* [17] and allows measuring the dependence of perceived loudness w.r.t. frequency. Since sounds are typically fluctuating (i.e., they vary in time and have different durations) and since *SPL* is an instantaneous measurement instead, the Equivalent Sound Level $L_{EQ(T)}$ is preferred [17] as the reference exposure descriptor in noise regulations and guidelines. It measures, in *dB(A)*, the steady sound level conveying the same sound energy of the actual time-varying noise source in a given place during a given time window *T* (where *T* typically ranges from 30 s to 24 h). In a more simplified explanation, $L_{EQ(T)}$ averages the *SPL* values measured during *T*, thus smoothing spikes and outliers.

Italian noise regulations [18] classify urban areas into six *acoustic classes* depending on their main usage and building typologies. As reported in Table 1, different threshold $L_{EQ(T)}$ values are provided for each of those classes. In addition, these thresholds are also expressed w.r.t. [10, 19]: time of the day (*diurnal*: 6a.m–10p.m.; *nocturnal*: 10p.m–6 a.m.); sensor position (*insertion values*: if near the source; *emission values*: if far from the source); road type (w.r.t. vehicle capacity and speed) and age (novel or already existing roads). The Italian laws adopt a precautionary approach, so that the law thresholds that cannot be trespassed (i.e., *limit values*) are always below the noise emission values representing a lower risk or a potential risk for human health (i.e., *quality values* and *attention values*, respectively).

Table 1. $L_{EQ(T)}$ threshold values [10, 18]. Law limits are grayed out. Reference values (15 m from the source): heavy truck 90 dB(A); congested road 80 dB(A); light car traffic 60 dB(A).

Acoustic Class	**Limit [dB(A)]**		**Quality [dB(A)]**		**Attention [dB(A)]**	
	day	night	day	night	day	night
C1. Protected (schools, hospitals)	45	35	47	37	50	40
C2. Residential	50	40	52	42	55	45
C3. Mixed (SOHO, suburban)	55	45	57	47	60	50
C4. Intense human activities	60	50	62	52	65	55
C5. Mainly industrial	65	55	67	57	70	60
C6. Exclusively industrial	65	55	70	70	70	70

3 Mobile Crowd Sensing (MCS) and Its Applications

The most recent analyses for the mobile market forecast that by the end of 2015 mobile cellular subscriptions will reach [20] a worldwide penetration rate of 97 % and 127 % in Western Europe (WE). In Q1 2015, mobile broadband subscriptions reached 535mn in WE only. By the end of the same year, the mobile broadband technology will represent the most dynamic market segment, with a penetration rate of 47 % and an overall network coverage of 69 % of the world population (89 % if we consider the urban population only). The prospected trend for year 2020 is even more evident: worldwide mobile subscriptions will amount 9.2 bn (6.1 bn for smartphones) [20] from the actual 7.1 bn (2.6 bn for smartphones). The increase for WE will amount 140 mn, although the 80 % of new subscriptions will come from Asia Pacific, the Middle East and Africa. As for the mobile traffic growth forecasts, the worldwide monthly data traffic per smartphone amounts 1.05 TB/month for Q1 2015 and it is expected to reach 4.9 TB/month in 2020, with a Compound Annual Growth Rate (CAGR) of 30 % [20].

From a socio-demographic point of view, 90 % of world population over 6 years of age will have a mobile phone by the end of 2020 [20]. In Italy, 59 % of users in the age 16–24 uses smartphones. This percentage increases up to 72 % for individuals ageing 25–34 and 70 % for subjects in the age 35–44 [21].

This success is due to many reasons, such as high data rates, reliable coverage, high Quality of Service, extreme portability, data plans and monthly bills less expensive than fixed-broadband plans. The highest smartphone penetration rates come from youngsters in urban scenarios, since they are the typical early adopters of new technological solutions and they are inclined to use their smartphones to perform many heterogeneous activities (e.g., social networking, audio/video streaming, online shopping, location-based services). Therefore, our application will benefit significantly from its diffusion across youngsters as primary data collectors.

Mobile pervasivity started to be leveraged more than one decade ago, when Burke et al. [22] proposed the notion of *participatory sensing* (PS) to describe how individuals provided with devices capable of collecting and analysing data may become “data source points” without the need of deploying ad-hoc sensor nodes around him and may share local knowledge on a broader scale. The first applications were aimed only at user’s self-monitoring in the healthcare sector but they rapidly broadened their scope so that the original definition of PS has been replaced by the Mobile Crowd Sensing (MCS) [2] paradigm, which allows collecting data directly from mobiles more effectively than traditional WSNs. In MCS, users can choose when monitoring an event (*participatory sensing*) or delegate their mobiles to send data automatically (*opportunistic sensing*). *Community monitoring* represents another increasing trend, aiming at involving larger and larger number of participants in sensing campaigns.

These aspects are particularly evident in urban monitoring scenarios, where four main application areas can be considered: (1) mobility-related issues (e.g., traffic monitoring, parking availabilities, road safety control [2]); (2) environmental monitoring (e.g., air [23] and water pollutants [24] control); (3) emergency management (e.g., flood alerting systems [25], earthquake immediate sensing [26]); (4) large-scale events monitoring and planning (e.g., follow groups of people attending festivals [27]).

As for noise monitoring, the majority of MCS applications are for personal use only: they reproduce the main functionalities of Sound Level Meters (SLMs) and allow users to check how loud their surrounding environment is (e.g., Advanced Decibel Meter[1], Sound Meter Pro[2]). However, they do not provide measurement aggregation on a geographical/temporal basis. Very few research works address urban noise mapping, such as the “Ear-Phone” project [28] where smartphones were used to predict outdoor sound levels, “NoiseSPY” [29], which exploited mobiles carried by bicycle couriers to collect noise data in Cambridge, or the “2Loud?” project [30] that uses iPhones to assess nocturnal noise within buildings near highways in Australia. One of their main limitations, however, is that users are only involved as data collectors but no specific platform functionalities are tailored to city managers for improving urban life quality.

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[1] https://itunes.apple.com/us/app/advanced-decibel-meter/id595718101?mt=8.

[2] https://play.google.com/store/apps/details?id=com.soundmeter.app&hl=it.

4 The Proposed System

The proposed system addresses multiple categories of users: on the one hand, city managers will be provided with a Web application suggesting how to reduce noise levels and where regulatory thresholds are exceeded. On the other hand, mobile users will be allowed not only to collect measurements but also to learn about noise metering and acoustic principles directly on their devices. Our approach also allows overcoming the drawbacks of traditional noise monitoring techniques, which are more accurate but much more expensive. By embedding users' comments, we also can integrate noise socio-acoustic surveys [31] to analyze the noise annoyance.

We followed a Data Warehouse (DWH) approach [32], according to which data are processed in an Extract-Transform-Load (ETL) pipeline: measurements are collected from sensors and then they are cleansed, transformed and stored in order to make them available for final users. Sensor data are suitable to be managed in a multidimensional model: in order to make data management effective, we propose the Dimensional Fact Model (DFM) [32] depicted in Fig. 1A, which also allows us to introduce the corresponding notation. The DFM is a conceptual model whose graphical expressivity and clarity allow representing concepts in a straightforward way, thus easing the comprehension of the multidimensional analyses that can be performed on data. The core element in a DFM is called a *fact* (the rounded box in Fig. 1A): it represents any concept relevant to decision-making processes and which evolves in time; our fact is represented by the noise measurements. Facts are described qualitatively by *fact attributes* and quantitatively by *measures* (i.e., numerical properties or calculations, enlisted in the bottom part of the fact in Fig. 1A). Our measures refer to both *SPL* and maximum/minimum/average $L_{EQ(T)}$. Each analysis coordinate of a fact is called a *dimension* and it consists of several *dimensional attributes* organized as a directed tree departing from the fact (the attributes are the circles connected by lines to the fact in Fig. 1A; the dimension is the root circle). Dimensional attributes qualify the finite domain of their dimension along with its different degrees of granularity (e.g., the temporal dimension can vary from seconds to days, weeks, months; a product is described by its name, series, brand, etc.). In our DFM, the following dimensions have been considered: time (both timestamp and date/month/year); geographical position (latitude, longitude, town, province, region and country); sensor type (external or embedded); device type (model and brand); measurement type; outlier condition. The dimension representing user's annotations refers to the noise source (uniqueness, type, location, annoyance, nuisance and distance from the observer) and it is optional.

As for the platform architecture, we propose an Android-based application to collect noise measurements via mobile-embedded microphones; it mimics a professional SLM and allows users to access a noise regulation repository. The mobile app collects peak, average and current values of *SPL* and $L_{EQ(T)}$ on customizable temporal windows, as required by EU and Italian noise regulations. Measurements are stored locally (short-term history) and sent to the applications hosted on a server farm for data aggregation (both in time and in space) and filtering. The data brokering functionality is achieved by using Orion[3], a Generic Enabler (GE) from FIWARE middleware [6] that offers publishing/subscribing operations on collected data. Another FIWARE GE, namely Cosmos[4], offers HDFS-based persistent storage capabilities in this first system prototype (but alternative implementation strategies are under evaluation). Additional tasks are performed on server side: correlation between annotated and opportunistic measurements or between measurements and vehicular traffic flows.

The logical architecture of the proposed platform has a three-layer structure (Fig. 1B): starting from the bottom, the first layer (data layer) consists of a non-persistent storage solution for mobile-hosted sensor data, the persistent HDFS-based component to host the complete measurement history (implemented via Apache Hive) and a persistent relational DB for noise regulations and guidelines. The second layer has context-brokering capabilities (for managing multiple sensors) as well as data integration, filtering and reporting functionalities (thanks to Pentaho CE[5], a freeware ETL application). The third layer (data presentation) offers a Web app for accessing data reporting and integration results. Mobile devices and a limited number of fixed noise monitoring stations represent data sources. We also developed a Web application for data visualization purposes, specifically tailored to city managers.

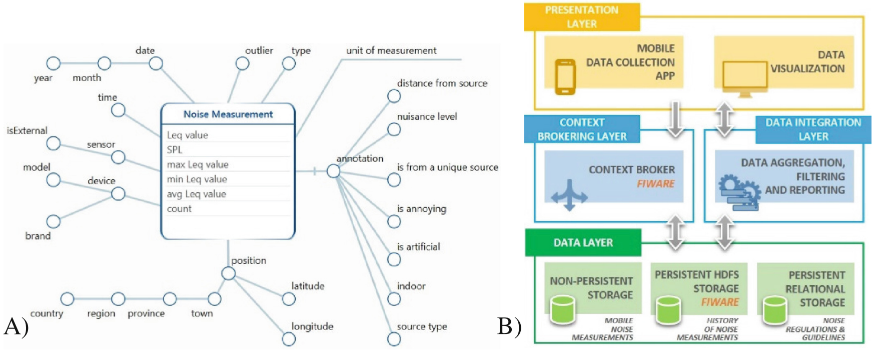

Fig. 1. DFM representation (on the left) and platform logical architecture (on the right).

5 Research Outcomes

The platform has been preliminary tested at our University campus. Subsequently, five students from our faculty performed a field test in a central area of the city of Lecce (Southern Italy). They collected nearly 80 measurements in a 1-h time window by moving across high-traffic hotspots (next to two roundabouts and alongside some 4-lane roads). We will now examine the mobile app at first and then the web app.

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[3] Orion: http://catalogue.fiware.org/enablers/publishsubscribe-context-broker-orion-context-broker.

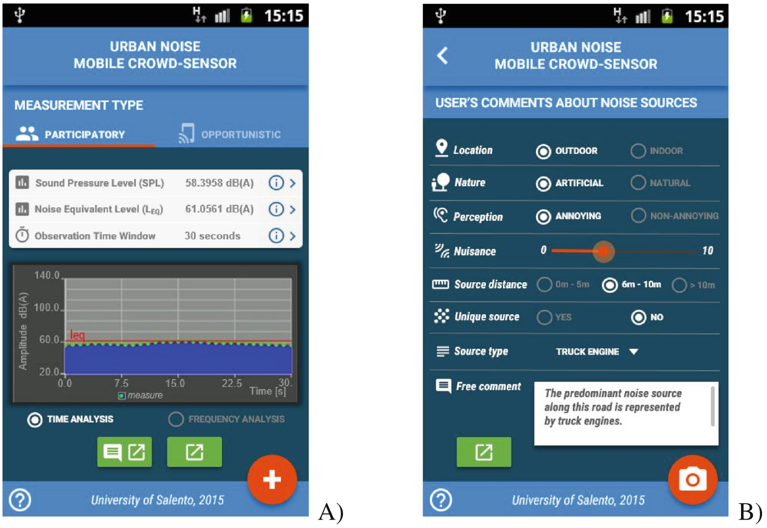
[4] Cosmos: http://catalogue.fiware.org/enablers/bigdata-analysis-cosmos.

[5] Pentaho Community Edition: http://community.pentaho.com/projects/data-integration/.

The user interface (UI) of the ad-hoc developed mobile app mimics a professional SLM, thus offering also to unskilled users a way for learning how to manage such kind of equipment as well as to understand which physical quantities are involved in noise monitoring campaigns. Figure 2A depicts the app page for the participatory measurements. Both $L_{EQ(T)}$ and *SPL* values are reported and plotted on a XY graph (users can switch between time and frequency analysis mode by switching on the radio-button placed below the graph area), as well as the selected observation time period *T*. Once the measurement ends, users can choose amongst: (1) starting a new measurement by discarding the current one (round orange button, bottom right corner); (2) sending the measurement (right green button, page bottom); (3) commenting and then sending the measurement (left green button, page bottom).

Figure 2B represents the app page where users can assess noise sources, in terms of: location (indoor/outdoor), nature (artificial/natural), annoyance, estimated distance from the observer, uniqueness, typology (by selecting amongst a set of predefined values such as truck engine, car traffic, construction site, crowd, machinery, etc.). It is also possible to quantify perceived nuisance levels, by activating a slider representing a psychometric 10-value scale [31], and to add free-text comments. The bottom right button allows users to take pictures of the area where noise measurements come from.

Mobiles embed normal directional microphones instead of professional metering equipment, thus potentially hindering measurement accuracy. We evaluated it instrumentally: we selected a 30 s steady, mid-level, broadband noise source and then we repeatedly compared measurements from different smartphone models against data obtained with a professional, portable, Class-1 SLM (i.e., DeltaOhm HD9019). We achieved an acceptable accuracy: data from mobiles were affected on average by a ± 5 dB bias, which confirms the most recent research works [33] and demonstrates mobile amenability to be leveraged as preliminary monitoring stations. In addition, we also implemented, as a step of the ETL process, a univariate algorithm for the outlier



MEASUREMENT TYPE: PARTICIPATORY

Sound Pressure Level (SPL) 58.3958 dB(A)

Noise Equivalent Level (L_{EQ}) 61.0561 dB(A)

Observation Time Window 30 seconds

● TIME ANALYSIS

Location ● OUTDOOR

Nature ● ARTIFICIAL

Perception ● ANNOYING

Source distance ● 6m - 10m

Unique source ● NO

Source type TRUCK ENGINE

Free comment: *The predominant noise source along this road is represented by truck engines.*

Fig. 2. Mobile UI: participatory measurements (on the left) and users' comments (on the right).

detection in order to remove measurements having an excessive sound level amplitude in a given temporal window. We opted for a slightly modified version of the Tukey's method [34], which is simple and quite effective with datasets having a not highly skewed lognormal distribution as the ones we achieved during the tests.

We also developed a Web application for city managers: it allows to georeference and visualize measurements coming from a given area as points in a *post map* (i.e., a discrete map where the colour ramp used to represent the measurement location points is directly proportional to the measured $L_{EQ(T)}$ values). Another view (Fig. 3) provides users with the interpolation of measurements achieved in the same area as an *intensity map* (i.e., a surface map where adjacent measurements are interpolated according to a given algorithm in order to compute $L_{EQ(T)}$ values also for those points where no measurements were actually performed). Intensity maps are extremely useful for understanding how noise levels are perceived throughout the urban environment without requiring to scatter all across the city mobile sensors. The rendering of both the maps described so far has been achieved by forwarding measurement data, after the ETL process, towards a CartoDB [35] instance, an open-source, cloud-hosted, geospatial database for map storage and visualization.

In addition, the intensity map offers the possibility to dynamically explore how noise level abatement interventions may impact on actual interpolated $L_{EQ(T)}$ measurements: by selecting from proper dropdown lists a given noise abatement measure, users can see how interpolated values could be reduced accordingly on that area. At this moment, we considered measures addressing traffic noise emissions (since they represent the most relevant cause of urban noise pollution). The system suggests, for each different abatement measures, the corresponding estimated impact on $L_{EQ(T)}$ and estimated average costs, as specified in Table 2. Further combinations and more configuration parameters are also possible for such noise abatement measures: they are actually under investigation in order to be implemented in the next prototype of our platform.


Select a noise abatement measure:

Low-noise asphalt: Thin Layer

from 40 to 30 km

Flow Reduction --mixed traffic --normal asphalt: 10%

Traffic calming: Roundabout

Exposure reduction: Noise barrier

Fig. 3. Web app: intensity map of interpolated L_{EQ} with suggested noise abatement measures (on the right). The interpolation refers to measurements collected within a 1-h time window.

City administrators can revolve to two different categories of interventions for traffic noise abatement: measures pertaining to the noise sources (vehicles, roads, traffic) and measures relating to the noise exposure. As for the first category, since municipalities cannot intervene on specifications of vehicles or tyres, we focused on traffic speed/volumes and road pavement techniques. Low-noise asphalts (e.g., thin-layer, double-layer, porous) are low-cost and significantly effective options for reducing traffic noise [36]. Moreover, they can be applied directly in noise hot spots without requiring any relevant environmental or architectonic modification. Similarly, speed limit enforcements, especially in the range 40-70 km/h, and traffic flow restriction measures are particularly useful, not only in terms of noise reduction but also for air quality and road safety [37]. Typically, such solutions have even lower costs for cities than low-noise asphalts but they may have collateral social costs due to travel time losses. Other possible interventions are vertical (e.g., speed bumps/humps, rumble strips) and horizontal (e.g., roundabouts) traffic calming measures [38]: however, administrators must evaluate their application w.r.t. the specific case since each speed reduction artefact may generate additional noise (e.g., once a vehicle reaches a road hump). Noise barriers are the most suitable solution for reducing noise exposure [39] but their average costs are quite relevant (nearly 300 €/m^2 instead of 20 €/m^2 for low-noise asphalts) and their environmental and visual impact is significant.

Conclusively, as reference values, we recall how a ± 2 dB(A) variation is barely noticeable by humans, a ± 3 dB(A) variation is perceptible, a ± 6 dB(A) is clearly perceived, a ± 10 dB(A) is perceived as the doubling/halving of the loudness of a sound.

In addition, we also considered privacy issues, in order to reduce concerns from mobile users about their potential tracking or identification. Indeed, any information or metadata capable of identifying the device owner is discarded and users are notified about this when they start the app for the first time. Mobile devices are only indexed thanks to their IMEI (International Mobile Equipment Identity) code, which do not allow going back to respective owners (therefore, mobiles are traceable but their owners are unknown to both platform managers and other application end users).

Table 2. Urban traffic noise abatement measures: expected impact on $L_{EQ(T)}$ and estimated costs (for vehicle speed/flow reduction measures the installation costs per traffic sign are reported).

Urban traffic noise abatement measure	Expected average impact on L_{EQ}	Estimated average cost
Low-noise road pavement installation [36]		
Two-layer porous asphalt	−5/6 dB(A)	29 €/m^2
Thin-layer asphalt	−2/−3 dB(A)	22 €/m^2
Porous asphalt	−2/−4 dB(A)	23 €/m^2
Stone mastic asphalt	0/−3 dB(A)	12 €/m^2
Dense asphalt concrete (ref. value)	0 dB(A)	17 €/m^2

(*Continued*)

Table 2. (*Continued*)

Urban traffic noise abatement measure	Expected average impact on L_{EQ}	Estimated average cost
Speed reduction (mixed traffic, normal asphalt) [37]		
From 40 to 30 km/h	−0.3 dB(A)	0.2–20 k€/sign
From 50 to 40 km/h	−1.4 dB(A)	"
From 60 to 50 km/h	−2.1 dB(A)	"
From 70 to 60 km/h	−1.8 dB(A)	"
Mixed traffic flow reduction (normal asphalt) [37]		
10 %	−0.5 dB(A)	"
30 %	−1.6 dB(A)	"
50 %	−3.0 dB(A)	"
75 %	−3.4 dB(A)	"
Traffic calming measures [38]		
Definition of a 30 km/h zone	up to −2 dB(A)	0.2–20 k€/sign
Installation of a roundabout	up to −4 dB(A)	150–350 k€
Night time restriction on heavy vehicles	up to −7 dB(A)	0.2–20 k€/sign
Installation of round-top humps	up to −2 dB(A)	500 €/m^2
Installation of flat-top humps	up to +6 dB(A)	500 €/m^2
Installation of round speed bumps	up to +2 dB(A)	200 €/m
Installation of multiple sets of rumble strips	up to +6 dB(A)	500 €/set
Interventions on noise exposure [39]		
Noise barrier (depending on height, design, material)	up to −10 dB(A)	200–400 €/m^2

6 Conclusions and Further Developments

The Mobile Crowd Sensing (MCS) paradigm can find numerous applications in urban planning, as users can explore systematically their habits or specific events within their cities for achieving more sustainable practices and ways of life. In this paper, a MCS-based platform for gathering noise measurements by using mobile-embedded microphones has been proposed. The platform consists of a mobile app allowing users to perform opportunistic/participatory measurements, a data warehouse system for managing data (storage, aggregation and filtering) and a web app providing city managers with multiple views about collected data. The web app also suggests possible noise abatement measures to city managers. The system has been preliminary tested in a central area of the city of Lecce and it assessed urban noise levels effectively; its deployment in a second city with multiple noise sources (airport, commercial/touristic harbour, railway, highway) is under way. Further improvements are actually under development: evaluating model scalability, introducing new monitoring scenarios (railways, airports), combining multiple noise abatement measures and introducing new setup parameters (city areas, noise barrier materials/shapes).

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