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Mobile crowdsensing accuracy for noise mapping in smart cities

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ABSTRACT

This paper deals with the problem of traffic noise in urban areas in terms of noise mapping. It explains in detail the Mobile Crowdsensing (MCS) method and, furthermore, compares the results obtained with this method with the results gained from the standard method that uses a sound level metre. The research done in this paper shows that the MCS method can make noise mapping easier, cheaper and less time-consuming in terms of creating representative noise maps developed on measurements but also noise maps developed on calculations and simulations. The main idea is to show that accuracy and precision of measurements obtained by using calibrated smartphones are acceptable. The paper suggests that when using the smartphone measurement application, the calibration of the measurement chain can be done in free field with class 1 sound level metre, and noise map can be checked in a much larger number of points (in comparison with the standard measurement method) and therefore, smartphones can be used as instruments for creating or even checking final noise maps in urban environment. Another advantage of this method is that citizens can engage in noise monitoring in urban areas and become aware of the noise pollution in their cities.

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Mobile Crowdsensing; IoT; noise pollution; noise map

1. Introduction

Serious noise pollution is one of the most unwanted consequences of rapid urbanization. Various studies have shown that long exposure to noise can result in different health issues, i.e. sleep disturbance, cardiovascular diseases, hearing loss and mental health problems [1–9]. Usually, the major traffic noise sources are vehicles and various industrial plants which both can be monitored. We can conclude that there is a serious need to carefully monitor such noise in urban areas, both in time and space, in order to identify areas with a negative impact on human health.

In these dynamic urban areas, the traditional measuring methods are not particularly suitable due to the expensive and static equipment which they use. On the other hand, the smartphone popularity, accessibility and their technological capabilities, as well as proliferation of different wearable sensors open a new perspective for a wide range of applications for environmental noise monitoring. Within smart cities, there is a service for all smartphone users called Mobile Crowdsensing (MCS). This service encourages users to move and enables them to collect and share sensor data in different urban areas. MCS services can produce detailed sensor readings and provide means to discover new phenomena in urban environments that otherwise cannot be measured by individuals, such as the occurrence

of traffic congestion, or environmental noise pollution monitoring. Smart cities benefit from recent development in Internet of Things (IoT) [10–14]. Thus, this development provides added value to existing public services and improves the quality of citizens' lives. Citizens' involvement in the process through MCS techniques increases the capabilities of these IoT platforms without additional costs. The main idea is that users carry their smartphones and continuously collect a large quantity of sensor readings, either from built-in or wearable sensors.

Related studies and research usually focus on noise pollution monitoring and the quality of collected data. An increasing number of MCS applications aims to use microphones in smartphone devices in order to measure noise levels and to group collected data, all in order to generate fine-grained noise maps. For instance, Noise Tube [15] is a citizen science project developed to measure personal exposure to environmental noise. It also records all measurements to specify noise sources and create city noise maps for the total of 241 cities around the world.

NoiseSpy [16] represents the working environmental noise sensing system, which uses the smartphone's microphone to assess sound levels in the surrounding environment. The purpose of the NoiseSpy project is to create an open platform to measure, record and localize

noise pollution by actively involving individuals who use their smartphones as noise sensors among other things.

Another example is NoiseMap [17], a participatory sensing application for noise measuring which sends collected data to an open urban sensing platform named “da-sense” for further processing.

The focus of this paper is Air and Noise Pollution Monitoring in Zagreb, capital of Croatia, by using MCS [18]. This paper explains the use of the proposed MCS ecosystem in the real-world through smartphone application for crowd-sensed noise and air quality monitoring and measurement. In this research, CUPUS: CloUdbased PUblish/Subscribe, an open-source middleware designed for mobile Internet of Things (IoT) environments which offers real-time acquisition and filtering of sensor data on mobile devices, efficient continuous data processing in the cloud, and near real-time delivery of processed sensor data from the cloud to mobile devices has been used [19]. The results obtained from MCS using wearable sensors and mobile application developed at the University of Zagreb, Faculty of Electrical Engineering and Computing are presented and discussed. The paper shows that the number of volunteers and locations of sampled data can significantly influence the accuracy of noise and air pollution maps. Also, the paper shows that it is possible to create noise and air pollution maps, simultaneously doing spatial and time averaging of sound pressure levels, but it is necessary to discuss the accuracy and precision of such noise mapping. So, this paper deals with the accuracy of measurement results obtained by one smartphone (i.e. iPhone) can serve as a certain guideline for future MCS measurements done via other smartphones.

2. Creating a noise map of the city

Two basic ways of tracking and measuring noise pollution are sound level metre measurements [20,21] and noise mapping calculations with the known acoustic sound power of sound sources (traffic, industry plants, etc.) [22]. A problem when using the sound level metre is that measurements need to be densely sampled in order to obtain the complete coverage of a certain area. The sound level metre takes the sound pressure level at a particular location and it must be calibrated before and after each set of measurements. In terms of traffic noise measurement, such manual data collection method at each measurement position can be very time consuming and expensive [23]. Another way of collecting data is to use noise mapping calculations with the known acoustic sound power of sound sources (traffic, industry, etc.). The outdoor sound attenuation is the sum of the reductions due to geometric spreading, air absorption, interaction with the ground, barriers, vegetation, and atmospheric refraction [24]. It is very difficult to calculate noise levels with all that input data (density of

traffic, average speed, roughness of road’s material, type of trains, airplanes) [25], especially in big cities with many cross-roads, dense traffic and enormous input data set for noise mapping calculation. These noise mapping calculations also need to be calibrated with real measurements in a few points of interest to check the input parameters’ accuracy [26].

The most critical input parameter for traffic noise modelling is the sound power of the road (modelled as a line source) as reported in [27]. The reported difference for the input sound power of the same line source (highway road), measured through periods of time, in different meteorological conditions, with excluded outliers from the results of laboratories which participated in interlaboratory comparison, was ± 9.6 dBA. In the same research, comparing the noise modelling and measurement results for noise indicator L_d , acceptable difference from the reference value (averaged results of all laboratories participated in Interlaboratory Comparison with excluded outliers) was ± 4.5 dBA for measured and modelled results at imission point.

As an example, we took a noise map of Zagreb, capital of Croatia [28], shown in Figure 1. Although the noise level L_d for traffic noise is calculated for the whole city of Zagreb, the obtained results for L_d , in the noise map, in the area where measurements are done, are calculated with data for traffic at intersections and roads with higher traffic frequency. Other sources of noise pollution such as smaller roads, where there is work at progress etc. are not considered. The reasons for this are; if all the existing roads were included, the calculations would be too complicated, or in other words, the calculation process would be very long. Therefore, significant data for all city roads is not available and is therefore not included in the simulation (e.g. number of cars per hour for the day and night, the percentage of trucks for a certain road etc.). Furthermore, noise indicator L_d for comparison with measured results could not be read from the noise map shown in Figure 1 because there is no data for quiet places (park surrounded with buildings) or places near smaller roads. Thus, to compare measured results for equivalent sound pressure levels (with the smartphone and sound level metre measurements) with the modelling results at the same locations, we took a noise map gathered with MCS, shown in Figure 4.

Furthermore, the Environmental Noise Directive [29] requires noise levels to be assessed from road traffic, railways, major airports and industry plants. There is no requirement to assess noise generated by other activities that may arise from construction work, sports and “pleasure” activities (pop concerts). All major cities must meet the requirement to create a noise map, which presents the annual average noise levels at a height of 4 m above the local ground level.

The Environmental Noise Directive requires noise levels to be assessed in terms of L_{den} and L_{night} [20].



Figure 1. Noise map of Zagreb, capital of Croatia, L_d for traffic noise [25].

L_{den} is the equivalent continuous noise level over a 24-h period, but with noise in the evening (from 7 pm to 11 pm) increased by 5 dB(A) and noise at night (from 11 pm to 7 am) increased by 10 dB(A), to reflect the greater noise-sensitivity of people at those times. L_{night} is the equivalent continuous noise level over the night-time period (from 11 pm to 7 am). L_{night} does not contain any night-time noise weighting.

A possible solution for the aforementioned issues is to encourage citizens to participate in the measurement process simultaneously doing spatial and time averaging of sound pressure levels. For that purpose, we have developed an MCS application which uses smartphone's microphone to collect noise data. This approach was in detail described in "Air and Noise Pollution Monitoring in the City of Zagreb" while using MCS [18]. Conclusions of that paper, in short, are that it is possible to make a city's noise map with respect to the following conditions:

- Smartphones that are used in measurements must be calibrated;
- It is necessary to gather a large amount of data in time and in space;
- In order to get the final noise map from the collected data it is necessary to apply data interpolation.

2.1. Calibration of used measurement devices in the free field

The smartphone application is calibrated for each smartphone in a free sound field (anechoic chamber) using a broadband signal (pink noise) which is shown in Figure 2. The obtained sound pressure levels in dB are



Figure 2. Smartphone application calibration for five smartphones.

compared with the results from B&K 2250 calibrated sound level metre at several different ranges of magnitudes (65 dB to 95 dB in 5 dB increments) in other words, following the recommended measurement procedure [30]. The calibrated smartphones and the sound level metre are located at 1 metre distance from the source, and the calibration is carried out for each sound level for the duration of 1 min (Overall Integration Time). Correction factors for all tested smartphones are stored on a server and used for the correction of measured outdoor noise.

2.2. Measurements gathered with MCS

Figure 3(a) shows the location and one of the volunteers' walking routes for collecting data. The data

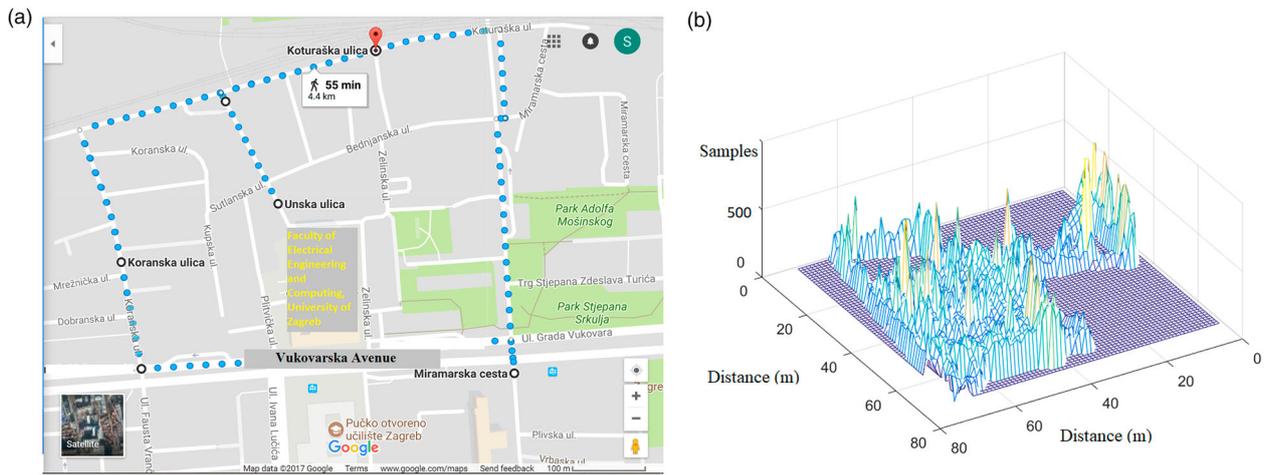


Figure 3. (a) The measured location and the route where data was collected; (b) an illustration of the collected samples distribution.

was collected during the field trial in June 2017. The smartphone was held in the volunteers' hand 1 m above ground. The volunteers were quiet during the data collection and they did not answer phone calls. A smartphone records sound pressure signal in the frames with duration of 1 second (48 kHz sample rate and 16 bits quantization). The mobile application converts the recorded sound pressure in dB and shows the equivalent sound pressure level (L_{eq}) for each second in dB, simultaneously doing spatial and time averaging of sound pressure levels. Additionally, Figure 3(b) shows an illustration of the collected samples distribution, in other words, the number of samples per walked metre [18]. In that way, space-time averaging of the collected data was made.

Furthermore, Table 1 shows a significant amount of noise data gathered for a typical urban sound environment which contains: the crossing of two major roads with heavy dense traffic, a park, a residential area and a business area in Zagreb. It is important to emphasize

Table 1. Collected data set.

Time range	2017-06-05 09:00 to 2017-06-07 15:00
Number of data points	287,831
Temperature readings	28,451
Pressure readings	28,451
Humidity readings	28,441
L_{eq} readings	145,607

that an interpolation method has been used in order to achieve full coverage of the area and to create a precise noise and air quality map. The ordinary Kriging method for the spatial interpolation was used [31]. It is based on the regression against observed z values of surrounding data points, weighted according to the spatial covariance values s . The Kriging method is one of the most widely used geostatistical interpolation methods for the noise data estimation [32,33].

Figure 4 shows a map of noise pollution obtained from the interpolated noise values, where values lower

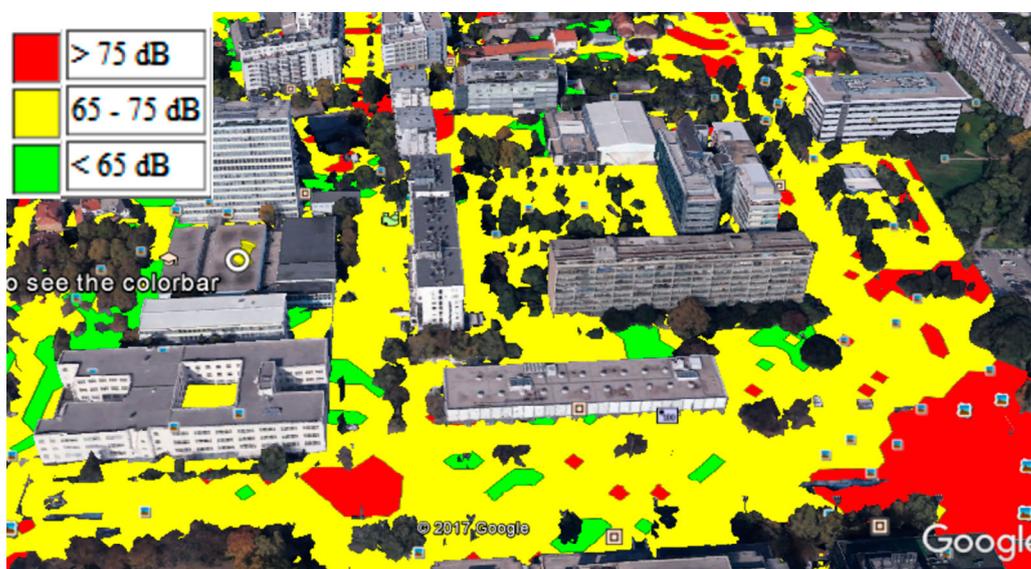


Figure 4. Measured noise level map for the observed area (from 9 am to 10 am).

than 65 dB are considered low, values between 65 dB and 75 dB are slightly elevated, and values greater than 75 dB show high noise levels.

3. The accuracy of measurement results obtained by MCS

The results of practical experience, from sensor calibration to data acquisition, are presented [18] and it can be concluded that the accuracy of noise and air pollution maps depends on the number of volunteers and locations of the sampled data. In order to determine the precision of these measurements and also the accuracy of the obtained noise map, a comparison has been made between the measurements of the MCS campaign with the B&K 2250 calibrated sound level metre at two locations shown in Figure 5. The first location is a noisy crossing near one of the busiest streets in the city of Zagreb (Vukovarska Avenue). Table 2 shows the number of vehicles and the allowed speed for the

intersecting roads [34]. The second location is a park that is 150 m away from the first site and is “protected” from all sides with tall buildings and as such is a quiet area within the city.

In the described locations, the measurements were performed with the sound level metre B&K 2250 and an iPhone 6S. The sound level metre and the smartphone were located at 1 metre height at the same distance from the noise source, i.e. at the same place, one next to the other (see Figure 6). At each location, L_{Zeq} (dB) was measured three times for a period of 3 min. Table 3 shows the sound pressure values measured with the sound level metre while Table 4 shows sound pressure values measured with iPhone 6S. Smartphone records the sound pressure signal in time frames with duration of 1 s (48 kHz sample rate and 16 bits quantization). The mobile application converts the recorded sound pressure in dB and shows the equivalent sound pressure level (L_{eq}) for each second in dB. In order to obtain a numerical value that presents L_{Zeq} (dB) for one

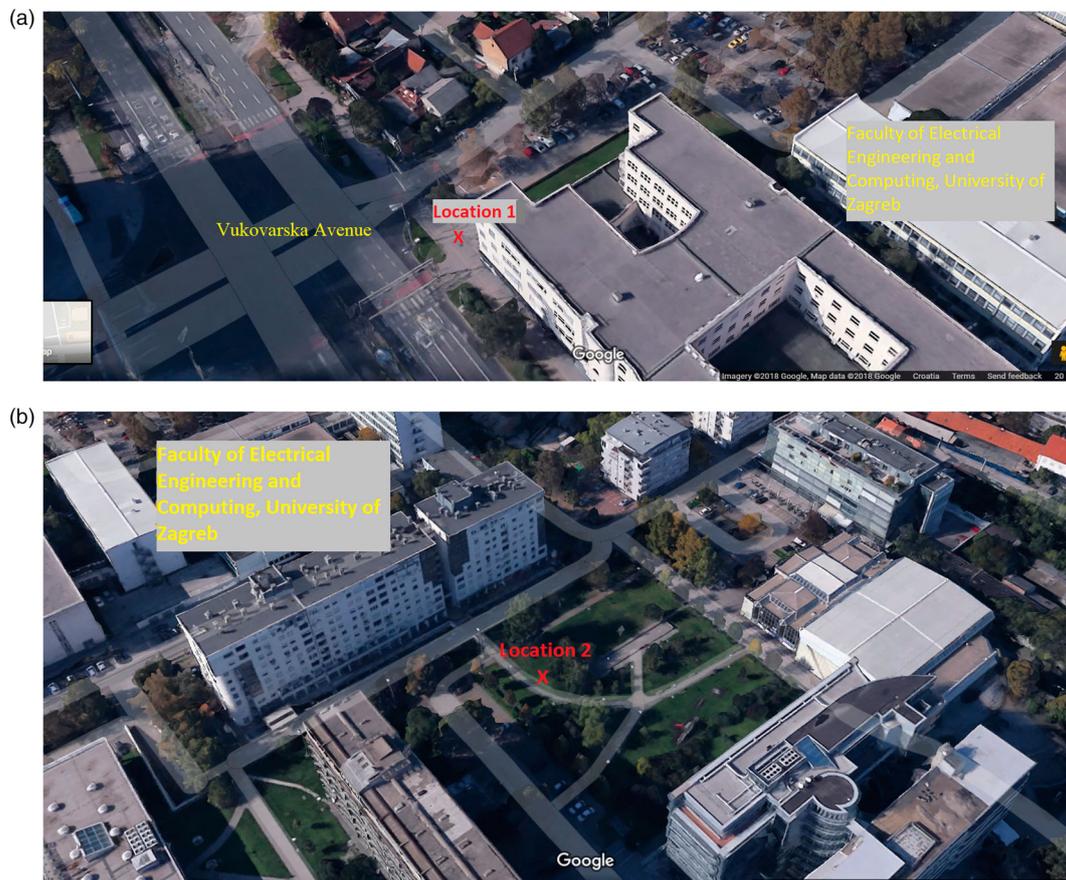


Figure 5. Measurement locations.

Table 2. Number of vehicles and allowed speed for the intersecting roads [31].

		Direction: East → West 6 am to 9 am				
Vukovarska avenue from Miramarska street to Savska street	CARS	HEAVY MOTOR VEHICLES (above 3.5t)	LIGHT MOTOR VEHICLES (below 3.5t)	PUBLIC TRANSPORTATION VEHICLES (trams)	Permitted vehicle speed [km/h]	
	3.956	69	212	42	60	
		Direction: West → East 6 am to 9 am				
Vukovarska avenue from Savska street to Miramarska street	Cars	Heavy motor vehicles (above 3.5t)	Light motor vehicles (below 3.5t)	Public transportation vehicles (trams)	Permitted vehicle speed [km/h]	
	3.956	69	212	42	60	

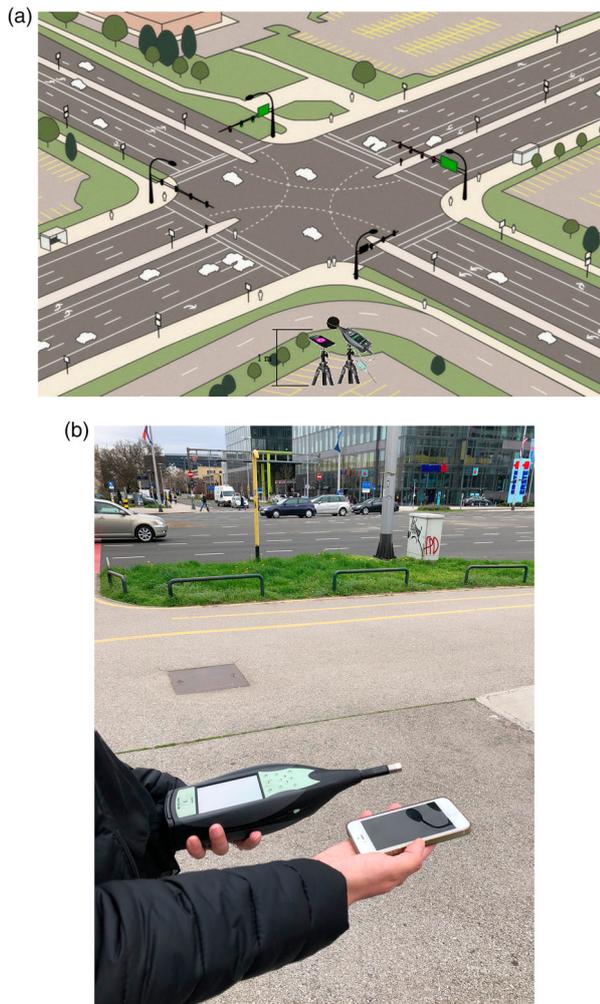


Figure 6. Parallel noise measurements with sound level metre B&K 2250 and iPhone S6.

measurement at a certain location, a mean value was calculated from 180 measured values that the smartphone has collected in 3 min of measurement.

The standard deviation from three measurements (for two locations, e.g. see Tables 3 and 4) is calculated as an estimation parameter for the overall measurement uncertainty (defined in [21]). The overall measurement

Table 3. Sound pressure level measured in two locations (three measurements) with sound level metre B&K 2250 in one third-octave bands from 50 Hz up to 20 kHz.

Location 1	M1	M2	M3	Location 2	M1	M2	M3
L_{Zeq} (dB)	73.74	75.69	74.99	L_{Zeq} (dB)	60.41	61.86	61.70
L_{Zmean} (dB)	74.88			L_{Zmean} (dB)	61.37		
Σ	0.99			Σ	0.80		
σ_x	0.57			σ_x	0.46		

uncertainty depends on several factors (instrument's class, source working conditions, distance from the source to the immission points, meteorological conditions, difference between residual noise level and the level of the noise source – traffic in this case) and it can be determined by knowing sensitivity coefficients for each component.

The usual expanded measurement uncertainty (for coverage probability 95% and cover factor $k = 2$) for the traffic noise is up to ± 4.5 dB [21,27]. However, at distances smaller than 50 m from the source (road) and with no significant influence of meteorological conditions traffic noise can be up to ± 1.1 dB as determined from interlaboratory comparisons in the measurement of traffic noise in Austria [35].

Table 5 shows the comparison of all measured results (iPhone S6 and sound level metre B&K 2250) with the results on noise map gathered with MCS at the same locations shown in Figure 4. Furthermore, it also shows the comparison of the calculated standard deviations for both measurement methods.

Currently, it is not possible to measure the dBA values with the developed smartphone application and in order to compare the measured values with the simulated noise map and its data, a correction factor is calculated from the sound level metre measurement. Since both the sound level metre and the smartphone application have measured the same noise spectrum, it is possible to apply the correction factor for the data obtained from the sound level metre to the data collected via smartphone application. The sound level metre has measured the L_{Zeq} (dB), the spectrum and L_{Aeq} (dBA)

Table 4. Sound pressure level measured at two locations with iPhone 6S (three measurements with integration time 1 s and averaging over 3 min in two locations).

Location 1	M1	M2	M3	Location 2	M1	M2	M3
Sample	L_{Zeq} (dB)	L_{Zeq} (dB)	L_{Zeq} (dB)	Sample	L_{Zeq} (dB)	L_{Zeq} (dB)	L_{Zeq} (dB)
1	63.90	68.38	74.69	1	65.97	53.03	56.15
2	65.43	70.24	70.07	2	65.74	55.69	52.11
3	62.56	72.53	79.08	3	62.21	52.06	55.50
4	63.82	72.14	77.22	4	57.96	53.25	53.91
5	65.55	69.71	73.41	5	57.75	53.03	54.22
6	65.49	66.68	75.59	6	56.10	56.10	56.33
178	75.15	...	68.76	178	56.84	...	57.99
179	81.82	76.31	76.06	179	56.12	53.29	59.61
180	75.40	75.91	71.17	180	55.97	51.69	56.05
L_{Zeq} (dB)	71.96	74.49	72.67	L_{Zeq} (dB)	63.95	52.23	58.17
L_{Zmean} (dB)	72.70			L_{Zmean} (dB)	62.91		
Σ	0.69			Σ	3.45		
σ_x	0.40			σ_x	1.99		

Table 5. Comparison of measured results at two different locations.

Location 1	Sound level metre	iPhone 6S	Noise map	Location 2	Sound level metre	iPhone 6S	Noise map
σ_x	0.57	0.40	–	σ_x	0.46	1.99	–
L_{Zmean} (dB)	74.88	72.70	> 65 dB and < 75 dB yellow	L_{Zmean} (dB)	61.37	62.91	< 65 dB green

Table 6. L_{Zeq} (dB) and L_{Aeq} (dBA) values measured in two locations (three measurements) with sound level metre B&K 2250.

Location 1	M1	M2	M3	Location 2	M1	M2	M3
L_{Zeq} (dB)	73.74	75.69	74.99	L_{Zeq} (dB)	60.41	61.86	61.70
L_{Aeq} (dBA)	65.73	66.43	67.43	L_{Aeq} (dBA)	49.14	51.58	50.22
Corr1	–8.02	–9.26	–7.56	Corr1	–11.27	–10.29	–11.48

Table 7. L_{Zeq} (dB) values measured at two locations with iPhone 6S, and calculated sound pressure level L_{Aeq} (dBA) values.

Location 1	M1	M2	M3	Location 2	M1	M2	M3
L_{Zeq} (dB)	71.96	73.34	72.67	L_{Zeq} (dB)	63.95	64.34	58.17
Corr1	–8.02	–9.26	–7.56	Corr1	–11.27	–10.29	–11.48
L_{Aeq} (dB)	63.95	64.08	65.12	L_{Aeq} (dB)	52.68	54.05	46.69

Table 8. Comparison of measured and calculated A-weighted results at two different locations.

Location 1	Sound level metre	iPhone 6S	Location 2	Sound level metre	iPhone 6S
L_{Amean} (dBA)	66.58	64.41	L_{Amean} (dBA)	50.43	52.10
Σ	0.86	0.64	Σ	1.22	3.92
σ_x	0.49	0.37	σ_x	0.71	2.26

values which are shown in Table 6. From the measured values of L_{Zeq} (dB) and L_{Aeq} (dBA), the correction factor Corr1 was calculated for both measurements at both locations. The correction factor Corr1 calculates the L_{Aeq} (dBA) values for the data obtained by smartphone measurements, shown in Table 7. A comparison between measured and calculated A-weighted results at two different locations is shown in Table 8.

It is now obvious that the difference between the measurement results obtained by using a smartphone and a calibrated sound level metre for the equivalent sound pressure levels at control points is in the range of expanded measurement uncertainty (± 4.5 dB), which is a common value in these types of measurements where the dominant sound source is road traffic [21,27], (applies to both Tables 5 and 8).

4. Conclusion

This research showed that noise maps can be accurately made by using applications for measuring environmental noise levels. The small differences between measured levels (when compared to the calibrated device e.g. B&K 2250) are caused due to different frequency characteristics of the smartphone's microphone. The smartphone's microphone calibration is done in the free

field; however, complex building surroundings cause the sound field to be more diffuse than free.

The requirement for a precise noise mapping with MCS method is gathering a large number of samples and space–time averaging of the collected data. On the other hand, the comparison of two methods discussed in this paper showed that MCS method can provide a sufficiently precise noise map, in other words, within the range of expanded measurement uncertainty (± 4.5 dB) which is present in such types of measurements where the dominant sound source is road traffic.

This method can make noise mapping easier, cheaper and less time consuming in terms of creating noise maps developed on measurements but also noise maps developed on calculations and simulations. Noise maps created on calculations need to be calibrated with real-time measurements done in a few points of interest in order to verify the accuracy of the input calculation parameters. When using the smartphone measurement application, the calibration can be done in a much larger number of points (in comparison with the standard methods) and therefore, the accuracy and the precision of the final noise map are much higher. The MCS's advantage is that the citizens can engage in noise monitoring in urban areas and become aware of the ever-increasing noise pollution in their cities. Thus, the aim is to encourage them to collect data and, in that way, help to create precise noise maps. Furthermore, that kind of data can be very useful in a concept of smart cities in terms of monitoring and preserving quiet places in urban areas.

This research has shown that it is possible to obtain a final noise map with A-weighted values gained by calibrating measured smartphone values (dB) with values (dBA) from the sound level metre (dBA) at known locations and spectrum. Nevertheless, future work will be focused on upgrading the smartphone application in terms of third-octave analysis and A-weight evaluation of collected data and on using this application in smart cities concept.

Disclosure statement

No potential conflict of interest was reported by the authors.

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