

# Characterization of A WASN-Based Urban Acoustic Dataset for the Dynamic Mapping of Road Traffic Noise

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**Abstract:** Road Traffic Noise (RTN) is one of the main pollutants in urban and suburban areas, negatively affecting the quality of life of their inhabitants. In the context of the European LIFE DYNAMAP project, two Wireless Acoustic Sensor Networks (WASN) have been deployed to monitor RTN: one in the District 9 of Milan, and another along the A90 motorway of Rome. Since the dynamic mapping system should be able to identify and remove those Anomalous Noise Events (ANE) unrelated to regular road traffic (e.g., sirens, horns, speech, doors, etc.), an Anomalous Noise Event Detector (ANED) has been included in the dynamic noise mapping pipeline to avoid biasing the computation of the equivalent RTN levels. After deploying the 24 low-cost acoustic sensor networks in both pilot areas, WASN-based acoustic datasets have been built to adapt the previous version of the ANED algorithm to run in real-operation conditions. In this work, we describe the preliminary results of the analysis of the 154-h WASN-based urban acoustic dataset obtained from the Milan city in terms of the main characteristics of ANEs. The results confirm the unbalanced nature of the problem (83.7% of the data corresponds to RTN), showing the urban WASN-based dataset a larger number of ANEs with higher local predominance than what was observed in the previous expert-based recording campaign, which underlines the importance of the accurate modelling of the urban acoustic environment to train the ANED properly.

**Keywords:** dataset; wireless acoustic sensor networks; dynamic noise mapping; low-cost sensors; road traffic noise; anomalous noise events; acoustic urban environment

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## 1. Introduction

It has been stated that noise pollution, mostly caused by traffic, is one of the main environmental pollutants in urban and suburban areas [1,2]. Road Traffic Noise (RTN) affects the quality of life of citizens negatively, provoking several health-related problems (e.g., see [3–5]). The European Noise Directive 2002/49/EC (END) [6], and the consequent definition of the Common Noise Assessment Methods in Europe (CNOSSOS-EU) [7,8] were defined in order to address this issue in an harmonised manner at the European level. Among the different requirements embodied in these regulations, the European member states are asked to tailor noise maps of specific areas of interest (e.g., agglomerations with +100.000 inhabitants and major infrastructures) every five years. The generation of noise maps has been typically tackled by means of precomputed acoustic models fed by representative acoustic data collected using certified sound level meters handled by experts [9]. However, some recent technological advances have allowed for the development of alternative approaches. The combination of the Internet of Things (IoT) paradigm together with the development of low-cost acoustic sensors has given the rise of the so-called Wireless Acoustic Sensor Networks (WASN), enabling the setting up IoT-based ubiquitous environmental noise monitoring in urban and suburban areas (see [10] for a recent review of the state-of-the art about this topic of research).

In the context of the European LIFE DYNAMAP project [11], a WASN-based dynamic noise mapping system has been designed and developed to determine the acoustic impact of road infrastructures. To this aim, the project has recently deployed two low-cost WASNs in the following pilot areas [12,13]: one in the District 9 of Milan as an urban area, and another in the A90 motorway surrounding Rome as a suburban area. Since the goal of the project is to monitor only RTN levels in real time, the system is asked to automatically identify and remove those Anomalous Noise Events (ANE) unrelated to regular road traffic (e.g., sirens, horns, speech, doors, etc.) from the noise levels computation, following the specifications of the END [6]. For that purpose, an Anomalous Noise Event Detector (ANED) [14] has been included in the dynamic noise monitoring pipeline to avoid biasing the computation of the A-weighted equivalent road traffic noise levels ( $L_{Aeq}$ ) of the area of interest due to the presence of ANEs. The ANED has been designed as a two-class classifier (RTN vs. ANE) to run in real time in the low-cost acoustic sensors of both WASNs.

Although the ANED algorithm has been trained and improved several times with different types of representative acoustic data [15], the recent deployment of the WASNs in the pilot areas has provided the possibility to collect acoustic data through the 24 low-cost acoustic sensors installed in their final locations. Taking advantage of this fact, a new dataset has been built so as to improve the ANED algorithm with respect to the previous implementation based on preliminary manual recordings [14]. As in the WASN-based suburban dataset (see [16] for further details), the WASN-based urban dataset includes data from weekdays and weekends, and environmental noise samples from the definitive location of the sensors in real-operation. In the previous recordings in the District 9 of Milan [17], the audio was recorded using a tripod placed on the street instead of the façades, where the low-cost sensors have been finally placed (see Figure 1). In this work, we describe the preliminary results of the analysis of the 154 h WASN-based urban acoustic dataset from the Milan area in terms of the main characteristics of the collected ANEs, comparing them to what was observed in the previous manual-based recording campaign.

Section 2 is devoted to describe the WASN-based urban acoustic dataset, including the WASN configuration, the recording and labelling processes, and the description of the main characteristics of the collected ANEs. In Section 3, several relevant aspects of the generated database are discussed, before describing main conclusions of this work together with the future research goals.

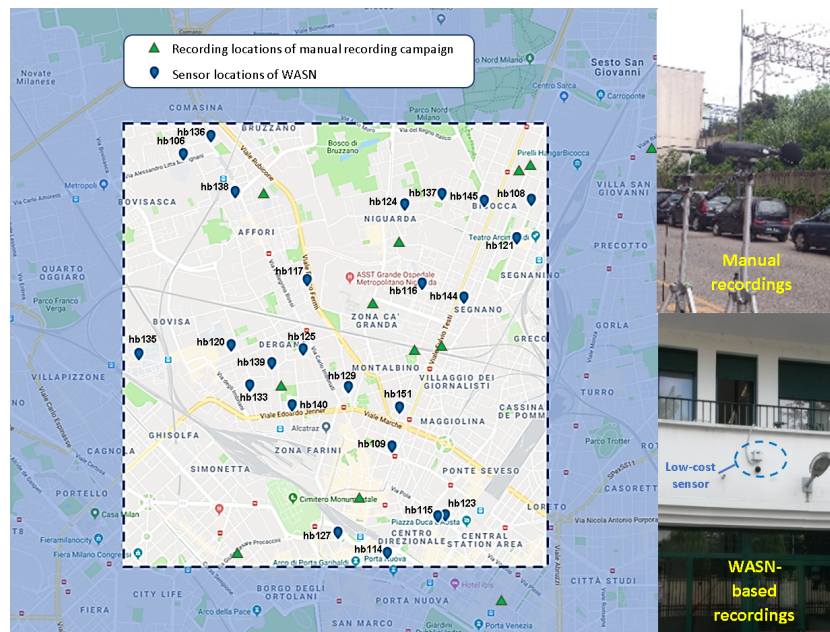
## 2. Development of the WASN-Based Urban Acoustic Dataset

In this section, we describe the process followed to create the urban acoustic dataset using the low-cost acoustic sensors of the WASN in Milan, together with the analysis of its main characteristics.

### 2.1. WASN Configuration and Recordings Methodology

Figure 1 shows the location of the 24 low-cost sensors of the WASN deployed in the urban area of Milan (District 9) together with locations considered for the previous manual recording campaign, which did not coincide in the final sensors positions due to they were not still planned during early stages of the DYNAMAP project.

Two days of the same week were sensed through the urban WASN, in order to capture traffic noise and anomalous noise examples in two different traffic conditions: one week day (Tuesday, November 28, 2017) and one weekend day (Saturday, December 2, 2017). The acoustic data were recorded in continuous audio clips from the first 20 minutes of each hour (considering a sampling frequency of 48 kHz), during 11 pre-selected hours in the week day (02:00, 03:00, 05:00, 08:00, 09:00, 11:00, 14:00, 15:00, 17:00, 20:00, 23:00) and at 9 different hours in the weekend day (02:00, 05:00, 08:00, 11:00, 14:00, 17:00, 20:00, 21:00, 23:00). The recordings were obtained from all the 24 sensors of the network. However, 4 out of the 24 sensors gathered a different amount of that to what was initially expected due to some operational problems. In this sense, it is worth mentioning that: *i*) sensor hb114 registered only 7 periods (03:00, 05:00, 06:00, 08:00, 11:00, 15:00, 18:00); *ii*) sensor hb116 did not record hours 02:00 and 03:00 during weekend; *iii*) sensor hb117 did not record hour 23:00 of the weekend;



**Figure 1.** Map of the recording locations during the manual campaign [17], and location of the DYNAMAP’s WASN sensors in Milan, including. Examples of each recording position on the right.

and *iv*) two weekday hours (15:00 and 23:00) and one weekend hour (14:00) were not observed by the sensor hb138. All the recordings were subsequently organized in separated WAV files of raw audio (one for each 20 minutes audio clip), and were labelled with information describing the sensor, the day and the initial time of the recording. A total of 463 files were obtained from the recording campaign, which encompasses 154 h and 20 min of audio.

## 2.2. Labelling Process and ANE Subcategories

The acoustic dataset was manually labelled by 5 experts in audio signal processing, who used Audacity software to perform the labelling process with the aid of visual information (waveform and spectrogram in dB) while listening to the recorded signals. The labelling process follows the methodology described in [16], asking the experts to classify each portion of the audio signal according to following criteria: *i*) those audio clips containing road-traffic noise should be labelled as RTN. They may contain all kinds of sounds coming from vehicle engines and tyres even if they are distant or practically nonexistent, if any other sound prevails; *ii*) those sounds unrelated to regular RTN, should be labelled as ANEs (several subcategories are identified by the experts during the labelling process); and *iii*) those audio passages containing a high diversity of sound sources should be labelled as complex sound mixtures (CMPLX).

During the labelling process of the WASN-based urban acoustic database, up to 26 urban-like sound subcategories (plus RTN and CMPLX) were identified and agreed by the experts (see an example in Figure 2). Among the different ANEs subcategories listed in Table 1, it can be observed that most of them belong to man-made sounds, mainly originated by means of transport (*airp*, *alrm*, *bike*, *brak*, *busd*, *horn*, *rubb*, *sire*, *tram*, and *tran*), but also other generated by electrical or mechanical sound sources (*bell*, *blin*, *door*, *glas*, *inte*, *musi*, *sqck*, *trll*, and *wrks*). Moreover, some of them were due to meteorological phenomena (*rain*, *thun*, and *wind*). Finally, sounds produced by people (*peop* and *step*) or animals (*dog* and *bird*) were also observed, being among those most present ANEs in the urban environment.

**Table 1.** Description of the 26 sound subcategories attributed to anomalous noise events found throughout the manual labelling process of the WASN-based urban acoustic database.

Label	Description	Label	Description
<i>airp</i>	Noise of airplanes and helicopters	<i>musi</i>	Music in car or in the street
<i>alrm</i>	Sound of an alarm or a vehicle beep moving backwards	<i>peop</i>	Sounds of people chatting, laughing, coughing, sneezing, etc.
<i>bell</i>	Church bells	<i>rain</i>	Sound of heavy rain
<i>bike</i>	Sound of bikes and bike chains	<i>rubb</i>	Rubbish service, sound of engine taking the container, emptying it and dropping it down
<i>bird</i>	Birdsong	<i>sire</i>	Sirens (ambulances, police, etc.)
<i>blin</i>	Opening and closing of a blind	<i>sqck</i>	Squick sound of door hinges
<i>brak</i>	Brakes and conveyor belts	<i>step</i>	Sounds of steps
<i>busd</i>	Opening bus door (or tramway), depressurized air	<i>thun</i>	Thunderstorm
<i>dog</i>	Barking of dogs	<i>tram</i>	Stop, start and pass by sounds of tramways
<i>door</i>	Closing doors (vehicle or house)	<i>tran</i>	Sound of trains
<i>glas</i>	Sound of glass crashing	<i>trll</i>	Sound of wheels of suitcases (trolley)
<i>horn</i>	Horns of vehicles (cars, motorbikes, trucks, etc.)	<i>wind</i>	Noise of wind (movement of the leaves of trees,...)
<i>inte</i>	Interfering signal from an industry or human machine	<i>wrks</i>	Works in the street (e.g. saws, hammer drills, etc.)

### 2.3. Characteristics of the Urban ANEs Collected by the WASN Sensors

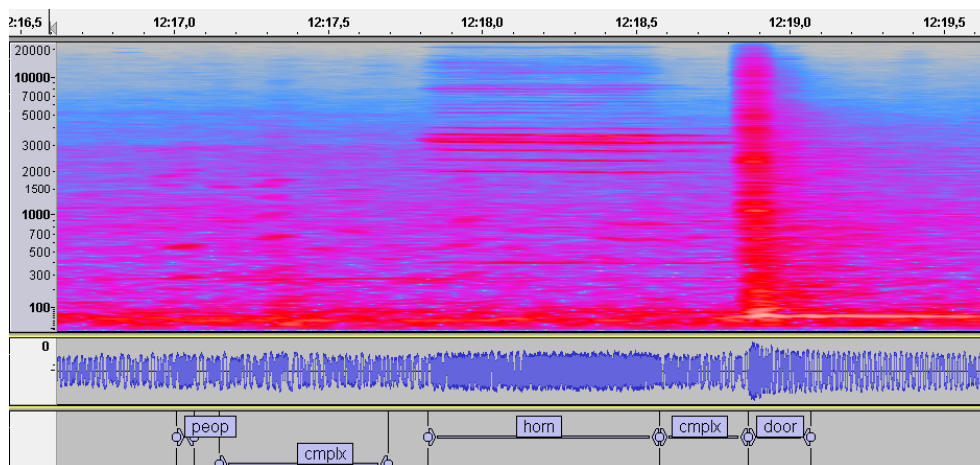
After the experts finished the labelling process, several analyses were conducted on the audio passages labelled as ANE to determine the main characteristics of collected ANEs in terms of the number of occurrences, their duration and acoustic salience –computed as the Signal-to-Noise Ratio (SNR) with respect to the background traffic noise.

Regarding the occurrences of ANEs, the most frequently observed ones were those of short nature usually attributed to urban environments, specially *peop* (22.2 %), *bird* (14.7%), *door* (14.7 %), *step* (13.7 %) and *brak* (12.7 %). Moreover, some events with moderate presence were found, such as *wrks* (4.1%), *horn* (3.7 %), *bike* (3.7 %), *dog* (2.5 %), *bell* (1.2 %) and *busd* (1.1 %). The remaining ANE subcategories were observed with low probabilities (less than 1 %), being *wind*, *blin* and *tran* rarely found in the recordings (less than 0.05 %), and, finally, *thun* was only identified once.

In what concerns the duration of the ANEs, events with the largest duration are *inte* (mean length 20.9 s), followed by sirens and airplanes (with median lengths between 8 and 21 s). Sounds of trains, tramways, rain and rubbish services show median length values between 5 and 8 seconds. Regarding the events that show a rather short duration, we found *blin*, *alrm*, *wind*, *trll*, *musi*, *wrks* and *brak* as sounds with median durations between 1 s and 3 s while the rest of observed ANE subcategories present a median length shorter than 1 s.

Another interesting question to consider beyond the mere presence of ANEs is the analysis of their potential impact on the acoustic environment. To this end, the duration and SNR of the ANEs have been studied, together with the total amount of time they appear in the WASN-based dataset. In order to determine the ANEs’ acoustic salience with respect to the background traffic noise, the SNR of each ANE was computed following the procedure described in [18]. The ANEs subcategories presenting the highest SNRs (median values between 4 dB and 7 dB) are *blin*, and *dog*, which were usually detected in streets with very low traffic conditions. Moreover, *glas* also presented quite high SNR values, followed by *tran*, *tram*, *bell*, *horn*, *door*, and *rubb* (median SNR values between 2 dB and 4 dB). *Inte*, *rain* and *wind* ANE subcategories presented very low SNR values, being most of them below 0 dB. The rest of anomalous noise events presented quite balanced positive and negative SNR values, since some of them present salient values with respect to the surrounding background noise, while the others remain under the level of the recorded background, thus, potentially having no effect on the computation of the RTN levels due its self-compensation.





**Figure 2.** Excerpt of a WASN-based recorded audio containing 3 ANEs with different Duration (D) and SNRs: *peop* with D=0.06 s and SNR=5.2 dB; *horn* with D=0.75 s and SNR=11.62 dB and *door* with D=0.21 s and SNR=7.55 dB. From top to bottom: the spectrogram, the waveform in dB and the labels.

Finally, if we take into account both the total recording duration of ANEs together with their SNR: tramways, door sounds, street works and people-related sounds contribute the most to the noise levels, resulting in a potential higher impact on the  $L_{Aeq}$ . In contrast, *wind*, *glas*, *tran* and *busd* are the anomalous events with the lowest combined values of SNR and total recorded duration. Finally, sounds that show high SNR values but with a moderate duration are dogs barking, alarms, bells and vehicle horns. Nevertheless, the computation of the real impact of these audio events on the equivalent noise levels for the generation of road traffic noise maps is left for future work.

### 3. Discussion and Conclusions

In this work, a first analysis of the 154-h WASN-based urban acoustic dataset recorded during two days (one labour day and one weekend day) in the District 9 of Milan has been presented. As a result of the labelling process of the audio dataset, up to 129 h 12 min and 35 s were classified as RTN (83.7 %), 13 h 16 min and 1 s were tagged with one of the ANEs subcategories (8.6 %), and the remaining 11 h and 51 min and 25 s were labelled as CMPLX (7.7 %).

After comparing the WASN-derived acoustic dataset with the previous one obtained from the manual recording campaign [17], substantial differences were found. Firstly, it must be pointed out that the WASN-based recording campaign was conducted during entire days on 24 locations (totalling 154 h of data). In contrast, during the manual recordings only up to 20 minutes of continuous audio were gathered at certain time periods in only 12 city locations (totalling 4 h and 24 min of data). Moreover, most locations were sensed only during the day (having only one location with acoustic data from the night period). A low-cost microphone connected to a ZOOM H4n digital recorder and a Brüel&Kjær sonometer were used at the street level, instead of the low-cost sensor installed in the façades, as it was still under development. Furthermore, it is to note that up to 11 new ANE subcategories have been identified across the WASN-based recordings (subcategories *alrm*, *bell*, *blin*, *glas*, *inte*, *rain*, *rubb*, *sqck*, *step*, *trll*, and *wrks*), being some of them quite predominant in several of the sensors’ locations. Finally, it is important to remark that in the WASN-based recordings the total amount of labelled ANEs (8.6%) is quite lower than the manual dataset (12.2%). This result confirms the unbalanced nature of the problem, besides the need of extensive recordings to characterize the urban environment properly.

Future work will be focused on adapting the ANED algorithm to run in real operation conditions by training it with the built WASN-based acoustic dataset. Moreover, we will keep analysing the database contents, paying special attention to the complex passages and their potential impact on the algorithm’s performance.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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