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DYNAMAP – Development of low cost sensors networks for real time noise mapping

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Abstract: The Environmental Noise Directive (END) requires that regular updating of noise maps is implemented every five years to check and report about the changes occurred during the reference period. The updating process is usually achieved using a standardized approach, consisting in collating and processing information through acoustic models to produce the updated maps. This procedure is time consuming and costly, and has a significant impact on the budget of the authorities responsible for providing the maps. Furthermore, END requires that simplified and easy-to-read noise maps are made available to inform the public about noise levels and actions to be undertaken by local and central authorities to reduce noise impacts. To make the updating of noise maps easier and more cost effective, there is a need for integrated systems that incorporate real-time measurement and processing to assess the acoustic impact of noise sources. To that end, a dedicated project, named DYNAMAP (*DYNamic Acoustic MAPping*), has been proposed and co-financed in the framework of the LIFE 2013 program, with the aim to develop a dynamic noise mapping system able to detect and represent in real time the acoustic impact of road infrastructures. In this paper, after a comprehensive description of the project idea, objectives and expected results, the most important steps to achieve the ultimate goal are described.

1 Introduction

DYNAMAP is a Life+ project aimed at developing a dynamic noise mapping system able to detect and represent in real time the acoustic impact due to road infrastructures. Goal of the project is the Directive 2002/49/EC (END) of the European Parliament and of the Council relating to the assessment and management of environmental noise [1]. The END states that noise maps must be provided and updated every five years in order to report about changes in environmental conditions (mainly traffic, mobility and urban development) that may have occurred over the reference period. However, the updating of noise maps using a standard approach requires that the responsible authorities collect and process new data related to such changes. This procedure is time consuming and costly and has a significant impact on the financial statements of the authorities responsible for providing noise maps.

To facilitate the updating of noise maps and reduce their economic impact, noise mapping can be automated by developing an integrated system for data acquisition and processing that is able to detect and report in real time the acoustic climate due to noise sources. This approach seems quite promising in areas where noise sources are well identified, such as those close to main roads. In complex scenarios, such as in agglomerations, further considerations and testing are needed to make the idea feasible.

The main project idea is focused on the research of a technical solution able to ease and reduce the cost of periodically updating noise maps, through an automatic monitoring system, based on customized low-cost sensors,

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and a software tool implemented on a general purpose GIS platform performing the update of noise maps in real time (i.e. dynamic noise maps).

The update of noise maps is achieved by scaling the noise levels of pre-calculated (basic) noise maps as a function of the difference observed between measured and calculated original grid data. A set of basic noise maps is foreseen for different sources, traffic and weather conditions.

In particular, the changes of *static* features (such as road geometry, pavement type) will determine an updating of the basic model information; this operation will be planned as a periodic check (at least once a year) during the operational running of the system. Basic noise maps are selected and scaled using the information retrieved from the sensors continuously measuring the sound pressure levels of the primary noise sources present in the area to be mapped.

Dynamap project has the aim to provide a map only related to road traffic noise. As a consequence, all other sources will be identified through a detection algorithm named ANED (see section 8 below) and removed from the noise levels connected with the map updating. Therefore, in order to guarantee the accuracy of the updating process, noise levels are first cleaned up from anomalous events by a specifically developed algorithm before being used to scale the basic noise maps. Scaled basic noise maps of each primary source are then summed-up to provide the overall noise map of the area. In this way, the need for several and expensive software licenses is extremely reduced and limited only to the preparation of the basic noise maps. Such a standalone dynamic mapping software (no need for running modeling software, except for the starting noise maps computation), together with low cost noise monitoring stations, makes the DYNAMAP system a very efficient and versatile noise mapping tool, virtually able to interface any existing or future noise modeling software, including the new European model CNOSSOS, which is expected to be operative for the fourth round of END.

The feasibility of this approach will be proved by implementing the system in two pilot areas with different territorial and environmental characteristics: an urban agglomeration and a major road.

The first pilot area will be located in the city of Milan and will cover a significant portion of the town including different type of roads and acoustical scenarios. Roads will be classified and assigned to a significant number of clusters, representative of the main traffic configurations. Twenty-four roads belonging to such clusters will be selected to measure the noise levels that will be used to update the basic noise maps. The second pilot area will be located in Rome, along the motorway A90 encircling the city. In this case, the sensors devices will be installed in hot spots where traffic counting is unavailable to feed the dynamic mapping system with real time information on noise levels. About 25 devices will be used to provide noise levels information alongside the road and dynamically update the noise maps.

Over the whole test period, as planned in the scheduled activity, the dynamic noise maps will be assessed to check their accuracy and reliability. The test will be limited to a significant number of sites (approximately 20) within the pilot areas and consists in measuring the noise temporal trend together with the corresponding vehicular flow rate. Noise measurements will be ,then after, compared to those provided by computed maps with the purpose to improve and refine the noise representation.

2 State of the art on real time noise mapping system

In the last few years some approach to dynamic noise mapping was attempted, but the high implementation costs bordered most of those projects just in research field. In the following paragraphs a short overview of the past experiences is reported.

2.1 Approaches to real time noise mapping

The usual approach to Real Time Noise Mapping consists in implementing a localized standard noise monitoring network, which continuously collects noise data, and transmits them to a data centre in which a noise mapping software is running. The role of the mapping software is to compute noise maps according to the information coming from the noise monitoring network, or to re-scale pre-computed partial noise maps taking into account the incoming noise data, and sum them together in order to obtain the updated noise map of whole area; in each case the idea is to publish results continuously on a web site. Of course it is a must that each noise monitoring terminal is influenced by only one road section to which the partial map is referred. Although during the last years the price of sound level meters has decreased and their features highly improved, noise monitoring terminals are still quite expensive, so that building up a monitoring network can be rather costly. This is one of the reasons why software manufacturers have not invested too much in developing dynamic noise mapping so far. In addition to the

Table 1: Analyzed systems.

System	Type
ACCON Italia	Scaling of pre-computed maps
Datakustik	Scaling and sum of pre-computed maps
Gdansk University	On-line calculation
GEIART	Cluster analysis on traffic model
Ghent	Simplified on-line calculation
IDASC CNR	Scaling of pre-computed maps
Laermometer	Citizens contributive mobile noise mapping (smartphone)
NoiseMote	Low cost sensor system
NoiseTube	Citizens contributive mobile noise mapping (smartphone)
NPL	Low cost sensor system
SADMAM	Scaling and sum of pre-computed maps

above mentioned approaches, some others technique were developed in the last years to obtain real time dynamic noise maps [2]. In Table 1 the main systems developed are listed, in alphabetic order, reporting the approach used to implement the maps.

As shown in the table, there are three major approaches to dynamic noise mapping: on-line calculation, map re-scaling and sum, and citizens contributive; the system called GEIART is slightly different from the others, as it does not directly measure noise levels to update the noise model, but it implements a vehicle counting system feeding a traffic model that drives the update of noise maps.

2.1.1 Real time calculation approach

In the real time calculation approach, the measured values coming from the noise monitoring network, are used as input data for the noise simulation software, to perform new calculations of noise maps. So, due to the fact that the role of the noise model server is to recalculate a complete noise map with continue update, in order to perform this job the noise model software should run continuously on a very powerful machine, able to perform calculations in a very short time. Gdansk University developed its system using this technology [3, 4].

Computation time can be reduced by using simplified calculation algorithms. The latter approach was followed by Ghent University to implement their own system [5].

2.1.2 Map scaling and sum approach

This approach is similar to the previous one in terms of infrastructure, but the noise mapping server plays a different role. In this case the new map is computed just as the sum of re-scaled precalculated maps, based on measured noise levels. As all calculation take place only once at the system startup, maps update rate can be very fast. This technology is implemented in systems developed by ACCON (scaling of a single map) [6, 7], IDASC [8], DATAKUSTIK and SADMAM [9, 10].

With this technology, two 'sub-approaches' are possible: the first one uses a function implemented inside the noise model software for scaling and summing the partial maps, while the second one uses an external GIS software to do the job, because no ray tracing calculation is needed to obtain new maps.

2.1.3 Citizens contribution

Thanks to the high diffusion of smartphones, a new technology for dynamic noise mapping started few years ago. The main idea consists in using citizens' smartphones to measure the noise levels and build up a noise map based on those measurements.

Two examples of this technology are Laermometer [11] and NoiseTube [12]. In both cases acquired noise data, together with localization coming from smartphone embedded GPS system, are sent by cellular phone to a web server able to manage data and present them as noise maps, also directly by using Google Earth platform.

Another kind of citizen-contributed measurement method is the one adopted in the *SENSEable Pisa* project [13], where low cost sensors were connected to citizen's wifi and placed in their outdoor private places (balcony, gardens, etc).

The DYNAMAP project, based on the above mentioned scaling and sum technology, considers some important aspects in order to achieve cheap, fast and reliable real time noise maps. More in details, the system involves low cost sensors capable of anomalous event recognition and cancellation [14, 15], traffic noise cluster analysis for mapping optimization [16], web based GIS software for updating and report the noise maps.

3 Road network analysis and pilot areas location

The implementation of the DYNAMAP system requires the identification of suitable sites to be used as pilot areas for project demonstration activities. Two pilot areas are foreseen to test the different requirements associated to agglomerations and major roads. The first pilot area is located in the city of Milan and will cover a significant portion of the town, including different type of roads and acoustical scenarios, while the second pilot area is located along a major road, *i.e.* the ring road (Motorway A90) encircling the city of Rome.

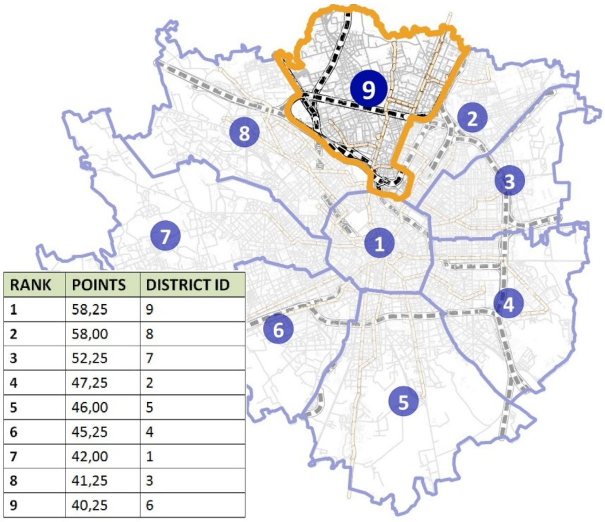
3.1 Milan: Pilot Area 1 selection

The selection of the pilot area related to the city of Milan was accomplished using a procedure specifically developed for the project. The procedure was applied to nine territorial areas corresponding to the districts of Milan Municipality (Figure 1), providing as final output a ranking list showing the scores assigned to such areas as a function of a number of weighted attributes associated to them. The procedure was based on georeferenced data retrieved from public administrations, *i.e.* Milan Municipality and the University of Milan-Bicocca. All this information was collected into a Geographic Information System (GIS), so as to support and automate the selection process.

The selection process was based on a ranking system, whose scores were given as a function of a series of descriptive attributes related to territory and mobility features, noise monitoring systems and air quality/weather stations availability, the criticality of the area in terms of noise levels, the presence of other noise sources and the access to communication channels (Wi-Fi access points).

The scores assigned to the selected attributes were then weighted using specific coefficients. The total score of each zone was finally obtained by adding the resulting values. In the end, the ranking list was achieved sorting (descending) the scores associated to the nine district zones of the city.

Figure 1 shows the ranking list achieved from the application of this methodology. The results highlight that districts 8 and 9 have achieved the highest scores. This was mainly due to the critical noise levels detected in these areas. Figure 1 also highlights that Milan district number nine was finally selected as urban pilot area for the DYNAMAP project. The choice of district 9 was mainly influenced by the availability of a consistent archive of 24 hours noise measurements and the presence of at least one permanent noise monitoring terminal. These features are of great importance as a thorough knowledge of the acoustic phenomenon in the area under examination is a key element for a successful development of the project.



RANK	POINTS	DISTRICT ID
1	58,25	9
2	58,00	8
3	52,25	7
4	47,25	2
5	46,00	5
6	45,25	4
7	42,00	1
8	41,25	3
9	40,25	6

Figure 1: Pilot area selected as urban test site for the Dynamap project and outcomes of the selection process.

District nine is located in the northern part of Milan and has a population of about 180.000 residents, with 40.000 citizens exposed to L_{den} values higher than 70 dB(A), as reported in the outcomes of the second round of END. The population of district nine is mostly annoyed by road traffic noise. As a matter of fact this area is characterized by major roads used by commuter traffic from the densely populated northern suburbs of the city. Furthermore, the selected pilot area includes two sensitive sites to be protected from noise as the greatest hospital in Milan (Niguarda) and the university district of Milano-Bicocca.

3.2 Rome: Pilot Area 2 selection

The pilot area of Rome is located along the ring road (A90 Motorway) surrounding the city. The ring road is a six lanes motorway, 68 km long, skirting many suburban areas where noise levels were found to be critically impacting on the residents. Critical areas are characterized by different scenarios where single or multiple noise sources are present, such as railways, crossing and parallel roads. Consequently, the overall noise level depends on the number and contribution of the sources existing in the area. As the Environmental Noise Directive states that only the primary source should be mapped, the contribution of the other sources must be eliminated or at least dramatically reduced. To that end, suitable sites should be identified to place the sensors, so as to contain the influence of the other sources as much as possible. However, in order to check the feasibility of deleting the contribution of other noise sources, including temporary spurious events, more complex scenarios have been foreseen to be part of the selected test sites.

As a matter of fact, Rome pilot area will be composed of many test sites, distributed along the motorway A90, representative of the main suburban scenarios. The final number of sites will be defined on the basis of the amount of sensors necessary to calibrate and update the maps. A maximum of 25 sensors is foreseen to be installed in hot spots where traffic counting is unavailable to feed the dynamic mapping system with real time information on noise levels.

To select the sites where the DYNAMAP sensors will be placed, a GIS tool was developed to collect and process information related to the 67 critical areas identified on the basis of the results achieved by ANAS, the Italian Road Administration, for the first and second cycle of END. For the selection process of the test sites, a lot of information was taken into account, such as noise levels, people and building exposed to noise, population density, the availability and position of variable message panels, the presence of power grid connections and communication networks, traffic counting systems and other noise sources that could influence the overall noise level.

In the end, the tool provided four ranking lists related to as many suburban scenarios:

A *Single road (simplest scenario):* this list consists of areas where only the primary source is present (A90 Motorway). Twelve sites were identified to host the DYNAMAP sensors;

B *Additional crossing or parallel roads:* this list includes areas with other crossing or parallel roads belonging to ANAS estate. Only one critical area complying with such requirements was found;

C *Railway lines running parallel or crossing the A90 motorway:* two of the sites belonging to this category were found to be compliant with such specifications;

D *Complex scenarios including multiple connections:* this lists refers to suburban scenarios where many connections to other roads are present, including the contemporary presence of additional noise sources, such as railways. Two critical areas were identified for this list.

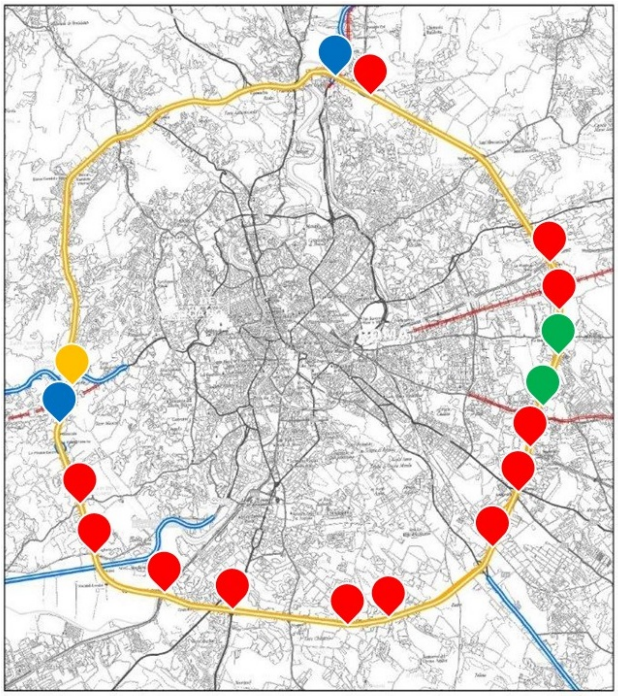


Figure 2: Rome pilot area. Different color codes identify the test sites belonging to the four scenarios: red (scenario A); yellow (scenario B); Green (scenario C) and blue (scenario D).

4 Collection of acoustic data

An acoustic levels database related to road traffic emission is needed as a base for a statistical analysis on noise trend in urban area of Milan.

The first activity involved the selection and storage of previous noise measurements. From all the historical data available, only those specifically related to road sources and with a duration of 24 hours were selected.

In Figure 3 the position of measurement points are shown.

The second phase of the study involved the planning and execution of a new acoustic monitoring campaign, closely related to the purposes of the DYNAMAP project.

In order to create a representative statistical sample of the entire road network of the city, the following general criteria were adopted to identify the measuring sites:

- homogeneous distribution on the entire metropolitan area and between the nine districts of Milan;
- uniform distribution between the different Italian road categories (A, D, E, F) and road subclasses (E1, E2, F0, F1; F2, F3);
- various urban scenarios (urban canyons with different conformation, open sound field, etc.);
- different road surface type;

- different traffic flow types (fluid continuous, pulsed continuous, pulsed accelerated or pulsed decelerated);
- no influence of other roads on the monitored road stretch;
- absence of other noise sources (tram lines, railways, airports, etc).

In the monitoring campaign, three different types of monitoring units have been used: fixed monitoring stations, semi-permanent monitoring stations, monitoring stations placed on cart or on mobile laboratory.

The monitoring activity was sized on a minimum measurement time of 24 hours, starting at 6 a.m. and eventually protracted for several days.

4.1 Processing of the measurements

Subsequently to the execution of the noise measurements, all acquired data were elaborated in a three steps procedure.

The first operation involved the exclusion from noise records of public holidays and anomalous days (such as days of school closures) in order to extrapolate only the acoustic data relative to a typical weekday.

The second operation concerned the correction of the acoustic data with weather data. The units of acoustic monitoring in fact are not equipped with weather stations, therefore, it was necessary to associate every single noise level with weather data of rainfall and wind speed measured by the closest weather stations belonging to ARPA (Regional Agency for Environmental Protection) located in the Municipality of Milan.

The third corrective operation on the original acoustic data involved the elimination of extraordinary or anomalous events (such as sirens, horns, airplane transits, noisy human activities, technical facilities, etc.), since their presence can affect and alter the equivalent noise level. In this phase, the identification of extraordinary events was based on the comparison and analysis of the sonograms.

This operation is important to extrapolate the noise level related to the single traffic source. In the operating scenario of Dynamap system, the identification and removal of anomalous events will be done in real time directly on noise levels acquired by the low cost sensors. To this end, one of the project partners (University La Salle of Barcelona), is developing a specific algorithm, named ANED (see Section 8).

4.2 Results of the noise monitoring campaigns

After the correction of the acquired data, the equivalent sound pressure level was calculated by integrating the acoustic data on different time intervals, respectively 5, 10, 15, 20, 30 and 60 minutes.

The succession of the equivalent noise levels on 24 hours represents the noise trend, which constitutes the basis for subsequent statistical analysis. Each noise dataset consists of 6 distinct temporal profiles obtained with different data sampling rates.

The total amount of trends acquired well describes the noise emissions of 99 roads of Milan (Table 2 and Fig. 3).

Table 2: Scheme of the noise monitoring campaign.

Functional class of road		Number of roads monitored
A – highways		4
D – principal arterial roads		9
E – collector arterial roads	E1	21
	E2	10
F – local roads	F0	17
	F1	10
	F2	14
	F3	14

5 Statistical analysis of the measured road noise

The Italian legislative classification of roads is basically dependent on the road geometry characteristics such as width, presence of reflecting surfaces, obstacles, type of paving, etc. Such features allow the road network of the city of Milan to be divided into 8 functional classes defined from type “A” to “F” and sub-classes. Figure 4 illustrates the 24 h mean normalized noise profiles, $\overline{\delta}$, of the 93 monitored sites (this number derives from the validation of the 99 sites investigated in the monitoring campaign and related to traffic data) with the corresponding standard deviation band as grouped by functional classes. $\overline{\delta}$ represents the mean normalized noise profile of roads belonging to the same functional class, each road being characterized by the following normalization expression:

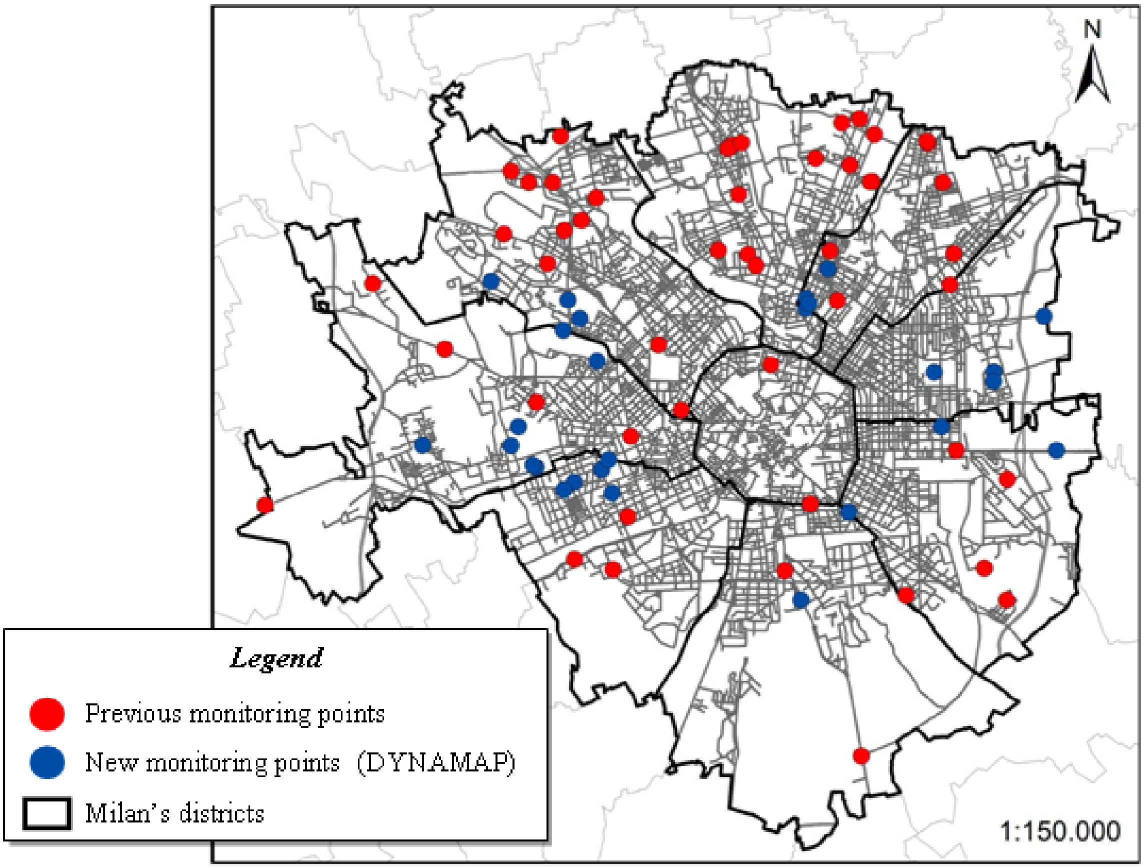


Figure 3: The location of noise measurements positions.

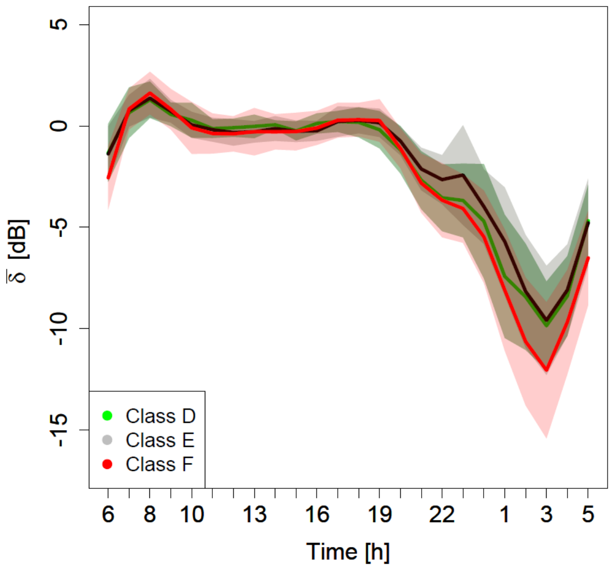


Figure 4: 24-h mean normalized noise level profiles, $\overline{\delta}$ of the 93 monitored sites with the corresponding standard deviation band grouped by functional classes. Roads of class A have been excluded because of poor statistical relevance.

$$\delta_{ij} = L_{Aeqh_{ij}} - L_{Aeqdj} \ \ [\mathrm{dB}] \ \ \begin{cases} i = 1, \ldots\ldots, 24 \\ j = 1, \ldots\ldots, 93 \end{cases} \qquad (1)$$

Here $L_{Aeqh_{ij}}$ is the jth hourly 24-h temporal series and L_{Aeqdj} the corresponding daytime noise equivalent level (06–22 h). The introduction of this normalization procedure was prompted by the non-homogeneous characteristics of the monitored hourly equivalent noise levels, LAeqh, due to different acquisition conditions. For all the 93 sites the morning rush-hour (time interval 7:30–8:30 a.m.) vehicle flow was also available.

The overlapping of the mean profiles, $\overline{\delta}$, and their standard deviation bands, shown in Fig. 4, over all the day and night period, suggests that roads which share similar noise behavior fall in different functional classes. This is the reason why we decided to approach the sampling issue not inside each functional group (stratified sampling) by firstly statistically analyzing the temporal profiles series, δ_{ij}, in order to obtain homogeneous groups of roads with similar noise behavior. This approach has the advantage of providing a better description of the real behavior of the complex road network of the city of Milan and, therefore, of improving the sampling efficiency [17–21] based upon

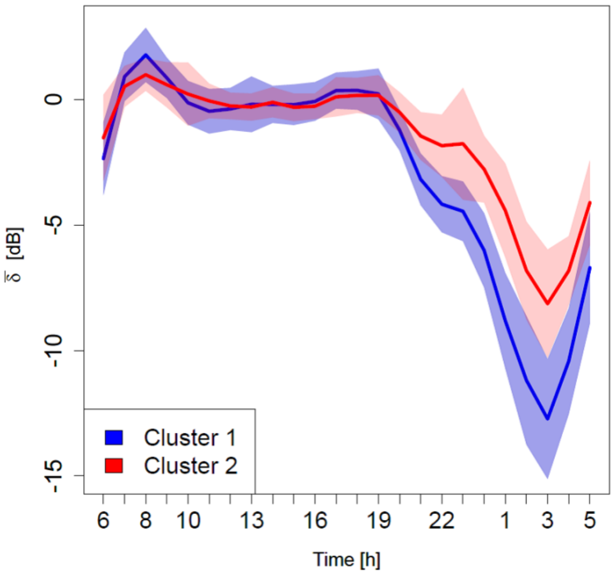


Figure 5: Mean normalized noise cluster profiles, $\overline{\delta}$ and the corresponding standard deviation band.

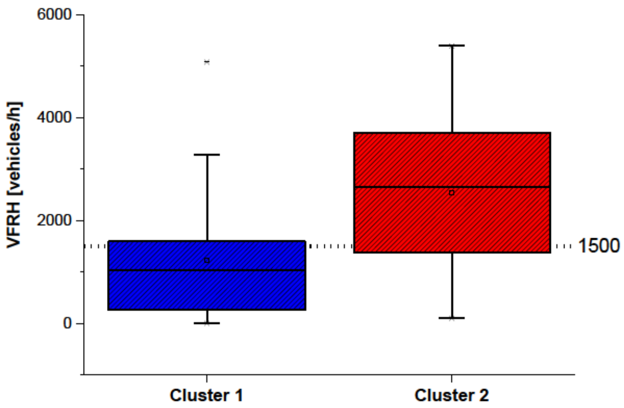


Figure 6: Box plots of the vehicle flow at rush hour (VFRH) for the two mean cluster profiles. Roads with traffic flow rate at rush hour < 1500 vehicles/hour can be associated with cluster 1; roads with traffic flow rate at rush hour > 1500 vehicles/hour to cluster 2.

cluster categorization. We applied an unsupervised clustering analysis to the 24-h hourly normalized level profiles, δ_{ij}, found to be statistically similar to one another. The analysis yielded a two-cluster solution. Most of “F” class roads falls in cluster 1 (56 temporal profiles), whereas the remaining classes are more homogeneously distributed in cluster 2 (37 temporal profiles). This result endorses the traffic noise is mainly linked to the effective role played by each road in the urban mobility and not exclusively by its “geometrical characteristics” (legislative classification). Figure 5 shows the profiles of the mean normalized noise values, $\overline{\delta}$, and the corresponding standard deviation band grouped by functional classes.

In order to classify and assign roads to each cluster, a non-acoustical parameter was chosen to help the association of each road (not in the sample) to one of the two found clusters. The non-acoustical parameter adopted so far is the vehicle flow at rush hour (VFRH). In Figure 6 the box plots for each mean cluster profile are depicted. Figure 6 shows that the interquartile range of the two clusters are quite well separated. Therefore, we can assume a vehicular flow at rush hour (VFRH) of 1500 vehicles/hour as threshold between the two clusters.

6 Acoustic modeling

The study of noise propagation in the urban area of Milan and in the suburban area of Rome is obtained by implementing a tridimensional model of the pilot areas inside an acoustic calculation software. Acoustic computations will be performed on the basis of the European standard algorithm for the vehicular traffic noise calculation (XPS 31-133/NMPB algorithm, [22]) and will provide a surface noise map for each area (basic noise map).

Thus, in the fully operational scenario of DYNAMAP these basic noise maps are updated in real time as a function of local noise levels acquired from source oriented low cost stations.

Some parameters of the calculation model will be changed according to significant variations of the environmental conditions, which induce a significant variation in the production or propagation of noise; thereby a new basic map, independent from acquired acoustic data variation, has to be produced. A sensitivity analysis of the acoustic model is needed to determine how sensitive is the noise model to changes of the main acoustic related variables.

The XPS 31-133/NMPB algorithm includes both the road sound power computation as a function of traffic input data, and the calculation of the environmental noise attenuation along each source-receiver propagation path; the identification of the most significant and relevant parameters to be analyzed lead to: meteorological conditions in extra-urban areas; traffic conditions in urban areas.

The sensitivity of the adopted acoustic model has been analyzed with respect to these two variables [23], that is considering how the values of the terms “weather conditions” and “traffic conditions” influence the environmental noise level or the noise level emitted by the source.

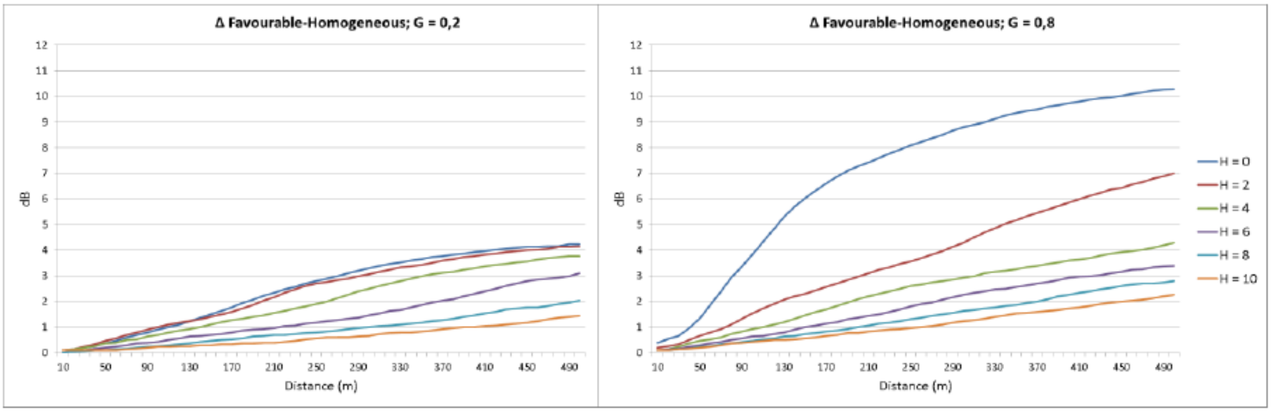


Figure 7: Differences between favourable and homogeneous conditions calculated noise levels. Ground Factor = 0, 2–0,8.

6.1 Sensitivity analysis of the acoustic model with respect to meteorological conditions

The XPS 31-133 algorithm takes into account the occurrence of homogeneous or favourable propagation conditions as a function of weather conditions. At a physical level, noise propagation conditions are linked to thermal and aerodynamic factors that can give rise to wind speed and temperature vertical gradients [24]. With positive vertical gradients, when a fixed threshold is reached, sound rays are refracted downward causing the enlargement of the affected area. With negative vertical gradients, sound rays are bent upward and the noise levels at receivers are lower than those detectable in neutral conditions (unfavorable refraction conditions).

Sound ray refraction induced by atmosphere layers determines a longer persistence of the sound wave at the ground level; also the effects of the terrain on the noise propagation path are therefore increased [25]. Interferences between sound wave and terrain, identified as reflection and absorption, are also related to the source height with respect to the receiver height [26]. Consequently, the height of the source, that is the roadway, relative to the ground level, modifies the effects and the dimension of the weather conditions influence field.

In long term noise levels calculation, as required by the END 49/2002, the influence of weather conditions is determined from the weighted energetic average of favourable and homogeneous (not favourable to propagation) yearly average levels [1]. The effect on the long term period of favourable conditions is expressed as an occurrence factor calculated from a statistical analysis of local meteorological data. These can be measured or evaluated according to general principles and refer to each angular sector of the noise field. In this case study the favourable conditions calculation has been done with an occurrence factor of 100%.

Some series of calculations have been done running XPS 31-133 algorithm in CadnaA noise modelling software [27], keeping other parameters fixed and varying just those related to meteorological conditions and other factors directly connected with them:

Constant parameters:

- Noise source: grade-level road, 10 km length, Lw'=100,3 dB(A).
- Calculation parameters: search ray distance, maximum reflection order.
- Array of 50 receivers, spaced 10 meters apart, from 10 to 500 m distance; receiver height: 4 meters.

Variables:

- Road height (H): ground level, road embankment 2 m, 4 m, 6 m, 8 m, 10 m.
- Ground factor (G): 0,0–0,2–0,4–0,6–0,8–1,0.
- Meteorology: favourable/homogeneous conditions.

Source-receiver relative height varies from −4 to +6 m.

In total 72 runs have been carried out. In the following graphs (Figure 7) some results are presented as difference between noise levels in favourable and homogeneous conditions. In the x-axis the source-receiver distance is shown.

From Figure 7 it can be noticed that an increase in noise levels occurs in favourable weather conditions; such an increase becomes relevant with increasing distance, starting from noise paths greater than 100 meters. This effect is greatly amplified in presence of absorbing soils and low road elevation.

As a consequence, basic noise maps should take into account this effect and provide different propagation scenarios as a function of weather conditions. Weather conditions can be retrieved from existing monitoring stations publishing free of charge data on the web with a time frequency of at least one hour.

6.2 Sensitivity analysis of the acoustic model with respect to traffic conditions

Information regarding the road network layout, land orography and the built up area shape, such as all the static features of the tridimensional model, are taken from a geographical information system database. Instead, the definition of the acoustic characteristics of the sources in the calculation model is based on data obtained from a macroscale traffic distribution model, developed by AMAT, one of the DYNAMAP project partners.

In typical urban areas, traffic conditions vary significantly with respect to the presence of connections, junctions, traffic lights and to the length of the road stretches. The temporal variability of flow conditions depends on short-time effects (traffic light duration) and on long-time effects, such as peak or low traffic periods. According to the XPS 31-133 method, these traffic conditions directly influence the computation of sound power emitted by a single road segment, beside static hourly traffic flows. The algorithm considers four flow conditions: continuous, accelerated, decelerated and interrupted. Other variables related to the traffic conditions and strictly connected to the estimated sound emission are: percentage of heavy vehicles, average speed.

The determination of the influence of these parameters on noise emission of a road is useful for the production of basic maps suitable in various traffic conditions, which may occur dynamically during the day.

With this purpose, sensitivity computations were carried out considering six percentage classes of heavy vehicles (from 0% to 5%; step 1%). For each of them, the relationship between LAw' (linear sound power level) and the variable average speed (five classes from 30 km/h to 50 km/h, step 5 km/h) was assessed considering the four traffic flow conditions.

The examined average speed and percentage of heavy vehicles ranges are typical of Milan urban traffic. The parameter "traffic flow conditions" results to be the most relevant in the calculation of emission levels; the effect of this parameter, in general, decreases with increasing average speed, but high percentages of heavy vehicles determine higher sound power levels – even in case of continuous traffic flow conditions – which increase as the speed values decrease.

The results obtained can guide the drawing of different basic noise maps of the urban environment, which should take into account the occurrence of interrupted flow conditions during certain times of the day, for example in presence of traffic congestion, slowdown or rush periods. The definition of periods of interrupted traffic can be carried out on the basis of the information contained in the traffic simulation model, by calculating the occupancy of each road stretch with respect to its maximum capacity.

7 Anomalous noise event detection algorithm

Automatizing the update of road traffic noise maps through the DYNAMAP system entails several consequences. One of them has to do with the fact that noise levels captured and measured by the network of low cost sensors would be represented on the dynamic maps regardless of their origin (*i.e.*, derived from road traffic or not). As a consequence, the resulting maps would not constitute a faithful reflection of the acoustic impact of road infrastructures.

For this reason, it is necessary to endow the DYNAMAP system with the ability to discern between road traffic noise and other types of acoustic events (*e.g.*, aircrafts, industries, works on the road, etc.), to exclude the latter from the noise level computation. To that end, the LIFE DYNAMAP project foresees the development of an anomalous noise event detection (ANED) algorithm. This algorithm will operate on the audio stream captured by the acoustic sensors with the main goal of identifying the presence of acoustic events unrelated to road traffic and activating an alert signal to exclude the corresponding audio passages from the computation of noise map levels.

The current design of the ANED algorithm follows a "detection-by-classification" approach [14], consisting in the binary classification of sequential audio segments as either "road traffic noise" or "anomalous noise event" following a semi-supervised machine learning approach.

The rationale of the ANED algorithm is based on the nature of anomalous noise events, which are prone to be i) highly local (*e.g.*, sensors located in roads near airports will often capture aircraft noise while others will rarely be affected by this type of noise), ii) unpredictable and highly diverse (*e.g.*, ambulance sirens or thundering), and iii) little likely to occur (*e.g.*, a bird or a cricket that approaches the sensor). For this reason, the ANED algorithm relies on building an acoustic model of road traffic and background noise during its training phase, since this is the type of

Table 3: Recognition accuracy of the ANED algorithm using different classifiers (FLD and KNN) and audio feature extraction techniques (GTCC and MFCC) under −12 dB and −6 dB RTN-to-ANE ratio scenarios.

	RTN-to-ANE = −12 dB				**RTN-to-ANE = −6 dB**			
	FLD		**KNN**		**FLD**		**KNN**	
	GTCC	MFCC	GTCC	MFCC	GTCC	MFCC	GTCC	MFCC
R (%)	91.46	87.22	87.70	83.35	84.56	84.79	79.97	76.82

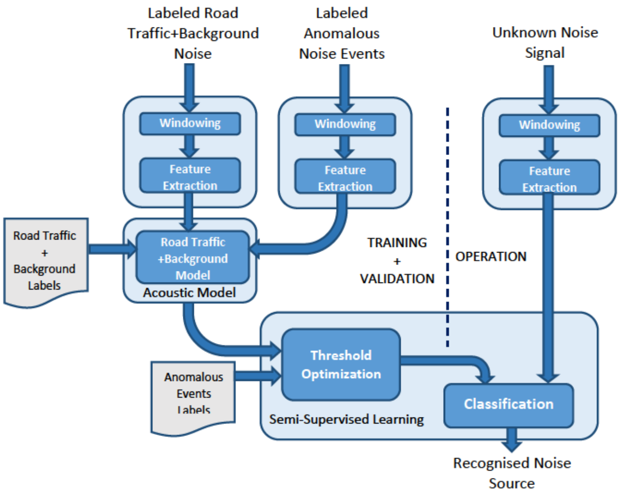


Figure 8: Block diagram of the anomalous noise event detection algorithm.

acoustic event the algorithm will be dealing with most of the time. Figure 8 depicts the architecture of the ANED algorithm.

The proposed algorithm is functionally divided into a training, validation and operation stages. During the training stage, only labeled audio samples of the predominant road traffic noise plus background noise (RTN+BCK) class are employed to build the corresponding acoustic model. Next, during the validation stage, labeled samples of both the RTN+BCK and anomalous noise event (ANE) classes are employed to adjust the decision threshold that allows the ANED algorithm to discriminate between them.

The technique for setting the decision threshold is inspired in automatic speaker verification systems [28], which are prone to *type I* and *type II* errors, *i.e.*, the positive identification of a speaker that should not be identified (*aka* false positives) and the negative identification of a speaker who should be identified by the system (or false negatives). In our anomalous noise event detection scenario, *type I* errors correspond to detecting as an ANE a signal frame containing RTN+BCK, while *type II* errors correspond to the opposite situation.

Following the approach described in [28], we apply the threshold optimization criterion that simultaneously minimizes *type I* and *type II* errors based on the analysis of the two-class (RTN+BCK and ANE) distances distributions with respect to the RTN+BCK acoustic model built during the training phase. The threshold optimization process is based on measuring distances between labeled RTN+BCK and ANE samples and the RTN+BCK acoustic model. Thus, the ANED algorithm should be implemented as a distance-based classifier (or at least as a classifier capable of providing a measure of the proximity be audio samples to the RTN+BCK acoustic model), such as k-nearest neighbors (KNN) or Fisher linear discriminants (FLD).

At signal level, the ANED algorithm divides the incoming audio stream into 30 millisecond frames, converting each windowed audio segment into a feature vector using either Mel Frequency Cepstral Coefficients (MFCC) or GammaTone Cepstral Coefficients (GTCC).

In preliminary experiments conducted using laboratory data, we have tested the proposed ANED algorithm under different RTN-to-ANE (*i.e.* signal-to-noise) ratio scenarios, using different classification and audio feature extraction schemes, obtaining the recognition accuracies presented in Table 3.

It can be observed that the proposed ANED algorithm is capable of consistently achieving recognition accuracies of anomalous noise events higher than 80% using different signal parameterization and classification schemes (for further details, see [15]).

However, as mentioned earlier, these tests have been carried out using laboratory data, *i.e.* synthetic mixtures of road traffic noise obtained from short recordings (made along the ring road surrounding the city of Barcelona) and *synthetic* anomalous events gathered from Internet repositories. However, it is important to realize that a key issue that affects the performance of the ANED algorithm is the reliability of the road traffic noise acoustic model built during the training phase.

In this sense, and given the diversity of operating scenarios foreseen in the LIFE DYNAMAP project – *i.e.*, the selected pilot areas located in Milan's urban centre and in the suburbs of Rome (see section 5 or [16, 29] for further details) –, it is necessary to build acoustic models that faithfully reflect the characteristics of road traffic noise in both

(a) Bruel & Kjaer 2250 sonometer. **(b)** Low-cost measuring device.

Figure 9: Recording equipment [30].

Figure 10: Examples of the recording devices installed in the ANAS S.p.A. portals situated on the A90 highway surrounding Rome [30].

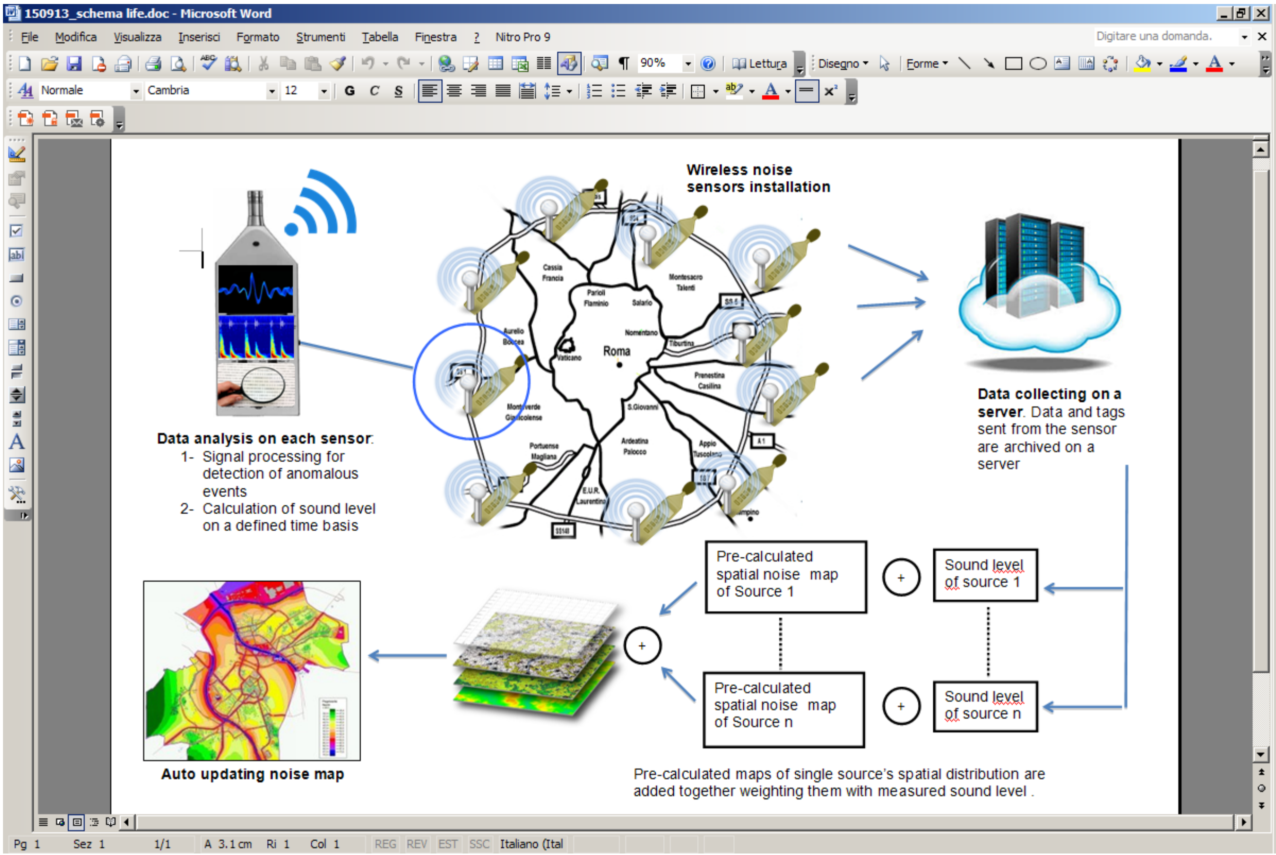
types of environments besides collecting *real* anomalous events. For this reason, an environmental noise recording campaign was conducted during May 2015 within the pilot areas where the two demonstrative versions of the DYNAMAP system will be implemented [30]. The specific recording sites were selected to obtain representative samples of the traffic conditions and acoustic characteristics of the two pilot areas.

Moreover, as the monitoring network of sensors of the LIFE DYNAMAP system will be composed of low cost acoustic sensors, the recordings were conducted with two measuring devices simultaneously: one low cost sensor developed by Bluewave [31] connected to a ZOOM H4n digital recorder, (see Figure 9b) and a Bruel & Kjaer 2250 sonometer (see Figure 9a), used as a reference. These dual recordings were conducted to allow the subsequent validation of the low cost acoustic sensor performance with respect to the standardized sound level meter.

More specifically, the first subset of recordings were conducted during two days in 6 sites along the A90 motorway in Rome, which constituted a representative subset of the 17 sites in this pilot area. The recording equipment were installed on 6 motorway portals owned by ANAS S.p.A (see Figure 10).

Next, the second subset of recordings were conducted in Milan's district 9 pilot area to collect urban road traffic noise samples in 12 locations at different times of day and night. These locations were selected to capture noise in diverse scenarios, such as one- and two-way roads, streets with fluid and heavy traffic, etc.

As a result of the four-day recording campaign between Rome and Milan, a total 9 hours and 51 minutes of audio were collected and prepared for the subsequent labelling and post-processing phase. These tasks were tackled using the Audacity freeware software, which was employed to normalize the recorded audio files in amplitude,



Data analysis on each sensor:
1- Signal processing for detection of anomalous events
2- Calculation of sound level on a defined time basis

Data collecting on a server. Data and tags sent from the sensor are archived on a server

Pre-calculated spatial noise map of Source 1 + Sound level of source 1

Pre-calculated spatial noise map of Source n + Sound level of source n

Pre-calculated maps of single source's spatial distribution are added together weighting them with measured sound level .

Figure 11: DYNAMAP working principle.

and to label the occurring events into a taxonomy of three main categories: road traffic noise, background city noise, and anomalous events. This latter class was further subdivided into 18 subtypes of events, such as people talking, music in car or in the street, or noise caused by tramways or trains, among others.

After labelling and post-processing the data, we obtained 7 hours, 48 minutes and 38 seconds of road traffic noise, 38 minutes and 37 seconds of background noise, and 25 minutes and 54 seconds of anomalous noise events. Therefore, as a result of this recording campaign, a considerable amount representative acoustic data has been collected in order to train, validate and test the ANED algorithm, processes that are currently under development to obtain the next version of the ANED algorithm.

8 The monitoring system

In Figure 11 the functional scheme of the Dynamap system is shown. It consists of monitoring stations detecting the noise levels near the source that gather, clean up and send data to a central server, where they are analysed, processed and used to scale the basic noise maps.

The noise monitoring stations will host the ANED algorithm to detect and remove anomalous events.

In this way it will be possible to obtain a more scalable and less complex system, thus avoiding the need for variable computational load at the central server (*e.g.* depending on the number of monitoring stations, the transmission of raw audio data or some type of acoustic parameters).

Each monitoring station will provide a classified output with a time frequency of one second. The output will be coded as follow:

00001 – 151021113200 – 58.0 – 0

where the first number is the sensor identifier, the second number is a timestamp, the third is a dB(A) level and the fourth one is an indicator standing for “road” or “non road” event. All those data will be stored in a remote web server by mean of wireless data communication system like GPRS or 3G.

Levels without spurious events will be averaged on a time period that will be defined in order to make the mapping model properly work. The magnitude order of this period should be ranging from some minutes to an hour. This time period will be the temporal base to update the map.

For each of the monitored road source and for the remaining road sources a complete noise map is calculated and saved for the entire mapping area by logarithmic sum of the single maps weighted with measured levels as shown in Figure 11. This application is nowadays extremely fast as no further recalculation of the sound propagation is required to adapt the noise map to the measured data.

8.1 Types of low cost noise monitoring networks

There are many ways of classifying a sensor network (according to network topology, to transmission protocols, etc.). For the purpose of this paper, sensor networks for environmental noise monitoring can be roughly distinguished in two different groups: embedded pc based and microcontroller based. These two kind of devices are described below.

- Embedded pc monitoring systems:

  In the last decade, the exponential growth in computing technologies made possible to significantly reduce the computers size. Currently it is possible to find low cost small computer boards (with a size less than 10 × 10 cm), equipped with high quality sound board. Such system can be equipped with gprs/3g/4g modem or Wi-Fi connection and a signal analysis software that processes incoming data from the sound board, using a cheap microphone. This kind of system presents the advantage of being unexpensive and can be remotely fully updated and reprogrammed. Moreover it can be coded with specific algorithms executing particular complex tasks as noise recognition, source position tracking etc. The disadvantage of those systems is the high power consumption, that is actually at least 2–3 W, so they need direct power supply or big solar panels making difficult the application for a very pervasive monitoring using hundred of sensors.
- Microcontroller and digital signal processor systems:

  The main advantage of this kind of system is the possibility of implementing low power applications (200 mW mean equivalent consumption or less) that allow to power these devices with solar panels or with other energy harvesting systems. The disadvantage of those systems is the reduced possibility to modify and remotely control the device in order to implement complex tasks. Well known standard noise monitoring systems compliant to class I IEC 61672 (such as Norsonic, Bruel& Kjaer, 01 dB etc.) are usually made using this kind of technology.

8.2 Technical details of the monitoring stations used in Dynamap project

Due to the prototypal nature of the sensors network to be installed, it is advisable to use a flexible system that can be remotely accessed and programmed in order to run and calibrate specific audio processing scripts. For this reason, it was decided to use embedded computers, instead of microcontrollers. Another advantage that can be attributed to this solution is the possibility of pre-processing data directly on sensor boards by implementing the ANED algorithm, thus avoiding to send many acoustic data to the central server, as mentioned before. This will also guarantee better scalability of the system, reducing the computational load on the central server if the number of sensing units is increased.

A first set of basic specifications that has been defined for each monitoring station is listed below:

- 40–100 dB(A) broadband linearity range
- 35-115 dB working range whit acceptable THD and narrowband floor noise level
- 1 second time base Leq(A) level
- Possibility of audio recording
- Internal circular backup data storage of calculated data
- VPN connection
- GPRS/3G/WiFi connection

Noise monitoring stations will be subjected to a periodic calibration, with respect to one or more frequencies to be defined. In this way it will be possible to assess the variation in time of the frequency response over the years.

Furthermore, it is foreseen to periodically store the minimum narrow band spectrum, detected during the quieter time intervals of the day (within night period), in order to evaluate the temporal evolution of the electrical noise level of the measuring chain.

9 Basic secondary aspects of the DYNAMAP project

In this paragraph some basic secondary aspects of the DYNAMAP project are described and discussed. Such basic secondary aspects include relevant issues that could strongly influence the success of the project, namely benefits and costs of the proposed solution, public response and user ability in consulting and managing the system (in compliance with the Environmental Noise Directive 2002/49/EC), future development of the system applications.

Indeed dynamic noise maps, although very appealing, could be inapplicable if their cost were judged unsustainable. Likewise, their added value would be negligible if the possibility of collating many data in real time couldn't be exploited to provide useful applications, such as the control and management of traffic to reduce noise emissions, the upgrade of the system towards smart integrated environmental maps (including air pollutions indicators, traffic flow information and meteorological conditions), user-friendly tools to inform and communicate to the public.

9.1 Expected cost and benefits of the DYNAMAP System

The project includes a comprehensive costs and benefits analysis in order to assess the feasibility and economic sustainability of the DYNAMAP system on a large scale. Aim of this study is to demonstrate that noise mapping costs can be reduced and that benefits can be improved by providing updated real time information on the acoustic climate of road infrastructures at any place and time. As a matter of fact, the success of the project mostly depends on the economic burden required to local and central authorities for implementing the system. Therefore, costs and benefits can't be considered secondary aspects for the success of the project, but basic specifications to be fulfilled to reach the final goal.

The cost-benefits analysis will be at first carried out locally in the two pilot areas (*i.e.* the A90 motorway surrounding the city of Rome and Milan district n° 9), and then extended to the whole ANAS network and the agglomeration of Milan, to demonstrate the feasibility and economic sustainability of the system.

A first estimate of the expected costs of the DYNAMAP system was calculated at the beginning of the project taking into account the expense that should be paid to prepare the pilot area located along the A90 motorway (Rome), where a minimum number of 25 monitoring stations will be installed. The calculation includes the cost of the monitoring stations, their installation and maintenance for twenty years, the cost related to the preparation of the basic noise maps. A final cost of 275 €/km was achieved.

Furthermore, whatever costs are, several benefits can be attributed to the Dynamap system, such as:

- a real time update of noise maps as a consequence of the automation of the mapping process;
- a faster response to noise mitigation request, thanks to the real time availability of updated dynamic maps;
- a prompt response to alert events associated to specific thresholds through interface devices to Intelligent Transportation System (ITS) (for instance, dynamic speed limits , traffic calming, etc.);
- a more comprehensive and reliable information on the environmental impact due to traffic noise, based on the number and type of additional sensors used to monitor the road network;
- a user-friendly tool to inform the public about noise pollution and other environmental issues.

All these aspects will contribute to increase the net present value of the system, whose impact will be deeply investigated in a later stage of the project (Action C3), where real costs and benefits related to the implementation of traditional and dynamic noise maps will be accurately monitored and analyzed.

9.2 Public response and users ability in consulting and managing the system

Another aspect that could influence the success of the project relies on public response and users ability in consulting and managing the system. The project will have a greater chance of attracting the public interest if user friendly interfaces and tools will be developed, so as to make the information gathered by the system usable on a large scale through easy to access applications.

In 2002 the Directive 2002/49/EC on environmental noise (END) introduced the obligation of providing environmental information and communication to the public. According to END, Member States shall ensure that strategic noise maps and action plans are made available and disseminated to the public. This information shall be clear, comprehensible and accessible. Furthermore, Member States shall ensure also that the public is consulted about proposals for action plans, given early and effective opportunities to participate in the preparation and review of the action plans, that the results of that participation are taken into account and that the public is informed on the decisions taken. As a matter of fact, involving the public in the preparation of noise action plans is one of the fundamental requirements of the END. According to the END, the most appropriate information channels should be properly selected in order to have a wide spread of information to the public.

To fulfill END requirements the DYNAMAP project includes the development of a software for real-time web presentation of the results to the public in a user-friendly format. This software application will be also designed to plot other environmental data, in addition to noise maps, such as air quality, weather and traffic conditions, when available.

To optimize the software application communication skills, the project foresees an iterative process where users ability in accessing information and managing the system will be checked through a series of tests addressed to system's operators and stakeholders.

Finally, the project entails the monitoring of action plans preparation for the agglomerations of Milan and Rome in the framework of the third cycle of the END, to check the effectiveness of the information delivered to the public and verify their actual participation in selecting and adopting proper noise mitigation measures. As consequence of the results achieved, corrective actions will be taken to meet users requirements and improve the accessibility of the software interface.

9.3 Future vision on system applications

A very relevant aspect as regards the deployment of the DYNAMAP system on a large scale is related to its evolution from its original conception towards a more complete, multimodal and informative tool. Indeed, endowing the DYNAMAP system with capabilities beyond the real time mapping of road noise traffic can be a distinctive factor that increases its acceptance and attractiveness.

For instance, DYNAMAP maps could be extended to inform about the volumetric concentration of pollutant agents in the atmosphere, thus providing a visual and constantly updated map of air quality. Another example could be the creation of maps displaying the value and evolution of meteorological parameters, such as air humidity or wind speed. This same idea could be expanded to create dynamic maps of human-caused environmental parameters, such as traffic density.

The possibility of having a real time map of traffic noise allows the development of multiple mitigating, short-term corrective and informative applications. The mitigating applications of the system are related to long term measures, and are of main interest to authorities. Based on the data acquired by the DYNAMAP system, the most critical areas in terms of noise and atmospheric pollution can be identified. In this way, action plans to mitigate the noise impact on people who live and work in those areas can be effectively addressed, such as the construction of acoustic barriers and low-noise pavements or planting of trees to compensate for air pollutants, traffic calming policies and ITS systems to control and manage vehicles speed and traffic flow in real time.

The detection of high traffic noise levels in certain areas at specific moments can be used with short term corrective and informative purposes, which can be of interest to both authorities and general public. An example of this includes the development of an early warning system based on the interconnection between the DYNAMAP system and electronic roadside informative boards, which can be used to inform drivers of alternative routes, or to display traffic related messages (for instance, dynamic speed limits). In these terms, the interest towards the project and its exploitation on a large scale could also be determined by the possibility in the future of linking the DYNAMAP system to ITS, thus contributing to reduce vehicles noise emissions through the control and management of the traffic flow.

Finally, the possibility of going into a deeper analysis of the noise data captured by the system, will make the system able to implement more advanced applications. Making use of the spectral decomposition of the noise signal provided by the sensors deployed in the project, it will be possible to go further than traffic vs. non-traffic noise discrimination, being able to recognize several types of noise sources. This will allow to achieve dynamic maps of different noise sources such as rail, cars, trucks or aircrafts, as well as to provide precious information on meteorological and traffic conditions (for instance, congested or smooth traffic, the presence of wind or rainfall).

10 Conclusions

In this paper, a comprehensive description of the Life+ DYNAMAP project is presented. The project involves the development of a dynamic noise mapping system able to detect and represent in real time the acoustic climate of road infrastructures. Main goal of the project is to reduce the cost of the noise mapping process and to provide authorities responsible for noise mapping activities with affordable and ready to use noise maps. Furthermore, the project foresees the development of a user-friendly tool to inform and communicate with the public fully compliant with END specifications.

The system will be composed of customized low cost sensors, measuring the sound pressure level of the noise sources present in the area to be mapped, and of a software tool, based on a GIS platform, able to automatically update the noise maps in real time. The system will be installed and tested in two very different sites: the first one located inside the agglomeration of Milan and the second one along a major road surrounding the city of Rome to assess its reliability and accuracy.

A dramatically reduced economic burden of noise mapping activities is expected from the DYNAMAP System, as well as more accurate and ready to use noise maps. Furthermore, it is envisaged that the idea of distributing low cost sensors to dynamically update noise maps will contribute in the future to enlarge the number of measured receivers, ideally extending the monitoring network to the whole territory to be noise mapped, with the advantage of ensuring updated and more reliable results.

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