Research Article

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LIFE Monza: comparison between ante and *post-operam* noise and air quality monitoring activities in a Noise Low Emission Zone

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Abstract: LIFE MONZA project (Methodologies fOr Noise low emission Zones introduction And management) aims at defining an easy-replicable method for the identification and management of the *Noise Low Emission Zones* (Noise LEZ), urban areas subject to traffic restrictions, usually introduced in order to ensure compliance with the air pollutants limit values, prescribed by the European Directive on ambient air quality 2008/50/EC, whose impacts and potential benefits regarding noise issues have been taken into account, tested and analysed in a pilot area of the city of Monza, located in North Italy. Noise LEZ has been established in Libertà district, introducing infrastructural interventions carried out by the municipality (*top-down actions*) and encouraging an active involvement of the citizens, in the definition of a more sustainable lifestyle (*bottom-up actions*). The analysis of potential effects on noise reduction due to the Noise LEZ can contribute to the implementation of the EU Directive 2002/49/EC, related to the assessment and management of environmental noise (Environmental Noise Directive – END), which introduces noise action plans, designed to manage noise issues and their effects, suggesting the adoption of urban and mobility planning. Noise and air quality monitoring activities have been carried out in pilot area in *ante* and *post-operam* conditions. The monitoring methods, the measurement techniques, the analysis procedures, able to describe the effects due to Noise LEZ establishment, for both the main environmental issues are reported in this paper, as proposals to be applied in other different contexts. Results of monitoring activities highlight a reduction of noise, in term of sound pressure levels, between *ante* and *post-operam*, during the day and particularly during the night period, and it is essentially due to the interventions realised. The effect of the Noise LEZ on air pollution seems to be negligible for combustion related pollutant and carbon fractions of PM, due both to the moderate spatial effects of the measures undertaken and confounding factors due to concomitant emission sources and meteorology.

Keywords: environmental noise, low emission zone, urban planning, top-down approach, bottom-up approach, noise monitoring system, air quality monitoring system

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1 Introduction

Noise and air pollutions are considered as major environmental risks for human health in Europe. Exposure to environmental noise has impacts on human physical and mental health and well-being [1]. It is estimated to cause 12.000 premature deaths and to contribute to 48.000 new cases of ischemic heart disease per year in Europe. Moreover, 22 million people suffer chronic high annoyance and 6.5 million people suffer chronic high sleep disturbance. Based on the implementation data of the Environmental Noise Directive (END) 2002/49/EC, relating to the assessment and management of environmental noise, an estimated 113 million people are affected by long-term day-evening-night road traffic noise levels of at least 55 dB(A), considered harmful to health [2]. The END aims at defining a common approach to avoiding and preventing noise exposure, requiring the noise assessment through noise mapping, the adoption of action plans able to prevent and reduce environmental noise, also defining and preserving areas of good environmental acoustic quality (quiet areas), ensuring that information on environmental noise and its effects is made available to the public. The potential of the END has yet to be fully realized, in particular regarding the noise reduction measures.

Air pollution increases the incidence of a wide range of diseases and has several environmental impacts, damaging vegetation and ecosystems. The road transport sector provides a significant contribution to the total anthropogenic emissions, together with other mobile sources, non-industrial combustion plants and combustion in energy and transformation industries. Control of exposure to air pollutants requires public authorities' actions at global, regional and local level. WHO produced and subsequently revised air quality guidelines [3, 4] that contain recommendations of targets for air quality and limits for the concentration of selected air pollutants derived from epidemiological and toxicological evidence. The Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe defined and established objectives for ambient air quality designed to avoid, prevent or reduce harmful effects on human health and the environment as a whole. The International Agency for Research on Cancer (IARC) concluded that there is sufficient evidence that exposure to outdoor air pollution causes lung cancer. Particulate matter was evaluated separately and was also classified as carcinogenic to humans [5]. Air pollution has been widely accepted and recognized by this time to have an impact in terms of cardio-vascular disease (CVD) as well as respiratory diseases than can lead to premature mortality. Ambient (outdoor air pollution) in both cities and rural areas was estimated to cause 3.7 million premature deaths worldwide in 2012 [6]. Atmospheric pollution is an extremely complex phenomenon. The burden of pollutant resulting from human activities and natural source evolves in time and space through the atmosphere. The transport, dilution, transformation and deposition mechanisms are driven by specific reactivity of the substances and the meteorological conditions, that are as well largely variable in time and space and govern the dynamics of air pollutants after emission. This lead to a non-linear relationship between emission and outdoor air pollutants concentrations.

Recent studies suggested four pathways that could explain combined effects of air pollution and noise exposure on several cardiovascular events. It was suggested that within these adverse pathways air pollution and noise may overlap and act synergistically [7, 8]. In order to improve the knowledge on additive or synergistic effects of simultaneous noise and air pollution exposure in humans, monitoring strategies and exposure assessment methodologies development are needed. Only a few studies addressed additive or synergistic effects of air pollution and traffic noise exposure in humans. Although most of them suggest that air pollution and traffic noise mostly act as independent risk factors of CVD incidence and mortality, the opposite effect was observed in some studies, suggesting the relevance of monitoring design as an important driving for the epidemiologic studies, particularly because the interpretation of results of studies on road traffic noise and air pollution is complicated by the appreciable co-linearity of these two environmental risk factors, particularly when traffic is the main noise source [9].

The realization of Low Emission Zones (LEZs), which are urban areas subject to different kinds of road traffic restrictions, has been primarily introduced in order to ensure compliance with the air pollutants limit values set by the European Directive on ambient air quality 2008/50/EC. It is a well-established measure carried out by the cities and the effects on air quality have been analyzed in detail, whereas the potential benefits about noise have not been addressed in a comprehensive manner. Restrictions of road traffic in urban areas can be adopted through environmental zones, city tolls, congestion charging, distinguished by vehicle types, speeds and emission standards and the interventions are often used as urban redevelopment. LEZs may cover a variable area that can include few roads or a large part of an urban area. Those zones aim mainly at reducing exhaust emissions of traffic related pollutant, particularly PM and nitrogen oxides NO_X. Policy measures (as LEZs) to reduce traffic by banning the most polluting vehicles are generally able to reduce circulating vehicles but they gave conflicting results on air pollution level [10, 11]. LEZs have been introduced in many European countries, mostly in Italy, and different regulations [12], at national and local levels have been developed, causing the need of a comprehensive and integrated management process, particularly regarding the environmental effects. LIFE MONZA project addresses these issues, aiming at introducing an easy-replicable method, and related guidelines, for the identification and the management of the Noise Low Emission Zone (Noise LEZ), an urban area subject to traffic restrictions, whose impacts and benefits regarding noise issues are taken into account. The infrastructural interventions, able to turn up the pilot area of Libertà district in Monza in a permanent Noise LEZ, named *top-down measures*, have been carried out by the municipality, and they are the restriction of vehicles speed, the definition of traffic zone with forbidden access to trucks, the lanes-width reduction and pedestrian crossings introduction and the substitution of the current asphalt with a silent one. In order to involve the inhabitants of the area, many different actions, named *bottom up measures*, as lessons and meetings in primary and high schools to raise awareness about noise effects, ideas contest for students, *pedibus* service for schoolchildren, have been realized. Other objectives of the project were the evaluation of complementary effects on the air quality and benefits on wellbeing conditions of the residents.

Paper contents are focused on the monitoring strategy adopted for joint air quality and noise assessment before and after the Noise LEZ establishment in the pilot area of the project and the related main results and lessons learned that could enable an in-depth characterization of the urban area, allowing to investigate potential synergies existing between the monitoring methods of the two environmental components and replicability in future assessments.

Noise and air quality monitoring methods tested in pilot area of LIFE MONZA Noise LEZ are following described, considering, about noise, the use of both traditional and standard measurements and the development of a Smart Noise Monitoring System, and about the air quality, both the assessment of temporal and spatial air pollution variability. The *ante* and *post-operam* monitoring results both for noise and air quality are then reported and, according to the parallel analysis of the two environmental issues, a discussion is carried out, based on the comparison of the results obtained by the monitoring campaigns in *ante* and *post-operam* phases, highlighting the effects of the Noise LEZ establishment.

2 Noise and air quality monitoring methods in LIFE MONZA noise low emission zone

2.1 Pilot area and implemented top-down interventions

The pilot area selected in the framework of the LIFE MONZA project consists of the Libertà district of the city of Monza shown in Figure 1.

In the selected pilot area a main road (Libertà street) and other roads affected by medium-low traffic are present. Significant average levels of noise pollution affect many citizens so that Libertà district is identified as a hotspot in the Action Plan of the city of Monza. The noise strategic map of the city of Monza, dated 2017, [13] highlights that in a range of 30 m from the Viale Libertà almost the 100% of the receivers are exposed to levels higher than 65 dB(A) during the day and 55 dB(A) during the night.

With the aim to reduce the noise pollution in the pilot area two main interventions have been designed and implemented for the Libertà street: the laying of new low-noise paving and the closing of the road to the heavy vehicles [14]. The low-noise asphalt represents the main instrument for the decrease, on large scale, of the traffic noise through interventions at the noise source and today several technologies are available based of composition, used materials and field of use.

For the laying of the asphalt, the typology "Dense graded at optimized weaving" has been chosen, which guarantees results of 3-4 dB(A) in term of acoustic abatement and an efficiency period about five years from the laying. This road surface has already been defined by "Progetto Leopoldo" whose results have been recognized by a deliberation of Regione Toscana in 2013 [15]. Progetto Leopoldo aimed to define a guideline for the design, building, control and maintenance of ordinary viability in Tuscany. This guideline allows to identify technologies, materials and kinds of interventions with the scope to improve the safety of the circulation and at the same time guarantees requests of eco-compatibility and duration. In the sample studied at Lucca, four years after the works a reduction of 5 dB(A) has been measured. In Figure 2 the section of Viale Libertà interested by the new asphalt laying is shown. In this road the work has foreseen the removal of the old road surface and the laying of 4 cm of link layer of Binder and following 4 cm of use-surface in Dense Graded.

The works to lay the new low-noise asphalt has started on Monday 17 September 2018 and finished on Saturday 22 (Figure 3).

Regarding the limitations of the traffic in the pilot area of Libertà district, the first one has started since 21 January 2019 and will continue up to the end of June 2020.

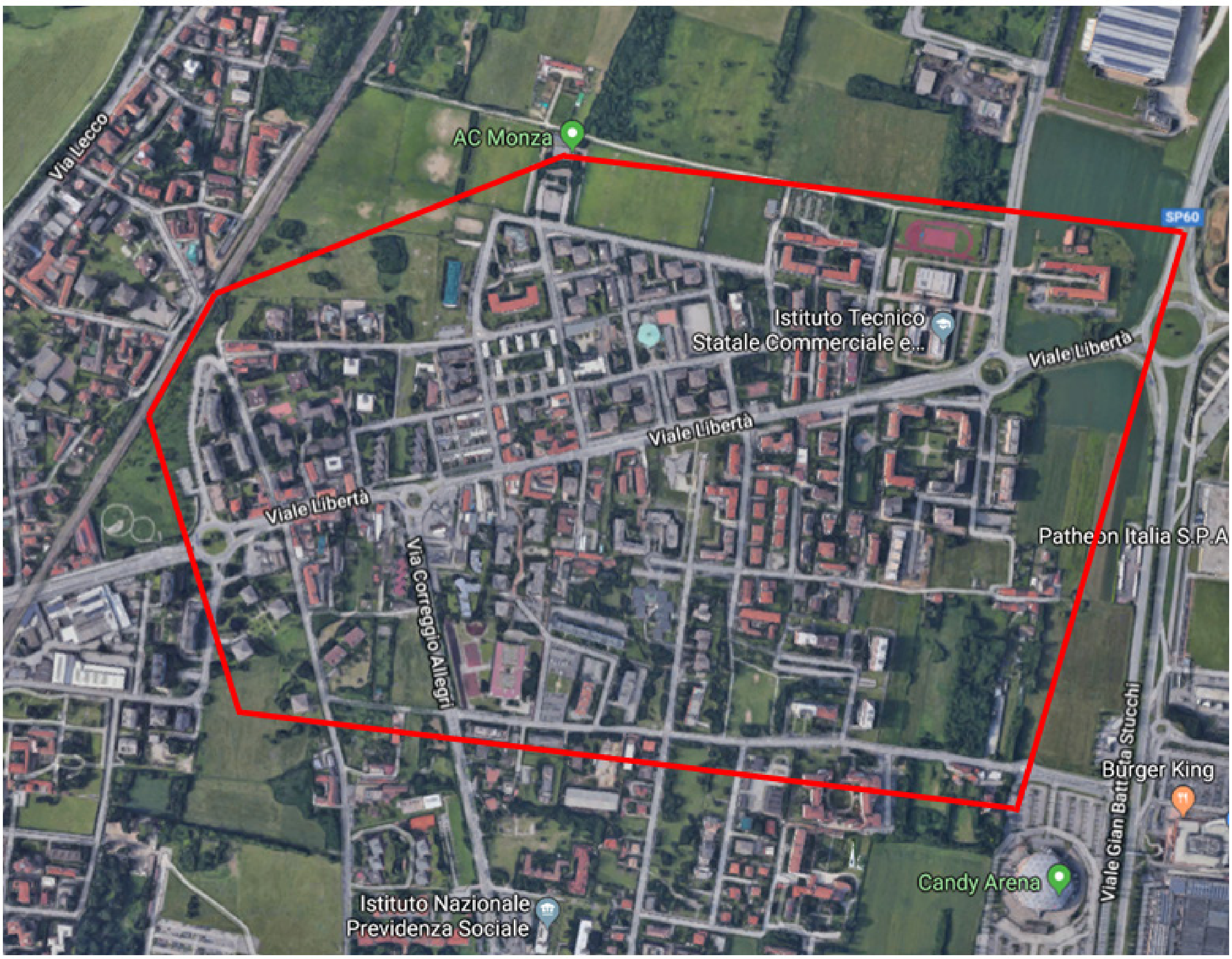


Figure 1: Perimeter of the pilot area ("Libertà" district, city of Monza)

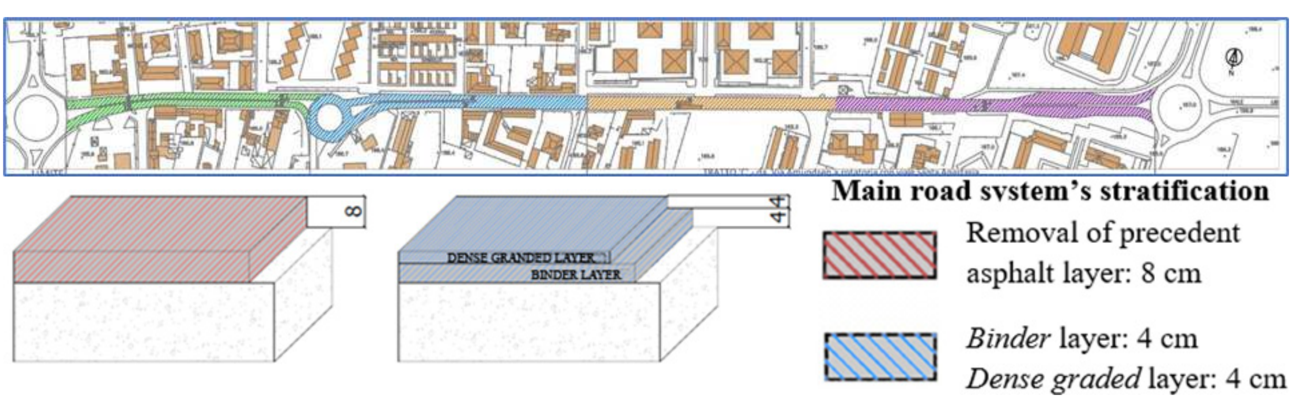


Figure 2: Detail of the design of low-noise pavement in Viale Libertà – Monza

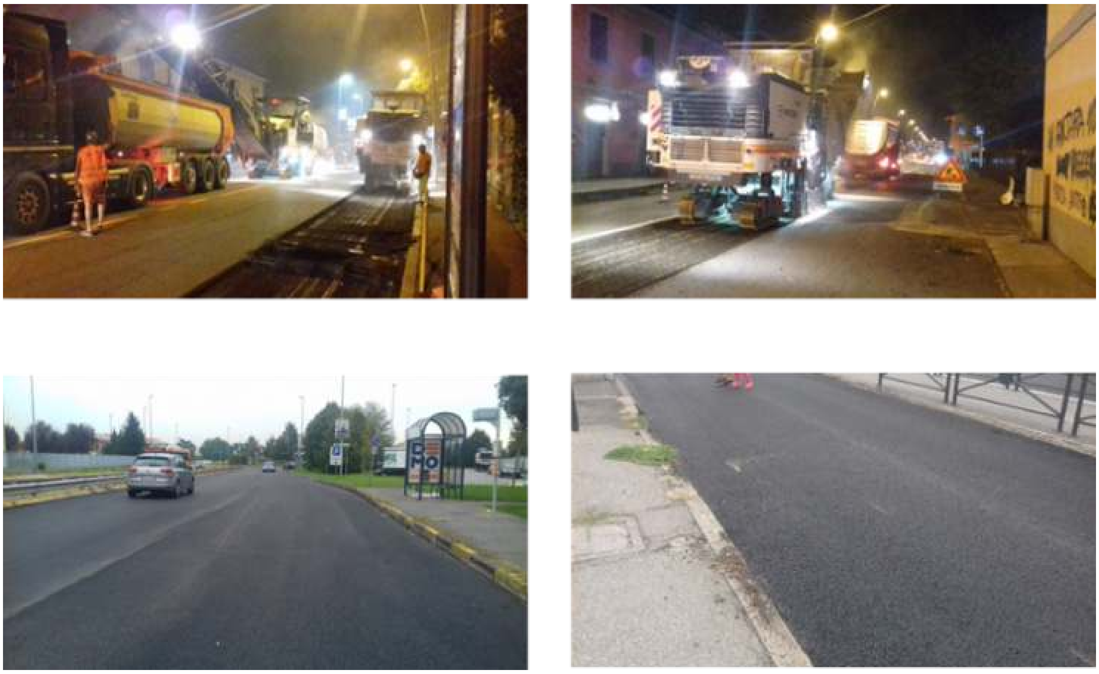


Figure 3: Works for the laying of new low-noise road surface in Viale Libertà (September 2018)

2.2 Structure of noise monitoring network (smart + traditional)

Among the activities carried out in the LIFE MONZA project, the noise monitoring has played a central role.

In fact, it has been planned both in the *ante* and *post operam* scenario, by using of both the class I instrumentation and a new low cost monitoring sensor network developed into the project [16, 17], in order to study the efficiency of interventions planned to reduce the traffic noise in this area. Moreover, some traffic counters were put in place to monitor road traffic flows.

In Figure 4 the noise monitoring positions are shown, together with the positions of traffic counters and low-cost sensors (*Smart Noise Monitoring System*, SNMS) to evaluate noise pollution both in ante and post scenario.

2.3 Class I noise monitoring system

For the correct determination of the levels expected in front of the receptors, an *ante-operam* and *post-operam* monitoring have been planned at some specifically identified receivers. In particular, it was planned to carry out weekly measurement campaigns in both the Spring/Summer period and the Autumn/Winter period relating to both noise measurements and traffic flows. The instrumentation used to perform noise measurements complied with the class I requirements according to regulations IEC 651 – EN 60651 and IEC 804 – EN 60804. These noise monitoring campaigns consisted of long-term monitoring campaigns (one-week duration) and short-term monitoring campaigns (one-hour duration).

In particular, the long-term monitoring campaign consists of a week noise monitoring and a week road-traffic counting in 2 positions located in external environment and in P01- Civic Centre and in P02- School Modigliani (see Figure 4). The microphones were placed on the roofs of the interested receivers, facing the roadway. The traffic counters (CT01 and CT02) have been positioned on the roadside, whose results evidence the subdivision in light and heavy vehicles in the time slots subject to phonometric measurements.

In the Autumn/Winter period, the *ante-operam* monitoring was carried out in the period between Monday 20 and Monday 27 November 2017, while the *post-operam* monitoring was carried out between Monday 21 and Monday 28 January 2019.

Likewise, in the Spring/Summer period, the *ante-operam* monitoring was carried out in the period between Monday 15 and Tuesday 23 May 2017, while the *post-operam* monitoring was carried out between Monday 6 and Tuesday 14 May 2019.

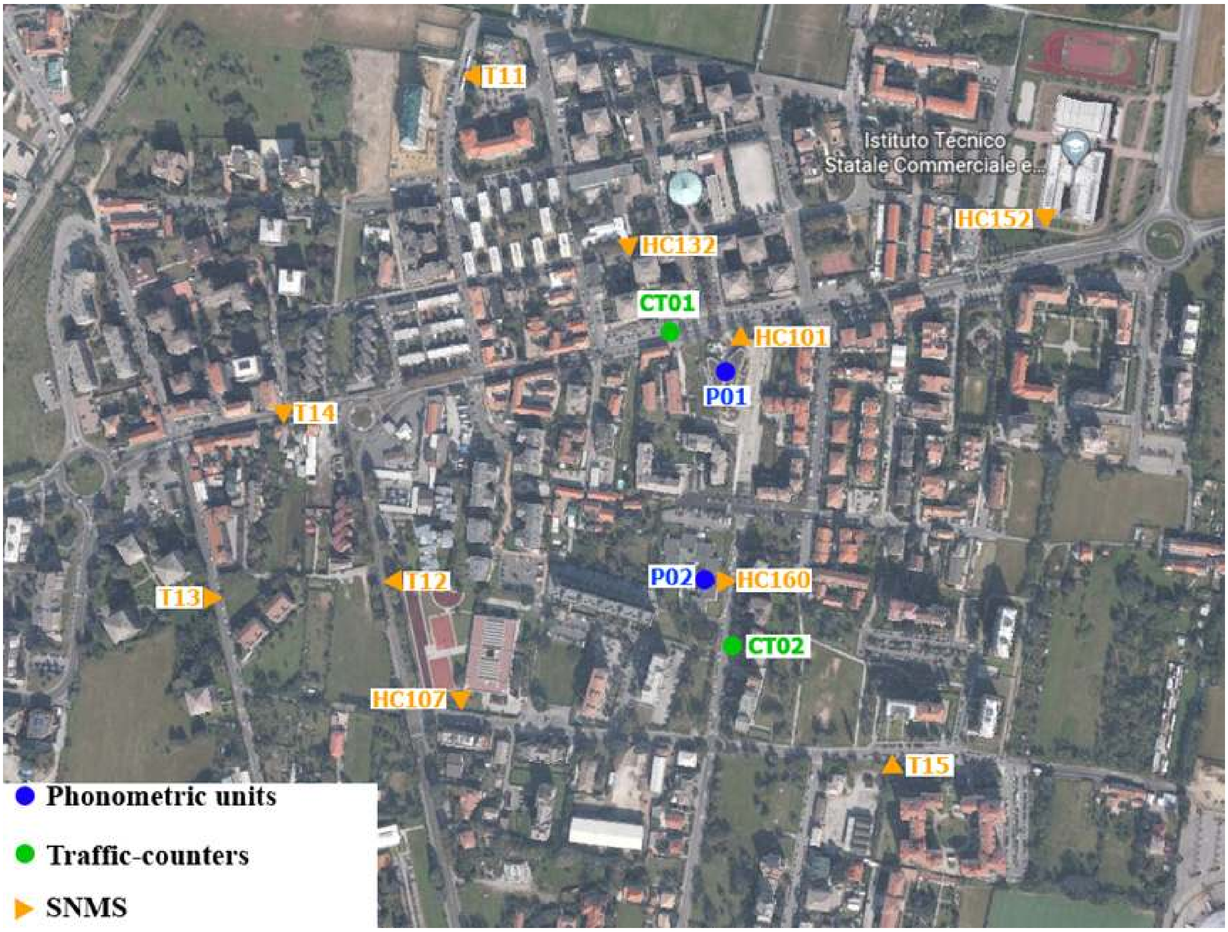


Figure 4: Different kind of measuring systems and related positions to monitoring noise in the pilot area

2.4 Smart noise monitoring system

The Smart Noise Monitoring System (SNMS) network is meant to adequately cover the pilot area and the different types of roads. As illustrated in Figure 4, 10 monitoring stations have been installed in the pilot area. In particular, 3 microphones have been placed along Viale Libertà, the main street where the traffic flow mix is expected to mainly change from ante to *post-operam* scenario. The other microphones have been uniformly distributed along other streets belonging to the pilot area [18]. The SNMS technical specifications were defined in [19] keeping in mind the aim of a long-term monitoring of acoustic parameters. These are expected to be useful to understand the variability of acoustic climate in the pilot area with mainly reference to the overall A-weighted continuous equivalent sound pressure level.

The 10 prototypes of the monitoring stations have been installed in the pilot area in June 2017 and, at the end of the LIFE MONZA project, will be given for free to the city of Monza that will take care of using them for monitoring activities in the three years after LIFE period.

2.5 Structure of air quality monitoring network

To achieve the project's objectives both temporal and spatial air pollution variability was to be assessed.

2.5.1 Temporal pattern

We aimed at evaluating the concentration levels, and their seasonal/daily variability, of the main air pollutants and some components of the particulate material (organic carbon, elemental carbon, black carbon) to characterize the area in question and compare it with the rest of the Monza urban area as well as with the agglomeration of Milan which the city belongs.

These data were used to assess, on the basis of the comparison of the results of the campaigns carried out before (ex-ante) and after (ex-post) the implementation of the Noise LEZ, any tangible effects, on a local level, on air quality.

Sampling was carried out using a mobile laboratory located in Viale della Libertà (inside the Noise LEZ).

Results were compared with those contemporary taken at a fixed site located nearby (via Machiavelli), outside the LEZ, and in a 20 km buffer around the Viale della Libertà, all belonging to the regional air quality network.

Several regulated pollutants (Directive 2008/50/EC) - airborne particulate matter ($PM_{2.5}$, PM_{10} mass concentration), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), benzene (C_6H_6), carbon monoxide (CO) and ozone (O_3) - were determined, using the respective European reference/equivalent methods (Directive 2008/50/EC).

Hourly (SO_2, CO, NO_2, NO_X, C_6H_6, O_3) and daily (PM_{10}, $PM_{2.5}$) averages were calculated.

PM_{10} samples were collected on quartz membrane filters: following the CEN/TR 16264:2011, these samples were analyzed to determine the carbonaceous component with TOT/TOR (Thermal-Optical Transmittance/Reflectance) instrumentation (Sunset Laboratory) which, by means of a thermo-optical process, allows to quantify the organic carbon (OC) and the elementary carbon (EC).

Continuous measurement of black carbon (BC), based on and aerosol light absorption properties were carried out using a Multi Angle Absorption Photometer (MAAP, Thermo).

Moreover, the particle number concentration (PNC) and size distribution in the 0.3 ÷ 10 μm range, were measured with aerosol particle sizers (OPC, Grimm, mod. 107) capable of counting particles with dimensions greater than 0.25 μm and classifying them into 31 dimensional classes.

Basic meteorological data (temperature, relative humidity, atmospheric pressure, rainfall, solar radiation, relative and absolute humidity, wind speed and direction) were taken from surroundings meteorological stations belonging to the regional meteorological service. Atmospheric profile data from the Milan Linate station were used to estimate the atmospheric mixing layer height (MLH).

Ex ante measurements were carried out in 2017/2018, (1 campaign representing each season) and was repeated during 2019 with the same schedule (Table 1).

Table 1: Ex-ante/ex-post monitoring campaigns, sites and pollutants

monitoring campaigns	
ex-ante	ex-post
I (04 – 22 May 2017)	**I** (20 Feb – 26 Mar 2019)
II (14 – 31 Jul 2017)	**II** (08 – 21 May 2019)
III (9 – 30 Nov 2017)	**III** (03 – 17 Jul 2019)
IV (31 Jan – 19 Feb 2018)	**IV** (30 Oct – 21 Nov 2019)
Pollutants	
SO_2, CO, O_3, NO_2, NO_2 p.s.*, Benzene p.s.*, Benzene Toluene, PM10, PM2.5, BC, OC, EC, TC, PNC	
Site	
Viale Libertà, 144, 20900 Monza MB	

*passive samplers

2.5.2 Spatial pattern

To assess the spatial and seasonal variability on the microscale (*i.e.* in the territory delimited by the Noise LEZ) of some pollutants tracing the emissions of internal combustion engines, statistical generalized additive models (GAM) were developed. GAM is a multivariate non-parametric method of analysis that was used with great results in Ecology (Zuur, 2009 e Zuur, 2012). GAM is able to model the non-linear effects of a number of covariates, to assess any simultaneous and combined contribution to the response variables (benzene and toluene mean concentrations assessed during each monitoring campaign using passive samplers). Any non-linear relationship was modelled without having to specify the non-linear functional form. The use of spline as "smoothing" functions allows to better approximate any local trends in particular intervals of the domain of existence of the explanatory variable (Clifford *et al.*, 2012). The measured air pollutants levels at various locations representative of the study area, were regressed against GIS-derived predictor variables as described in section 2.5.3.

The study domain was a 4 km^2 square area around the sampling point located in Viale della Libertà assumed as the domain's and Noise LEZ's center.

Vehicular traffic related pollutants (benzene, toluene, NO_2) sampling was made also using passive samplers (Ring, Aquaria and Radiello, Fondazione Maugeri, respectively for VOC's and NO_2).

Duplicate samplers, provided with weather protective shelters, were deployed at 2.5 m above the ground, placed on lamp post, utility poles or street signals.

Aromatic volatile organic compounds (VOCs) were extracted with carbon disulfide then detected and quantified using internal standard capillary gas chromatography performed on a Gas Chromatograph (HewlettePackard Inc., USA) with MS detection. NO_2 measures was carried out by means a Ions Chromatograhy (Metrohm-881 Compact IC pro – Anion – MCS).

25 points were selected across the study domain to represent the microscale spatial variability of air quality variously distributed according to the distance from the main roads in the study domain (4 km^2) both inside and outside the Noise LEZ. The sites represent a wide range of possible scenarios that characterize the Noise LEZ and surrounding area context. There were sites located less than 50 m from a high traffic road in densely populated neighbourhoods (traffic sites) as well as sites over 200 m from a high traffic road in low density residential areas (urban background sites).

Microenvironmental criteria for site selection [20, 21] were strictly followed.

2.5.3 Spatial variability assessment using GAM model

Generalized additive statistical models [22] were developed which allow to estimate with high spatial resolution (20×20 m) in the study domain the concentration of pollutants monitored with passive samplers. GAM is a multivariate non-parametric method of analysis able to model the non-linear effects of a number of covariates, to assess any simultaneous and combined contribution to the response variables (benzene and toluene mean concentrations assessed during each monitoring campaign using passive samplers). Any non-linear relationship was modelled without having to specify the non-linear functional form.

GIS-derived predictor variables

GIS-derived predictor variables related to road traffic flows, distances from nearest road, building volume representative of urban canyon, road length, land use variables by Urban Atlas of Copernicus Land Monitoring Service (commercial area, high density and low density area) were eval-

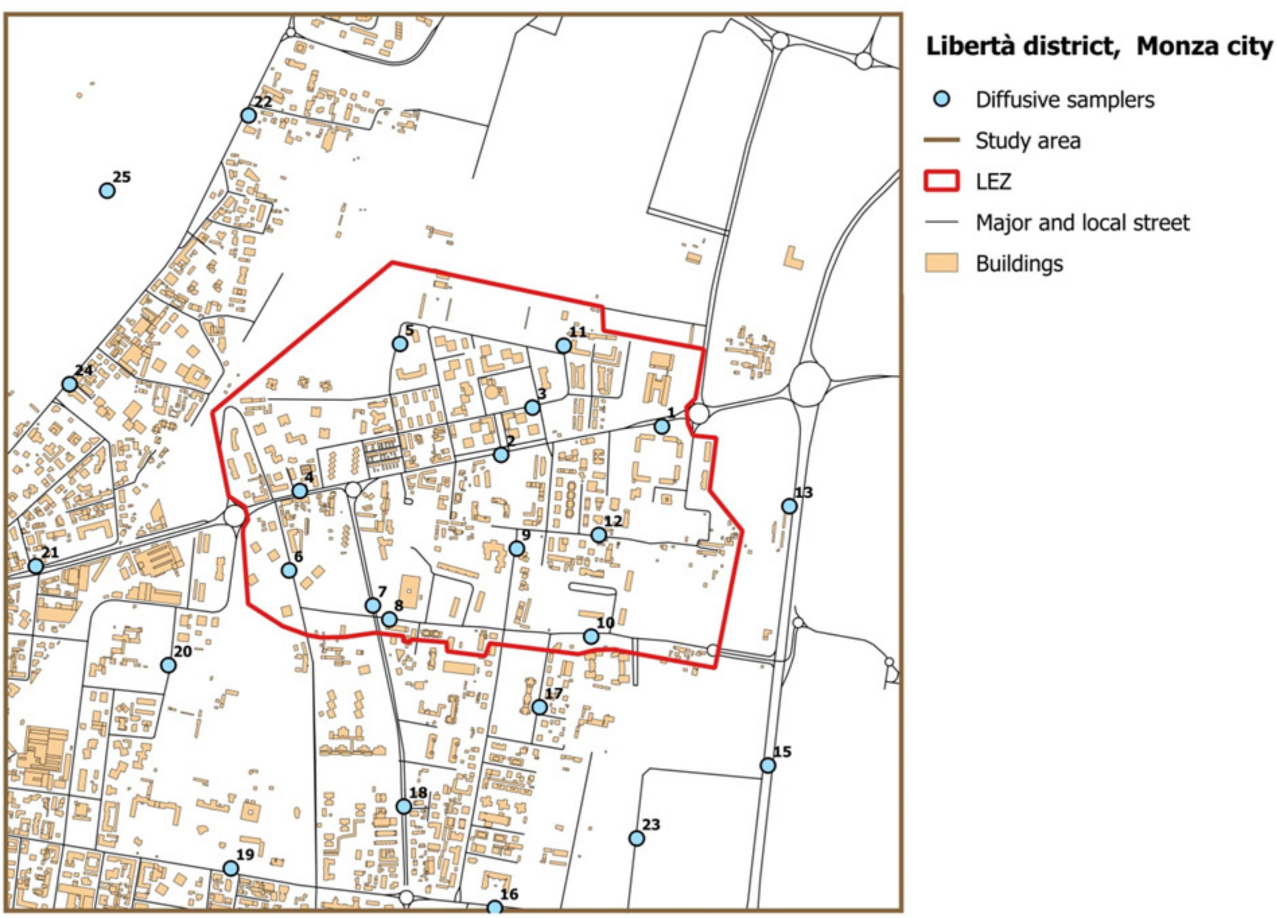


Figure 5: Benzene and toluene diffusive samplers

uated in each monitoring site and in varying buffer size (25, 50, 75 e 100 m). Details on variables calculation are provided in the Online Supplement Y, Table Y2. Starting from traffic flow measurements carried out using the traffic counters described in section 2.1, traffic variables were estimated by attribution to each node within the study domain.

Model development

The explanatory variables described have been selected as potential regressors in the GAM models starting from the correlation matrix with the response variable and performing a stepwise forward selection procedure with groups of variables on the basis of the best correlation with the response variable ($p<0.01$).

Test checks with various basis-dimension functions (k parameter) were performed to select the best splines for each variable. The smoothing parameter was chosen controlling the balance between likelihood function and overfitting, convergence of the iteration algorithm, the significance of the EDF (Effective Degree of Freedom) parameter which represents the complexity of smoothing in terms of curve sinuosity (the higher the EDF value the greater the spline non-linearity). Residual Normality was graphically checked.

Model evaluation

The choice of the best model for each season and pollutant was done via the Akaike Information Criteria (AIC), the GCV (Generalized Cross Validation), the BIC (Bayesian Information Criterion) to control the improper adaptation phenomena due to overfitting.

Each model was validated with the Leave-One-Out Cross Validation (LOOCV) method [23]. The performance measures evaluated were the R^2, the adjusted R^2 and the Root Mean Square Error (RMSE) values.

3 Results of noise and air quality monitoring campaigns in LIFE MONZA noise low emission zone

3.1 Ante and *post-operam* monitoring results for noise according to Class I Noise Monitoring System

Referring to the long-term monitoring performed by using the class I instrumentation, taking as reference the position identified as P01 (Figure 6), located on the roof of the Civic Centre facing the Libertà street, the comparison

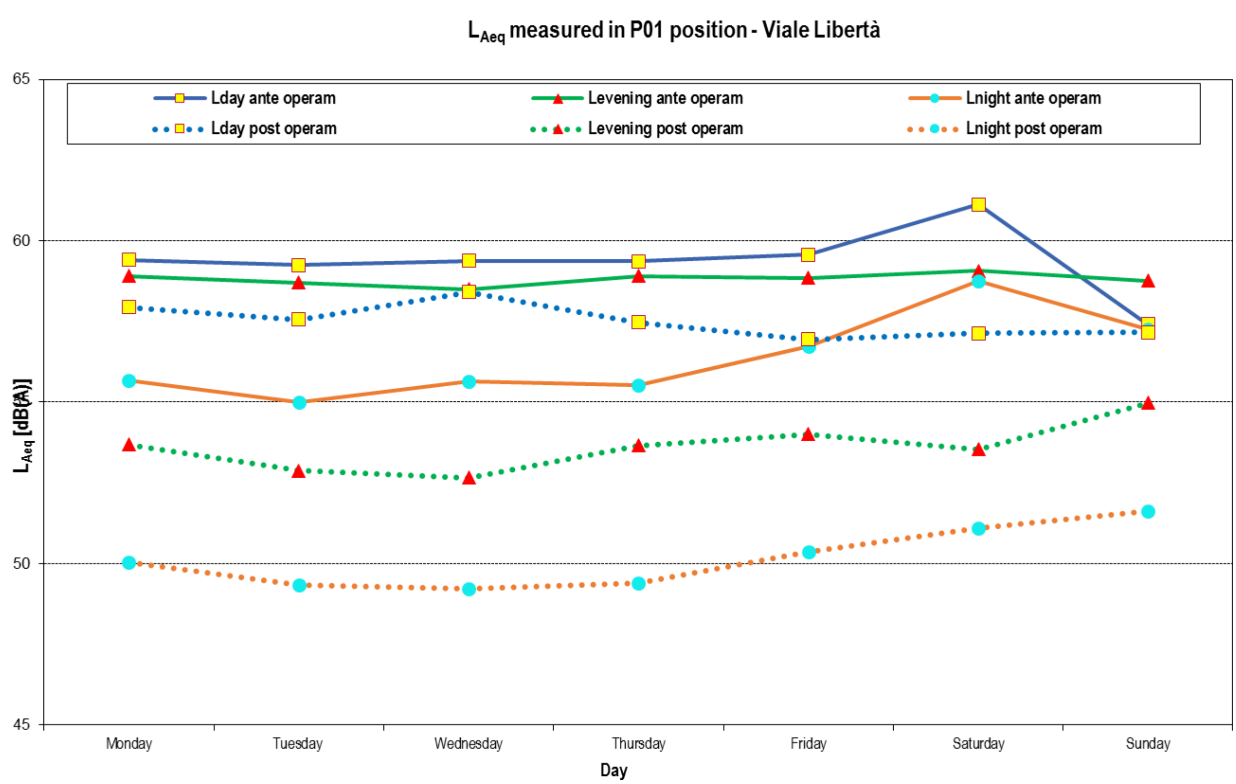


Figure 6: Comparison of sound pressure levels recorded in ante and post operam in the position of the Civic Centre P01

between the monitoring activity carried out in November 2017 and in January 2019 has been made.

Referring to the traffic flow data, on the base of the road-traffic counting performed in the ante and post operam scenarios, it's possible to affirm that, in the time period "Day", there is a very good alignment between data of the ante and *post-operam* scenarios. Also in the "Evening" and "Night" periods the deviations of the traffic flows between ante and *post-operam* scenarios are of a small entity (lower than 10%). Finally, referring to heavy vehicles, in all the periods a reduction of the heavy vehicles in the order of 30% between the configuration ante and *post-operam* is appreciable.

3.2 Ante and *post-operam* monitoring results for noise according to smart noise monitoring system

With reference of one sensor placed along Libertà street (Figure 4), HC101, in this chapter the results of the two interventions achieved in the Libertà district (new low-noise pavement laying and limitation of heavy vehicles

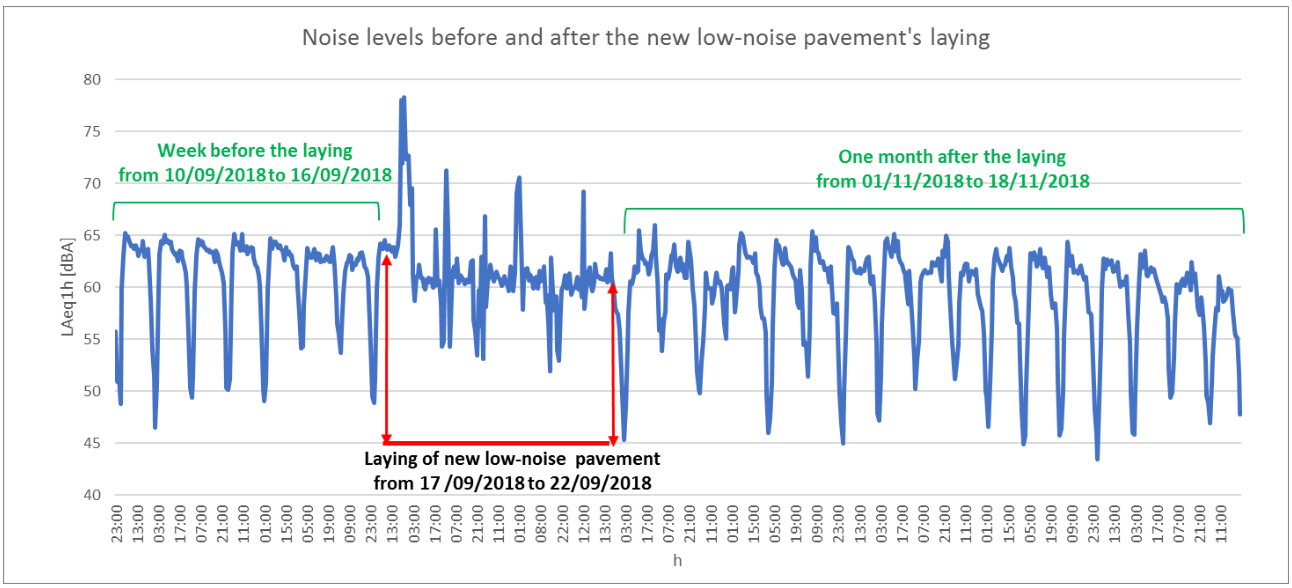


Figure 7: Noise levels recorded by the sensor HC101 before, during and after the laying of the new road surface

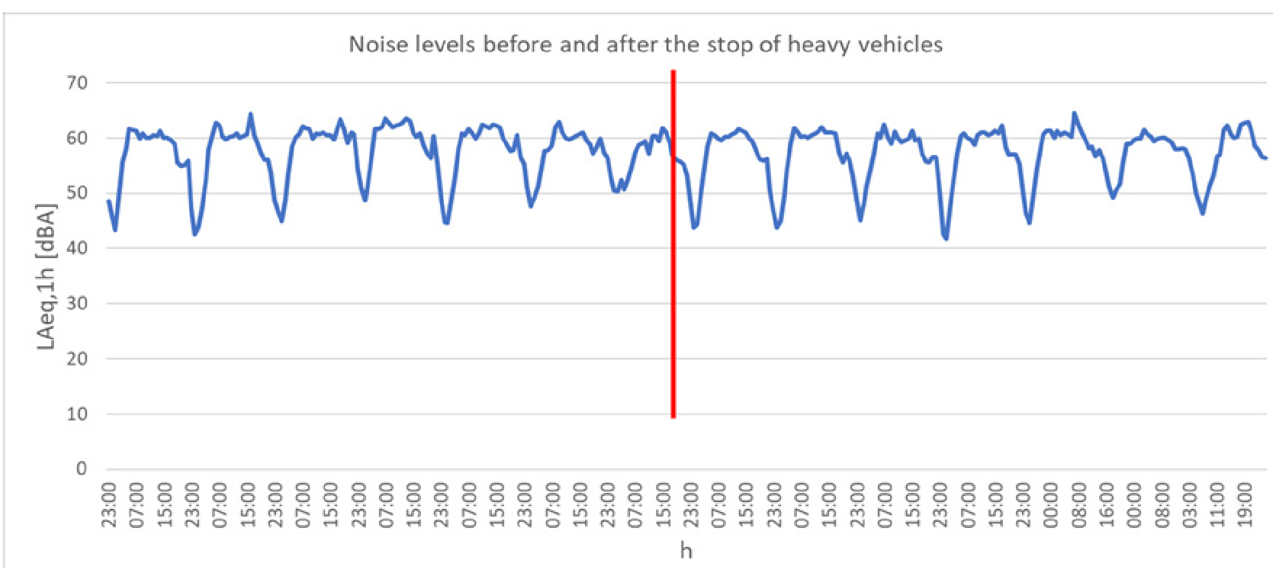


Figure 8: Noise levels recorded by the sensor HC101 before and after the stop of heavy vehicles

Table 2: Analysis of the results obtained for the acoustic descriptor L_{day}, $L_{evening}$ and L_{night} by the low-cost sensors and class I systems

	Period	L_{day} (06-20) [dB]	$L_{evening}$ (20-22) [dB]	L_{night} (22-06) [dB]
Class I Instrumentation	Nov-17	59.5	58.8	56.5
Sensor HC101	Nov-17	64.6*	62.5*	59.2
	Difference	5.1	3.7	2.7
Class I Instrumentation	Jan-19	57.5	53.7	50.3
Sensor HC101	Jan-19	60.4	57.0	53.0
	Difference	2.9	3.3	2.7

Table 3: Comparison of the results obtained for the acoustic descriptor L_{day}, $L_{evening}$ and L_{night} between the two measurement systems used in the monitoring of the ante and post-operam

	Period	L_{day} (06-20) [dB]	$L_{evening}$ (20-22) [dB]	L_{night} (22-06) [dB]
Class I Instrumentation	Nov-17	59.5	58.8	56.5
	Jan-19	57.5	53.7	50.3
	Difference	2	5.1	6.2
Sensor HC101	Nov-17	-	-	59.2
	Jan-19	-	-	53.0
	Difference	-	-	6.2

passage) will be illustrated. This sensor has been placed in correspondence of the façade of the Civic Centre and the results take account of the façade's reflection. In particular, Figure 7 shows the contribution of the new laying of low-noise asphalt in Viale Libertà: on the left of the graphic the A-weighted continuous equivalent sound pressure level, "LAeq", is reported for a week before the intervention, in the middle of the diagram the sound pressure level recorded during the laying is present and in the right of the graphic there is the time history starting trend to one month after the works, recorded for eighteen days. The month after the works was not considered for analysis because it is a necessary period for the settling of the paving. Focusing on these first elaboration data, it is possible to see a visible noise reduction due to the laying of the new low-noise road surface.

Furthermore, referring to the same sensor HC101, in Figure 8 the trend of noise levels in the week before and after the limitation of the passage for the vehicles larger than 3,5 ton (performed on 21st of January 2019), has been reported. However, in this case, the effect of this action is not clear visible on the time history of sound pressure level recorded.

3.3 Validation of the smart system with a traditional noise measurement chain

Such as shown in the following Table 2, from the results of the noise monitoring carried out in January 2019 it turns out that sound pressure levels measured by the low-cost sensor are averagely 3 dB higher than the ones measured by the and class I system in all periods analysed (Day, Evening and Night time). This difference is caused by the different position of the microphones: the low-cost one is placed on the facade of the Civic Centre building and measured noise levels are affected by reflective phenomenon, whilst the class I one is placed on the roof of the same building. This stability of results seems to make the low-cost sensors usable for noise monitoring in the place of class I instrumentation.

Instead, in the measurements of November 2017 only in the "Night" period the difference cited above is equal to 3 dB, while in "Day" and "Evening" times there are bigger deviations probably due to the activities happened nearby of the entrance of Civic Centre and therefore near the sensor. In the light of these considerations, the results in "Day" and "Evening" periods have not been used for the comparison of the results.

Table 4: Ex-ante and ex-post summary of the hourly pollutant concentration statistics (mean and standard deviation) at the four sites

ex-ante	**I** (04 – 22 May 2017)		**II** (14 – 31 Jul 2017)		**III** (9 – 30 Nov 2017)		**IV** 31 Jan - 19 Feb 2018)	
	mean (µg/m^3)	st.dev.	mean	st.dev.	mean	st.dev.	mean	st.dev.
SO_2	3.7	1.4	3.9	2.1	5	1.3	5.3	2.2
CO (mg/m^3)	0.4	0.2	0.7	0.1	1.2	0.4	1	0.3
O^3	90.3	31.7	142.4	31.3	–	–	11.1	7.6
NO_2	37.6	8.8	26	6.6	47.1	8.9	56.9	8.6
NO_2 p.s.*	–	–	–	–	–	–	40.4	19.7
Benzene p.s.*	–	–	0.4	0.1	–	–	1.2	0.2
Benzene	–	–	0.3	0.1	3.3	1.8	2	1.1
Toluene	–	–	1.6	1.2	13.3	4.5	7	4.5
PM 20	16.7	5.7	17.9	8	52.9	25.7	44.1	22.8
PM 2.5	12.2	3.9	10.3	3.5	40.7	20.5	32.9	17.9
BC	2	1.2	1.7	1	6.7	3.4	4.3	2.5
OC	5.5	1	6.1	1.4	15.5	4.9	11.3	3.9
EC	1.6	0.4	1.4	0.4	4.7	1.7	2.7	0.9
TC	7.1	1.3	7.6	1.7	20.2	6.1	14	4.5
PNC (Cn cumulate pp/l)**	–	–	10827	18110	50973	91793	487016	69449
ex-post	**I** (20 Feb – 26 Mar 2019)		**II** (08 – 21 May 2019)		**III** (03 – 17 Jul 2019)		**IV** 30 Oct - 21 Nov 2019)	
	mean (µg/m^3)	st.dev.	mean	st.dev.	mean	st.dev.	mean	st.dev.
SO_2	–	–	–	–	5.1	2.5	2.4	0.7
CO (mg/m^3)	0.8	0.2	0.6	0.3	0.7	0.3	0.9	0.2
O^3	30.8	16.6	50.7	10.6	78.8	12.7	18.5	5.6
NO_2	60.4	15.7	38.8	6.3	26.4	7.0	37.3	9.0
NO_2 p.s.*	35.4	2.5	30.9	3.3	22.0	2.5	22.5	2.9
Benzene p.s.*	0.9	0.04	0.7	0.1	0.5	0.01	1.4	0.1
Benzene	1.0	0.5	0.3	0.1	0.6	0.3	1.0	0.3
Toluene	5.0	3.9	2.0	0.8 3.5	1.7	4.3	2.1	
PM 20	38.3	16.2	16.0	4.4	19.7	6.1	20.9	6.3
PM 2.5	–	–	–	–	15.3	3.9	15.9	5.3
BC	3.7	1.9	1.6	0.4	1.1	0.3	3.1	0.8
OC	9.0	8.9	4.5	0.6	6.1	1.0	6.6	1.5
EC	2.2	0.9	0.9	0.2	0.8	0.2	1.6	0.6
TC	11.1	4.1	5.4	0.7	6.9	1.2	8.5	2.0
PNC (Cn cumulate pp/l)**	–	–	–	–	39170	6713	47621	10114

*passive samplers **particle number concentration
Unit of measurement of pollutants [µm/m^3]

3.4 Ante and *post-operam* monitoring results for air quality

3.4.1 Air quality status and trend in the study area

The summary of the concentration statistics at all the monitoring sites is given in Table 4.

Monza is a medium sized city belonging to a large urban agglomeration, Milan plus 106 small town surroundings, the largest in the Po valley with 3.593.025 inhabitants. The Po Valley is largely devoted to intensive agricultural and livestock farming, as well as important industrial and commercial activity, producing ample amounts of NOx from vehicles, NH_3 from agricultural activities, PM from residential heating, mainly from biomass burning devices and COV from solvent use in industry, vehicles and from agricultural activities due to biogenic emissions.

Moreover, the presence of the Alps and the Apennines often limits the air currents between Northern Italy and the rest of continental Europe, favouring the accumulation of air pollutants. Figure 9 shows hourly distributions of the wind speed in the different measurement periods. The study area is characterized, as the whole Po valley, by frequent wind-calm conditions, and mechanical turbulence therefore generally low. Particularly winter seasons is characterized by frequent thermal inversion at low altitude and low mixing layer heights, high pressure and calm wind

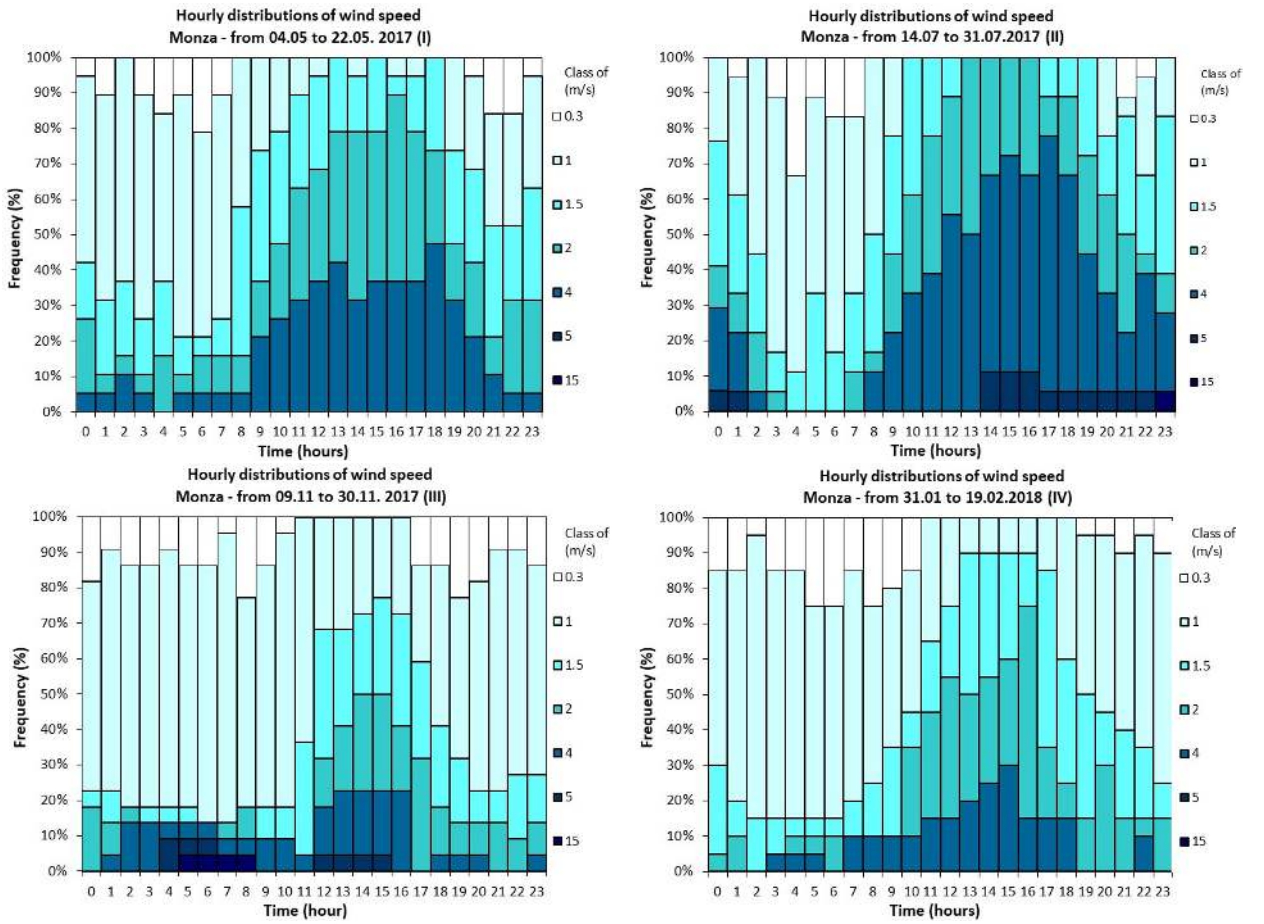


Figure 9: Hourly distributions of the wind speed in the different measurement periods

conditions so that the area is frequently plunged in a stable and stagnant atmosphere.

At the same time, fog often forms in the valley in fall and winter when temperature inversions trap cool, moist and polluted air near the surface.

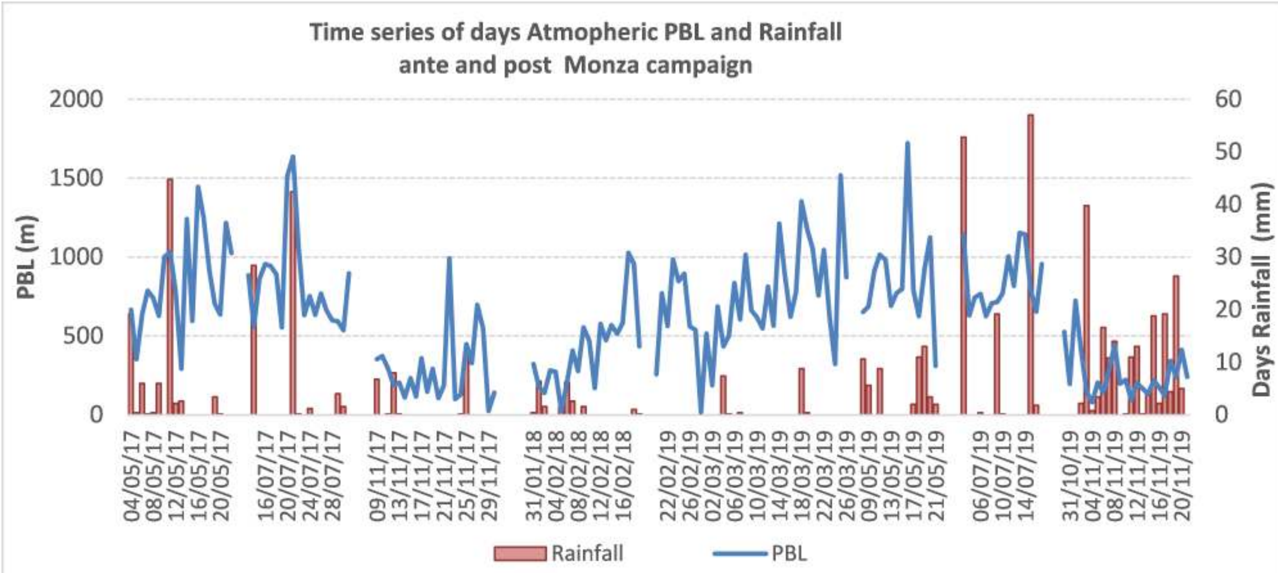
When fog forms, sulphur oxides, nitrogen oxides, and other polluting gases are taken up or 'scavenged' by fog water droplets. Once absorbed into the droplets, the gases oxidize more rapidly than they otherwise would, becoming sulphates, nitrates, and other types of aerosol particles. What the fog and humidity do is accelerate the process of converting gaseous pollutants into haze-causing aerosols.

Such extreme conditions favourable to pollutant accumulation, can last several days, as shown in Figure 10 that shows some meteorological parameters in different seasons. Usually the meteorological conditions that characterise the cold seasons are responsible for the rise in NO_x and other pollutants concentration in the Po Valley: as an example Figure 11 shows the NOx dependencies by wind speed and direction differences among seasons.

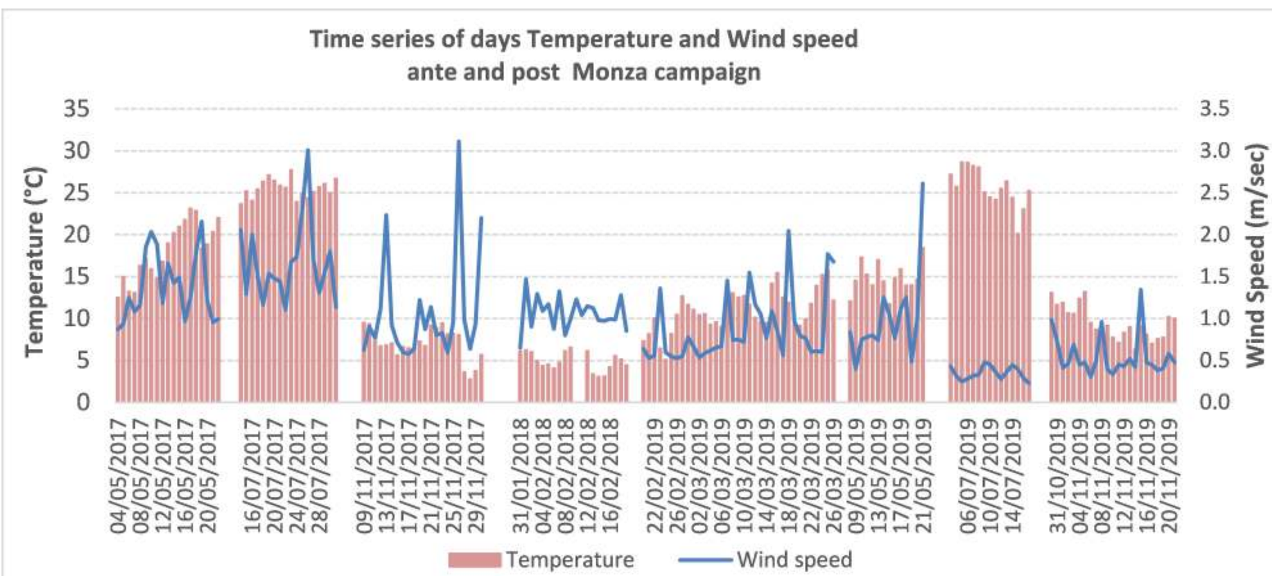
The atmospheric conditions that characterize the different seasons have important repercussions on the particulate matter levels and composition. PM_{10} winter levels in the Po Valley's cities are significantly higher than those of the other major Italian cities, while this difference is less pronounced in the summer when the atmospheric phenomena described are less (Figure 12).

The average daily concentrations of the "temporary" site of Monza - Libertà were compared with those of the whole Lombardy region's network and in particular with the same measured in the fixed station of Monza - Via Machiavelli. The measurements carried out at the two sites in Monza show consistent trends with each other particularly for traffic related pollutants and are generally above the 75th regional percentile, in line with the typical values detected in urban traffic stations and without presenting specific critical issues.

Moreover it's worth to note the excellent agreement between the PM_{10} and total carbon (OC + EC) measurements carried out in the Noise LEZ zone and those carried out far



(a)



(b)

Figure 10: Monza: ex-ante and post measuring campaign; Daily Temporal pattern for some atmospheric parameters

away within the Milan agglomerate, very consistent and contained in a narrow range of values (Figure 13).

The average values of the winter period were higher than those of the summer period in all the stations considered, as expected, partly due to the weather conditions more favourable to the accumulation of pollutants and partly due to the additional sources of pollution (*e.g.* heating buildings).

Noticeably, the OC fraction represents a large portion of PM_{10}, with highest values (again) during winter (see Figure 14).

The average OC concentration over the "winter" period was ever higher in Monza than in Milan, around 4 μg/m^3 during ex ante-opera campaigns, and 1.6 μg/m^3 during ex post-opera. In general, moving away from Milan downtown, towards the pre-Alpine and alpine area, the use of the wood as a heating source tends to increase, and this represents a not negligible carbon source.

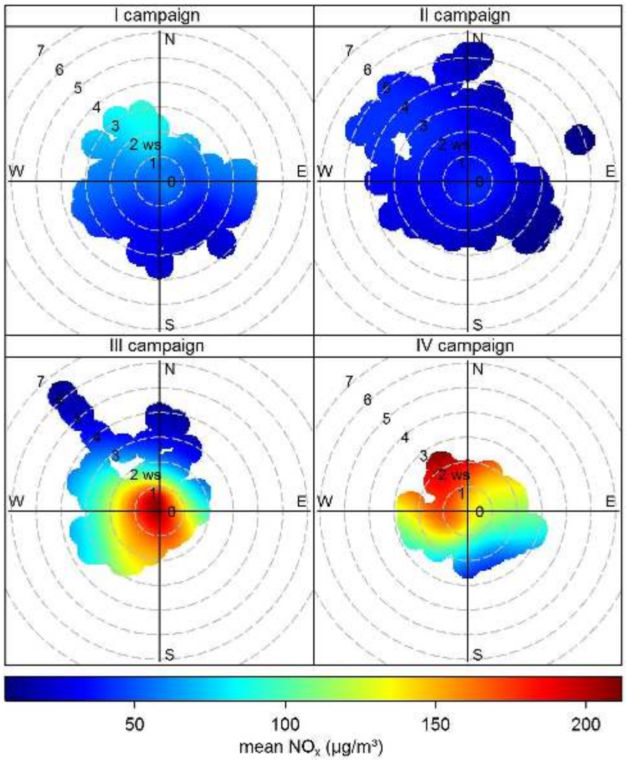


Figure 11: Monza, Viale della Libertà. Ex-ante measuring campaign. Polar plot showing the NOx mean concentrations variability by wind speed and direction. For each polar plot, the radial dimension is an indicator of wind speed (m/s). Further away from the center of the plot, the wind speed is higher

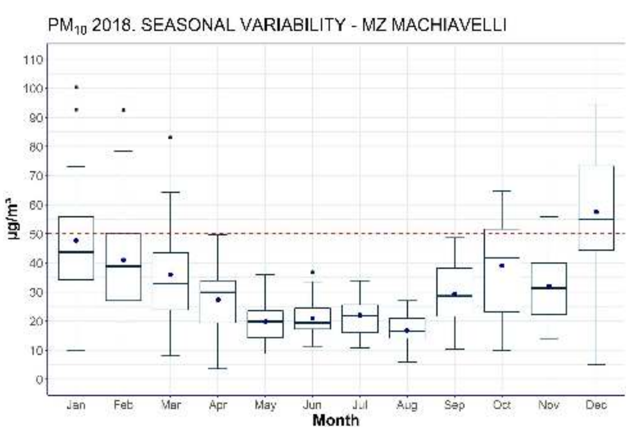


Figure 12: Monza, PM_{10} daily averages distribution by month, showing typical seasonal variability

3.4.2 Spatial variability assessment

Table 5 shows the benzene GAM models developed by season and period (ex-ante and ex post).

Variables included were the sum of buildings volumes in a 75 m radius buffer and the ratio between the average daily traffic and the distance from the nearest road (vehicle/day*m).

For benzene, the summer model, ex ante phase, explains 80% of the deviance (adjusted-R^2 = 0.76, RMSE = 0.14 µg/m^3) while in winter, 77.8% (adjusted-R^2 = 0.69, RMSE = 0.18 µg/m^3). A very similar pattern was found in the ex post phase, respectively in summer (R^2 = 70.1%, adjusted-R^2 = 0.65, RMSE = 0.19 µg/m^3) and in winter (R^2 = 70.5%, adjusted-R^2 = 0.66, RMSE = 0.12 µg/m^3).

The models explained a large portion of variability (explained variance ranging between 70.5% and 80%).

Table 6 shows the toluene GAM models developed by season and period (ex-ante and ex post).

Variables included were the sum of the volumes of the buildings in a buffer with a radius of 75 m and the ratio between the average daily traffic and the distance from the nearest road (vehicle/day*m).

The same variables as for benzene were found to explain the toluene spatial variability. However, the toluene GAM models showed a lower explained deviance compared to that found for benzene. Summer ex-post levels were often lower than the method limit of detection, not allowing to develop a reliable model for this season.

The benzene ex-ante and ex-post winter surface concentrations that were estimated from GAM models are showed in Figure 15.

4 Discussion: analysis of ante and *post-operam* monitoring results for noise and air quality

4.1 Comparison between ante and *post-operam* results for noise

The interventions realised in Viale Libertà of the city of Monza (new low-noise pavement's laying and the limitation of the heavy vehicles passage for the means larger than 3,5 ton) provide very good results in terms of abatement of the traffic noise in the pilot area of LIFE Monza project.

In particular, in terms of noise monitoring with class I instrumentation, the reduction in terms of sound pressure levels measured in the "Day" period, between ante and post-operam, is equal to 2 dB. In the "Evening" and "Night" period this reduction is higher, until 6 dB in the night period.

The following considerations can be made in this respect:

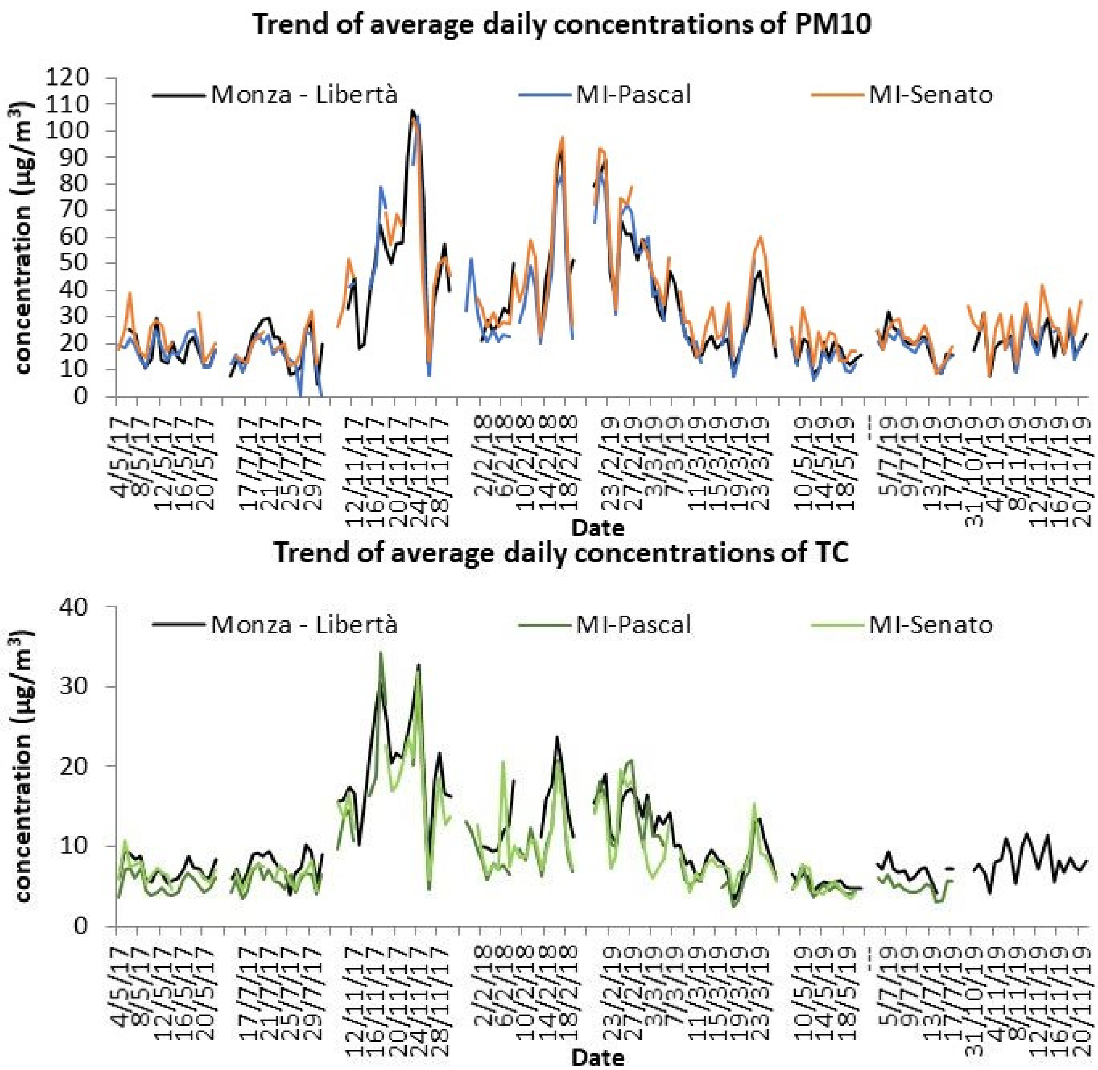


Figure 13: Average daily PM_{10} (a) TC (b) concentrations measured in Monza – Libertà compared with those measured in Milan – Pascal and Milan – via Senato

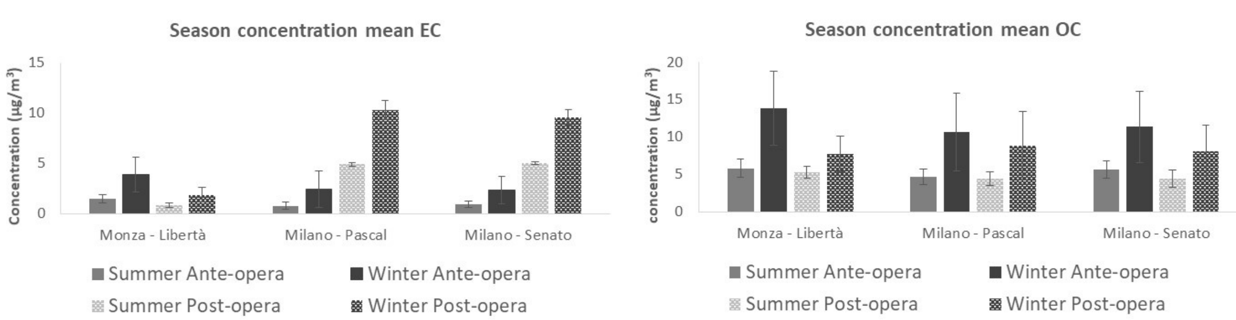


Figure 14: Average concentrations of OC and EC on the two measurement periods "summer" (from 4/5/2017 to 22/5/2017 and from 14/7/2017 to 31/7/2017 in ex-ante operam, from 8/5/ to 21/5/2019 and from 03/7/ to 17/7/2019 in ex-post operam) and "winter" (from 9/11/2017 to 30/11/2017 and from 31/1/2018 to 19/2/2018 in ex-ante operam, from 20/2/ to 26/3/2019 and from 20/7/ to 21/11/2019 in ex post-operam)

Table 5: Benzene, GAM models performance and summary statistics of leave one out cross-validation (LOOCV)

	R^2 adj	Explained variance	GCV	AIC	BIC	RMSE
Summer ex-ante	0.756	80%	0.0054	−59.183	−51.409	0.14
Winter ex-ante	0.687	77.8%	0.019	−28.169	−17.938	0.18
Summer ex-post	0.649	70.1%	0.0852	−47.137	−40.351	0.19
Winter ex-post	0.663	70.5%	0.012467	−37.390	−31.288	0.12

Table 6: Toluene, GAM models performance and summary statistics of leave one out cross-validation (LOOCV)

	R^2 adj	Explained variance	GCV	AIC	BIC	RMSE
Summer ex-ante	0.613	67.9%	0.32617	43.754	51.134	0.72
Winter ex-ante	0.535	58.7%	0.35324	44.544	49.928	0.64
Winter ex-post	0.452	52.1%	0.3808	4.8077	5.4218	0.67

Table 7: NO_2, PM_{10} and BC mean values over the ex-ante and ex-post sampling period. Percent different comparison among measurement carried out inside (MZ-Libertà) and outside (Mz-Machiavelli) the Noise LEZ

		MZ LIBERTA'	MZ MACHIAVELLI
PM_{10} – average (µg/m^3)	Ex ante	**32.8**	**33.6**
	Ex post	**27.0**	**27.1**
	diff %	*−18%*	*−19%*
PM_{10} – 90.4 percentile (µg/m^3)	Ex ante	**60.4**	**72.8**
	Ex post	**51.1**	**59.1**
	diff %	*−15%*	*−19%*
NO_2 – average (µg/m^3)	Ex ante	**41.9**	**41.2**
	Ex post	**40.7**	**43.5**
	diff %	*−3%*	*5%*
BC – average (µg/m^3)	Ex ante	**3.80**	**2.92**
	Ex post	**2.75**	**1.98**
	diff %	*−28%*	*−32%*

– in the “Evening” and “Night” periods, when there are passages of only light vehicles and the traffic is fluid, there is a great result because the intervention of low-noise laying mainly works on the rolling noise;
– in the “Day” period, when there isn’t fluid traffic with the presence of situations of “stop and go” due to a traffic light, the efficacy of the laying of road surface is lesser precisely because this kind of intervention principally works on the rolling noise.

Moreover, repeating the same analysis based on the low-cost sensor, it is possible to observe an excellent alignment between the noise levels’ differences obtained between the two different measurement systems (Table 3).

After a comparison between the results obtained with instruments in class I and the Smart Noise Monitoring System (SNMS) it is possible to deduce that also the “low cost” monitoring sensors provide reliable data to evaluate the acoustic performance of interventions.

Results regarding traffic flows confirm that the attenuation observed in the graphic in Figure 5, in term of sound pressure level, is essentially due to the interventions realised.

In particular, a very good attenuation is obtained in the “Evening” and “Night” periods probably due to the presence, in these periods, of traffic flow moving in a fluid mode able to increase the performance of the low noise paving intervention.

Figure 15: Benzene winter concentration levels (µg/m³) estimated from GAM models before (left) and after (right) Noise LEZ implementation

4.2 Comparison between ante and *post-operam* results for air quality

In order to evaluate confounding factors related to the pollutants temporal pattern (drive by meteorology) and other possible difference due to contemporary city and region wide measures undertaken to tackle air pollution in 2019 (not already in force in 2017/2018), we compared the ex post vs ex ante averages calculated over all the monitoring campaigns and we cross checked the differences found at monitoring stations inside the Noise LEZ and outside. Table 7 shows the comparison carried out for NO_2, PM_{10} and BC.

For PM_{10}, comparing annual averages, we found inside the Noise LEZ (Viale della Libertà) values lower ex-post by 18% vs ex-ante.

The same happens outside Monza-Machiavelli (−19%). Generally, considering other monitoring sites outside the LEZ, a consistent difference between ex-post and ex-ante was found, ranging between −27% and 3%. The ante-post opera ratio measured at Monza Libertà represents the 30th percentile in air quality network ratio distribution (Figure 16).

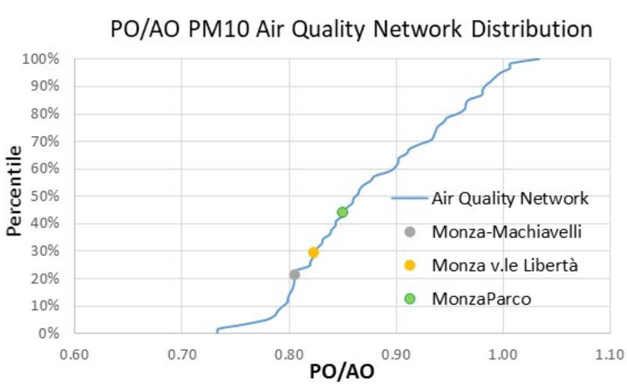


Figure 16: Ratio of the averages AO and PO measured

Thus, it would seem that there are not significant reduction effects for PM_{10} mass concentrations attributable to the introduction of the Noise LEZ.

Similar figures can be detected from the comparison among percentiles (90.4 percentile, representing the occurrences of more than 36 daily mean over 50 $\mu g/m^3$).

If we look at the NO_2 concentrations, it seems that the eventual effect due to the Noise LEZ alone was too little to be highlighted. Indeed, a small reduction (−3%) was observed inside the Noise LEZ while a small increase (+5%) was observed outside. However, the same happens comparing other stations outside the LEZ, that showed both small increase and little reduction, thus making ineffectual the attempt to remove the confounding factors.

The BC is of particular interest since previous studies have showed that focusing on specific “components” of PM, like black carbon, or parameter (*e.g.* particle number concentration) more related with exhaust vehicles emission, seems to be more suitable for assessing the impact of LEZs on local scale air quality [7], particularly when the LEZs involve traffic restriction for heavy duty diesel vehicles [8]. However in our case, the large reduction observed between ex post and ex ante monitoring campaigns seems to be largely due to confounding factors, since it was observed with the same order of magnitude both inside (−28%) and outside the Noise LEZ (−32%).

Assessing the microscale spatial variability of air pollution is still challenging. Models results are comforting in terms of the ability of the GAM model developed to describe the spatial variability of pollutants and to identify the variables that "explain" at least in part this variability.

In all cases, from the analysis of all the variables identified in the study, those with greater explanatory character were those related to the volume of the buildings in buffers with a radius of 75 meters and those related to the average daily traffic and the distance from the nearest road. This is a very satisfactory result which confirms the analysis of literature and which sees in the foreground as representative variables of the spatial pattern, in addition to traffic distribution, also some parameters indirectly linked to a potential "canyon effect" created by the presence of buildings in correspondence of local roads around a few meters from the measuring point.

5 Conclusion

In order to assess the environmental effects of a Noise Low Emission Zone, considering air quality conditions and environmental noise reduction, monitoring activities have been carried out in the Libertà district, the pilot area of the project, located in Monza.

Reduction of noise have been observed, in term of sound pressure levels, between ante and post-operam, and it is essentially due to the interventions realised. Positive effects can be detected during the day and particularly during the night period, probably due to the more fluid night traffic conditions. The comparison between the results obtained using Class I instruments and the Smart Noise Monitoring System (SNMS) highlights that also the “low cost” monitoring sensors provide reliable data, able to evaluate the effects of the interventions.

Noise monitoring and evaluation methods can be applied in other contexts, at different scales, being valid instruments, able to evaluate the Noise LEZ effects on noise decrease.

The effect of the Noise LEZ on air pollution seems to be negligible for combustion related pollutant and carbon fractions of PM, due both to the moderate spatial effects of the measures undertaken and confounding factors due to concomitant emission sources and meteorology.

To going deeper on this topic, statistical approach allowing to meteorologically normalise the pollutant concentrations time series are needed [22, 23] but outside the scope of the present paper.

Monitoring with passive samplers has made possible to highlight the existence of a statistically significant spatial gradient on the microscale and its seasonal variability (the study domain is very small, only 4 km^2).

The results are comforting in terms of the ability of the GAM models developed to describe reliably the spatial variability of traffic related pollutants and to identify the variables that "explain" at least in part this variability.

The monitoring and assessment strategy can be easily transposed to other small scale effectiveness studies aimed to evaluate the ancillary effects on air quality of Noise LEZ's implementation.

The noise and air quality assessment criteria, developed and tested in the pilot area of LIFE MONZA project confirm the validity of conducting the analysis of both environmental issues in a joint way, in order to allow a comprehensive understanding of the effects of a Noise Low Emission Zone establishment.

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