Assessment of the impact on air quality of noncompliant NOx emissions from Diesel vehicles in real driving conditions

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Summary

Synthesis

The **"Road transport"** sector represents about **75%** of **nitrogen oxides emissions** (NOx = NO + NO_2) that insist on the Municipality of Milan and **Diesel-powered vehicles** contribute approximately 93% to these emissions (source Air Emissions Inventory source - INEMAR - Lombardy Region).

Starting from these data and thanks to a previous study, supported by the Italian association “Cittadini per l’Aria”, the EPHA (European Public Health Alliance) has funded a further research to estimate the impact on air quality and citizens’ health of “extra emissions that diesel vehicles show in real situations, with respect to the emission standard that the new models must comply with, according to EU directives, during the type-approval tests before being placed on the market.

The research has been performed by a complex modelling system which considers:

- the atmospheric pollutant emissions from vehicular traffic and from other sources;
- their dispersion and chemical transformations that take place in the atmosphere due to meteorological parameters;

The vehicular traffic emissions in Milan urban area, were estimated on data (e.g. geometric and structural characteristics of the road network, traffic flows, etc.) provided by the Environment and Territory Mobility Agency (AMAT in Italian) of the Municipality of Milan and the official European method COPERT 5 (COmputer Program to calculate Emissions from Road Traffic). COPERT 5 is the most updated version of the traffic emissions calculation program developed by the EEA (European Environment Agency) as part of the CORINAIR program.

Two emission scenarios have been considered:

- **ex-ante**: corresponding to the base case emissions;
- **Diesel Emission Standards Compliance (DESC)**: hypothetical scenario in which all Diesel vehicles were supposed to comply with the emission standards in force at their homologation time.

The reference year of this study is **2018**, the same of the circulating fleet composition on which the road traffic emission calculation is based.

Even if the homologation tests try to simulate real world situations, differences between real and test-driving cycles persist due to different factors: actual conditions of circulating vehicles (e.g.: equipment, age, state of maintenance), driving styles, traffic situations, road surface and related infrastructures maintenance, etc. For these reasons the DESC scenario should not refers to a realistic situation and therefore, a third intermediate emission scenario was elaborated, considering real emission factors associated with optimal real drivers’ behaviours and traffic situations.

The importance of this study is in the facts that it can help understanding how much the situation differs from the ideal one, i.e. what room for improvement exists in practice, and also in light of the "Dieselgate" scandal, that broke out in 2014, involving some among the most important world car manufacturers, and that consisted in the manipulation of the tests for the control of atmospheric emissions, in the United States performed on already circulating vehicles of a certain mileage, rather than in the homologation phase.

The results relating to the simulation of the "ex-ante" scenario show, for Milan urban area, yearly averaged NO_2 concentrations higher than the limit value (40 $\mu g/m^3$) in a large part of the municipal area (with an average value of 44.3 $\mu g/m^3$). These estimates are confirmed by data from the air quality network of ARPA Lombardy, the Regional Agency for Environmental Protection, which highlight the ability of the modelling system to reproduce the observed NO_2 levels with enough precision.

The results relating to the DESC scenario provide an answer to the question: *what would the NO_2 levels in the city be if the ideal conditions for the homologation phase of Diesel-powered vehicles could be reproduced?* The average annual NO_2 ground-level air concentrations corresponding to this scenario show high NO_2 values in a much smaller portion of the territory and on average lower than the limit value (area average of 37.7 $\mu g/m^3$) with an average reduction therefore equal to -14.9%.

From the results of these simulations, an abacus was built through which it is possible to quantify the contribution of Diesel vehicles to urban air quality, compared with what can be attributed to the ideal deployed scenarios. This plot provides useful answers to questions like: *what is the maximum extent of air quality levels reduction due to not compliance to emission standards of real world Diesel vehicles in real world driving situations? To which Euro standard referring Diesel vehicles must extend the ban on circulation within the Milan area (Municipality of Milan) in order to fall within the limit value relating to the average annual concentration (40 $\mu g / m^3$)*?

The plot shows that improving at best the road network capacity and drivers' virtuosity is not enough to by itself to ensure the return of average air quality levels within the regulatory limits while that could be achieved instead if Diesel vehicles emitted in compliance with registration standards. The effect of "Dieselgate" scandal is evaluated able to contribute by 2% to the present average air quality levels.

1. Introduction and objectives

In Diesel engines the air-fuel mixture always has a lean dosage and even in full load operation, i.e. with the accelerator fully pushed, a considerable amount of excess air (and therefore nitrogen and oxygen) remains in the combustion mixture. The formation of a considerable quantity of nitrogen oxides is therefore inevitable.

The abatement of these pollutants is far from easy and requires particularly sophisticated solutions, unlike what happens in Otto cycle engines, in which the use of an effective reducing catalyst is generally sufficient.[1] For this reason, in recent years bans have been introduced on the circulation of Diesel-powered vehicles in urban areas in order to reduce NO_2 levels and improve air quality. For example, the federal court of Leipzig established, last February 2018, that German cities can resort to the measure of the ban on the movement of Diesel cars.

More recently, on 2 August 2018, the Council of the Municipality of Milan approved the provision establishing Area B, an area almost as vast as the city limits (i.e. 72% of the entire municipal area), at the inside of which, since 21 January 2019, entry to petrol Euro 0 and Diesel Euro 0, 1, 2, 3 vehicles will be forbidden and gradually, by successive steps until 2030, to all Diesel vehicles.

Nitrogen dioxide is a pollutant with a prevalent secondary component, as it is the product of the oxidation of nitrogen monoxide (NO) in the atmosphere; only in a minor proportion it is emitted directly into the atmosphere. The main emission source of nitrogen oxides ($NO_X = NO + NO_2$) in urban areas is vehicular traffic; other sources are civil and industrial heating systems, power plants for energy production and a broad spectrum of industrial processes[2].

With the enactment of Legislative Decree 13/08/2010 n. 155, the legislator has transposed the European Directive 2008/50 / EC (Relating to the quality of the ambient air and for cleaner air in Europe), operating at the national level the same reorganization and simplification of the existing rules to protect air quality, made in the European sector legislation. Regarding nitrogen dioxide, Legislative Decree 155 has set the legal limit on the average annual concentration at 40 $\mu g/m^3$.

On the other hand, the European Commission, as well as the United States federal government, have been pushing road vehicle manufacturers for years towards increasingly ambitious technological challenges, by imposing lower and lower emission standards ("Euro standards"), which must be verified on "in the catalog" vehicles at the time of registration and subsequent placing on the market. These limits are very challenging in particular for nitrogen oxides emitted by Diesel fuelled vehicles, so much so that some car manufacturers in the recent past have succumbed to the temptation to also manipulate the verification tests of these emission standards ("Dieselgate" scandal).

To estimate the impact of these bans both on air emissions and air quality, EPHA, the European Public Health Alliance, considering the previous project carried out in the recent past by “Cittadini per l’Aria”, an Italian association federated with EPHA, asked ARIANET to carry out simulations aimed at estimating the impact, on air quality and citizens’ health at the end, of emissions of vehicles powered by Diesel fuel circulating in the Milan urban area on average annual concentrations of NO_2.

The contribution assessment of Diesel-fuelled vehicles to NO_2 concentrations in Milan urban area, otherwise known as "Source Apportionment Analysis", was carried out using the atmosphere

[1] https://www.automoto.it/news/motori-e-inquinamento-gli-ossidi-di-azoto.html
[2] http://www.salute.gov.it/imgs/C_17_paginaRelazione_1438_listaFile_itemName_4_file.pdf

chemistry model **FARM** (description in appendix A.1) with "zero-out" modelling technique. This approach is based on the analysis of the effect of changes in emissions on the air quality levels of a given pollutant and in this case it provides answers to the following questions:

- *what is the maximum extent of air quality levels reduction due to not compliance to emission standards of real-world Diesel vehicles in real world driving situations?*
- *To which Euro standard referring Diesel vehicles must extend the ban on circulation within the Milan area (Municipality of Milan) to fall within the limit value relating to the average annual concentration (40 µg / m^3)?*
- *Is any "Dieselgate" effect detectable?*

The availability of experimental information provided by the continuous monitoring network managed by ARPA Lombardy has made it possible to firmly anchor the modelling results to the observed air quality levels.

2. European emission standards for road vehicles

2.1 *Emission Standards*

Since 1992, European emission standards (EURO) define the acceptable limits for exhaust emissions of new vehicles, according to specific European Union directives staging the progressive introduction of increasingly stringent standards. For each vehicle type (category and fuel), different standards apply, and they refer to emissions of nitrogen oxides (NO_X), total hydrocarbon (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO) and particulate matter (PM).

Focusing on Diesel powered vehicles, NO_X emission standards for passenger cars, light and heavy commercial vehicles are summarized in the following tables[3]. As it will be explained better later, the stages of Euro 5 and Euro 6 standards (a, b, c, d) differ by adopted control test.

Standard Euro 6 application is parted in some phases (Table 4) according to the progressive introduction of a new test procedure (WLTP - Worldwide harmonized Light vehicles Test Procedure) instead of former NEDC (New European Driving Cycle), an additional RDE (Real Driving Emission) test and more challenging limits for this RDE test.

Table 1. Decreasing NO_X emission limits for Diesel passenger cars

Diesel Cars	*Date*	*NO_X (g/km)*	*HC+NO_X (g/km)*
Euro 1	1992.07	-	0.97
Euro 2 DI (IDI)	1996.01	-	0.9 (0.7)
Euro 3	2000.01	0.5	-
Euro 4	2005.01	0.25	-
Euro 5 a,b	2009.09	0.18	-
Euro 6 b,c,d	2014.09	0.08	-

[3] https://Dieselnet.com/

Table 2. Decreasing NO_X emission limits for Diesel light-duty

Diesel LDV	*Standard*	*Date*	*NO_X (g/km)*	*$HC+NO_X$ (g/km)*
N1, Class I (<1305kg)	Euro 1	1994.1	-	0.97
	Euro 2 DI (IDI)	1997.01	-	0.9 (0.7)
	Euro 3	2000.01	0.5	-
	Euro 4	2005.01	0.25	-
	Euro 5 a,b	2009.09	0.18	-
	Euro 6	2014.09	0.08	-
N1, Class II (1305 -1760 kg)	Euro 1	1994.1	-	1.4
	Euro 2 DI (IDI)	1998.01	-	1.3 (1)
	Euro 3	2001.01	0.65	-
	Euro 4	2006.01	0.33	-
	Euro 5 a,b	2010.09	0.235	-
	Euro 6	2015.09	0.105	-
N1, Class III (>1760 kg)	Euro 1	1994.1	-	1.7
	Euro 2 DI (IDI)	1998.01	-	1.6 (1.2)
	Euro 3	2001.01	0.78	-
	Euro 4	2006.01	0.39	-
	Euro 5 a,b	2010.09	0.28	-
	Euro 6	2015.09	0.125	-

Table 3. Decreasing NO_X emission limits for Diesel heavy-duty

Diesel HDV	*Date*	*NO_X (g/kWh)*
Euro I	1992	8
Euro II	1996.01	7
Euro III	2000.01	5
Euro IV	2005.01	3.5
Euro V	2008.01	2
Euro VI	2013.01	0.4

Table 4. Euro 6 standard application phases

	Euro 6b	Euro 6c	Euro 6d (temp)	Euro 6d
Applicable to new type-approvals (models) from	01/09/2014	N/A	01/09/2018	01/01/2020
Applicable to all new cars from	01/09/2015	01/09/2018	01/09/2019	01/01/2021
Laboratory test[37]	NEDC	WLTP	WLTP	WLTP
Applicable RDE NO_x limit for diesel vehicles	no RDE test required	no RDE test required	168 mg/km	114.4 mg/km[38]
Applicable RDE NO_x limit for petrol vehicles	no RDE test required	no RDE test required	126 mg/km	85.8 mg/km

Source: ECA, based on EU legislation.

2.2 *Emission standards verification*

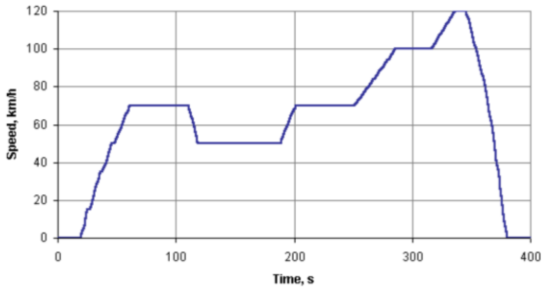
Compliance to EURO standard is determined by running the engine at a reference test cycle, needed to ensure adherence to regulations. These are laid out in standardized emission test cycles used to measure emissions performance against the regulatory thresholds applicable to the tested vehicle.

Since the Euro 3 regulations in 2000, performance has been measured using the NEDC protocol based on theoretical driving profiles and described by a sequence of fixed speeds, gear shift points and accelerations. NEDC offer possibilities for manufacturers to engage in what is called 'cycle beating' to optimize engine emission performance only for the corresponding operating point of the test cycle, while emissions from typical driving conditions would be higher than expected, potentially undermining the standards and public health[4].

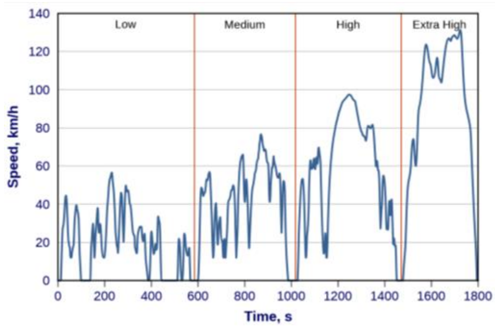
Since 2014 some studies documented the wide discrepancy that exists between official certification of nitrogen oxides (NO_x) from new Diesel passenger cars and actual NO_X emissions from those vehicles during real-world operation, *revealing additional emissions during live road tests* performed with *Portable Emissions Measurement Systems (PEMS).* The European Commission's Real Driving Emissions (RDE) working group proposed then the introduction of on-road PEMS testing as part of the passenger-car type-approval process in the EU.

2.3 *Emission standards and real-world emissions*

In September 2017, the European Union introduced the new test procedure WLTP (see next figures), aimed to ensure a better representation of the real operation of light duty vehicles and their technologies during the approval. WLTC tests are always performed in the laboratory on a dynamometer, following more realistic cycles, on completion of which road tests called RDE (Real Driving Emissions) are also scheduled to detect nitrogen oxides



		UDC	EUDC
Duration	s	780	400
average speed	km/h	19.0	62.6
Maximum speed	km/h	50.0	120.0
Path length	km	4.052	6.955
Time at idle	%	30.8	10.0



		LOW	MIDDLE	HIGH	EXTRA-HIGH
Duration	s	593	431	455	323
Average speed	Km/h	18.8	39.7	56.5	92
Maximum speed	Km/h	56.5	76.6	97.4	131.3
Length	km	3.09	4.75	7.14	8.24
Time at idle	%	25.3	10.7	6.6	2.2

Figure 1. NEDC (upper) and WLTC (Worldwide harmonized Light vehicles Test Cycles, bottom) speed time profile and characteristics

4 http://www.theicct.org/sites/default/files/publications/ICCT_EU_fuelconsumption2_workingpaper_2012.pdf
http://www.transportenvironment.org/docs/Bulletin/2006/2006-02_bulletin146_web.pdf

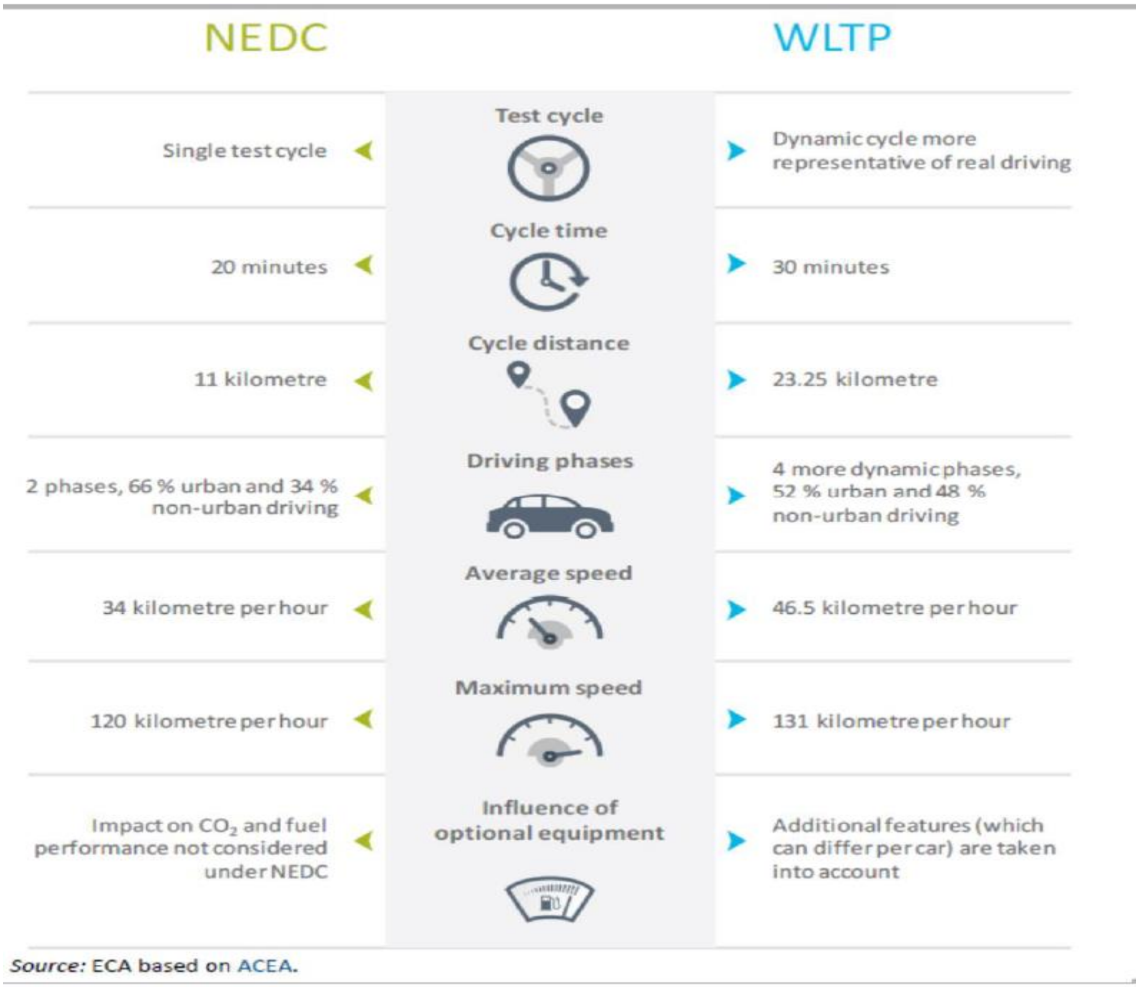


Figure 2. Main differences between NEDC and WLTP

Differences between real-world and standard compliance test emissions, are not just due to WLTP and RDE weakness' but also to motorists' behaviour and road inadequate infrastructure service level to accommodate it.

As shown in the next figure, vehicle emission factors are functions of speed, showing a minimum between 50 and 80 km/h. In the urban context, the average vehicles speed increases when traffic situations are more regular and this facilitates a decrease of emissions; on the contrary, in an extra-urban context (fast roads) traffic regularity increases if average speed decreases. Thus, road traffic emissions depend significantly on drivers' individual behaviour and the state of the road infrastructure too:

- virtuous driving behavior includes, for example, keeping a regular run (respecting the safety distance, avoiding pressing the accelerator too deeply, …) and the vehicle efficiency (keeping the correct tire pressure and regular vehicle maintenance, ...);
- it is instead up to the municipal administration to supervise and to maintain the state of the road infrastructures, correcting the problems that could reduce its capacity (not perfect state of the road surface, incorrect or inexistent traffic lights plans at intersections, wild parking, insufficient protections at interaction points among the various modes of transport, …).

Without any road infrastructure supervision also the virtuous driving behaviour is limited and the effectiveness of any measure limiting the circulation of most polluting vehicles would already start to be lacking.

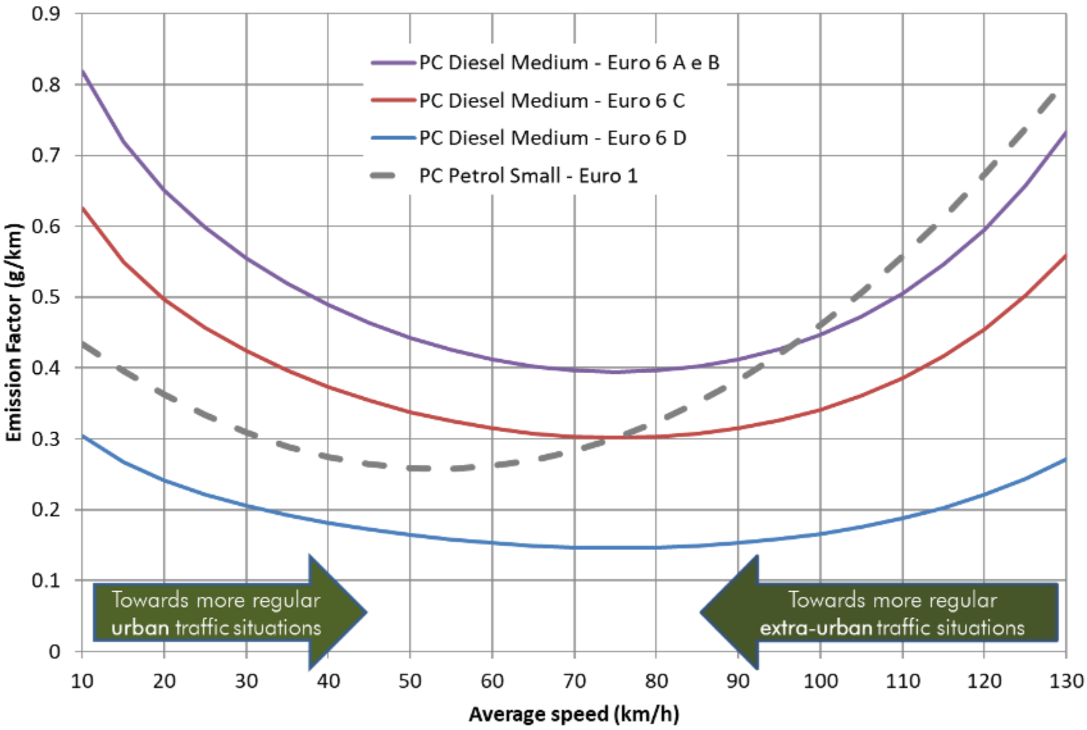


Figure 3. Speed dependent emission factor examples (COPERT 5)

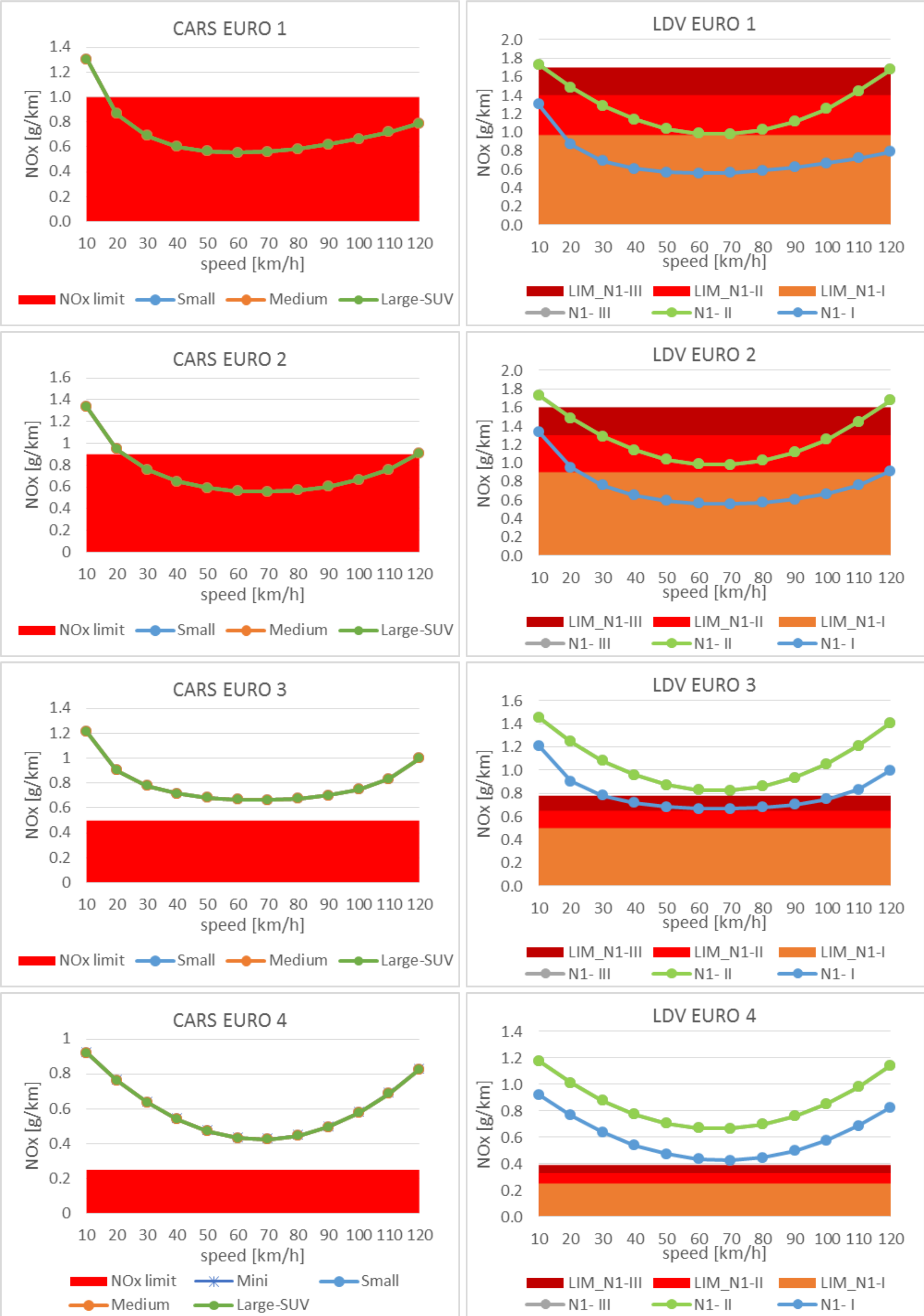
2.3.1 COPERT methodology

Emissions data collection, performed by means of most widely used measurement techniques, constantly feeds and updates a common European database used to estimate road transport emissions.

Traffic Emission Factors (EFs) are empirical functional relationships between pollutant emissions and the activities causes them, varying depending on different driving parameters. EFs are the results of intense experimental activities that have been collected and continuously updated. EFs may have different resolution according to their intended use: the COPERT methodology is the main road transport emissions model of the EMEP/EEA Atmospheric Emissions Inventory Guidebook[5] and considers how emission factors (g/km) vary depending on the traveling speed in real condition.

Focusing on Diesel powered light vehicles, the comparison between COPERT EFs and emission limits are shown in the following plots (Figure 4), while for Heavy-Duty the comparison can't be shown as the limit in g/kWh depends on the specific consumption of each vehicle and not on the distance travelled. From EURO3 standards, real emissions (COPERT curves) are higher than the progressively more stringent limits (red histogram), claiming for the development of new technologies, in aftertreatment system, to meet future regulations for “Euro 6d and beyond” diesels vehicles.

[5] https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-i/view


CARS EURO 1
NOx [g/km]
speed [km/h]
NOx limit
Small
Medium
Large-SUV
LDV EURO 1
NOx [g/km]
speed [km/h]
LIM_N1-III
LIM_N1-II
LIM_N1-I
N1- III
N1- II
N1- I
CARS EURO 2
NOx [g/km]
speed [km/h]
NOx limit
Small
Medium
Large-SUV
LDV EURO 2
NOx [g/km]
speed [km/h]
LIM_N1-III
LIM_N1-II
LIM_N1-I
N1- III
N1- II
N1- I
CARS EURO 3
NOx [g/km]
speed [km/h]
NOx limit
Small
Medium
Large-SUV
LDV EURO 3
NOx [g/km]
speed [km/h]
LIM_N1-III
LIM_N1-II
LIM_N1-I
N1- III
N1- II
N1- I
CARS EURO 4
NOx [g/km]
speed [km/h]
NOx limit
Mini
Small
Medium
Large-SUV
LDV EURO 4
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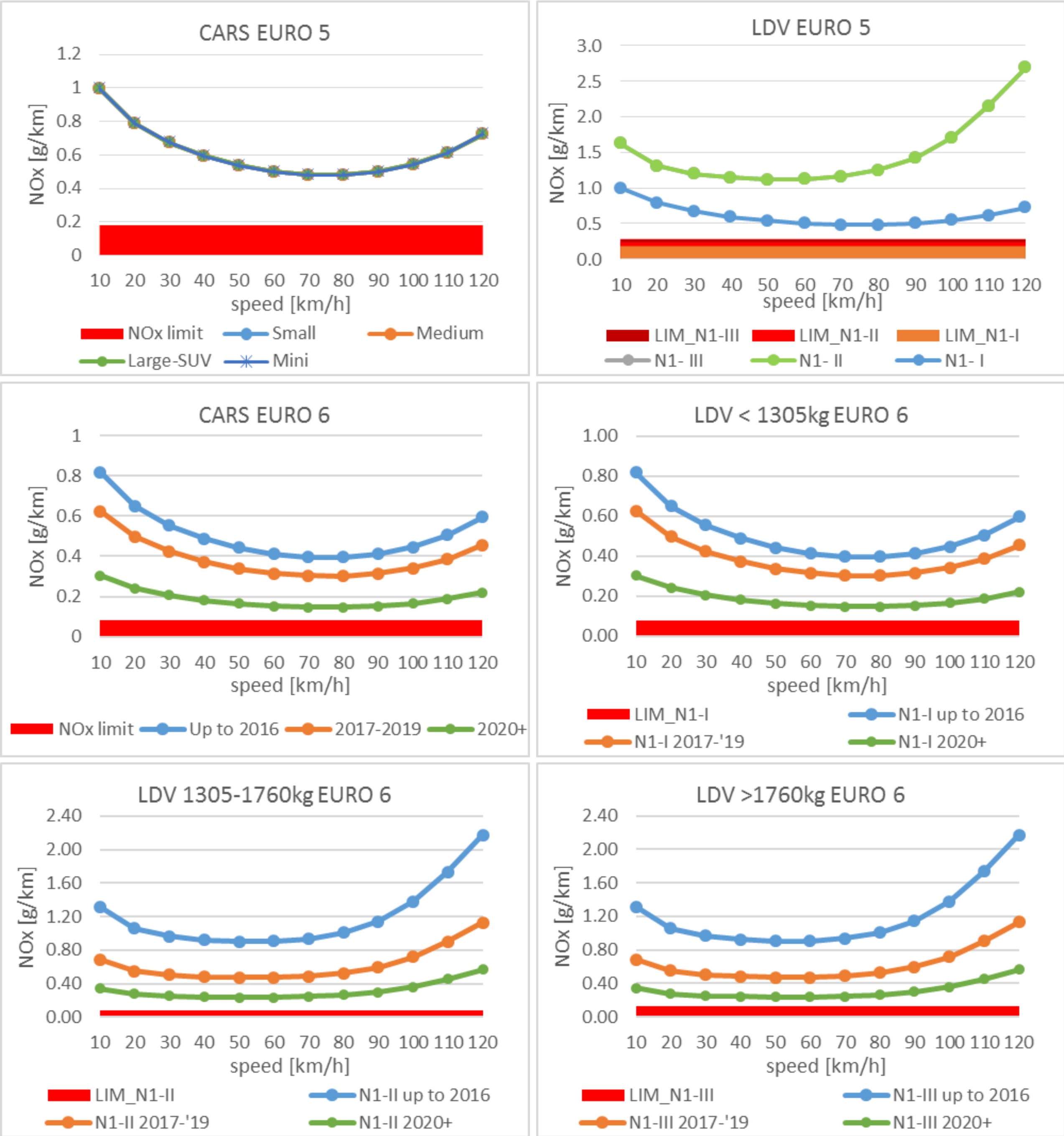

Figure 4. Comparison between NOx emission standard (red bar) and speed dependent emission factors by light vehicle category and EURO class

3. Territorial and methodological framework

The modelling simulations were carried out following the same approach considered in the mentioned study performed for the Association “Cittadini per l’Aria”. Coherently with that study, we considered a calculation domain that includes the Municipality of Milan and covers an area of 35x35 km^2. The calculation grid used for meteorological and dispersion simulations has the following characteristics:

• 70 cells along x direction;

• 70 cells along y direction;

• 500 m of horizontal resolution;

• UTM coordinates 32 (WGS84) of the South West corner of the domain equal to 499.5 km East, 5021.5 km North.

The choice of this domain responds to the need to consider the emissions produced both by the city of Milan and the surrounding urban areas that influence the NO_2 levels detected in Milan following transport and atmospheric dispersion processes. Since the compliance assessment of NO_X emission standards by Diesel vehicles in real situations and the corresponding impact on NO_2 levels are the main goals of this work, the use of an atmospheric chemistry model, capable of considering the chemical-physical processes giving rise to the formation of secondary pollutants as NO_2, is recommended. For this purpose, we used the atmospheric chemistry model FARM, at the base of the national modelling system MINNI[6] and applied by various Italian ARPA's, including ARPA Lombardy.

The model was still applied to the above domain and to the period February 11 to March 11, 2017 during which the campaign " NO_2 - NO thanks" took place. The selection of this period permits to evaluate the model performance also considering the large number of NO_2 measurements collected during the experimental campaign (see Appendix A.2).

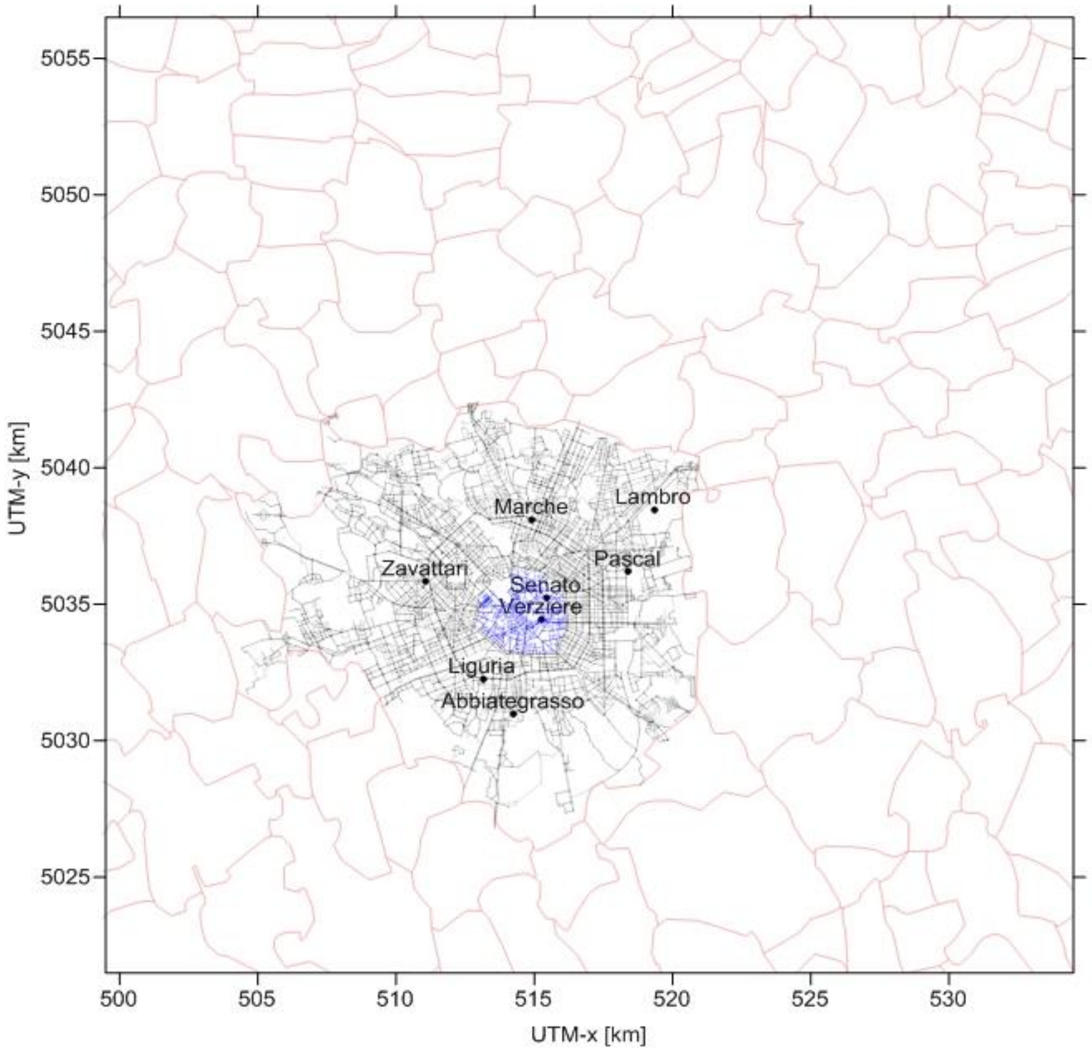

Figure 5. Computational domain. Limits of municipalities in red color. Milan road network: in blue inside "Area C" LTZ, in black outside "Area C". The location of NO_2 ARPA Lombardy monitoring stations is shown too.

[6] https://www.enea.it/it/in-evidenza/progetto-minni

4. Emissions

The emission estimation in the study area, modulated for the reference period (February, 11th to March, 11th 2017) was carried out starting from:

1. regional emissions inventory named INEMAR (INventario EMissioni ARia) provided by the regional agency for the environment (ARPA Lombardy) for 2014 at the municipality level;
2. a bottom-up approach to estimate traffic emissions within Milan urban area based on the official European COPERT 5 (COmputer Program to calculate Emissions from Road Traffic) methodology, using detailed road traffic data (e.g. integrated network geographic layer, geometric and structural characteristics of the road network, traffic flows), provided by AMAT, and information on the distribution of circulating vehicles, for the year 2018, provided by ACI (Automobile Club of Italy) and the Italian Environment Ministry.

4.1 *INEMAR inventory*

INEMAR (INventario EMissioni ARia), represents the database of atmosphere emissions generated by each source identified by CORINAIR European classification at municipality level for different pollutant and different fuel. Activity data indicator (e.g.: fuel consumption, paint production or material burned), emission factors, statistics data for spatial and temporal disaggregation are required information collected in INEMAR.

Data are split into SNAP categories (Selected Nomenclature for Air Pollution) with anthropogenic and natural sources organized in 11 macro sectors, 56 sectors and 360 activities.

In detail, the 11 macro sectors:

1. Public power, cogeneration and district heating plant;
2. commercial, institutional and residential combustion plants (eg: domestic boiler, stoves or fireplace;
3. industrial combustion (eg: power and heat industrial plant; iron and steel furnaces and cement plant);
4. production processes (chemical, wood and food industries);
5. extraction and distribution of fossil fuels (eg: fuel dispenser);
6. solvent use (eg: industrial and domestic paint application, Chemical products manufacturing or processing);
7. road transport (eg: passenger cars, light and heavy duty vehicles, gasoline evaporation from urban to highway roads);
8. other mobile sources and machinery (eg: railways, military vehicles, air traffic and maritime activities);
9. waste treatment and disposal (eg: waste incineration, solid waste disposal on land and cremation);
10. agriculture;
11. other (eg: vegetation, firework and tobacco combustion).

Figure 6 and in Table 5 show a synthetic view of principal pollutants (CO, SO2, NOx, NMVOC, PM2.5 and PM10) respectively, in terms of percentage distribution and annual emission for each macro sector. The purpose is to underline the critical sources over the computational domain.

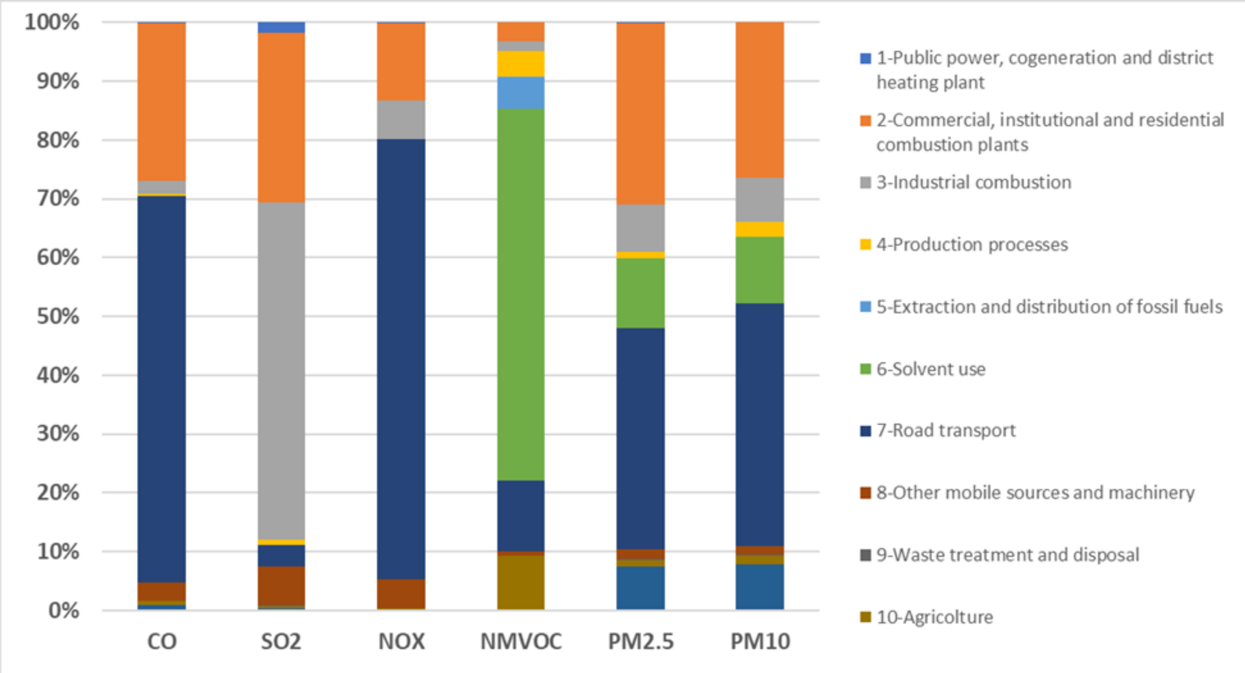

Figure 6. Percentage distribution of different macro sectors for municipality within computational domain

Table 5. Annual emissions [t/year] generated by municipality within computational domain

	CO	SO2	NOX	NMVOC	PM2.5	PM10
1-Public power, cogeneration and district heating plant	32	14	32	5	1	1
2-Commercial, institutional and residential combustion plants	8353	233	3107	1368	807	826
3-Industrial combustion	700	461	1539	716	208	240
4-Production processes	121	8	13	1850	30	75
5-Extraction and distribution of fossil fuels	0	0	0	2277	0	0
6-Solvent use	0	0	0	26714	311	356
7-Road transport	20405	30	17664	5087	976	1299
8-Other mobile sources and machinery	983	52	1138	302	44	44
9-Waste treatment and disposal	24	1	17	2	7	7
10-Agricolture	208	4	62	3809	29	43
11-Other emissions	270	2	9	107	192	249
Total	31095	806	23580	42238	2604	3141

Focusing on NOx, road transport is the principal source with an annual emission of 17664 tons per year, more than 70% of total NOx emission. For PM2.5 and PM10 the percentage contribution decreases to 40% while for residential and commercial combustion (macro sector 2) is almost 30% of total emission. In terms of annual emissions, road transport generates 976 tons per year of PM2.5 and 1299 tons per year of PM10 while macro sector 2 produces 807 tons per year of PM2.5 and 826 tons per year of PM10. Industrial and residential/commercial combustion contribute respectively for 60% and 30%. Observing NMVOC, the main source is macro sector 6 (solvent use) which contributes for more than 60%.

In order to detail emissive regime of Milan, Figure and Table 6 describe the percentage and annual emissions of different sources.

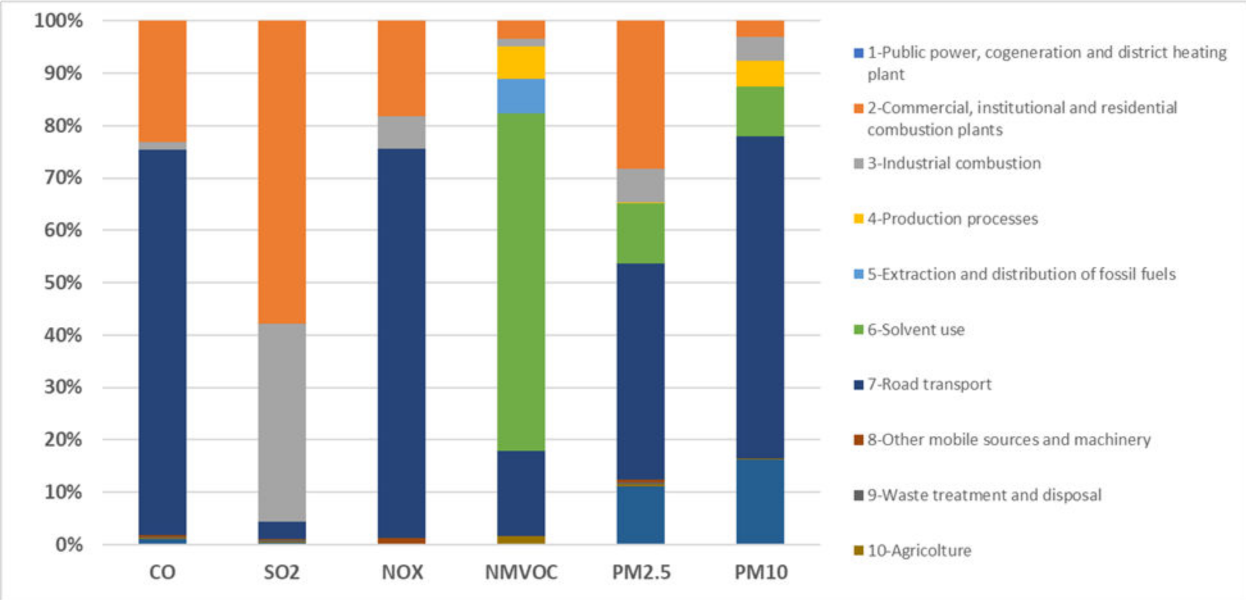

Figure 7. Percentage distribution of different macro sectors for Milan municipality

Table 6. Annual emissions [t/year] generated by Milan municipality

	CO	SO2	NOX	NMVOC	PM2.5	PM10
1-Public power, cogeneration and district heating plant	0	0	1	0	0	0
2-Commercial, institutional and residential combustion plants	1979	138	1107	370	177	4
3-Industrial combustion	121	90	369	155	40	6
4-Production processes	0	0	0	677	1	6
5-Extraction and distribution of fossil fuels	0	0	0	715	0	0
6-Solvent use	0	0	0	6970	71	12
7-Road transport	6277	8	4514	1755	259	77
8-Other mobile sources and machinery	28	0	59	8	4	0
9-Waste treatment and disposal	6	1	8	0	3	0
10-Agricolture	16	0	3	158	2	0
11-Other emissions	97	1	3	16	70	20
Total	8524	239	6064	10821	626	125

Road transport could be considered the main source for many pollutants (CO, NOx, PM2.5 and PM10) also for Milan municipality. In particular, NOx total emissions is 6064 t/year and the traffic contribution is more than 70% 4514 t/year. For SO2 and NMVOC industrial and commercial combustion and use solvent are considered the main sources over Milan.

To point out the relevance of Milan emissions, about 26% of total domain NOx emissions are concentrated in Milan urban area.

4.2 Milan road traffic atmospheric polluting emissions estimation

4.2.1 Road network and traffic

The made estimate relates to the atmospheric emissions of road traffic that travels through the Milan network, including the sections of ring roads and motorways between the municipal borders. This traffic network, shown in the following figure, is the result of a simulation carried out by AMAT and relating to the morning rush hour.

Traffic flows are briefly represented in the figure as equivalent vehicles (equivalent vehicles / hour), but the network includes vehicle flows divided into 5 macro-categories: cars, motorcycles, light commercial vehicles (i.e. commercial vehicles with a length <7.5 m), medium commercial (length between 7.5 and 12.5 m) and heavy commercial (length greater than 12.5 m).

Figure 8. Road network considered for the estimation of vehicular emissions on the urban scale. The traffic flow of the west ring road section south of the Settimo Milanese junction is indicated as a reference.

This traffic flows network is still related to 2017; as shown in the next figure, made from ISTAT (Italian Statistical Institute) data[7], road traffic in the three main Italian urban areas did not increase significantly between 2015 and 2018: In Milan, it increased only by 2.5% in 3 years and reached saturation in 2017.

[7] https://www.istat.it/it/archivio/236912

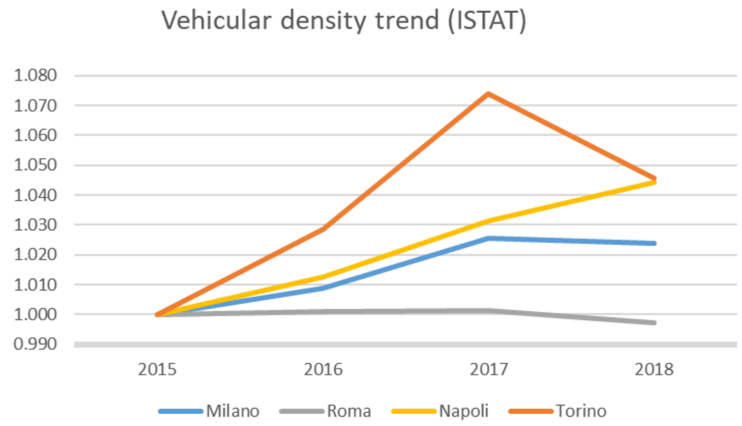

Figure 9. Vehicular density trends in the 3 main Italian urban areas.

The instrument used for the estimation of air polluting emissions from road traffic is TREFIC (road Traffic Emission Factors Improved Calculator), fully compliant with the COPERT methodology but specially developed by ARIANET to feed dispersion models. TREFIC is included in the ERMES (European Research on Mobile Emission Sources) list of derivatives models from the official ones inspired by the European Commission[8].

For the emission estimation, data from the AMAT traffic model used are in particular:

- Morning rush hour flows (from 8 to 9), divided by motorbikes, cars, light commercial vehicles (LDVs), medium + heavy commercial vehicles (HDVs);
- average flow speeds;
- road types (urban or highway).

4.2.2 Circulating fleet composition

To distribute the circulating vehicles based on power, capacity, power supply, Euro category, a fleet of vehicles was built on the basis of the most recent ACI data (2018)[9] of registered vehicles in the Province of Milan, and the total national annual mileage by COPERT category of source: Ministry of the Environment[10].

The figure below shows examples of views of the obtained circulating vehicles fleet, Diesel cars represent 31.9% of vehicles circulating in the Province of Milan, petrol ones 33.7%; the Diesel Euro 6, Euro 5 and Euro 4 respectively represent 9.1%, 17.1% and 13.0% of circulating cars.

Since “Area C” Milan LTZ includes more restrictive access rules than the rest of the municipal area, for the roads belonging to this restricted traffic area a dedicated fleet has been considered, excluding:

- Petrol Euro 0 cars and LDVs; Diesel up to Euro 3 cars and LDVs;
- all HDVs.

Despite in the morning rush hours (between 8 and 10), light commercial vehicles are prohibited, they have not been excluded if their access is granted in other periods based on fuel and Euro class.

[8] https://www.ermes-group.eu/web/other_models

[9] http://www.aci.it/fileadmin/documenti/studi_e_ricerche/dati_statistiche/autoritratto2018/Parco_Veicolare_2018.zip

[10] www.sinanet.isprambiente.it/it/sia-ispra/serie-storiche-emissioni/dati-trasporto-stradale/at_download/file

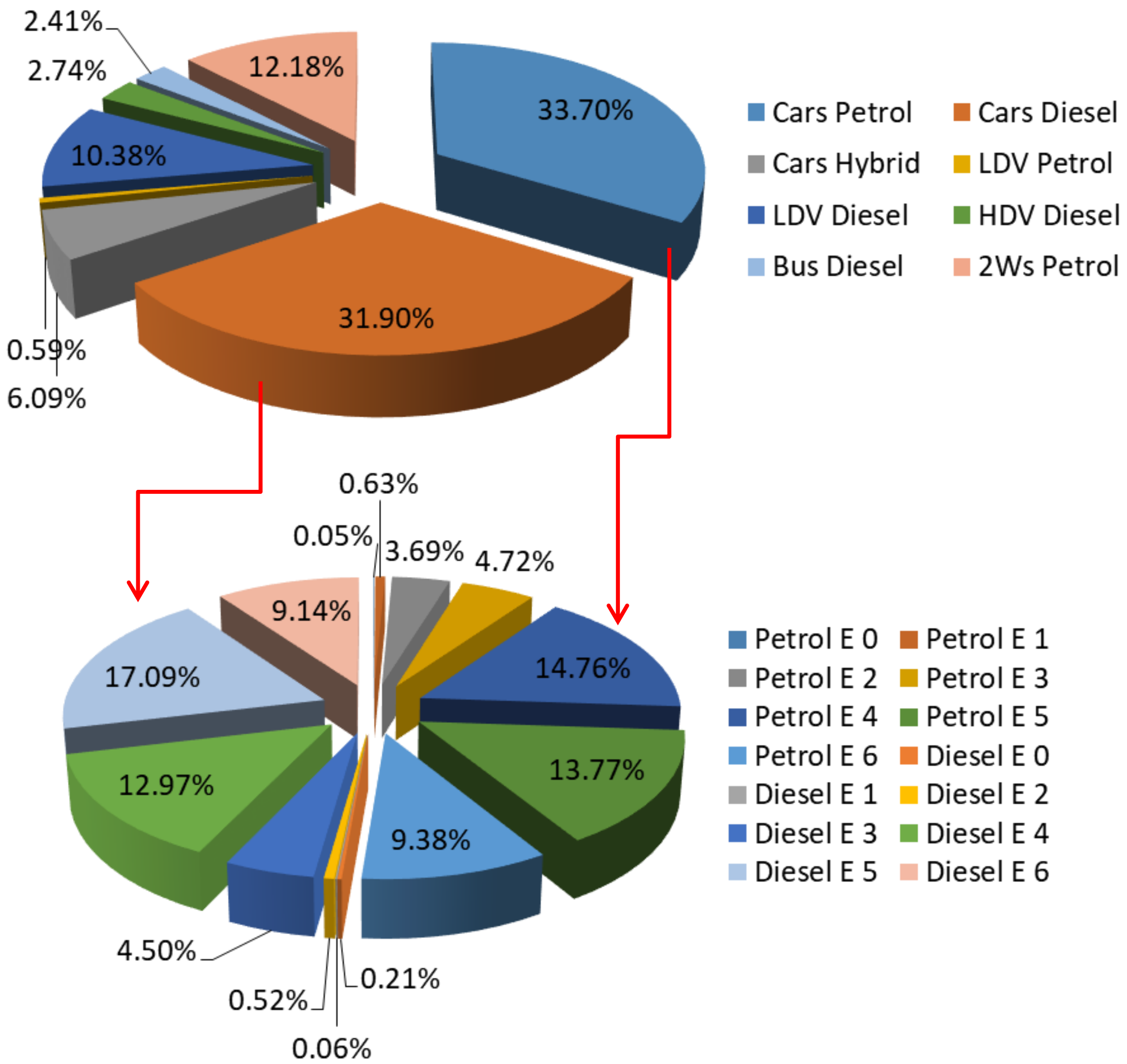

Figure 10. Circulating vehicles fleet composition - Province of Milan, year 2018. Above: vehicles by macro-categories and fuel; below: cars by fuel and Euro category (left side: Diesel, right side: petrol, excluding hybrids).

4.2.3 Road traffic emission model

Road traffic air pollutant emissions estimation was carried out by applying TREFIC, developed by ARIANET in accordance with the official European COPERT 5 methodology.

COPERT is published and scientifically reviewed by experts from the UNECE LRTAP convention (Convention on Long-Range Transboundary Air Pollution) and adopted throughout Europe except in Austria, Germany, Sweden and Switzerland; it collects and keeps updated the database of emission factors (EFs, emissions in terms of mass of pollutant per travel unit [g / km]), relating to individual vehicles belonging to coded categories.

EFs for each pollutant are characterized by profiles with speed, related to different traffic conditions: congested urban, non-congested urban, extra-urban, highway.

The emissions on a road network, aggregated by section, were calculated by characterizing the network links by length, traffic situation, average travel speed and vehicles flows distinguished by macro-categories.

TREFIC allows to calculate emissions, for many of the typical air pollutants from road traffic (including NO_X), by selecting the COPERT EFs corresponding to the specific vehicle types included in the flows of each road network link, on the basis of:

- fuel: petrol, Diesel, LPG, CNG;
- engine displacement for cars and 2-wheelers, capacity in case of commercial vehicles;
- vehicle age, or more precisely registration year and overall mileage.

The vehicle age allows to trace the technology, regulated by the various directives which in Europe have over time standardized the maximum emissions of the new produced engines. This information also allows to correct the EFs according to the efficiency and maintenance status of the vehicle itself.

As COPERT EFs are averages of measures taken during real driving cycles, the study allowed to highlight the inconsistencies already mentioned between emission standards and real emissions.

4.2.4 Road traffic emission scenarios

Modelling simulations have analysed the consequences on air quality of two limit road traffic emission scenarios:

- **Ex-ante** or **base case** – real emissions from road traffic in Milan;
- **DESC** (Diesel Emission Standard Compliance) – road traffic emissions in Milan if Diesel vehicles were compliant with Euro emission standards.

A third emission scenario, intermediate between the two previous ones and not used in an air quality simulation, has been calculated to estimate the relative contribution on air quality of the two terms that are involved in the problem: weakness of standard tests to represent real-world emissions and distance of real traffic situations from optimal ones determined by drivers' virtuous behaviour and best infrastructure design and maintenance state:

- **OTS** (Optimal Traffic Situations) - road traffic emissions in Milan if all vehicles on all network streets (including fast speed roads like urban motorways) had rush hours **average speed between 40 km/h and 70 km/h**. In the following table, as a reference, average speeds for the two network and scenarios.

Table 7. Ex-ante and OTS scenarios average speeds for the two Milan municipality networks

Scenario	Inside Area C	Outside Area C
Ex-ante	15.6 km/h	24.9 km/h
OTS	40.0 km/h	41.3 km/h

4.3 *Results of the emissions estimation*

The traffic network of the Municipality of Milan, created by AMAT, and the composition of the circulating fleet updated to 2018 were used to estimate the pollutant emissions.

Starting from the emissions network, the contributions of individual vehicle categories were assessed, distinguishing in particular those of Diesel vehicles registered according to the different Euro standards.

The emissions for the morning rush hour are represented in the following figure. It should be noted that the emissions map differs from that of traffic flows because road by road can change the average travel speed and the distribution between the macro categories. Since this representation is per length unit, the most congested urban intersections emerge, beyond the two links of the outer ring included in the municipal borders.

As a result of this phase of emissions calculation, an emissive comparison balance of the various scenarios was developed.

Figure 11. NOx emissions at peak times (kg / h / km) for the traffic network of the Municipality of Milan.

4.3.1 Present situation

Emissions balance

The next table describes NO_x and NO_2 emissions generated by road transport within Area C (city center of the urban area) and the other part of the city for the base scenario. Area C generates about 2% and 3% of total NO_x and NO_2 emissions produced by Milan road transport respectively.

Table 8. Road transport emissions in the rush hour within Milan municipality [kg/h] for the "base case"

Urban area	NO_X	NO_2
no Area C	1 129	281
Area C	27	9
Total	1 156	290

The following figure compares the percentage contributions to NO_X emissions of various Euro categories of Diesel vehicles. Most of the NO_X Diesel vehicle emissions in Milan derive from Euro 5 (37%) Euro 3 (24%) and Euro 4 segments (17%). Euro 6 vehicles already contribute to NO_X emissions by 9%.

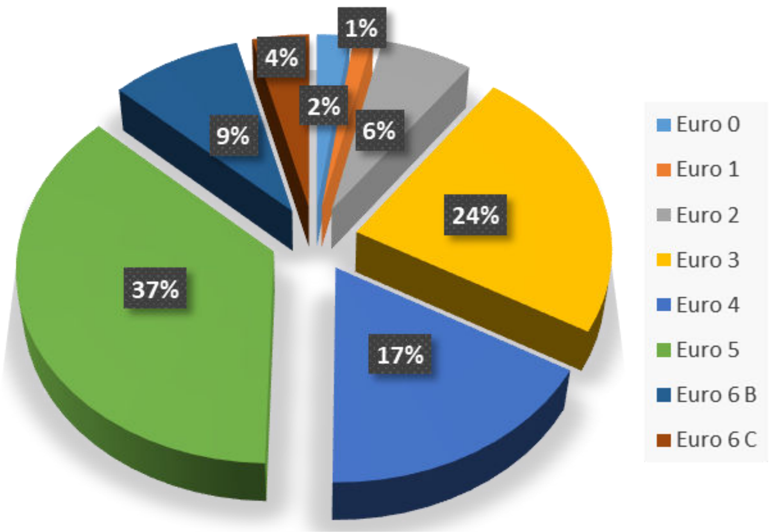

Figure 12. Percentage comparison of NO_X emissions from the various Euro segments of Diesel vehicles.

Annual emission estimation

Table 9 shows the comparison for annual emissions of different pollutants by road transport between INEMAR official data and TREFIC estimation. This comparison can be only indicative as the reference year of circulating fleet used in TREFIC calculations (2018) is different from the INEMAR one (2014).

Table 9. Emissions comparison between TREFIC estimation for the "base case" and INEMAR annual report for road transport (macro sector 7)

[t/y]	CO	NOx	NH3	SO2	N2O	PM2.5	PM10	NMVOC
TREFIC	10730	4859	59	23	65	356	523	1913
INEMAR	6277	4514	50	8	44	259	336	1755

Although the two approaches are different, TREFIC estimates are very similar to INEMAR ones, particularly for nitrogen oxides,, ammonia and NMVOC. The main differences are visible for carbon monoxide, particulate matter (PM2.5 and PM10), sulphur dioxide and N_2O, due to the higher sensitivity of TREFIC bottom-up approach to low speed situations, that implies higher fuel consumption calculations too. Moreover, TREFIC bottom-up approach brings to a more realistic and detailed spatial distribution of emissions over the municipality.

4.3.2 Study scenarios: Diesel emission standards compliance and optimal driving situation

Table 10 shows the NO_X and NO_2 emissions estimated for the road traffic emissive scenarios DESC and OTS respect to the base case.

Table 10. NOx and NO_2 road transport total emissions and percentage reduction for emissive scenario

[t/y]	NOx	NO_2
Base case 2018	4859	1218
(OTS)	*(3521)*	*(813)*
DESC	2201	413
Total reduction [%]	55%	66%

As we can see from the previous table the total percentage reduction is more than 50% for both pollutants while OTS is roughly intermediate between DESC and the base case.

4.3.3 Time profiles

Temporal profiles allow to disaggregate the annual emission data into hourly value for the reactive simulation. For each vehicular category (passenger cars, light duty vehicles, heavy duty vehicles, etc) as well as road travelled (urban, rural and highway) 3 temporal profiles were defined: daily, weekly and monthly modulation. The next figure shows the daily and weekly profiles adopted by FARM.

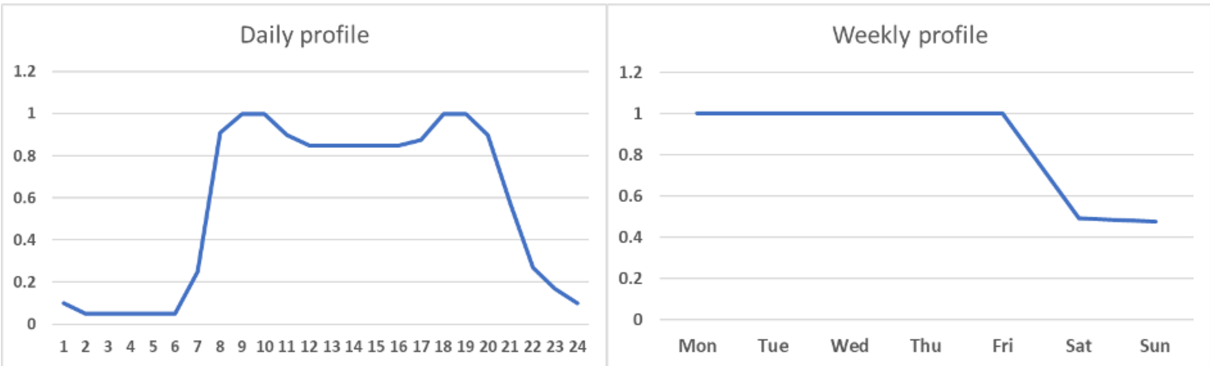

Figure 13. Daily and weekly profiles for road transport emissions estimated by TREFIC for Milan

The daily profile is like a “standard” with symmetric peaks at morning and evening rush hours. Weekly profile does not underline variations during working day (Monday-Friday) while during the weekend the total traffic volume decreases significantly. Monthly profile is assumed constant during the entire year.

5. Modelling simulation results

A modelling system, based on the chemical transport model FARM, was used to simulate air quality over the calculation domain shown in Figure 1 for the meteorological period February 11 to March 11, 2017. The system includes the following components:

- TREFIC for estimating road traffic emissions based on the information provided by AMAT;
- a module for the preparation of the emission input to the FARM model starting from the data contained in the INEMAR inventory and TREFIC output;
- WRF model for the three-dimensional reconstruction of meteorological fields;

- boundary conditions, or concentrations at the edges of the calculation domain to consider the flows of pollutants from areas outside the calculation domain.

Appendix (A.1) provides a brief description of the modelling system. To answer the question referred to in the introduction, two simulations were carried out:

1. the present situation corresponding to the limitations in force in the reference period ("Base case");

2. the scenario DESC in which the NO_X emissions from all Diesel fuelled vehicles were estimated using the Euro standards instead of real situation emission factors.

Appendix A.2 reports the preliminary assessment activity of the applied modelling methodology. In this context we used the NO_2 measurements collected both by ARPA monitoring network and during the "NO_2, No grazie!" campaign. The modelling system can consider also other pollutants, the assessment was extended to PM10, PM2.5 and "Black Carbon" measurements collected at ARPA stations. A good agreement between observed and predicted concentrations was evidenced.

Yearly averaged NO_2 concentration fields were processed, using the methodology reported in Appendix A.3 (Figure 14). The analysis of the "base case" map evidences that a large portion of the Milan urban area is exposed to annual NO_2 concentrations higher than the limit value and that the highest values, including the absolute maximum of about 60 µg/m^3, are found along the northern ring roads of the city centre. The analysis of the scenario DESC map evidences a significant reduction of NO_2 levels with an absolute maximum of about 47 µg/m^3. For this scenario, the city centre as well as the southern and the western portions of the Milan metropolitan area and other smaller areas would respect the yearly limit value for this pollutant.

As anticipated in the introduction, this map provides an answer to the question: *what would be the NO_2 levels in the Milan urban area if Diesel vehicles will compliant the emission standards?* The next table summarizes the overall results obtained inside the city borders. On average, NO_2 levels are over the threshold of 40 µg/m^3 while the DESC scenario seems able to reduce them by 15%. The following discussion paragraph includes a detailed analysis of various emission terms involved.

These estimates are confirmed both by the levels recorded by the local monitoring network. Figure 15 shows the comparison between the trends of the average annual NO_2 concentrations detected by the measuring stations located in the Region and in the metropolitan city of Milan (regional and provincial averages). These trends, while showing a decrease from 1990 to 2016, evidence levels above the limit value in the Milan metropolitan area in the years 2015-2017.

Table 11. Calculated average annual NO_2 concentrations (in red values above the limit of 40 µg/m^3)

Parameter	Base case	Scenario DESC	Difference
Spatial average inside Milan borders	**43.3**	**37.7**	**-6.6 µg/m^3 (-15%)**

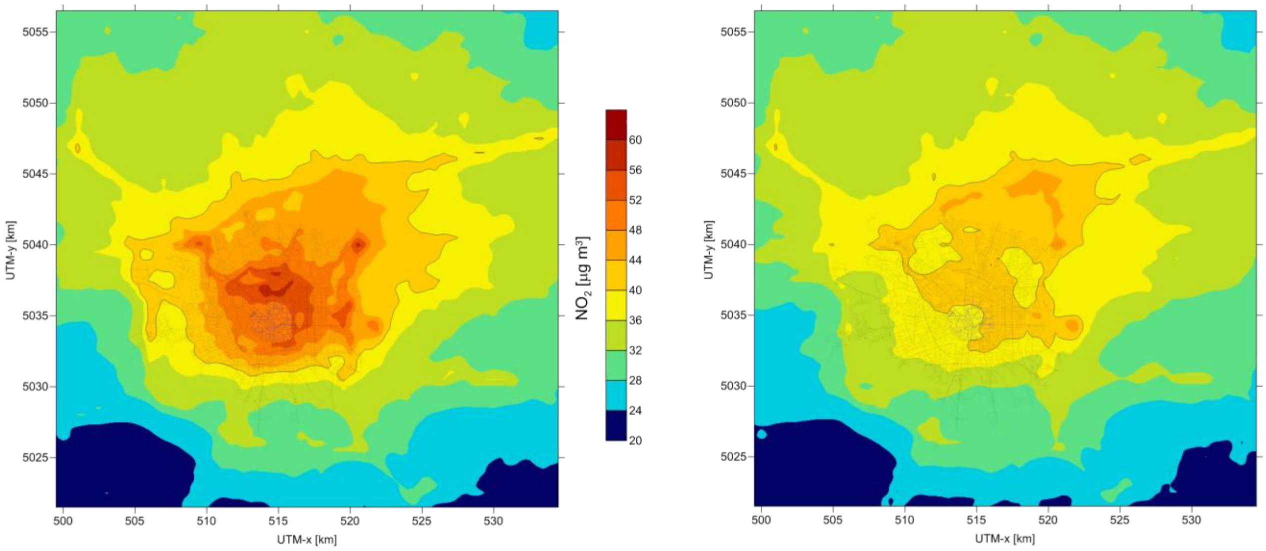

Figure 14. Yearly averaged NO_2 concentration fields for the "base case" (left) and the scenario DESC (right). Values expressed in µg/m³ (the limit value for this parameter is 40 µg/m³)

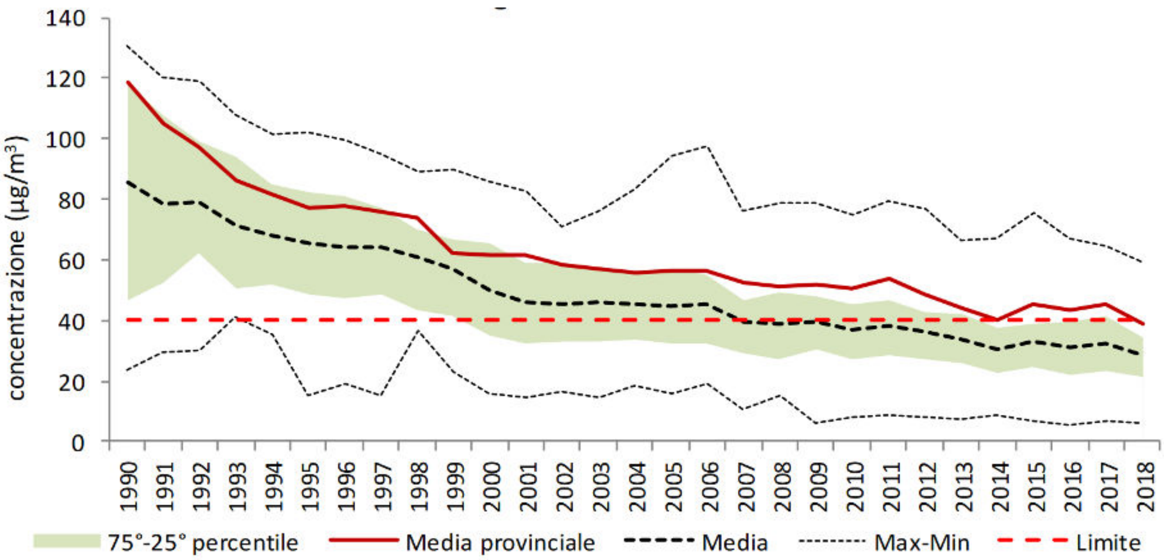

Figure 15. Comparison between yearly trends of NO_2 concentrations recorded at regional level and at stations located in Milan metropolitan area. Source: *ARPA Lombardy, Rapporto Annuale sulla Qualità dell'Aria – Anno 2018*[11].

6. Discussion and conclusions

In this report the results of a research funded by EPHA (European Public Health Alliance) are presented, with the purpose of estimating the impact on air quality of emissions from of Diesel-powered vehicles circulating in the Milan urban area.

The assessments were based on the results of photochemical atmospheric dispersion model which considers as input the emissions of atmospheric pollutants from vehicular traffic and other relevant

[11] https://www.arpaLombardy.it/qariafiles/RelazioniAnnuali/RQA_MI_2018.pdf

sources and their dispersion and chemical transformations that take place in the atmosphere due to meteorological conditions.

As the focus of the study was to estimate the impact of actual emissions that Diesel vehicles exhibit in the real situations with respect to the EURO standards that the new models must comply, two configurations were considered:

- **ex-ante**: corresponding to the emission framework for 2018;
- **Diesel Emission Standards Compliance (DESC)**: ideal scenario in which all Diesel vehicles are supposed to comply with the emission standards in force at their homologation time.

As a comprehensive representation of this study results, the plot below shows the calculated NO_2 annual average level in Milan with the significance of various contributions and along the abscissa the foreseen progressive improvement in air quality depending on the progressive disappearance of the older euro Diesel categories. In the following table it is also shown the single calculated contribution of all Diesel Euro categories.

All shown contributions are extrapolated assuming linear the relation between emissions and concentration levels.

The legislative limit on the annual average of NO_2 is highlighted in red too, so that the average respect of this air quality standard is shown achievable only if the circulation of Diesel cars Euro 3 and lower is prevented considering the present situation without further interventions.

From this point of view, adopting measures to put the road network infrastructures in the ideal service levels, and to force drivers to keep a virtuous driving behaviour, is equivalent to stop circulating Diesel vehicles Euro 3.

If Diesel vehicles were compliant with emission standards in real driving conditions, no further actions would be needed to respect the law air quality limit, at least on average.

Once the constant background is established (including contribution of non-Diesel vehicles and the other pollution sources), the improvement effect of other actions is quantified:

- The DESC scenario could reduce the NO_2 annual levels by 15% on average;
- Inside the DESC scenario, a significant role (7%) is due to the weakness of the homologation tests in reproducing real behaviour of vehicles;
- Another important role is played by traffic regularity (8%) that wears off the differences between peak and off-peak hours, due to virtuous motorists' behaviour and road enough infrastructure service level to accommodate it (scenario OTS).
- The remaining 19% is due to emissions from Diesel vehicles that comply with Euro emission standards.
- The difference (15%) between the Base case annual average of NO_2 (44.3 $\mu g/m^3$) and DESC Scenario one (37.7 μg/m3) is thus due to the combined effect of optimal driving styles and traffic situations and the gap between the real emissions of Diesel vehicles and standard limits, in practice the non-representativeness of the real situation in the homologation tests of the vehicle.
- The rescaled gap between penultimate and ultimate bars shows what can be considered as the "Diesel gate" effect (2%) as rescaled difference between contributions of Diesel Euro 6 B and Euro 6 C Diesel vehicle emissions. Rescaling is needed to account for the less incidence of Euro 6 C vehicles on the circulating fleet in Milan.
- These results will provide further insights on the effectiveness of measures aimed to reduce the impact of Diesel vehicles on air quality levels and consequently on citizens' health.

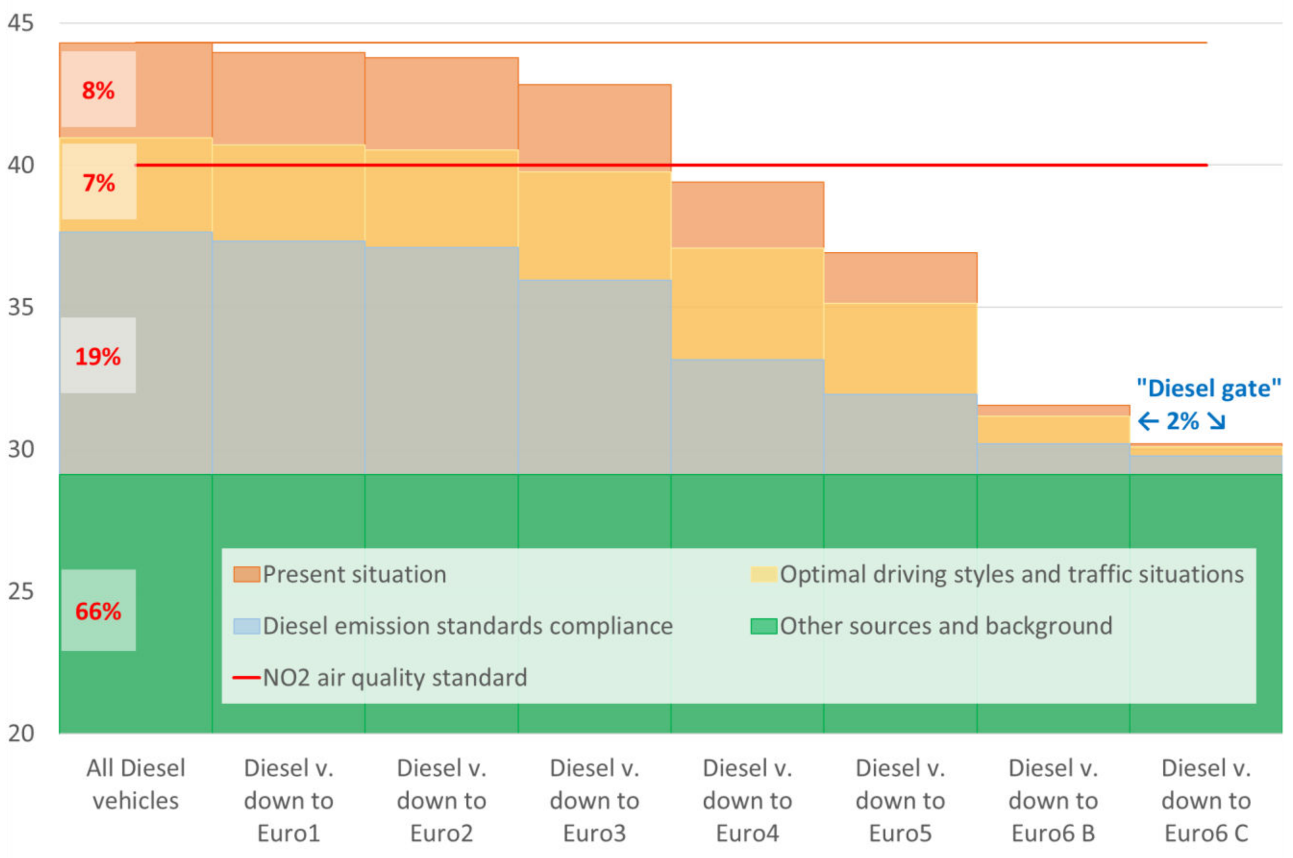

Figure 16. Leftmost bar: average air quality level in Milan (NO_2 annual average, µg/m^3, year: 2018) and contributions of various terms analyzed in the study. Other bars: air quality levels attainable in case of progressive Euro standard Diesel vehicles circulation blocks.

Table 12. Contributions of all Diesel Euro categories and groups of them on the average annual NO_2 concentration (in red values above the limit of 40 µg/m^3)

Diesel vehicles	Non-Optimal driving styles and traffic situations	Diesel emission standards non-compliance	Diesel emission standards compliance	Other sources and background	Total
All	3.3 (8%)	3.3 (7%)	8.5 (19%)	29.1 (66%)	44.3 (100%)
down to Euro1 (Euro1 – Euro6)	3.3	3.4	8.2	29.1	44.0
down to Euro2	3.3	3.4	8.0	29.1	43.8
down to Euro3	3.1	3.8	6.8	29.1	42.8
down to Euro4	2.3	3.9	4.0	29.1	39.4
down to Euro5	1.8	3.2	2.8	29.1	36.9
down to Euro6 B	0.4	1.0	1.1	29.1	31.5
Euro6 C	0.1	0.3	0.7	29.1	30.2
Euro 0	0.1	-0.1	0.3		0.3
Euro1	0.0	0.0	0.2		0.2
Euro2	0.2	-0.4	1.2		0.9
Euro3	0.7	-0.1	2.8		3.4
Euro4	0.5	0.7	1.2		2.5
Euro5	1.4	2.2	1.7		5.4
Euro6 B	0.3	0.6	0.4		1.3
Euro6 C	0.1	0.3	0.7		1.1

Appendix A - The Modelling System

A.1. Components of the modelling system

The modelling system used in the study is divided into a series of pre- and post-processors and models, suitably integrated with each other, for the simulation of the different processes that contribute to determining the air quality in a given geographical area: characteristics of the site, meteorological variables, emissions, dispersion, deposition and chemistry of the atmosphere. This system allows to simulate these processes from the regional to the local scale considering both short and long-term periods (study of critical episodes / assessment of air quality standards). The system includes three-dimensional transport models and is therefore able to consider the complexity of the territory (orography and land use) and weather-spreading situations that evolve over time and are not homogeneous in space. The following figure shows a diagram of the components of the modelling system and of the data flow.

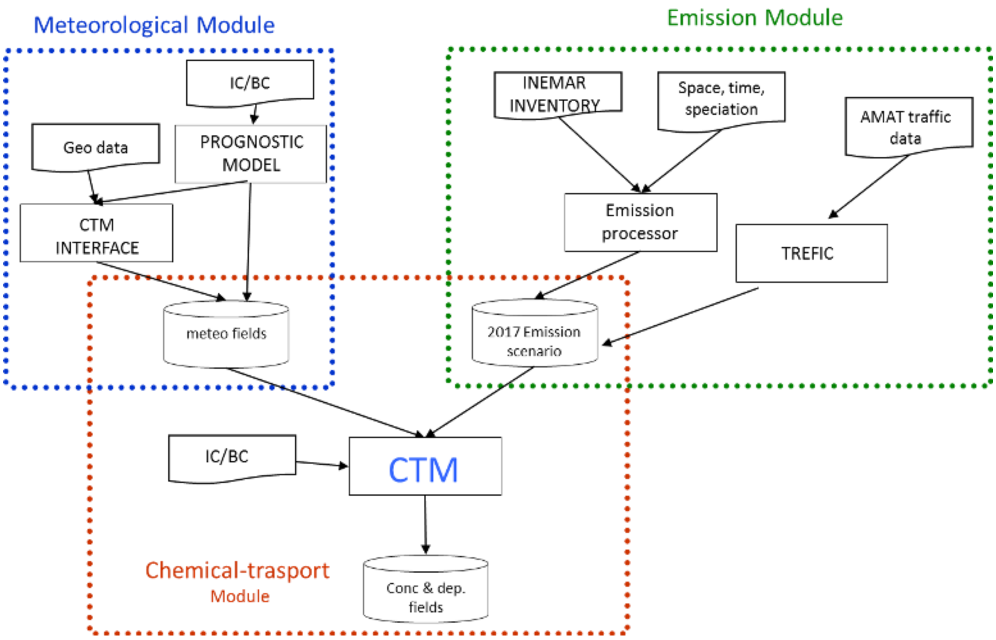

Figure 17. Modelling system used in the study

The system used in this study is based on the Chemical Transport Model (CTM) FARM (Flexible Air quality Regional Model) which considers the transport / diffusion and chemical-physical processes involving airborne pollutants. The system includes the following modules which prepare FARM input data:

- Meteorological module: based on the WRF prognostic model, for the three-dimensional reconstruction of meteorological fields (wind, pressure, temperature, humidity), and on an interface module for the calculation of additional parameters as vertical and horizontal diffusivity, dry deposition rate, natural emissions, etc.;
- Emission Module: it prepares the emission input from the data contained in the inventory of INEMAR emissions and produced by the TREFIC model based on the information provided by AMAT;
- Boundary condition Module: it prepares concentrations at the edges of the calculation domain to consider the flows of pollutants from the external areas (boundary conditions). The concentration fields produced by the QualeAria modelling system (http://www.qualearia.it),

which produces daily weather and air quality forecasts at European and national scale, have been used.

A.2. Model evaluation

As indicated by the D.Legs. 155 (Implementation of Directive 2008/50 / EC relating to the quality of ambient air and for cleaner air in Europe), the assessment of the ability of a model to describe the problem to which it is applied can be carried out using different methods. Most commonly, this evaluation is performed using a series of indicators (performance indices) which describe the model's ability to approach the measures. However, the following factors must be considered:

3. congruence of the spatial resolution of the model and of the spatial representativeness of the measure; as indicated by the aforementioned Legislative Decree, "To determine the uncertainty of the model it is therefore necessary to operate, as far as possible, the comparison of the simulated concentrations with the data obtained from a set of measuring stations having spatial representativeness congruent with the spatial resolution of the model ";

- modelling uncertainties; the model is not a duplication of reality but a partial representation of it and therefore affected by uncertainties related to the input data (emissions, meteorology, initial state), the description of the dynamics and atmospheric chemistry and the hypotheses introduced in the model itself (the developers of the model make a selection between what remains inside the model, which will be an integral part of it, and what will instead be consciously excluded).

In this study, the evaluation was carried out by using the information provided by the air quality monitoring stations, managed by ARPA Lombardy, present in the Milan urban area and the "NO2, No Grazie!" campaign sampling points (Figure 18).

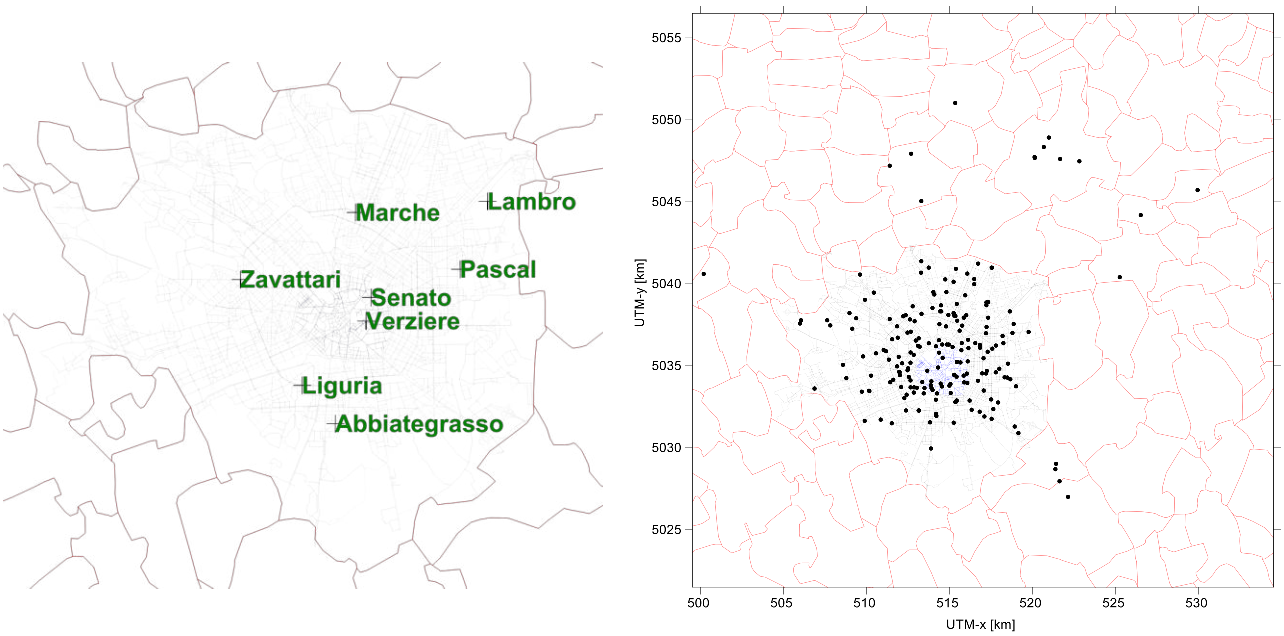

Figure 18. Location of ARPA monitoring stations (left) and "NO2, NO Grazie!" campaign sampling points (right).

The following figure (Figure 19) shows the comparison between the NO_2 concentrations measured at ARPA stations and those calculated by the modelling system during the "NO2, No Grazie!" campaign period (from February 11 to March 11, 2017). The examination of this figure highlights the model's ability to reproduce the concentrations observed throughout the simulation period with a good approximation (an overestimation of observed levels for the first week of simulation is evidenced, that could be ascribed to an overestimation of domestic heating emissions).

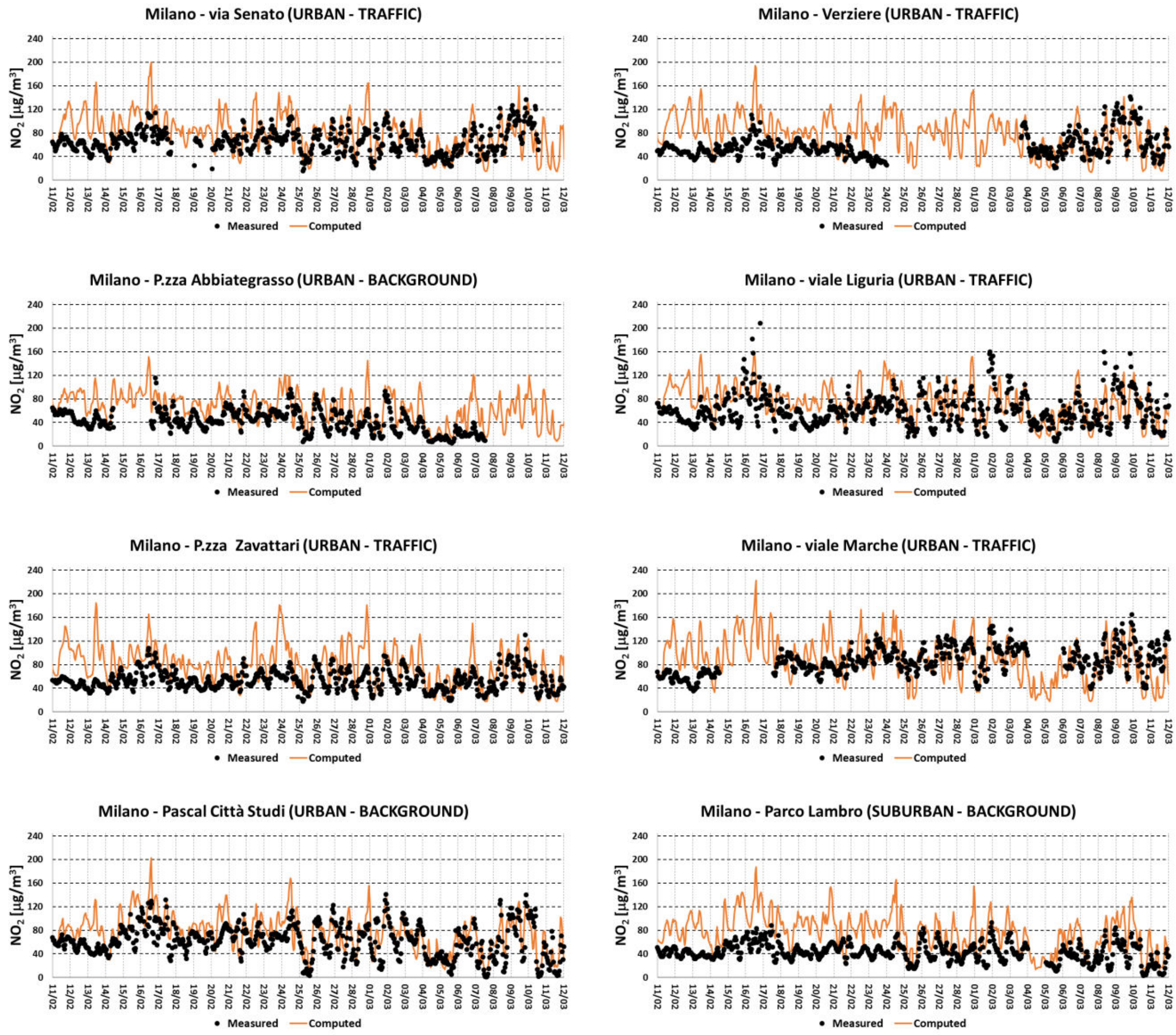

Figure 19. Comparison between daily measured (ARPA stations) and calculated of NO_2 concentrations during the period 11/2-11/3/2017 ("via Senato" and "Verziere" stations are located in LTZ Area C, "Parco Lambro" station is located in a city park).

The "scatter charts" of Figure 20 show the comparison between the monthly average concentrations measured and calculated in correspondence with the ARPA stations and the sampling points of the "NO2, No grazie!" campaign. The data are displayed through a collection of points where the position on the horizontal and vertical axes is determined respectively by the measurements and the model estimates. This representation is useful for visualizing the degree of correlation (i.e. linear dependence) between the two variables. If the points are arranged along the straight-line y = x there is a correlation equal to 1 or a direct and absolute correlation. An examination of these figures shows that the points tend to be arranged along this straight line and above it, thus indicating an overestimation of the observed values (generally lower than 50%).

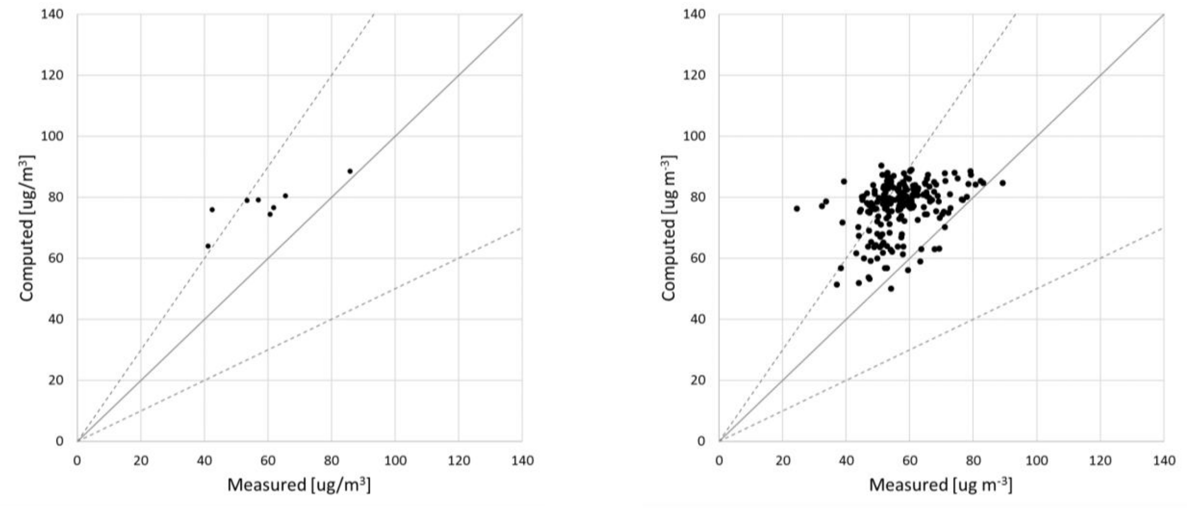

Figure 20. Comparison between monthly average concentrations measured and calculated in correspondence with the ARPA stations and the sampling points of the "NO2, No Grazie!" campaign.

Since the modelling system can consider other pollutants, Figure 21 shows the comparison between observed and predicted PM10, PM2.5 and "Black Carbon" the concentrations at ARPA stations. An examination of these figures shows that the model faithfully reproduces the measured concentrations and that the decrease in PM10 and PM2.5 levels since the end of February is attributable to the lower contribution of heating systems. This decrease is not observed for the "Black Carbon" which in urban areas can be used as a tracer for the emissions of internal combustion engines and the wide range of chemical species (and of various toxicities) transported by it, including organic compounds such as PAH (Polycyclic Aromatic Hydrocarbons).

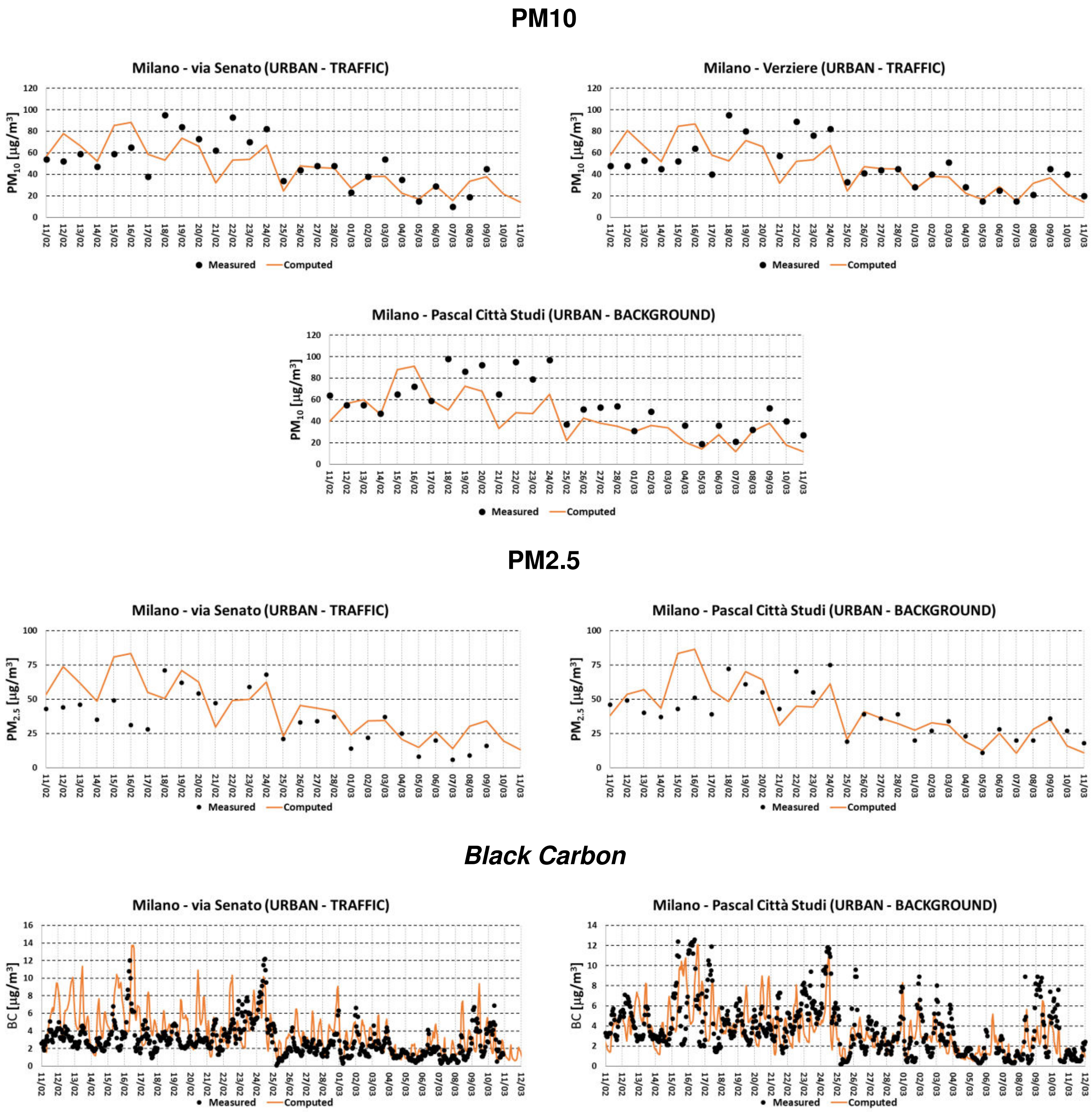

Figure 21. Comparison between measured (ARPA stations) and calculated PM10, PM2.5 and Black Carbon concentrations during the period 11/2-11/3/2017.

To further evaluate the performance of the model in the following table, with reference to nitrogen dioxide and PM10, the results relating to the following statistical indicators used for the evaluation of the performance of dispersion models are presented: average, standard deviation; Fractional Bias (FB), Root Mean Square Error (RMSE), fraction of predictions within a factor of two of the observations (FAC2) and Index of Agreement (IA, Willmott, 1981). Considering O_i and P_i the observed and predicted values, the above statistical parameters are defined as follows:

Mean [µg m-3]: $\bar{O} = \frac{1}{N}\sum O_i$ **and** $\bar{P} = \frac{1}{N}\sum P_i$;

Standard Deviation [µg m-3]: $\sigma_O = \sqrt{\frac{1}{N-1}\sum(O_i - \bar{O})^2}$ **and** $\sigma_P = \sqrt{\frac{1}{N-1}\sum(PO_i - \bar{P})^2}$;

Fractional Bias [adimensional]: $FB = \frac{2(\bar{O}-\bar{P})}{(\bar{O}+\bar{P})}$,**'acceptable' model performance values: -0:3 < FB < 0:3;**

Root-mean-square error [µg m-3]: $RMSE = \sqrt{\frac{\sum_{i=1}^{n}|(P_i-O_i)|^2}{n}}$;

FAC2 [adimensional]= fraction of data that satisfy: $0.5 \le \frac{P_i}{O_i} \le 2$; **'acceptable' model performance values: FAC2 > 0.5;**

Index of Agreement [adimensional]: $IA = 1 - \frac{\sum_{i=1}^{n}(P_i-O_i)^2}{\sum_{i=1}^{n}(|P_i-\bar{O}|+|O_i-\bar{O}|)^2}$.

The 'acceptable' model performance values are derived from Chang and Hanna (2004).

Table 13. CTM evaluation of NO_2 and PM10 predictions

Pollutant	*Station*	*# data*	$\bar{O}$	$\bar{P}$	σ_O	σ_P	*RMSE*	*FB*	*IA*	*FAC2*
NO_2	Marche	574	85.75	88.05	23.58	32.67	34.12	-0.03	0.56	87.63
	Liguria	696	60.65	74.43	27.63	29.21	30.81	-0.20	0.69	84.34
	Abbiategrasso	540	41.11	63.84	19.10	25.68	30.48	-0.43	0.62	72.04
	Zavattari	696	53.48	78.86	17.07	31.86	36.67	-0.38	0.53	81.32
	Verziere	514	56.97	78.52	20.66	31.60	38.67	-0.32	0.48	73.93
	Lambro	672	42.48	77.58	16.05	30.43	41.87	-0.59	0.49	61.91
	Senato	613	65.47	82.14	21.21	32.01	30.80	-0.23	0.66	91.84
	Pascal	696	61.74	76.56	27.79	31.09	27.60	-0.21	0.78	86.06
	Overall	***5001***	***58.35***	***77.55***	***25.59***	***31.26***	***34.13***	***-0.28***	***0.65***	***87.63***
PM_{10}	Verziere	28	47.14	45.22	21.73	21.12	17.72	0.04	0.79	100.00
	Senato	27	50.93	48.45	22.64	20.27	17.37	0.05	0.80	100.00
	Pascal	28	55.96	42.91	23.11	21.38	20.87	0.26	0.78	92.86
	Overall	***83***	***51.35***	***45.49***	***22.52***	***20.81***	***18.74***	***0.12***	***0.79***	***97.59***

The analysis of the Index of Agreement (IA), that is a measure of the skill of the model in predicting variations about the observed mean (IA$\in$ [0,1], with 1 indicating the best agreement; a value above 0.5 is generally considered to be a good result), indicates a good performance for PM10 and acceptable results for NO_2. These performances are confirmed by FAC2 parameter; nevertheless, an overestimation of observed NO_2 concentrations is shown (negative FB values).

A.3. Yearly averaged NO_2 concentrations

To provide a realistic estimation of the area above the legal limit for this pollutant (annual average of 40 μg m^{-3}), the hourly NO_2 concentration fields, computed by the dispersion model, have been averaged over simulated period (from February 11 to March 11, 2017) and then processed as follows. First, following factors have been computed:

- α: given by the ratio of average concentrations measured at ARPA stations respectively during the year 2017 ($meas_{2017}$) and the simulation period ($meas_{period}$). This factor permits to move from period to the year averages;
- β: given by the ratio of average concentrations computed ($comp_{period}$) and measured ($meas_{period}$) at ARPA stations during the simulation period. This factor permits to correct the computed concentrations considering the modelling uncertainties (induced by the input information, emissions and meteorology, and related to the model itself).

In the following table the data used to derive α and β factors are presented.

Table 14. Measured and predicted NO_2 concentrations at the ARPA monitoring stations averaged over the simulated period and over whole 2017 (measured data only)

	Marche	Liguria	Parco Lambro	P.zza Abbiate-grasso	P.zza Zavattari	Verziere	Senato	Pascal Città Studi
$meas_{period}$	85.8	60.6	42.5	41.1	53.5	57.0	65.5	61.7
$comp_{period}$	88.5	74.4	75.9	64.0	78.9	79.1	80.5	76.6
$meas_{2017}$	64.4	55.9	35.1	35.0	50.5	48.1	54.1	44.5
$\alpha = \frac{meas_{2017}}{meas_{period}}$	0.75	0.92	0.83	0.85	0.94	0.84	0.83	0.72
$\beta = \frac{meas_{2017}}{comp_{period}}$	0.97	0.81	0.56	0.64	0.68	0.72	0.81	0.81

The α and β values averaged over the eight monitoring stations are 0.84 and 0.75 respectively. Then multiplying the averaged NO_2 concentration fields, over simulated period, computed at each point of the modelling domain by their product (e.g. $\bar{\alpha} \cdot \bar{\beta} = 0.63$) we obtain a realistic estimation of yearly averaged NO_2 levels over the modelling domain.

References

Chang, J.C., Hanna, S.R., 2004. Air quality model performance evaluation. *Meteorology and Atmospheric Physics*, **87**, 167-196.

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