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Discrepancies between EU type approval limits and real-world vehicle emissions: Impact assessment on air quality in Lombardy

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Ilaria

ABSTRACT

Air pollution negatively affects human health, natural ecosystems, and climate. Improving air quality is therefore important for the protection of our societies, especially for sensitive subjects, as well as for protecting the environment.

The recovery process undertaken in Lombardy in recent years has led to improvements in air quality, but the level of several pollutants is still not compliant with the limits. Specifically, in Lombardy we observe high levels of nitrogen oxides (NO_X), ozone (O_3), particulate matter (PM10), volatile organic compounds (VOC), and ammonia (NH_3).

Road traffic, especially linked to diesel-based vehicles, remains a main source of air pollution, particularly for PM10 emissions and nitrogen oxides, contributing to the lack of compliance with the limits. In 2015, the scandal involving Volkswagen guilty of using instruments designed to manipulate laboratory tests, brought to light the problem concerning discrepancies between EU type approval limits and real-world vehicle emissions.

The present study aims at quantifying the effect on air quality generated by the pollutant emissions exceeding EU type approval limits. It is based on data from the INEMAR emission inventory of Lombardy for the year 2017 which represents the real-world emission scenario.

In the first phase of the study we compare road transport emissions data with an alternative scenario compliant with the EU legislation, in order to quantify the excess of pollutant. In the second phase of the study, vehicle emissions are modelled using the air quality modelling system ARIA Regional to perform air quality simulations. The vehicle categories investigated are passenger cars, light duty vehicles, mopeds, and motorcycles and pollutant compared are NOx, CO, PM10, VOC, and NMVOC.

The results obtained show that full compliance with the NO_X emission limits for passenger cars and light duty vehicles, leads to the reduction of 36.6% of these emissions, which corresponds to 18.6% of the total NO_X emitted in Lombardy by all activities. Over 90% of these emissions are attributable to Diesel vehicles. These reductions lead to a non-negligible benefit on air quality.

The regional average NO_2 concentration falls by 16% and the average concentration of PM10 and PM2.5 falls by 0.8%. The compliance scenario generates on the other hand an increase in the regional average concentration of O_3 by 2.5%. These values are spatially highly variable inside the region depending on the orography and land use. Overall, the study shows that emissions from traffic exceeding the approval limits contributes to the noncompliance with the air quality limits and target values required by the European regulation. A comparison with EU limits and target values shows that under the compliant scenario, the limits on the annual average concentration of NO_2 would be satisfied in all the areas under consideration.

SINTESI

L'inquinamento atmosferico influisce negativamente sulla salute umana, sugli ecosistemi naturali e sul clima. Perseguire obiettivi di miglioramento della qualità dell'aria è importante per la protezione della salute, in particolare quella dei soggetti sensibili, oltre che per la protezione dell'ambiente.

Il processo di recupero, intrapreso negli ultimi anni in regione Lombardia, ha portato a miglioramenti della qualità dell'aria, tuttavia gli obiettivi europei non sono ancora del tutto raggiunti e inquinanti quali ossidi di azoto (NO_X), particolato (PM10), ozono (O_3), composti organici volatili (COV) e ammoniaca (NH_3) sono presenti in concentrazioni elevate.

Il traffico stradale è una delle maggiori fonti di inquinamento atmosferico, in particolare per le emissioni di PM10 e degli ossidi di azoto e fornisce un contributo importante al mancato raggiungimento dei limiti. Nel 2015 lo scandalo che ha coinvolto il gruppo Volkswagen, accusato di utilizzare strumenti atti a manomettere i test di laboratorio sulle emissioni allo scarico, ha messo in luce il problema relativo alle discrepanze tra i limiti di omologazione e le reali emissioni dei veicoli su strada.

Il presente studio ha l'obiettivo di quantificare l'effetto sulla qualità dell'aria generato dalle emissioni di inquinanti eccedenti i limiti europei di omologazione. Lo studio è basato sui dati dell'inventario INEMAR (INventario EMissioni ARia) riguardanti le emissioni in Lombardia per l'anno 2017.

La prima fase dello studio presenta un confronto tra i dati sulle emissioni reali dei trasporti su strada e uno scenario alternativo conforme a quanto previsto dalla normativa UE, al fine di quantificare l'eccesso di inquinanti prodotto dai veicoli. Segue poi seconda fase di valutazione modellistica della qualità dell'aria, svolta tramite l'utilizzo del sistema modellistico ARIA Regional, per valutare la variazione che l'eccesso di inquinanti calcolato nella prima fase apportata alla qualità dell'aria.

Tale confronto è stato effettuato per tutti gli inquinanti il cui limite è definito dalla normativa sull'omologazione, ovvero NOx, CO, PM10, VOC e NMVOC, e le categorie di veicoli prese in esame sono autovetture, veicoli commerciali leggeri, motorini e moto.

I risultati ottenuti mostrano che lo scenario conforme ai limiti di omologazione porta ad una riduzione delle emissioni di NO_X dal settore traffico del 36.6%, in gran parte associata ai veicoli Diesel. Questo si traduce nel risparmio del 18.6% delle emissioni totali di NO_X prodotte in Lombardia. Tali riduzioni portano ad un beneficio in termini di qualità dell'aria non trascurabile.

Lo scenario conforme presenta una riduzione del 16% delle concentrazioni medie regionali di NO_2 e una riduzione dello 0.8% delle concentrazioni di PM10 e PM2.5, mentre porta ad un aumento del 2.5% della concentrazione media regionale di O_3. Questi ultimi valori sono molto variabili nelle diverse zone della regione in funzione di orografia e usi del suolo. Complessivamente lo studio mostra che le emissioni da traffico eccedenti i limiti di omologazione apportano un contributo non trascurabile alle emissioni che concorrono nel mancato rispetto dei limiti per la qualità dell'aria. Un confronto con i limiti e i valori obiettivo mostra che lo scenario conforme porta al rispetto del limite sulla concentrazione media annua di NO_2 in tutte le aree in esame.

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INTRODUCTION

Air pollution is an environmental and a social problem because it negatively affects both human health and natural ecosystems and climate (EMEP/EEA, 2019). As a result, improving air quality is important for the protection of our societies, especially for sensitive subjects, as well as for protecting the natural environment.

The European Union (EU) has introduced several policies to ensure good air quality and harmonise the objectives and plans in place across the entire European Union territory. The most effective policies are structural, with a long-time horizon, and large-scale effects. However, it is also important to implement local policies that integrate into regional plans for the improvement of air quality; in order to direct and prioritise interventions, these need to be adequately supported by tools for the preventive evaluation of their effectiveness. (SNPA, 2018)

As part of its air quality control plans, the Lombardy region established in 2013 a regional plan for intervention on air quality (PRIA), updated in 2018. Wherever the level of one or more pollutants exceeds reference values, the plan aims to ensure that these are lowered below the limits in the shortest possible time. This must be achieved while also safeguarding the areas where, instead, the levels of pollutants are already below the limits. Traffic emissions play an important role in air pollution. Hence, a synergy between PRIA and the regional program on transport mobility (PRMT) is essential.

The recovery process undertaken in Lombardy in recent years has led to improvements in air quality, but the level of several pollutants is still not compliant with the limits. Specifically, in Lombardy we observe high levels of nitrogen oxides (NO_X), ozone (O_3), particulate matter (PM10), volatile organic compounds (VOC), and ammonia (NH_3).

This region's situation is particularly critical due to a geographic conformation that is predisposed to the accumulation of pollutants. Road traffic, especially linked to diesel-based vehicles, remains a main source of air pollution, particularly for PM10 emissions and nitrogen oxides, contributing to the lack of compliance with the limits.

Several studies since 2007 (Rubino et al., 2007) have shown that the laboratory cycle used until 2017 to measure emissions from light vehicles undergoing type approval (New Emission Driving Cycle - NEDC) does not accurately estimate the exhaust emissions of vehicles. As a result, emissions produced by road vehicles result up to seven times higher than those recorded in dynamometric bench tests (Weiss et al., 2011). Considering the large contribution of on-road traffic to the production of air pollutants, the noncompliance of vehicles' emissions with the type approval limits contributes in a significant way to the noncompliance with the air quality limits.

Shortcomings in the testing schemes of the NEDC together with limitations in the compliance protocols that determine how emission levels are verified and how penalties are imposed, allowed vehicle manufacturers to exploit legal loopholes observing the letter of a regulation while disregarding its spirit and intent. It was only the use of an illegal defeat device by Volkswagen that finally crossed the line and shed a light on the broader underlying problems of vehicle emissions testing and compliance systems (Mock & German, 2015).

1.1. Objective and structure of the study

In the footsteps of previous studies, which have calculated the impact of the exceedances of the EU type approval limits on air quality and then on human health at European level (Jonson et al., 2017; Chossière et al., 2018), this study is intended to quantify the effect of these exceedances on air quality in Lombardy. For this purpose, we compare road transport emissions data collected in the emission inventory of the Lombardy region (i.e. INEMAR dataset, representing the base case, referred to as *INEMAR* scenario) with those calculated under an alternative scenario (referred to as *compliant* scenario) where light vehicles are assumed to fully comply with EU type approval limits.

Vehicle emissions data under the two scenarios are fed to the air quality modelling system ARIA Regional to perform air quality simulations and quantify the impact of the non-conformity with EU type approval limits. The vehicle categories investigated are passenger cars, light duty vehicles, mopeds, and motorcycles.

First the study presents a description of the evolution of the type approval legislation together with the evolution of type approval tests and their issues. Then we describe the general framework for air quality in Lombardy in 2017, with particular focus on the main pollutants whose dynamics are influenced by the application of the alternative compliant scenario. After an explanation of the principles at the basis of the INEMAR inventory realization, which is built following the European guidelines, the compliant scenario is presented. Finally, after an explanation of the structure of the modelling system ARIA Regional and its implementation, we evaluate the results under the compliant scenario comparing them with the INEMAR scenario representative of the real situation.

2

LEGISLATION

2.1. Type approval legislation

Since the 1970, European standards were introduced for the approval of new vehicles in the automotive sector. This was a starting point for continuously evolving European-wide legislation aimed at controlling the emissions produced by road traffic.

In this section we present a summary of the evolution of European regulation related to vehicles type approval; this is to clarify the contribution to air pollution deriving from the vehicular fleet circulating in Lombardy, and the results achieved in the limitation of vehicular emissions. Emission limits are summarised in *Tables 2-1 and 2-2*.

ECE Regulation

The European Union started to regulate vehicles emissions in 1970 with the introduction of ECE Regulations, through the Council Directive 70/156/EEC, relating to the type approval of motor vehicles, and the Council Directive 70/220/EEC, relating to measures to be taken against air pollution by gases from positive-ignition engines of motor vehicles. The ECE Regulations established restrictions on pollutants mass emissions by each vehicle category and introduced coded laboratory test cycles. Tests for light vehicles (<3.5 t) including mopeds and motorcycles are carried out on a dynamometric roller bench for the entire vehicle, while the same tests for heavy vehicles are carried out only on the engine.

The ECE 15 regulation for light vehicles was implemented in Italy only in 1975. It introduced limits for atmospheric emissions of carbon monoxide (CO) and hydrocarbons (HC) from gasoline vehicles. Four subsequent amendments in the years up to 1983 increased the severity of these limits and added regulation limits on NO_X emissions too, expressed as the summation of NO_X and HC. For the introduction of limits on particulate matter and for diesel-engine vehicle emissions, we have to wait until 1988 when ECE 83 was introduced by the Directive 88/76/EEC.

Pollutant emissions are monitored performing three different kinds of tests. The type I test verifies the average emission of gaseous pollutants in a congested urban area after a cold start and it is carried out with the standard Urban Driving Cycle (UDC) representative of the urban pattern of European cities. Limits on pollutants emission are referred to the mass of pollutants collected during the test cycle. The type II test, instead, measures carbon-monoxide emissions at idling speed, after test I is terminated. Finally, the type III test verifies emissions of crankcase gases (Sanger et al., 1997).

Euro regulation

Euro 1: It was introduced by the Council Directive 91/441/EEC, implemented in Italy with the Ministerial Decree of 28/12/1991. Euro 1 standards impose more stringent emission limits for passenger cars (M1 category vehicles), that require the adoption of the catalytic converter. The new UDC+EUDC test cycle performed on a chassis dynamometer, is composed of four repetitions of the UDC cycle and an Extra Urban Driving Cycle EUDC. No distinction is made between diesel and gasoline vehicles and emission limits are expressed in mass of emitted pollutant per travelled kilometre (g/km). Two more test type were also introduced: the type IV test on evaporative emissions and the type V test on the durability of anti-pollution devices, measured after 80,000 km travelled or applying deterioration factors to emissions of the type I test.

The Directive 93/59/EEC, implemented in Italy with Transport Ministerial Decree of 4/09/1995, is an update of the Directive 91/441/EEC and it is the first directive related directly to light duty vehicles (N1 category). It introduced emission limits distinguished by vehicle mass and the reduction of the maximum speed in the Extra Urban Driving Cycle EUDC for lower powered vehicles (Sanger et al., 1997).

Euro 2: It was introduced by the Directive 94/12/EEC. Euro 2 standards introduced more restricted limits, with distinctions between diesel and gasoline vehicles.

Euro 3: It was introduced by the Directive 98/69/EEC and first applied in 2000. Euro 3 standards define emission limits for both diesel and gasoline passenger cars and light duty vehicles. Separate limits for NO_X and HC are also defined. The Directive also included a revised light duty cycle (eliminating the initial 40 second idle period with no emissions measurements) and a cold start (-7°C) emissions test (Dartoy et al., 2006). The important novelty introduced is the On-Board Diagnostic (OBD) system. An OBD system consists of a computer incorporated in a vehicle's electronics for detecting operational malfunctions within the engine control system. This monitoring system indicates when emission thresholds are exceeded by the Malfunction Indicator Light (MIL) located on the instrument panel, and a "fault code" is registered to indicate the damaged system that might also generate higher emissions. Since 2006 the OBD system equipment is mandatory in all light vehicles (DieselNet, 2019).

Euro 4: It was introduced by the Directive 98/69/EC B and was applied since January 2006. Euro 4 standards introduced more stringent emission limits that require the adoption of Diesel Particulate Filter (DPF) for most diesel vehicles (Sanger et al., 1997).

Euro 5: It was introduced by the Regulation EC 715/2007 and started being applied for type approval in September 2009. Euro 5a standard introduces more stringent emission limits on particulate emissions. While the lower emission limit did not prescribe a particular technology, they required the introduction of diesel particulate filters (DPFs). (Dartoy et al., 2006). NO_X limits were lowered and the limit on particulates mass is extended to petrol engines, applicable to direct injection engines only. Euro 5b was introduced by the Regulation 692/2008 and was applied since September 2011 for new vehicles. It established for the first time an emission limit on particle numbers (PN) for diesel engines in addition to the particle mass limit.

Euro 6: It was introduced by the Regulation EC 715/2007 and started being applied in 2015. The Euro 6a standard imposed a further, significant reduction of NO_X emissions from diesel engines (68% compared to the previous Euro 5) and established similar standards for gasoline and diesel-powered vehicles. Indeed, a number-based approach to emissions of PM in addition to the mass-based approach was adopted for both. Further regulations succeed generating variations in Euro 6 standards. In particular, the Euro 6b required lower limit on PM mass emissions for diesel and gasoline vehicles and Euro 6c from September 2018 reduced again PM limit for gasoline vehicles. Euro 6c legislation also introduced an innovation in the laboratory procedure to perform the type I test. The Worldwide Harmonized Light-Duty Vehicles Test Cycle (WLTC) was the new chassis dynamometer tests for the determination of emissions and fuel consumption for light-duty vehicles, replacing the European NEDC. The tests have been developed by the UN ECE GRPE (Working Party on Pollution and Energy) group. The WLTC cycles are part of the Worldwide harmonized Light vehicles Test Procedures (WLTP), published as UNECE Global technical regulation 15 (GTR 15). With the Euro 6d-TEMP in January 2019 it was introduced a cycle for the evaluation of the on-road Real Driving Emission (RDE) thanks to the use of Portable Emissions Measurement Systems (PEM). Performing both the laboratory and the on-road test was required. Emissions calculated performing the RDE on-road cycle are compared with not-to-exceed (NTE) limits for NO_X and PN. NTE limits are expressed as the adopted emission limits established for the WLTC multiplied by a conformity factor (CF) representing the margin of uncertainty of the PEMS measurement. Conformity factors are provided for NO_X in two phases: the first values, more permissive introduced with the temporary phase of Euro 6d-TEMP, while more restrictive value will be introduced with the Euro 6d type approval since January 2020 for newly developed models and from January 2021 for all new vehicles. Conformity factors for PN emissions is fixed at the value of 1.5 (Giechaskiel et al., 2018).

A list of all emission limits for passenger cars and light duty vehicles is presented in *Table 2-1* (Otto cycle, that is positive ignition, fuelled with gasoline) and *Table 2-2* (Diesel cycle, that is compression ignition, fuelled with gasoil).

Positive ignition								
		Mass	**CO**	**THC**	**NVHC**	**NOx**	**HC + NOx**	**PM**
		kg	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km
PASSENGER CARS	EURO 0	1251-1470	18756	1876		2937	5429	
	EURO 1		2720				970	
	EURO 2		2200				500	
	EURO 3		2300	200		150		
	EURO 4		1000	100		80		
	EURO 5		1000	100	68	60		5
	EURO 6		1000	100	68	60		5
LDV	EURO 1	M ≤ 1250	2720				970	
	EURO 2	M ≤ 1250	2200				500	
	EURO 3	M ≤ 1305	2300	200		150		
	EURO 4	M ≤ 1305	1000	100		80		
	EURO 5	M ≤ 1305	1000	100	68	60		5
	EURO 6	M ≤ 1305	1000	100	68	60		4.5
	EURO 1	1250 < M ≤ 1700	5170				1400	
	EURO 2	1250 < M ≤ 1700	4000				600	
	EURO 3	1305 < M ≤ 1760	4170	250		180		
	EURO 4	1305 < M ≤ 1760	1810	130		100		
	EURO 5	1305 < M ≤ 1760	1810	130	90	75		5
	EURO 6	1305 < M ≤ 1760	1810	130	90	75		4.5
	EURO 1	1700 < M	6900				1700	
	EURO 2	1700 < M	5000				700	
	EURO 3	1760 < M	5220	290		210		
	EURO 4	1760 < M	2270	160		110		
	EURO 5	1760 < M	2270	160	108	82		5
	EURO 6	1760 < M	2270	160	108	82		4.5
MOPEDS	EURO 0 4T	250	30625	5550				
	EURO 0 2T	250	27200	11000				
	EURO 1 4T		13000	3000		300		
	EURO 1 2T		8000	4000		100		
	EURO 2		5500	1000		300		
	EURO 3		2000	300		150		
MOTORCYCLES	EURO 0		8000	5000				
	EURO 1		6000				3000	
	EURO 2		1000				1200	

Table 2-1: EU emission standards for gasoline vehicles.

Compression ignition								
		Mass	**CO**	**THC**	**NVHC**	**NOx**	**HC + NOx**	**PM**
		kg	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km
PASSENGER CARS	EURO 0	1251-1470	18756	1876		2937	5429	
	EURO 1		2720				970	140
	EURO 2		1000				700	80
	EURO 3		640			500	560	50
	EURO 4		500			250	300	25
	EURO 5		500			180	230	5
	EURO 6		500			80	170	5
LDV	EURO 1	M ≤ 1250	2720				970	140
	EURO 2	M ≤ 1250	1000				900	100
	EURO 3	M ≤ 1305	640			500	560	50
	EURO 4	M ≤ 1305	500			250	300	25
	EURO 5	M ≤ 1305	500			180	230	5
	EURO 6	M ≤ 1305	500			80	170	4.5
	EURO 1	1250 < M ≤ 1700	5170				1400	190
	EURO 2	1250 < M ≤ 1700	4000				1000	140
	EURO 3	1305 < M ≤ 1760	800			650	720	70
	EURO 4	1305 < M ≤ 1760	630			330	390	40
	EURO 5	1305 < M ≤ 1760	630			235	295	5
	EURO 6	1305 < M ≤ 1760	630			105	195	4.5
	EURO 1	1700 < M	6900				1700	250
	EURO 2	1700 < M	5000				1600	200
	EURO 3	1760 < M	950			780	860	100
	EURO 4	1760 < M	740			390	460	60
	EURO 5	1760 < M	740			280	350	5
	EURO 6	1760 < M	740			125	215	4.5
MOPEDS	EURO 0 4T	250						
	EURO 0 2T	250						
	EURO 1 4T							
	EURO 1 2T							
	EURO 2							
	EURO 3							
MOTORCYCLES	EURO 0							
	EURO 1							
	EURO 2							

Table 2-2: EU emission standards for Diesel vehicles

2.2. Evolution of vehicles emissions test

New European Driving Cycle (NEDC)

The New European Driving Cycle (NEDC) is a standard test to measure exhaust emissions on a chassis dynamometer and was used until 31 August 2017 for new vehicle types and until 31 August 2018 for older vehicles. The NEDC procedure is composed of four repetitions of the UDC cycles representative of the urban pattern of European cities and an Extra Urban Driving Cycle (EUDC). The UDC cycle (*Figure 2-1*) is characterised by an average speed of 18.7 km/h, with a maximum of 50 km/h and it has to be carried out with a cold start, at a temperature in the 20-30 °C range. The EUDC is characterised by an average speed of 62.6 km/h and a maximum of 120 km/h. The underlying principle of this approach is to ensure that manufacturers certify their vehicles in a replicable manner and that all vehicles are held to the same standard.

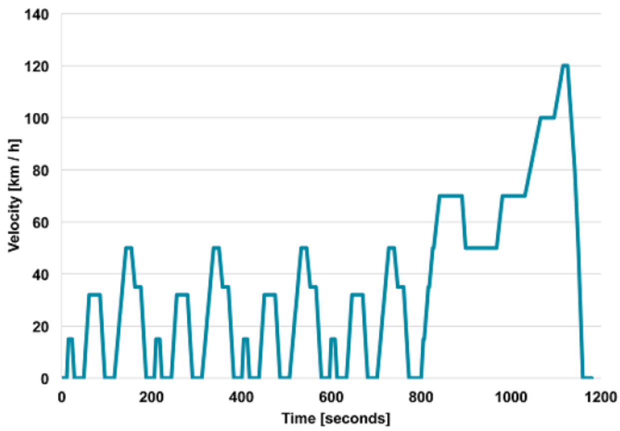

Figure 2-1: The NEDC Driving Cycle

Worldwide harmonized Light vehicle Test Procedure (WLTP)

Several studies claim that NEDC is unrepresentative of real-world cars and driving for multiple reasons. Much of the technology introduced to improve efficiency of cars is far more effective in the test than on the road; additionally, accessories like vehicle lights, air conditioning, or other auxiliary power requirements are not considered during the test. Moreover, test procedures get outdated and can be easily manipulated by carmakers (Mock et al., 2013; Dings, 2013).

For these reasons, in 2017 the EU Regulation 1151/2017 introduced the WLTP test procedure as the new procedure for exhaust emission laboratory tests on a dynamometer. Starting from 1 September 2017 for the new models and from 1 September 2018 for all new vehicles, the WLTP is the test procedure in force for the homologation of vehicles.

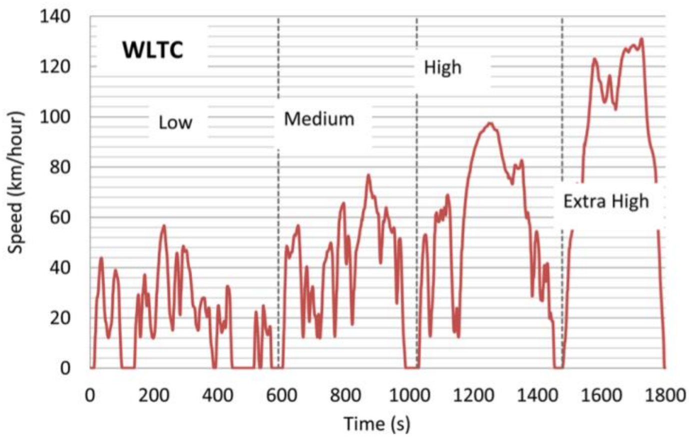

Figure 2-2: The WLTC Driving Cycle

While the old NEDC test determined test values based on a theoretical driving profile, the WLTP cycle was developed using real-driving data, gathered from around the world. The WLTP procedure covers driving conditions that span from urban traffic to highways.

The WLTP driving cycle is divided into four parts with different average speeds: low, medium, high, and extra high (*Figure 2-2*). Each part contains a variety of driving phases, stops, acceleration and braking phases. Therefore, the WLTP test procedure is much more dynamic than the previous NEDC. For a certain car type, each powertrain configuration is tested with WLTP for the car's lightest (most economical) and heaviest (least economical) version. WLTP was developed with the aim of being used as a global test cycle across different world regions, so that pollutant and CO_2 emissions as well as fuel consumption values would be comparable. However, while the WLTP has a common global 'core', the European Union and other regions will apply the test in different ways depending on their road traffic laws and needs. (ACEA, 2020)

	NEDC	WLTP
Test cycle	Single test cycle	Dynamic cycle more representative of real driving
Cycle time	20 minutes	30 minutes
Cycle distance	11 kilometres	23.25 kilometres
Driving phases	2 phases, 66% urban and 34% non-urban driving	4 more dynamic phases, 52% urban and 48% non-urban
Average speed	34 kilometre per hour	46.5 kilometre per hour
Maximum speed	120 kilometre per hour	131 kilometre per hour
Influence of optional equipment	Impact on CO_2 and fuel performance not considered under NEDC	Additional features (which can differ per car) are taken into account
Gear shifts	Vehicles have fixed gear shift points	Different gear shift points for each vehicle
Test temperatures	Measurements at 20-30°C	Measurements at 23°C, CO_2 values corrected to 14°C

Table2-3: Main differences between NEDC and WLTP test procedures. (Source: https://www.wltpfacts.eu/)

Real Driving Emissions (RDE)

A new Real Driving Emissions (RDE) test procedure has been introduced to complement the laboratory tests, in addition to the WLTP test, with the goal of establishing an even more representative pollution test for cars and light commercial vehicles.

The on-road RDE test is aimed at reducing the differences between tests results and real-world driving conditions. In particular, with the introduction of on-road tests, it will no longer be possible to manipulate the results, especially by using software to detect test bench conditions. For the RDE test, vehicles will be equipped with so-called PEMS technology (Portable Emissions Measurement System) for mobile emissions measurement.

The RDE procedure was developed between 2015 and 2018 in four packages. The Regulation 2016/427/EU, first RDE package (RDE1), introduces on-road testing with PEMS, defining the basic features of the RDE measurement. The Regulation

2016/646/EU (RDE2) added dynamic boundary conditions as well as a limit for altitude gain and introduced RDE conformity factors for nitrogen oxides (NO_X) emissions in two phases. Both regulations were further developed by Regulation 2017/1154/EU (RDE3). The third RDE package also introduces a not-to-exceed (NTE) limit for emissions of particulate number (PN), the addition of a cold start element to the test procedure, specific provisions for testing hybrid-electric vehicles, as well as a calculation procedure for taking into account regeneration events, such as for diesel particulate filters. These three packages are applied for the certification of new-types of vehicles since September 2017 and for all vehicles since September 2018.

The fourth RDE package, after the results of revisions of the PEMS measurement uncertainty (Giechaskiel et al., 2018), introduced variations to the conformity factor for nitrogen oxide (NO_X) amending Regulation 2017/1151/EU. As a result, an RDE test will only be passed successfully if the NO_X emissions from light vehicles are below a threshold of 114 mg/km for diesel cars and 86 mg/km for gasoline cars, corresponding to a conformity factor value of 1.43 (lower than the older 1.5 value of the RDE3). This will be required from January 2020 onwards for newly developed Euro 6d models. The emissions of a valid RDE test are compliant with the regulation if the reported distance-specific mass of emissions (i.e.: the emission factor as mass/km) is below the corresponding NTE limit.

The temporary Euro 6d-TEMP conformity factor for NO_X remains unchanged at the value of 2.1 until the end of 2019 for new types of vehicles and until the end of 2020 for all new vehicles. The conformity factor for particulate number emissions also remains at 1.50, as defined in the third package of the RDE regulation. Carbon monoxide (CO) is included in the RDE measurements but remains excluded from any NTE limit (ICCT, 2018)

The RDE4 act ensures transparent and independent control of emissions of vehicles during their lifetime. Type approval authorities will have to check each year the emissions of vehicles already in circulation with "in-service conformity" testing (ISC). Type approval authorities, independent parties, and the Commission will be able to perform officially recognised tests through accredited laboratories and technical services (EC, 2018).

The RDE test does not require compliance with any fixed driving cycle and can be conducted under any environmental condition. Boundaries have been set to define what constitutes a valid RDE trip. A broader range of parameters, each with ample margins of tolerance, allows the test to cover a broad spectrum of driving possibilities.

RDE trips cover three types of operation classified on speed: urban, rural, and motorway. A car traveling up to 60 km/h will be operating in urban conditions; at 60 to 90 km/h, in rural conditions; and above 90 km/h, in motorway conditions. The mix should be evenly distributed for each category as shown in *Table 2-4*, within a 10% tolerance (ICCT, 2017).

Trip specifics		**Provision set in the legal text**
Total trip duration		Between 90 and 120 min
Distance	Urban	>16 km
	Rural	>16 km
	Motorway	>16 km
Trip composition	Urban	29% to 44% of distance
	Rural	23% to 43% of distance
	Motorway	23% to 43% of distance
Average speeds	Urban	15 to 40 km/h
	Rural	Between 60 km/h and 90 km/h
	Motorway	>90 km/h (>100 km/h for at least 5min)

Table 2-4: Distance and speed specifications for each urban, rural, and motorway part of the RDE test (ICCT, 2017)

3

AIR QUALITY IN LOMBARDY

The EU Directive 2008/50/EC on ambient air quality and cleaner air for Europe is implemented in Italy via the Legislative Decree 155/2010, which defines the standards for air quality assessment. Namely, the Legislative Decree 155/2010 defines limit and target values for specific pollutants in ambient air, regulates air quality assessment criteria, and requires the implementation of air quality plans where limits are exceeded.

Air quality monitoring in Lombardy is based on a combination of fixed measurements and modelling techniques. Therefore, the regional monitoring network that measures data with hourly or daily time resolution is supported by air quality modelling through the chemical transport model system ARIA Regional. The information that is obtained is compared with limits and targets set by the Legislative Decree 155/2010.

3.1. Territorial subdivision

In order to carry out the air quality assessment, regional authorities must provide for the classification of areas and agglomerations. In Lombardy this measure has been implemented with the Regional Decree 2605 of 30 November 2011 by dividing its territory as follows (*Figures 3-1 and 3-2*):

- Urban agglomerations of Milan, Bergamo, and Brescia

  Characterized by:

  - Population greater than 250,000 inhabitants or less than 250,000 inhabitants but with population density greater than 3,000 inhabitants per km^2.
  - Higher PM_{10}, NO_X and VOC primary emissions.
  - Meteorological conditions generally unfavourable for pollutants dispersion.

- High density of population, industrial activities, and traffic.

- Zone A: highly urbanized plain

  Characterized by:

  - High density of population, industrial activities, and road traffic.
  - Higher primary PM10, NOX and VOC emissions.
  - Meteorological conditions generally unfavourable for pollutants dispersion.

- Zone B: plain area

  Characterized by:

  - Average population density, with important presence of agricultural and livestock breeding activities.
  - High primary PM_{10} and NO_X emissions, although lower than Zone A.
  - High NH_3 emissions density.
  - Meteorological conditions generally unfavourable for pollutants dispersion.

- Zone C: mountains

  Characterized by:

  - Low population density.
  - Lower primary PM_{10}, NO_X, anthropogenic VOC, and NH_3 emissions.
  - Important biogenic VOC emissions.
  - Mountainous terrain.
  - Meteorological conditions more favourable for pollutants dispersion.

  Zone C is further divided in C1 (pre-alps and Apennine), which is more influenced by pollutant transport from the plain, and C2 (Alps), which is only for ozone characterization.

- Zone D: valley floor

  - Portions of the territory of the Municipalities included in zones C and A main valleys, at altitude less than 500 m.a.m.s.l. (Valtellina, Val Chiavenna, Val Camonica, Val Seriana and Val Brembana).
  - Meteorological conditions frequently unfavourable for pollutants dispersion due to lapse rate inversion

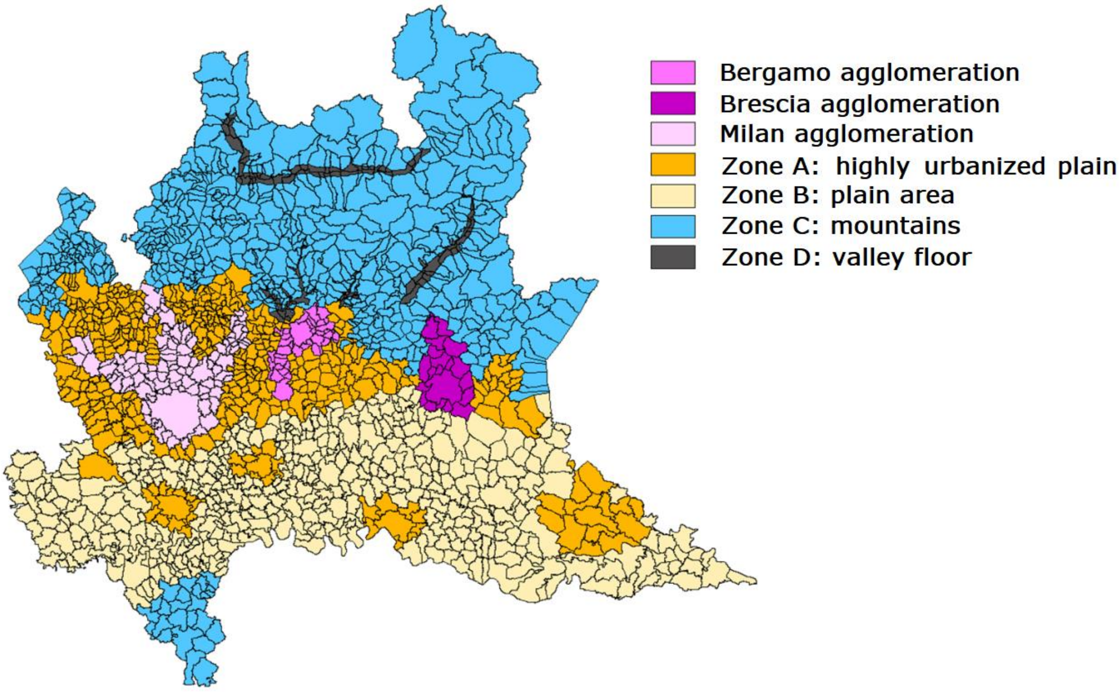

Figure 3-1: Lombardy zoning map (Source: D.G.R. 2605 of 30 November 2011, all. 1)

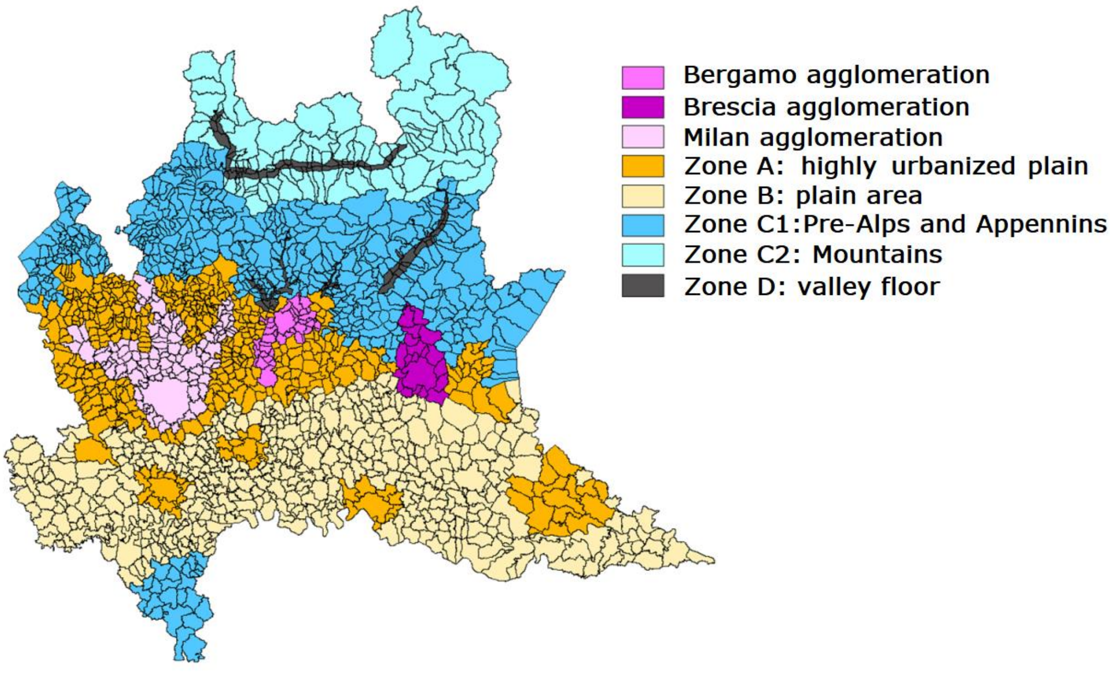

Figure 3-2: Lombardy zoning map for ozone assessment (Source: D.G.R. 2605 of 30 November 2011, all. 1)

3.2. Monitoring network

As of 2020 the air quality monitoring network of Lombardy counts 98 monitoring stations; out of these, 84 are included in the air quality assessment program and provide data with hourly or daily resolution. The stations are distributed throughout the region according to the population density and the type of territory as defined by the Legislative Decree 155/2010. Monitoring stations are installed both in background areas far from localized sources thus providing information about diffuse pollution, and in areas where pollutant concentrations reach higher values, thus aiming to monitor critical situations.

For this reason, depending on the type of station and on the characteristics of the area where which they are located, monitoring stations are classified as:

- Traffic (T): located next to roads with medium-high traffic intensity and, therefore, mainly influenced by local traffic emissions.
- Background (B): influenced by the integrated contribution of all the sources placed upwind of the station with respect to the predominant wind directions at the site.
- Industrial (I): mainly influenced by single industrial sources or by neighbouring industrial areas.
- Urban (U): located in urban area and mainly affected by urban sources (i.e.: domestic heating and urban traffic).
- Sub-urban (S): located in a suburban environment, where both built-up and non-urbanized areas are present.
- Rural (R): located in non-urban and non-suburban area.

Monitoring stations continuously measure NO_X, SO_2, CO, O_3, PM_{10}, $PM_{2.5}$, benzene (all with hourly average resolution), PM10 PM2.5, (both with hourly or daily average resolution) concentrations providing punctual data. Additionally, PM10 samples are collected and further analysed for their elemental composition (As, Cd, Ni, Pb) and toxic organic compounds (Benzo(a)pyrene), as requested by the Legislative Decree 155/2010.

A list of the monitoring stations whose data are used in this study with the relative pollutants monitored is presented in the Annex I.

3.3. Monitored pollutants

The pollutants considered in this study do not include the whole series of air pollutants measured from the air monitoring system mentioned above but only those affected by the variation in the emission scenario. These pollutants are nitrogen dioxide, fine particulate matter. Additionally, ozone is also considered because the emission scenario considered differs for the emission rates of ozone precursors. For these pollutants, we present here a description of the generating processes, of their effect on the environment and on human health, and a framework of their spatial distribution in Lombardy.

3.3.1. Nitrogen dioxide

Nitrogen oxides (NO_X) are composed by nitrogen dioxide (NO_2) and nitrogen monoxide (NO). They originate from high temperature combustion processes in both stationary (e.g. power plants, heating systems) and mobile sources (e.g. road traffic). Nitrogen oxides are mainly produced by the direct oxidation of atmospheric nitrogen (N_2) as thermal NO_X. They are produced in lower amounts from the oxidation of nitrogen present in fuels, but also from the oxidation of atmospheric N_2 by hydrocarbon radicals generated during the process (prompt NO_X).

$$N_2 + O_2 \rightarrow 2NO \quad (3.1)$$

$$2NO + O_2 \rightarrow 2NO_2 \quad (3.2)$$

About 5-10% of total NO_X is composed by NO_2 while the remaining part is composed by NO. In the ambient air the ratio between NO and NO_2 concentrations does not remain the same: NO_2 share increases because it is generated as a secondary pollutant by NO oxidation. For this reason, NO_2 is mostly a secondary pollutant generated in the air (3.2), while NO is a primary pollutant directly generated during the combustion process (3.1).

Exposure to elevated concentrations of NO_2 may contribute to the development of asthma and potentially increases susceptibility to respiratory infections. People suffering from asthma, both children and the elderly, are generally at greater risk for the health effects of NO_2.

Nitrogen dioxide is a highly toxic compound generating acute and chronic effects on human health. Epidemiological studies confirm that exposure to elevated concentrations of NO_2 may contribute to a reduction in lung functions and increase bronchitis in asthmatic children. Nitrogen oxides also generate an environmental impact due to its wet/dry deposition on plants that reduces the photosynthesis activity (WHO, 2006).

Nitrogen dioxides have a short atmospheric lifetime (just a few hours). Being generated from urban sources, they tend to be present at high concentrations throughout the city, with lower concentration in the surrounding rural areas.

The air quality limit for atmospheric concentration of NO_2 is set at 40 µg/m^3 as annual average value, whereas NO, despite being monitored, is not limited by any regulation.

In the data recorded for the year 2017, the NO_2 regional annual average is 32 µg/m^3, therefore below the limits. Yet, levels exceeding the limits are registered in the urban agglomerations and in a few stations located in Zone B. In the urban agglomeration of Milan most of the stations (15 out of 18) exceed the annual limit, especially at urban traffic stations, where annual values in the 55-65 µg/m^3 have been observed *(Figure 3-3)*. The high values at traffic stations confirm that traffic emissions are among the main sources for NO_2 pollution is.

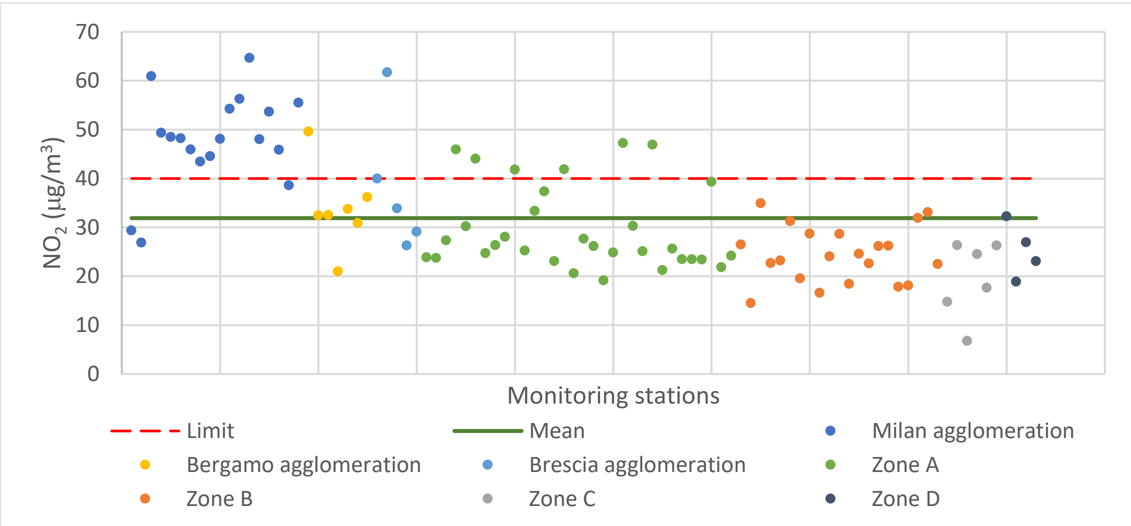

Figure 3-3: NO_2 annual average concentration measured in each monitoring station.

Figure 3-4 represents the average annual concentration of NO_2 in the whole region. It shows maximum values in correspondence of areas with high traffic density, which are the agglomerations of Milan, Bergamo and Brescia and the main arterial roads.

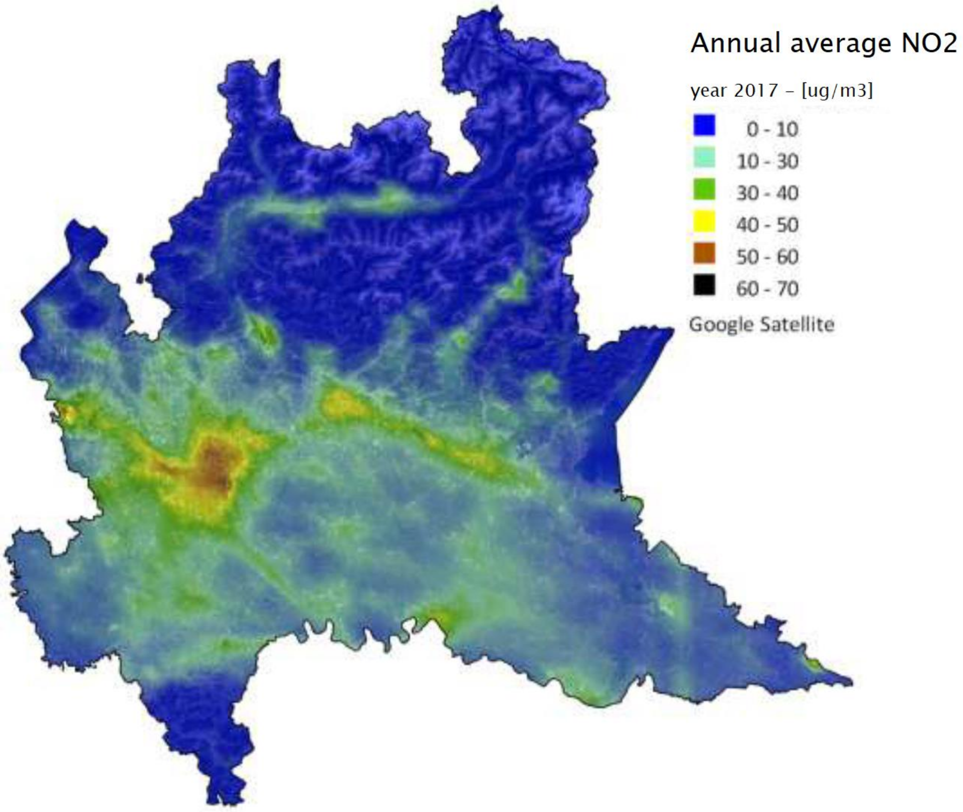

Figure 3-4: Map of annual average NO_2 concentration. (Source: Rapporto annuale sulla qualità dell'aria 2017)

For the protection of human health, the Legislative Decree 155/2010 also requires for NO_2 also a limit on hourly basis set on 200 µg/m^3, which cannot be exceeded more than 18 times per year. This threshold is defined as the level beyond which there is a risk to human health for the whole population even from short-period exposure. As such, upon violation of the limit immediate measures have to be implemented. In Lombardy, this limit was generally respected in 2017, although a few hours of excess were registered, especially in the agglomeration of Milan.

As reported in details in section 4.3, in 2017 road transport was responsible in Lombardy for about half of the total amount of NO_X emissions, which resulted to be higher in urban centres than in rural and mountainous areas.

3.3.2. Ozone

Ozone (O_3) in nature is mainly present in the stratosphere where it absorbs most of the sun's ultraviolet radiation. In the troposphere, ozone is a strong oxidant; it is highly unstable and toxic for human health, dangerous for the respiratory system even at low concentrations, and also causing irritation of eyes and throat, coughing, and reduced lung function. Tropospheric ozone at high concentration damages also the vegetation by reducing photosynthesis and generating chlorosis or necrosis of the leaves (WHO, 2006).

Tropospheric ozone is a secondary pollutant that is generated from the reaction of nitrogen dioxide and high solar radiation intensity. The production of tropospheric ozone peaks during the summer due to the abundance of highly intensive solar radiations.

$$NO_2 + h\nu(\lambda < 420nm) \rightarrow NO + O^* \quad (3.3)$$

$$O^* + O_2 \rightarrow O_3 \quad (3.4)$$

$$NO + O_3 \rightarrow NO_2 + O_2 \quad (3.5)$$

This cycle of reactions occurs relatively fast and an equilibrium in O_3 production is rapidly reached, which is an approximate photostationary state (3.6). As long as NO is present in sufficient concentration, ozone and NO react back to generate NO_2.

$$NO_2 \leftrightarrow NO + O_3 \quad (3.6)$$

However, in the polluted atmosphere, the oxidation of chemical reactive hydrocarbons by OH^* radical, can lead to the formation of peroxy radicals RO_2^* like hydroperoxyl HO_2, which react with nitrogen monoxide generating nitrogen dioxide.

$$RH + {}^*OH \rightarrow R + H_2O \quad (3.7)$$

$$R + O_2 \rightarrow RO_2^* \quad (3.8)$$

$$RO_2^* + NO \rightarrow NO_2 + RO^* \quad (3.9)$$

$$HO_2^* + NO \rightarrow NO_2 + {}^*OH \quad (3.10)$$

Reactions (3.9) and (3.10) of NO-to-NO_2 conversion operated by free radicals, also generate an increase of the level of nitrogen dioxide. NO_2 production without O_3 destruction, results in O_3 accumulation in the troposphere. The presence of high concentrations of nitrogen dioxide and bright sunshine result in high ozone concentration. The highest ozone concentration is reached in the afternoon of sunny summer days.

Ozone concentration is an indicator for photochemical smog, which in Lombardy reaches its highest level in suburban and rural areas. Due to NO_X titration, that is the ozone abatement process carried out by nitrogen monoxide (3.5), and due to the competitive reaction of nitric acid ($HONO_2$) formation operated by $^*OH$ radicals, in the highly urbanized areas where NO_X emission is the highest, tropospheric ozone concentration is not the highest. As a result, areas affected by higher amounts of road traffic emissions are not significant for photochemical smog monitoring.

Considering the large scale that characterises the formation and transport of tropospheric ozone, a reduction of O_3 concentration is not linear with the related reduction of precursors concentration. In urban areas, moreover, decreasing NO emissions can even lead to a localized increase in O_3 concentrations. This increase, on the contrary, is not detectable in rural stations, where concentration levels of O_3 tend to be more stable, as it is not directly influenced by sources' activity.

The amount of ozone produced is strongly dependent on the VOC/NO_X ratio present in air. On this assumption are based the photochemical air quality models. Isopleths depicting peak ozone concentrations are developed through computer simulations on the basis of VOC and NO_X emissions and concentrations, on the reactivity of the organic compounds, and on the meteorological conditions. Knowledge of the atmospheric chemistry leading to ozone formation, together with the use of ozone isopleth diagrams, provides a qualitative understanding of the relationship between O_3 concentrations and VOC and NOx emissions, to estimate the fractional change in precursor emissions consistent with producing the desired peak ozone concentrations (Seinfeld, 2012; Committee on Tropospheric Ozone Formation and Measurement et al., 1991).

The isopleths' graph shows how depending on the VOC/NO_X ratio the reduction of one or the other precursor can lead to a different effect in O_3 peak concentration. For VOC/NOx ratios to the right of the diagonal ridge line (typical of rural areas and of suburbs downwind of centre cities), lowering NOx concentrations results in lower peak concentrations of ozone. At VOC/NOx ratios to the left of the ridge line (characteristic of some highly polluted urban areas) lowering NOx at constant VOC will result in increased peak ozone concentrations until the ridge line is reached. In this region of the graph the NO_2 effectively competes with the VOCs for the $^*OH$ radical. Therefore, as NOx is decreased, more of the *OH radical pool is available to react with the VOCs, resulting in greater formation of ozone (Seinfeld, 2012; Committee on Tropospheric Ozone Formation and Measurement et al., 1991).

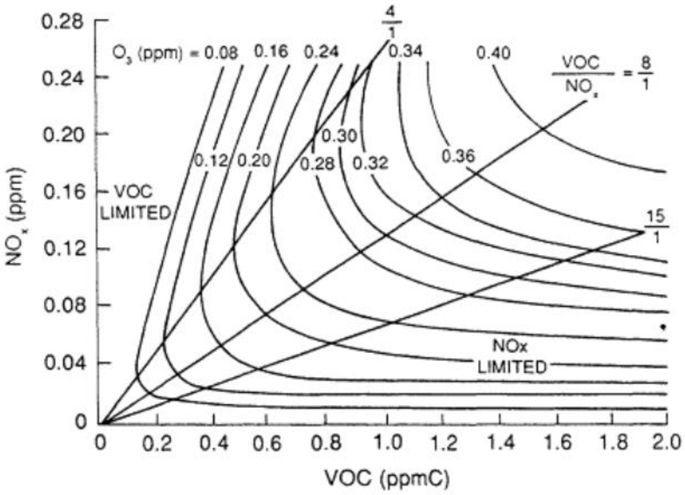

Figure 3-5: Typical ozone isopleths used in EPA's EKMA model. (Seinfeld, 2012).

The main sources of ozone precursors in Lombardy are road transport as regard NO_X and CO emissions, solvents evaporation as regard VOC, agriculture as regard CH_4 and VOC, and biomass combustion in heating systems as regard CO.

Ozone concentration varies with seasons but also within night and day due to different conditions of solar radiation, temperature, wind velocity and atmospheric stability.

The map in *Figure 3-6* shows the spatial distribution of the emissions of ozone precursors in 2017 in form of an aggregated indicator. NO_X, NMVOCs and to a lesser extent CH_4 and CO contribute to the formation of ozone. In order to express their potential contribution in form of an aggregated indicator, it is applied an appropriate weight factor called Tropospheric Ozone-Forming Potentials (TOFP) to the emissions of each of them (1.22 for NO_X, 0.11 for CO, 0.014 for CH_4 and 1 for non-methane VOCs).

Ozone precursors are emitted in higher quantities in the agglomeration of Milan and the highly urbanized plane, but their emission is also significant in the rural area.

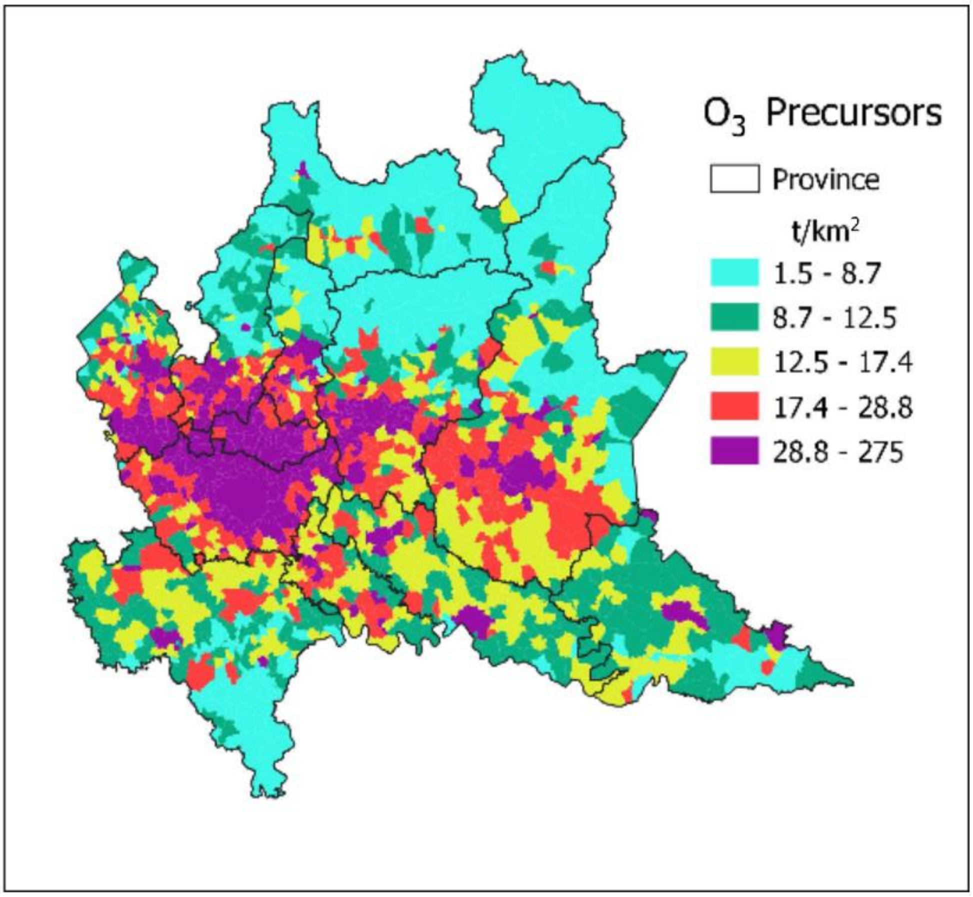

Figure 3-6: Map of spatial distribution of ozone precursors emissions in Lombardy (NO_X, NMVOCs, CH_4 and CO) (INEMAR - ARPA Lombardia, 2020)

The legislative decree 155/2010 requires for ozone concentration the compliance with different target and limit values for the protection of human health and the environment.

The ozone target limit for human health protection is set at 120 µg/m^3 calculated as the maximum eight-hour average cannot be exceeded on more than 25 days in a year.

In 2017 the number of exceedances of the 120 µg/m^3 threshold for O_3 is always higher than 25, as shown in *Figure 3-7*.

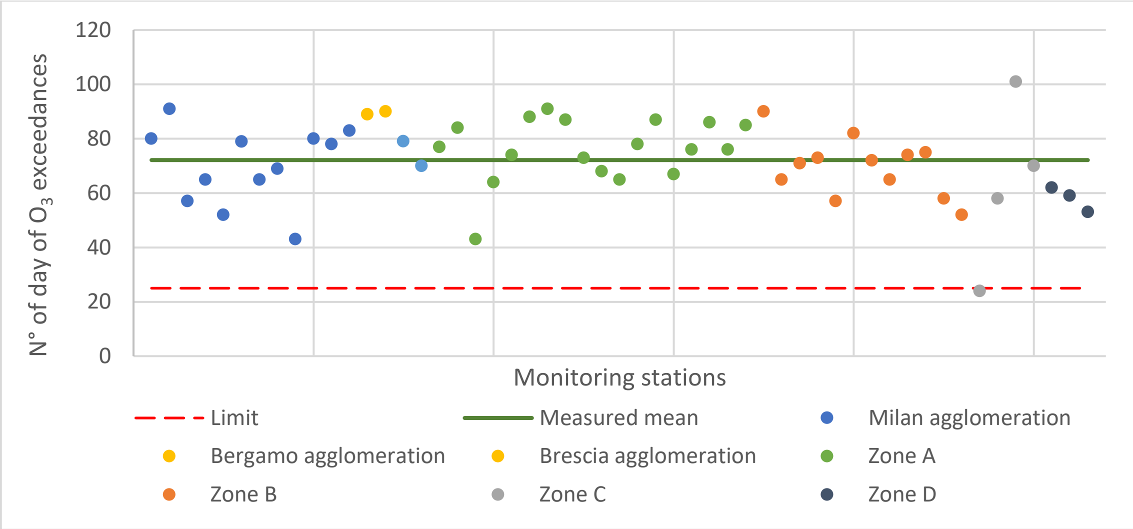

Figure 3-7: Number of annual O_3 target limit exceedances measured in each monitoring station.

In order to protect human health from brief exposure to high concentrations, ozone has to comply with an information threshold of 180 µg/m^3 and with an alarm threshold of 240 µg/m^3, calculated on hourly mean. The information threshold is the ozone level above which even short-term exposure increases risk for human health for particularly sensitive groups of the population, therefore requiring immediate and appropriate communication. Monitoring stations register an annual average of 56 exceedances, with a higher number of exceedances of the information threshold in background suburban stations, especially in the agglomeration of Bergamo. The alarm threshold, on the other hand, represents the level above which short-term exposure represents a risk for the entire population; exceeding the alarm threshold therefore requires taking immediate action. This threshold is rarely exceeded.

The Legislative Decree 155/2010 also provides a target value for the protection of the vegetation, based on the AOT40 parameter (Accumulated Ozone exposure over a Threshold of 40 ppb). This target limit is set at 18,000 µg/m^3·h and is calculated as the sum of the differences between hourly ozone concentration and 40 ppb (80 µg/m^3), for each hour (between 8.00AM and 8.00PM) when the concentration exceeds 40 ppb during the period of highest vegetation activity, which is between May 1st and July 31st. The spatial distribution of AOT40 values computed for 2017 are reported in *Figure 3-8*. Higher values of ozone are registered in the pre-Alpine zone due to the local specific ratio between emissions of VOCs and NO_X, but also due to the contribution of precursor transport from nearby urban areas.

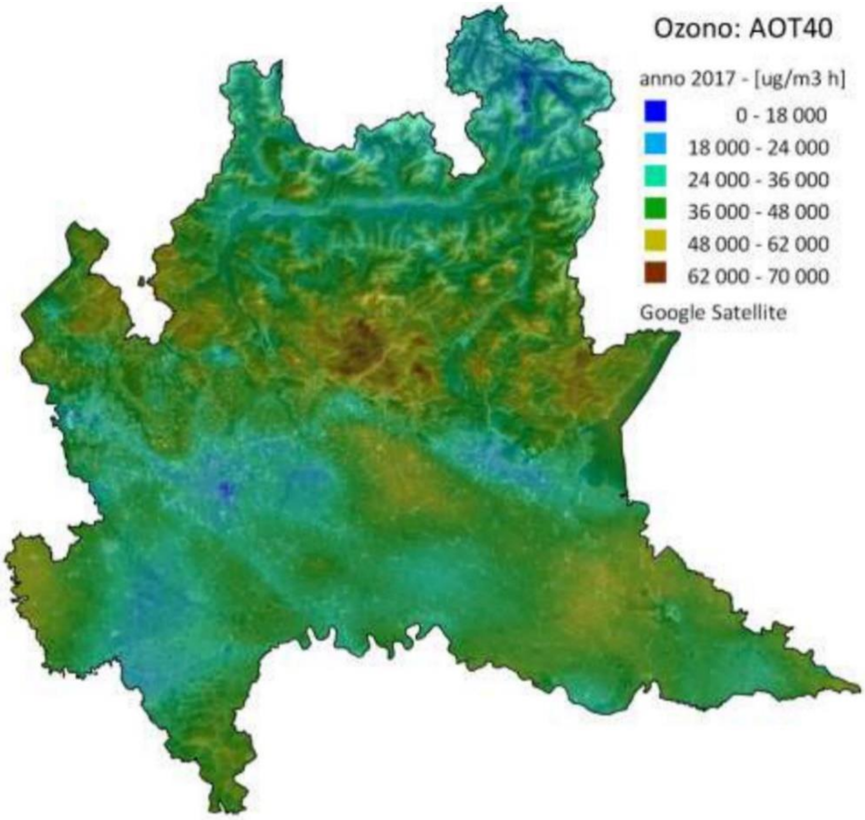

Figure 3-8: Map of accumulated Ozone exposure over a Threshold of 40ppb. (Source: Rapporto annuale sulla qualità dell'aria 2017)

The highest contribution to the emission of ozone precursors derives of road traffic and solvents evaporation, followed by agriculture.

3.3.3. Particulate matter

The relevant part of particulate matter for air quality is composed by solid and liquid particles suspended in the atmosphere for a time that is sufficient for being subjected to diffusion and transport phenomena. Such particles can be either primary or secondary and cover a wide range of sizes, between 0.1 and 100 microns.

Particulate matter (PM) can have either a natural or anthropogenic origin and, depending on the sources generating PM, it can be composed by several substances with a large variety of chemical and physical properties. The main anthropogenic sources of PM are road traffic, heating systems and industrial combustion; among the natural sources, the main responsible for particulate matter production are soil erosion, marine spray, volcanoes, forest fires and pollen dispersion. In 2017 in Lombardy, fine particulate matter is mainly emitted by non-industrial combustion processes, that is heating systems, and by road transport, accounting for the 43% and the 23%, respectively.

The particles of the largest size tend to precipitate quickly, and, therefore, they are not of particular interest for air quality monitoring. Conversely, PM10 and PM2.5, considered by European legislation on air quality, play an important role. They are classified as the fraction of particles that can be collected by a selection system with 50% efficiency, for respectively 10μm and 2.5μm aerodynamic diameters (UNI EN 12341/2014).

PM10 represents an indicator for the inhalable fraction of particulate matter. It can be divided between the coarse fraction (>2.5 μm), the fine fraction PM2.5, that is an indicator of risk to health and is mainly generated by gases but also by combustion processes, and, finally, the ultrafine fraction (<100 nm).

We can divide PM10 and PM2.5 according to their chemical composition and to the origin of the constituents. Primary organic matter (POM) and secondary organic aerosols (SOA) are composed of elemental and organic carbon compounds, while secondary inorganic aerosols (SIA) are composed of inorganic ions like, nitrates, sulphates, and ammonium. The remaining part is composed of particles with both natural and anthropogenic origins like crustal, metallic elements and others. Particulate matter feature and composition are highly variable among seasons, due to the variability of atmospheric conditions and sources' activity.

The gaseous precursors of SIA are NO_X, SO_2 and NH_3, while VOCs are precursors of organic SOA. Sulphur dioxide, once oxidized to SO_3 by reactions involving hydroxyl radical OH* or hydrogen peroxide (H_2O_2) can lead to the generation of ammonium sulphate ($(NH_4)_2SO_4$) through the following reactions involving NH_3:

$$SO_2 \rightarrow SO_3 + H_2O \rightarrow H_2SO_4 \tag{3.8}$$

$$2NH_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4 \tag{3.9}$$

NO_X available in high quantities in the most urbanized areas, together with ammonia lead to the formation of ammonium nitrate (NH_4NO_3) according to the following reactions.

$$2NO_2 + O_3 \rightarrow N_2O_5 + O_2 \quad (3.10)$$

$$N_2O_5 + H_2O \rightarrow 2HNO_3 \quad (3.11)$$

$$NH_3 + HNO_3 \rightarrow NH_4NO_3 \quad (3.12)$$

Due to the complex and partially unknown composition of the inhalable fraction of PM, the air quality regional model FARM inside its aerosol modules divides PM10 in subspecies, in order to treat particles dynamic and their interaction with gas phase species. The results of the simulation for the INEMAR scenario shows that PM10 concentrations can be split on average as such: total carbon (TC), including elemental carbon (EC) and SOA; accounts for 40% of PM10 mass, SIA (sulphate, nitrate, and ammonium) for approx. 36%, a residual fraction of unspecified primary anthropogenic particles (PANT) for approx. 22%, and primary natural particles (PNAT) for 3% (*Figure 3-9*).

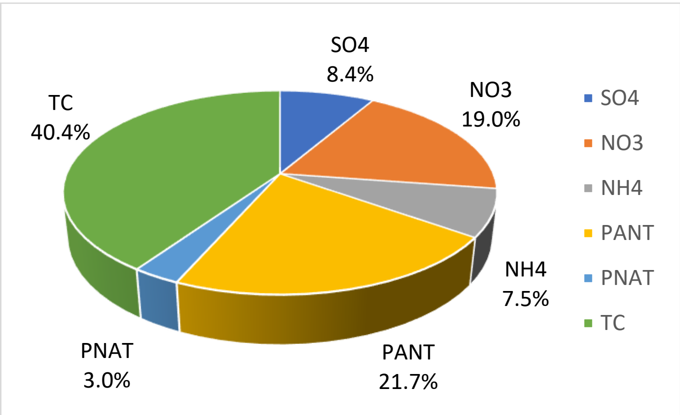

Figure3-9: Composition of the average concentration of PM10 in 2017 in Lombardy.

Particulate matter affects human health as it can penetrate inside pulmonary alveoli and generate acute and chronic effects, which depend on how deep the particles can go in the lungs and what type of substances they carry. Among the effects, we have respiratory problems, chronic bronchitis, asthma, premature mortality increases from cardio-respiratory diseases and lung cancer. Particulate matter can also affect the climate as it decreases visibility and reduces solar radiation (WHO, 2006).

The Legislative Decree 155/2010 for the protection of human health establishes concentration limits for PM10 but also for PM2.5 due to their different behaviour towards human health.

PM10 must comply with a daily limit of 50 µg/m^3 that cannot be exceeded more than 35 days in a year and an annual limit of 40 µg/m^3.

The measured annual average PM10 concentration in the region in 2017 is lower than the limit value, but locally exceedances are measured in the highly urbanized areas, as shown in *Figure 3-10*.

Conversely, the PM10 daily limit is exceeded all over the region, with the average value of exceedances doubling the acceptable limit set at 35, as shown in *Figure 3-11*.

The limit to protect human health for PM2.5 is 25 µg/m^3 as annual average concentration and the average measured value in 2017 is very close to it. Exceedances of this target limit are registered all over the region, especially in the urbanized area, as shown in *Figure 3-12*. From these figures we can see that for the average concentration of both PM10 and PM2.5 values are rather homogeneous all over the region without large spatial gradients except for lower values registered in the mountain (zone C and D). This shows that particulate matter sources are distributed in the whole plain area and PM pollution is a regional scale phenomenon.

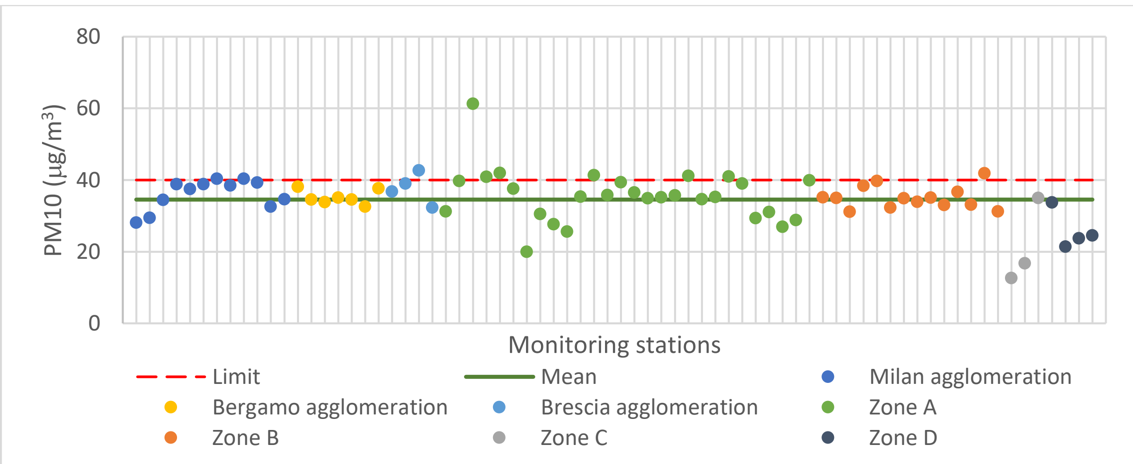

Figure 3-10: PM10 annual average concentration measured in each monitoring station.

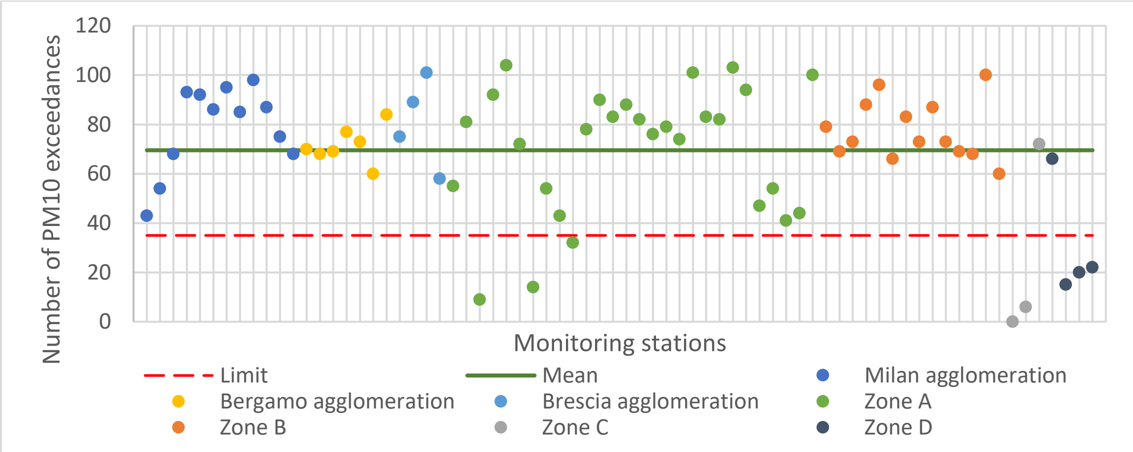

Figure 3-11: Number of annual PM10 target limit exceedances, measured in each monitoring station.

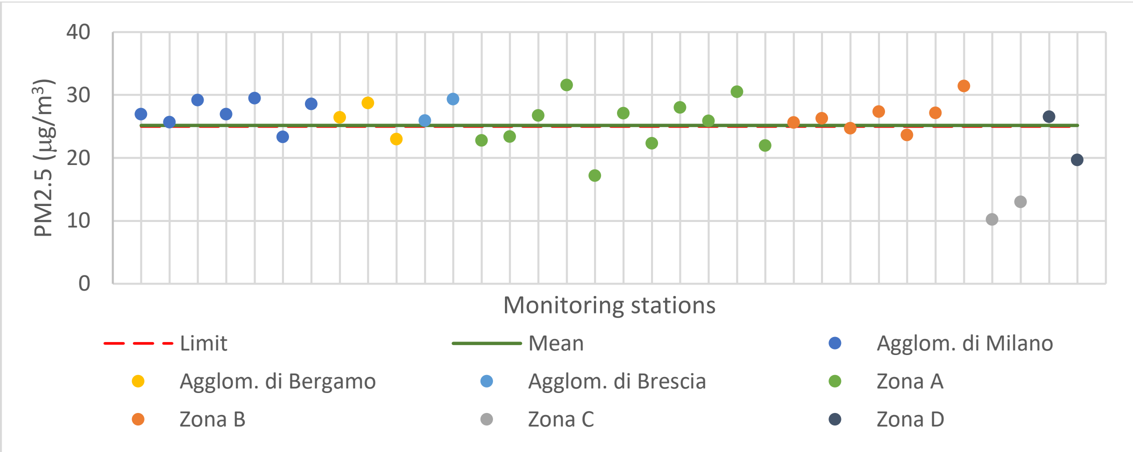

Figure 3-12: PM2.5 annual average concentration measured in each monitoring station

Maps in *Figures 3-13 and 3-14* represent the spatial distribution of PM10 and PM2.5 annual average concentration all over the region of PM10 and PM2.5 for 2017. Higher concentrations of particulate matter are measured at the largest agglomerations as well as at minor urban centres, while in the mountain areas concentrations are almost zero.

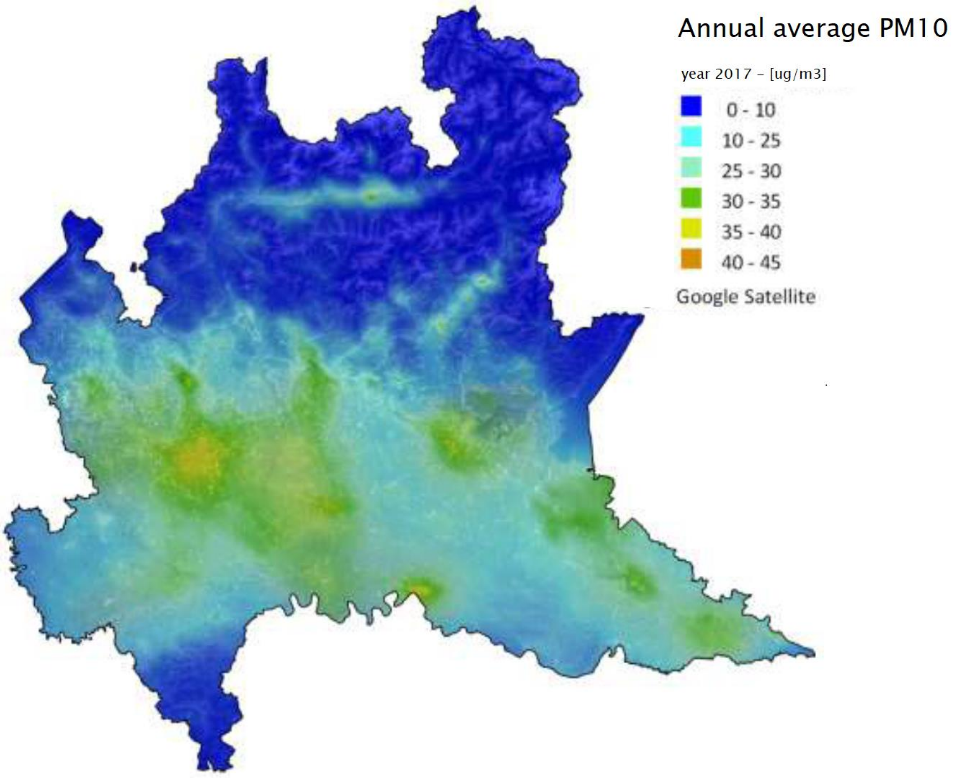

Figure 3-13: Map of annual average PM10 concentration in 2017. (Source: Rapporto annuale sulla qualità dell'aria 2017)

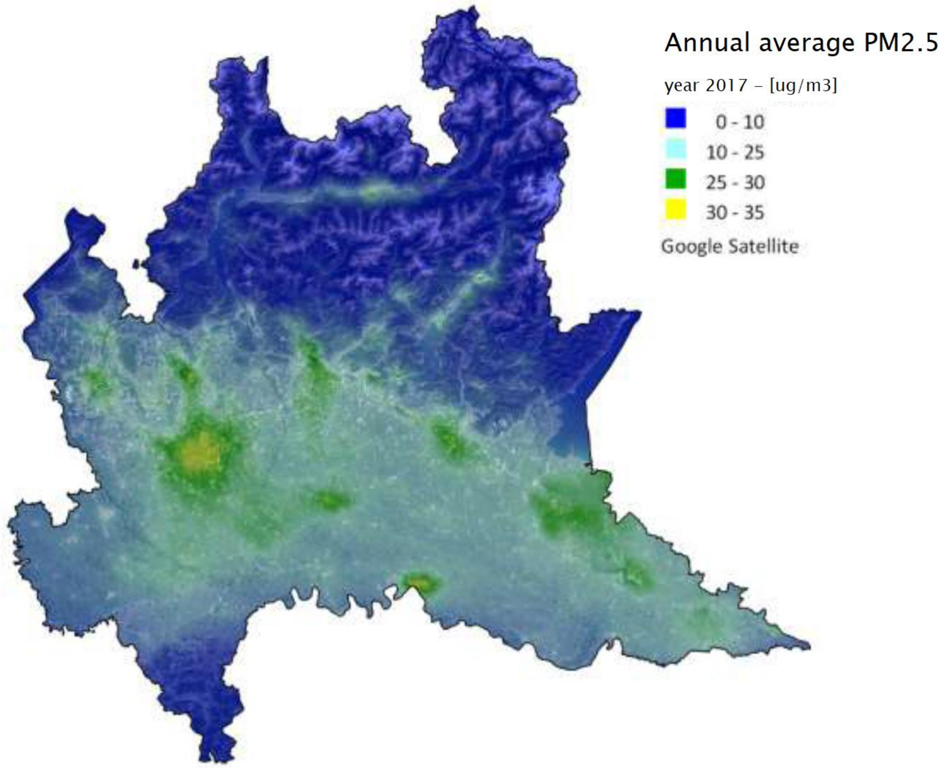

Figure 3-14: Map of annual average PM2.5 concentration in 2017. (Source: Rapporto annuale sulla qualità dell'aria 2017)

4

POLLUTANT EMISSIONS IN LOMBARDY

4.1. INEMAR database

The emissions of pollutants in the atmosphere in Lombardy are calculated and collected by the air emissions inventory INEMAR.

INEMAR is a database created under Lombardy's regional plan for air quality (PRQA), with the aim to create the inventory of emissions into the atmosphere. Since 2003 it has been managed and developed by ARPA Lombardia, but after an inter-regional agreement in 2006 its use has been shared with other Italian regions.

INEMAR is aimed at estimating emissions of different air pollutants with municipal detail for different types of activities, according to the guidelines presented in the EMEP-CORINAIR emission inventory guidebook (EMEP/EEA, 2019). This guidebook is the European technical guidance to facilitate reporting of emission inventories by country. It provides common procedures for emission inventories realization, with the purpose of ensuring transparency, consistency, completeness, comparability, and accuracy. It also provides estimation methods and emission factors for inventory compilers at various levels of sophistication. The Task Force on Emission Inventories and Projections TFEIP contributes to the preparation and review of the emission guidebook by harmonising emission factors and establishing methodologies for the evaluation of emission data and projections.

The current version of the INEMAR inventory has been uploaded at the end of 2019 and is referred to 2017. This data is currently available in a draft form; it is still under public review and it is due to be consolidated in the final version within the end of 2020.

INEMAR is composed of several tables that collect data processed by sixteen different modules, through specific calculation algorithms.

The guidebook groups the sources emitting pollutants into sectors which include energy, industrial processes, agriculture, and waste. Each sector includes individual source categories (e.g. road transport) and subcategories (e.g. passenger vehicles).

In INEMAR emissions are grouped by eleven source categories, which are characterised according to the Selected Nomenclature for Air Pollution, by the type of process generating them and are listed as follows:

1. Combustion in energy and transformation industries
2. Non-industrial combustion plants
3. Combustion in manufacturing industry
4. Production processes
5. Extraction and distribution of fossil fuels and geothermal energy
6. Solvent and other product use
7. Road transport
8. Other mobile sources and machinery
9. Waste treatment and disposal
10. Agriculture
11. Other sources and sinks

Each one of these source categories plays a different role in the production of pollutants.

4.2. INEMAR traffic module

The INEMAR traffic module estimates the emissions from urban and suburban road traffic in Lombardy, at subcategory level, by applying the COPERT IV methodology to the data available for the Lombardy Region; this is done in accordance to the indications provided by the Emission Inventories Guidebook. The COPERT software is a European tool to calculate emissions from road transport. It is part of the Air Emissions Inventory Guidebook (EMEP/EEA, 2019; Ntziachristos, Gkatzoflias, Kouridis, & Samaras, 2009).

The COPERT methodology is based on emission factors deriving from real tests on the road, not on homologation factors. The purpose of the emissions inventory is to estimate, as accurately as possible, the real emissions, not the theoretical ones.

The COPERT software reproduces the best representation of reality that nowadays we are able to produce. It takes into account many factors, including car fleet, mileage, road speed, percentage of hot and cold distance travelled, environmental temperature and other factors that allow to replicate the behaviour of the entire vehicle fleet circulating in the area in question. The methodology is standardized to better allow comparisons among the emissions in the different European States.

The level of complexity of the methodology for the road transport emission assessment can be different depending on available data. Three tiers are provided from the Emission Inventory Guidebook that span from the simpler tier 1 based on average emission factors, referred to aggregated activity data, to the more complex tier 3 based on emission factors, referred to more refined activity data, to be calculated by means of sophisticated models.

Vehicles of each category (i.e. cars, light duty vehicles, heavy duty vehicles and motorcycles) in INEMAR database are shared among the vehicle class according to the composition of the registered fleet. Each vehicle class is identified by fuel, engine size, and Euro class. The combination of vehicle class and category is uniquely identified by a code named "Copart", as generated from a combination of COPERT and Artemis methodology (e.g. gasoline powered passenger cars with engine size > 2 litre, Euro 1 type approved).

Pollutants emission produced by road transport vehicles are divided in exhaust and non-exhaust emissions, due to the physical phenomenon from which they originate.

Exhaust emissions are generated as the product of internal combustion in an engine and include a range of pollutants, namely: SO_2, NO_x (such as NO_2), NMVOC, CH_4, CO, CO_2, N_2O, NH_3, PM2.5, PM10, TPS (Total Suspended Particles), Cd, Cr, Cu, Ni, Pb, Se, Zn. Exhaust emissions account for both hot and cold emissions. Hot emissions are produced when the vehicle is running from the moment the engine and the abatement systems reach the operating temperature. On the other hand, cold emissions are produced when the vehicle starts to move up to the moment when the engine reaches 70 °C, or the catalyst reaches the light-off temperature i.e. the activation temperature.

Non-exhaust emissions include both particles produced by road, tyre, and brake wear and evaporative NMVOC emissions. The evaporative emissions are due to the evaporation of the most volatile fraction of the fuel, through the various components of the vehicle's fuel system, and are significant only for petrol-powered vehicles. INEMAR database does not include resuspensions of fine particles from roads surface.

Based on the different calculation approaches adopted, the traffic module differentiates between linear and diffuse emissions, whose calculation requires a specific algorithm. Exhaust and non-exhaust emissions are included in both linear traffic (LT) and diffuse traffic (DT) modules, which are executed in sequence (*Figure 4-1*).

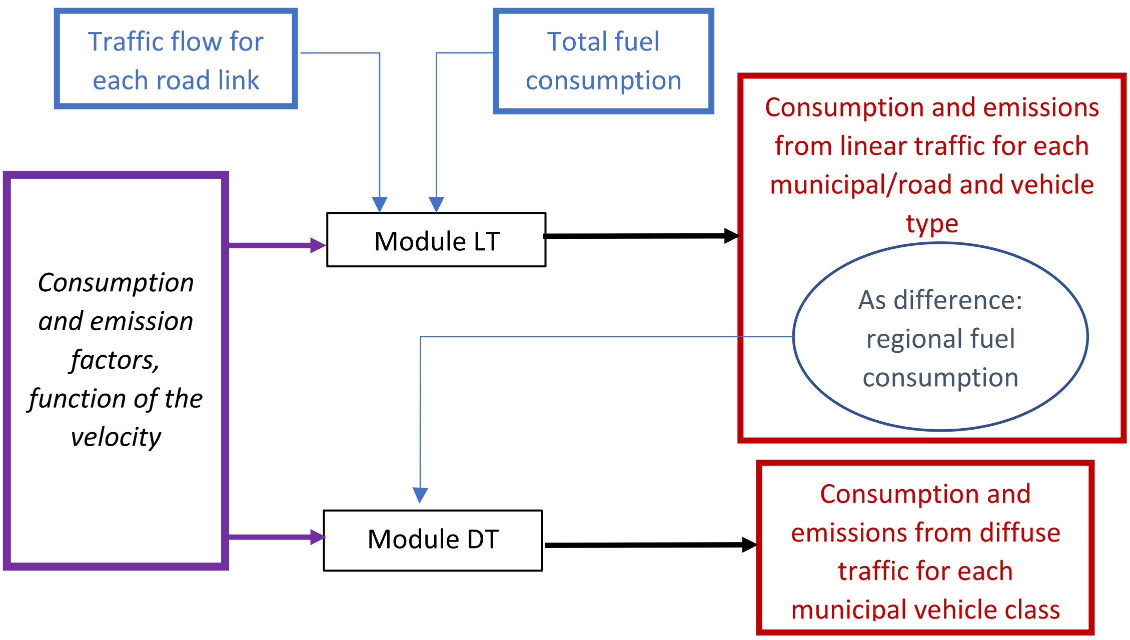

Figure 4-1: Summary scheme representing input and output data from linear and diffuse traffic modules.

The linear traffic module allows to calculate the emissions based on traffic flows. Linear emissions are produced by road transport on extra-urban and motorway road networks and they are estimated based on the number of vehicular passages on each segment of road present in the network in *Figure 4-2*.

The diffuse traffic module calculates non-linear traffic emissions, generated in urban areas, which include paths with non-homogenous characteristics of traveling speed and outflow. Their estimation is based on fuel sales data. Fuel consumption data are shared among municipalities and vehicle categories according to the municipal population, the composition of the registered fleet and the expected average annual distance travelled by vehicles of each category.

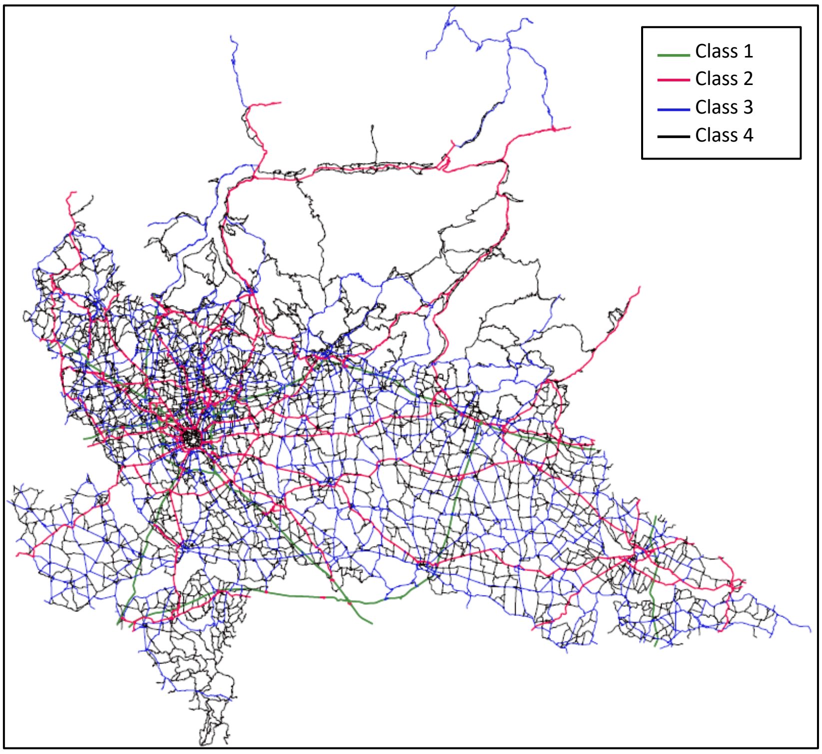

Figure 4-2: Map of the Lombardy roads network. (Source : https://www.here.com/navteq)

The methodology used for the calculation of pollutant emissions follows the tier 3 methodology indicated in the Emep Guidebook, based on emission factors referred to each vehicle class and their activity data. The total emissions of a specific pollutant are the result of the sum of emissions generated from all vehicles deriving from a spatial and temporal aggregation.

4.2.1. Linear emissions calculation

The calculation algorithm is used for each single segment of road present in the roads network shown in *Figure 4-2* and for each travel direction. The resulting emissions can be presented at level of the single segment or spatially aggregated at municipality level.

Hot exhaust emissions

Hot exhaust emissions are generated when the vehicle is in motion and both the engine and the abatement systems reach the operating temperature. They are expressed in metric tonnes/hour and can be different according to the time profile depending on the month, day, and hour.

The hourly emissions of the specific pollutant considered from a vehicle of a specific class (identified by the Copart code) on a single road lane are calculated as follows:

$$E_{L,HOT} = N \cdot L \cdot EF_{HOT}(v) \cdot CF_{AGE} \cdot CF_{COMB} \cdot CF_{W,S}$$

where:

- N: number of vehicles crossing the path in one hour.
- L: travelled distance (km).
- $EF_{HOT}(v)$: emission factor (g/km), function of vehicles and their speed.
- CF_{AGE}: correcting factor to simulate the progressive deterioration of the engine performances.
- CF_{COMB}: correcting factor taking accounting for the effect of the different quality of fuels.
- $CF_{W,S}$: correcting factor used for heavy duty vehicles, considering the load of the vehicle and the slope of the path.

The number of total vehicles crossing the path in one hour is a function of the vehicular category and of the time profile, as mentioned above. The number of vehicles of each category crossing the path in one hour derives from traffic allocation models and from flow monitoring studies.

The vehicular flows are divided into classes of vehicles covered according to the product between the number of vehicles registered in the region and the annual travelled distance attributed to them by the origin-destination matrix.

Hot exhaust emissions depend upon a variety of factors, including the distance that each vehicle travels, its speed, its age, the fuel, the engine size, its weight, and the path's slope. For this reason, the emission factor requires a series of correcting factors accounting for these characteristics.

The emission factor for a specific pollutant emitted by vehicles is expressed as function of the velocity along the road segment. This velocity derives from the outflow curve (e.g. *Figure 4-3*) related to the segment that describes the relation among the average vehicular speed and the flux density.

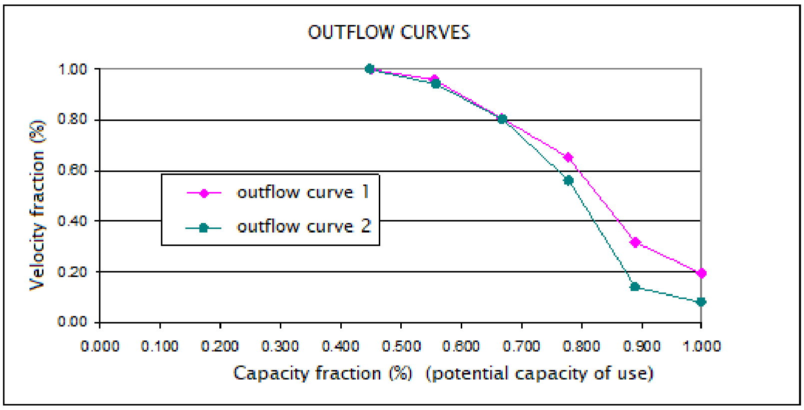

Figure 4-3: Example of outflow curve (INEMAR - ARPA Lombardia, 2020).

Cold exhaust emissions

In the linear traffic emissions calculations, the COPERT methodology considers a fraction of the mileage of each vehicle as carried out with both the engine and abatement system cold, therefore with a higher emission factor than under running conditions (cold-start over-emissions). The methodology also attributes this surplus of emissions to the urban environment.

The calculation procedure described for hot exhaust emissions is applied to the single, typically extra-urban, road section, where the running conditions can be considered fully operational. The hypothesis that a fraction of the length of each road link is travelled with a cold engine would result in an overestimation of emissions particularly for roads with the higher traffic flows. For this reason, cold emissions are included only in urban diffuse emissions.

Wear emissions

Brake, tires, and road wear generate particulate matter emissions; these are calculated for each vehicle class as:

$$E_{WEAR} = N \cdot L \cdot EF_{WEAR} \cdot CF_V \cdot f$$

where:

- N: number of vehicles crossing the path in one hour.
- L: length of the path (km).
- EF_{WEAR}: emission factor (g/km) of the total particulate matter function of the process (brake, tires, or road wear).
- CF_V: correcting factor, function of the vehicular velocity.

Evaporative emissions

The evaporative emissions considered in the linear traffic module are only the hot running losses generated during the gear of the vehicle. They can be expressed as a function of the travelled distance, of the temperature and of the climatic conditions.

The pollutant present in evaporative emissions are only VOCs emitted by gasoline powered vehicles.

4.2.2. Diffuse emissions calculation

Diffuse emissions are generated by vehicles circulating on-roads not included in the network considered for the linear emissions.

Hot exhaust emissions

The hot exhaust emissions estimation is based on fuel sales data. The fraction of fuels which is not part of linear traffic consumptions is shared among municipalities and vehicle categories according to the population of the municipality, the composition of the registered fleet and the expected average annual distance travelled by vehicles of each category. The travelled distance is no more related to the single segment, but is the distance travelled in the municipality from vehicles of the specific class identified by the Copart code.

The hourly emissions of a specific pollutant from a vehicle of the specific class for each municipality are calculated as follows:

$$E_{D,HOT} = \frac{C}{CF(v)} \cdot EF(v)$$

where:

- $EF(v)$: emission factor (g/km), function of vehicles and their velocity.
- C: fuel consumed by the vehicle class, in the specific municipality at a specific hour.
- $CF(v)$: fuel consumption factor (g/km), function of vehicles class and their velocity.

Unlike in the linear module, in the diffuse module the vehicles travelling speed is not related to the outflow curves of the single road segment, but is aforethought depending on the time profile, on the different vehicle categories, and on the population density of the single municipality. The travelling speeds are calculated on the basis of studies on urban traffic plans.

Cold exhaust emissions

The cold exhaust emissions are calculated only for urban diffuse emissions as said above. They can be calculated as a function of the fraction of the overall regional distance travelled by each category of vehicles, divided among all the municipalities.

$$E_{D,COLD} = \frac{C}{CF(v)} \cdot \beta \cdot CF_{\beta} \cdot (EF_{HOT} \cdot CF_{FUEL} \cdot (R_{HC} - 1) + f(P_C))$$

where:

- β: fraction of the distance travelled with cold engine and abatement system, function of the total travelled distance and of the temperature.
- CF_{β}: correcting factor of β for gasoline vehicles.
- R_{HC}: E_{COLD}/E_{HOT} ratio
- $f(P_C)$: function of the average cumulative distance

The emissions deriving from the fraction of distance travelled with cold engine are calculated taking into account the expected thermal excursions in each area of interest, according to the climate and the season.

Wear emissions

The calculation of wear emissions is performed at the same way as its calculation in the linear traffic module, differing only for the travelled distance, that in the diffuse traffic module is related to the whole municipality.

Evaporative emissions

Diffuse evaporative emissions are given by the sum of the following contributions:

- Hot running: emitted during hot engine running.
- Warm running: emitted while driving with a cold engine and abatement system.
- Hot soak: emitted at the end of a journey with a hot engine.
- Warm soak: emitted at the end of a journey concluded with cold engine.
- Diurnal: emitted in function of the ambient temperature.

While the running hot and warm emissions are functions of the travelled distance, hot and warm soak emissions are functions of the number of travels.

4.3. Atmospheric pollutant emission framework

The latest version of the INEMAR inventory, available for 2017, presents methodological improvements as well as updated data, compared to the previous version considering data for 2014. A comparison between two inventories shows a general reduction of all emissions during these three years, but an increase for CO, CO_2, and NMVOC. Numerical data for a few interesting pollutants from the two inventories are synthetized in *Table 4-1* and *4-2* grouped by source categories.

The reduction of approx. 5600t of NO_X is mainly due to reductions in road transport and industrial combustion. Particulate matter also decreased, as consequence of an improvement in industrial and non-industrial combustion sectors, solvents use, road transport and waste treatment.

Regional pollutant emissions in 2014						
Source categories	NO_X	CO	NMVOC	CH_4	PM2.5	PM10
	t/y	t/y	t/y	t/y	t/y	t/y
1. Combustion in energy and transformation industries	6,437	10,919	600	1430	136	144
2. Non-industrial combustion plants	10512	76409	9835	6740	7989	8186
3. Combustion in manufacturing industry	19364	12868	3506	851	1457	1775
4. Production processes	1503	21016	12706	171	347	611
5. Extraction and distribution of fossil fuels and geothermal energy	0	0	6785	73957	0	0
6. Solvent and other product use	57	48	78382	0	912	1039
7. Road transport	62910	67,015	14825	1245	3440	4644
8. Other mobile sources and machinery	12387	5,837	1600	28	585	588
9. Waste treatment and disposal	3154	1,250	1128	78623	38	39
10. Agriculture	687	2,106	56841	220912	526	1045
11. Other sources and sinks	56	1,632	32057	4743	601	772
Total	117067	199101	218267	388700	16031	18843

Table 4-1: Atmospheric emissions in Lombardy in 2014, grouped by source categories

Regional pollutant emissions in 2017						
Source categories	NO_X	CO	NMVOC	CH_4	PM2.5	PM10
	t/y	t/y	t/y	t/y	t/y	t/y
1. Combustion in energy and transformation industries	8227	6665	773	1474	190	197
2. Non-industrial combustion plants	11308	61033	7725	1079	7383	7567
3. Combustion in manufacturing industry	17072	12109	3283	693	1137	1344
4. Production processes	1664	33260	11241	169	368	651
5. Extraction and distribution of fossil fuels and geothermal energy	0	0	7403	77815	0	0
6. Solvent and other product use	122	53	75205	1	669	745
7. Road transport	56787	83169	16866	1139	2857	4072
8. Other mobile sources and machinery	12469	4752	1240	27	578	579
9. Waste treatment and disposal	2643	1103	875	66222	33	34
10. Agriculture	697	2221	60791	220761	548	1075
11. Other sources and sinks	484	13804	55314	5572	1280	1606
Total	111472	218169	240717	374952	15042	17869

Table 4-2: Atmospheric emissions in Lombardy in 2017, grouped by source categories

The percentage contribution of each source category reported in Table 4-1 and Table 4-2 for NOx and particulate matter are displayed in Figure 4-4 to Figure 4-6. Road transport accounts for 51% of the annual regional NO_X emissions; for PM10 it gives a smaller but still important contribution (23%). For PM10 emission the most important role is played by non-industrial combustion, that is domestic and tertiary-sector heating, with about 42%. The contribution of road transport in PM2.5 emission is similar to those for PM10 (19%), but a more important contribution is observable from non-industrial combustion (49%).

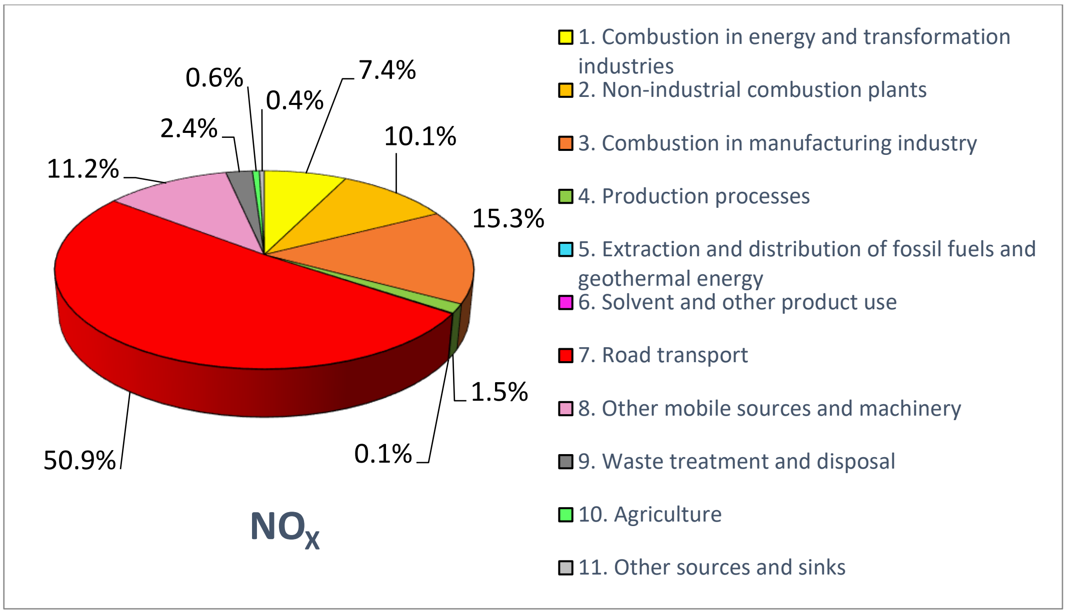

Figure 4-4: Percentage contribution of each source category to NO_X emission in 2017 (INEMAR - ARPA Lombardia, 2020)

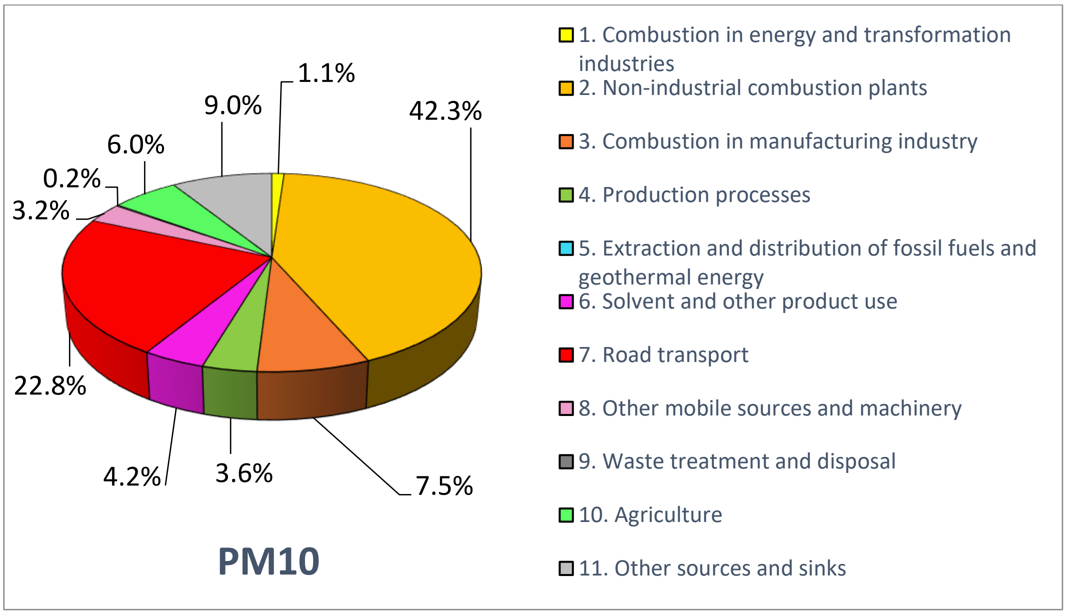

Figure 4-5: Percentage contribution of each source category to PM10 emission in 2017 (INEMAR - ARPA Lombardia, 2020)

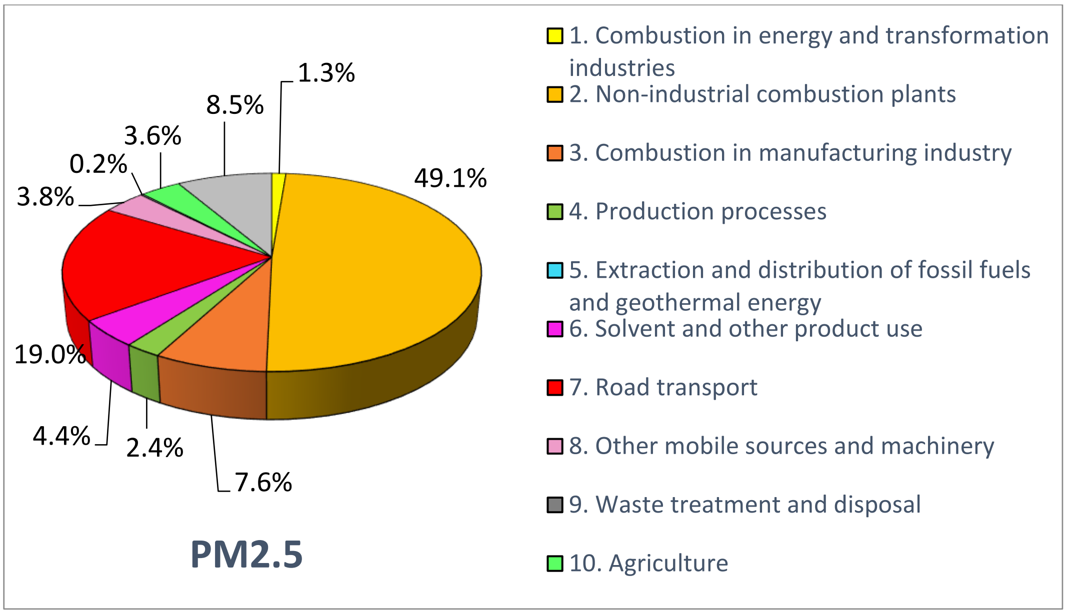

Figure 4-6: Percentage contribution of each source category to PM2.5 emission in 2017 (public review)

The map in Figure 4-6 shows the spatial distribution of nitrogen oxides emission all over the region, expressed in t/km^2. NO_X emissions are higher in urban areas, particularly in the Milan agglomeration and along the principal motorways connected to it since road traffic is one of the main sources of NO_X. Comparing it with the fraction of NO_X generated by road traffic in Figure 4-7, the large contribution of this category can be observed as the pollutant is widespread in the same areas. Local peaks present in the map of total NO_X emissions do not appear in the map of the fraction generated by road traffic, since they originate from other sources.

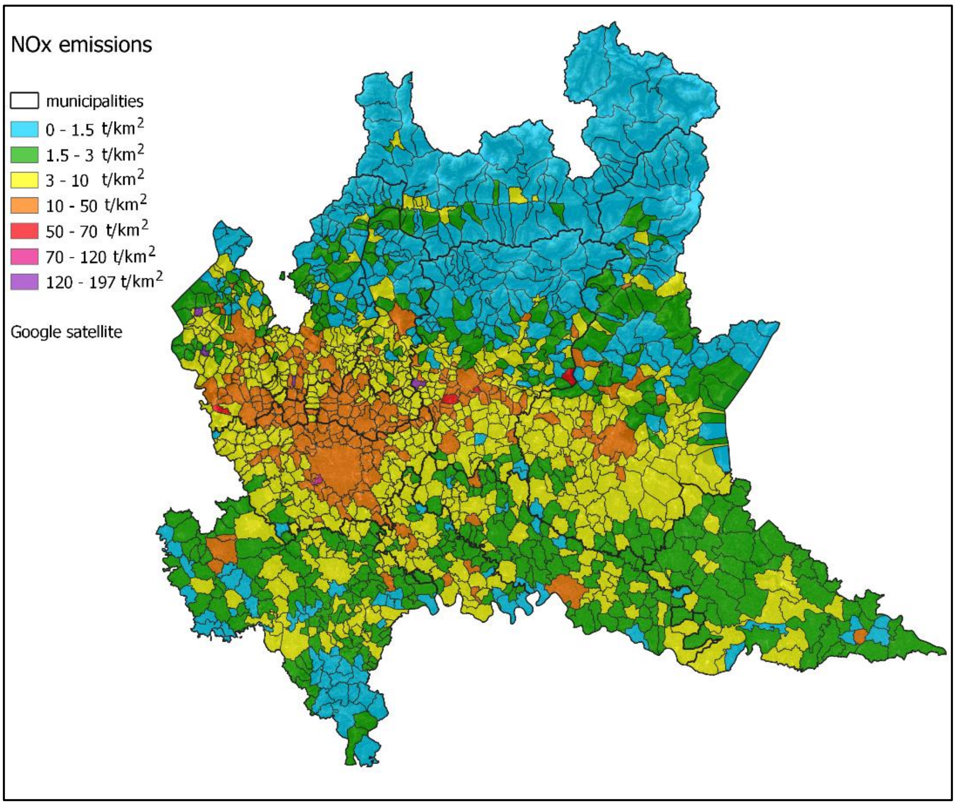

Figure 4-6: Map of NO_X total emissions in 2017 in Lombardy (INEMAR - ARPA Lombardia, 2020)

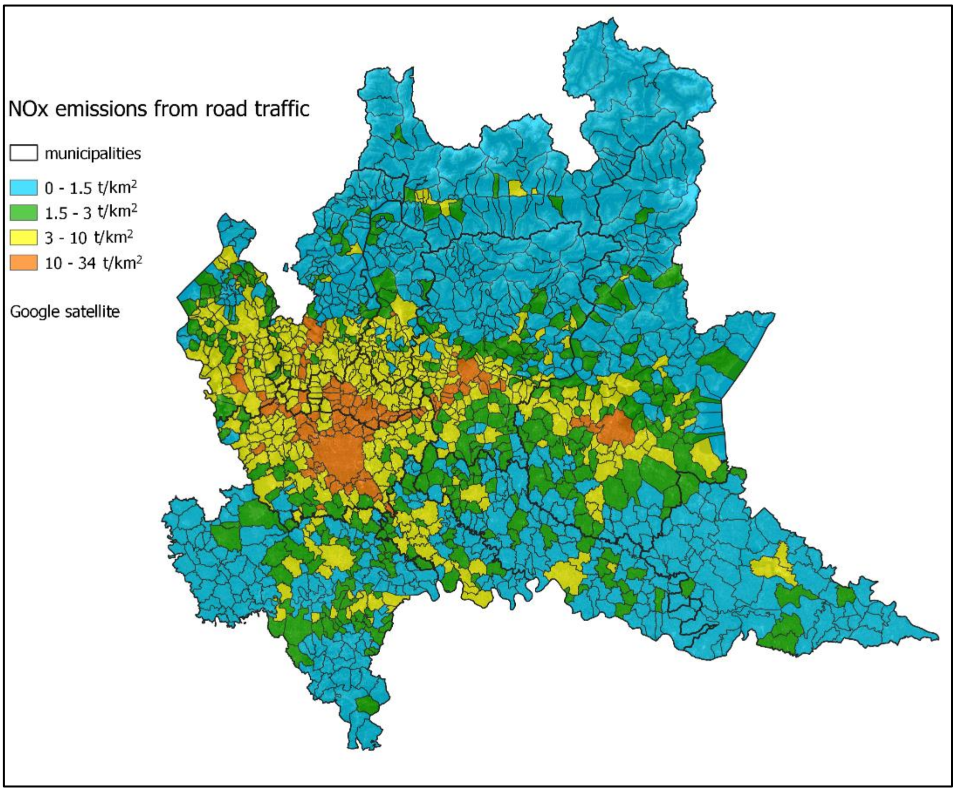

Figure 4-7: Map of NO_X emissions from road traffic in 2017 in Lombardy (INEMAR - ARPA Lombardia, 2020)

4.3.1. Road traffic emissions

The vehicular fleet, in line with indications from the EMEP Guidebook (EMEP/EEA, 2019), can be divided into several categories. These are: passenger cars, light duty vehicles, heavy duty vehicles, mopeds, and motorcycles. Each of these contributes to pollutant emissions in different amounts, as shown in the pie charts in figures from *4-8* to *4-10*. Passenger cars and light duty vehicles generate together approx. 65% of NO_X emissions and 75% of fine PM emission from road traffic.

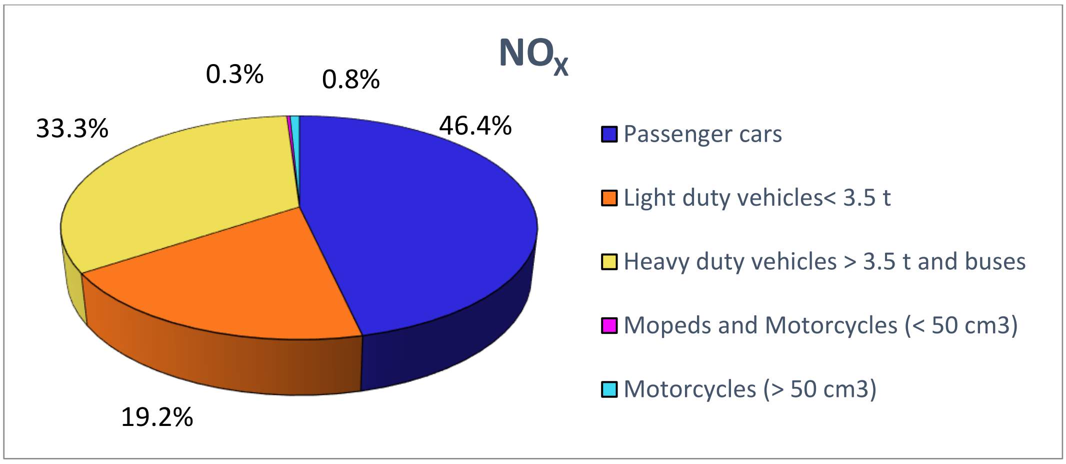

Figure 4-8: Contribution of each vehicle category to the total NO_X emitted by road traffic in 2017

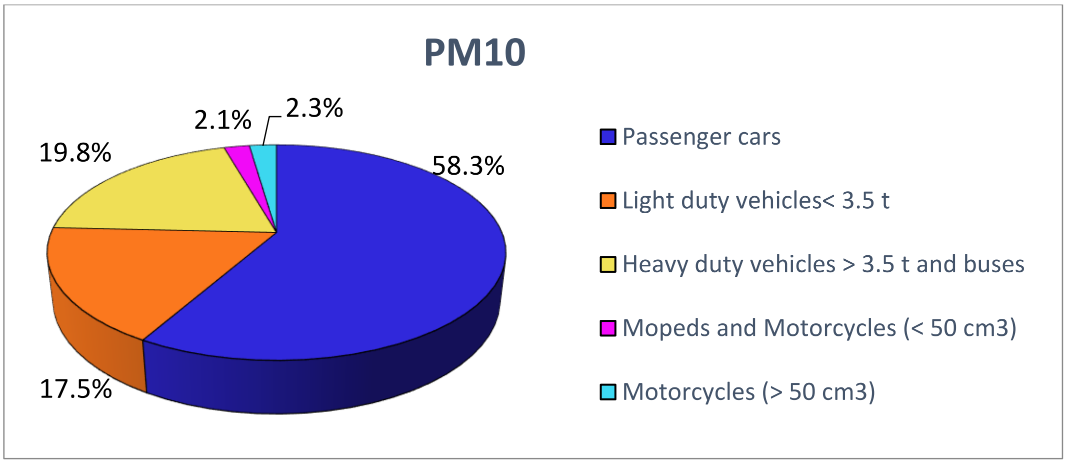

Figure 4-9: Contribution of each vehicle category to the total PM10 emitted by road traffic in 2017

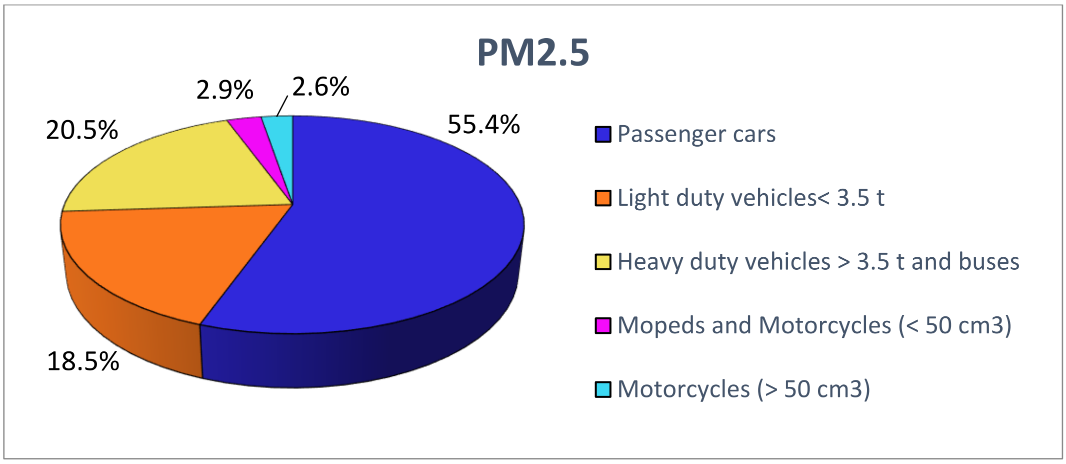

Figure 4-10: Contribution of each vehicle category to the total PM2.5 emitted by road traffic in 2017

Splitting the emission data by kind of fuel, it results that the highest amount of pollutant is released by gasoline and diesel vehicles, because LPG and methane-fuelled vehicles are almost negligible in the circulating fleet. Diesel-powered vehicles account for approx. 92% of the total NO_X emitted by road traffic and 73% of fine particulate matter. On the other hand, gasoline powered vehicles generate more CO, VOC and NMVOC.

Fuel	NOx	CO	VOC	NMVOC	PM10
Gasoline	6.9%	70.3%	79.8%	79.7%	21.9%
Diesel	91.6%	11.9%	9.0%	8.8%	73.2%
LPG	1.2%	14.2%	8.2%	8.7%	2.8%
Methane	0.3%	3.6%	3.0%	2.8%	2.2%
Total	100%	100%	100%	100%	100%

Table 4-3: Contribution of vehicles powered by different fuels to pollutant emissions from road traffic in 2017

Looking at emission data split by vehicle category and fuel type, we find that passenger cars and light duty vehicles, powered by both diesel and gasoline, added together are the category of vehicles that mostly contributes to pollutant emissions from road traffic, immediately followed by heavy duty vehicles category, that is almost entirely powered by diesel. Diesel powered vehicles are those mainly contributing to NO_X emissions. Therefore, they are more involved than others in the changes generated in the alternative compliant emission scenario object of this study.

5

COMPLIANT EMISSION SCENARIO

This study is intended to quantify the effect of the exceedance for vehicles of EU type approval limits for pollutants air concentrations in the Lombardy region. For this purpose, we compare road transport emissions data collected in the INEMAR dataset (the INEMAR scenario) with those calculated for an alternative scenario characterized by vehicle emissions complying with EU type approval limits.

European regulation sets emission limits on diesel and gasoline vehicle's exhaust emissions for NOx, CO, PM10, NMHC and THC. Regulatory emission limits are defined in terms of emission factors, that represents the mass of pollutant emitted per unit of distance travelled (g/km).

Basically, the compliant scenario presented here is created by replacing the emission values of pollutants exceeding the limit, with the limit itself. More specifically, this operation is carried out following a two-step procedure that combines both top-down and bottom-up approaches. First, INEMAR scenario annual emission data of each vehicle class in the fleet circulating in the region, as identified according to COPART classification and CORINAIR activity, are disaggregated at municipality level. According to the COPART code classification, the vehicular fleet can be divided in a list of 273 element based on vehicular category, fuel, displacement, and Euro class. Since regulatory limits refer to exhaust emissions, only combustion-generated emissions are considered, neglecting evaporative and wear emissions. The emission data selected, expressed in metric tonnes per year, are divided by the annual number of kilometres travelled in each municipality by the specific vehicle class. This operation generates a list of emission factors expressed in mass over unit distance (g/km), related to each COPART code for each municipality. We compare these emission factors of the INEMAR scenario with the regulatory emission limits and then replace them with the limit when this latter is exceeded. After this substitution, we can calculate the annual vehicular emissions of the compliant scenario and adding to it the before neglected evaporative and wear emissions, we build the new emission factors of the compliant scenario. Due to their relevance (approx. 65% of PM10 is due to wear emissions and 19% of VOC is due to evaporative emissions) these contributions generate a not negligible variation of the obtained results.

Vehicles category involved are passenger cars, light commercial vehicles, mopeds, and motorbikes. Heavy duty vehicles and buses are not included in this study even if they give an important contribution to the emission of the analysed pollutants, especially for NO_X. This choice is driven by the difference in the expression of the emission limits. Indeed, emissions from this vehicular category are limited as mass of pollutant per unit of power generated by the engine (g/kWh). Therefore, the procedure for the implementation of the alternative scenario would have gained a major level of difficulty, requiring a detailed study of this category, with a more complex evaluation also affected by a further level of uncertainty.

5.1. Variations in the emission framework

We chose to use for our analysis the data from INEMAR 2017, after comparing them with the ones from the INEMAR inventory of 2014. This choice was based on observed NO_X emissions for the two years under consideration since NO_X is the pollutant exceeding its limits the most.

Despite the increase over the years in the total number of circulating vehicles in the region, the results of the comparison show lower annual emissions of total NO_X in 2017 than 2014, respectively 56,787 t and 62,911 t. This reduction is due to the renovation of the fleet of passenger cars and light duty vehicles circulating, with a decreasing number of more polluting old vehicles, from Euro 0 to Euro 4, and a simultaneous increase in more modern vehicles, Euro 5 and in particular Euro 6.

Several studies demonstrate that Euro 5 and Euro 6 vehicles emit more NO_X than expected from homologation (Weiss et al., 2011; Suarez-Bertoa et al., 2019). Indeed, we find that, while in 2014 NO_X emitted by gasoline and diesel vehicles exceeded expectations by 41%, in 2017 they exceeded them by 65%. The higher value in 2017 is due to the limits themselves having become more stringent. Note that the value we compare to is not the value we would have had with vehicle emissions set exactly as the limit; instead, it is a lower value, because in accordance with the procedure described above, when recorded emission data are lower than emission limits they are not modified. Based on these findings, we decided to set our analysis on data of INEMAR 2017.

Analysing the fuel type, it is possible to see the contribution to NO_X emissions of vehicles with different fuel and based on different Euro class in the bar chart reported in *Figure 5-1*. More modern vehicles are equipped with more efficient emission control systems, therefore present lower NO_X emission factors EF regardless of the fuel with which they are powered. Looking at EF of newer vehicles, it stands out almost a non-decreasing value for diesel vehicles over years. The introduction of more modern control systems to follow the increasingly stringent emission limits required for NO_X, is not sufficient to reduce its emission factors for diesel vehicles at the level of vehicles powered by other fuels.

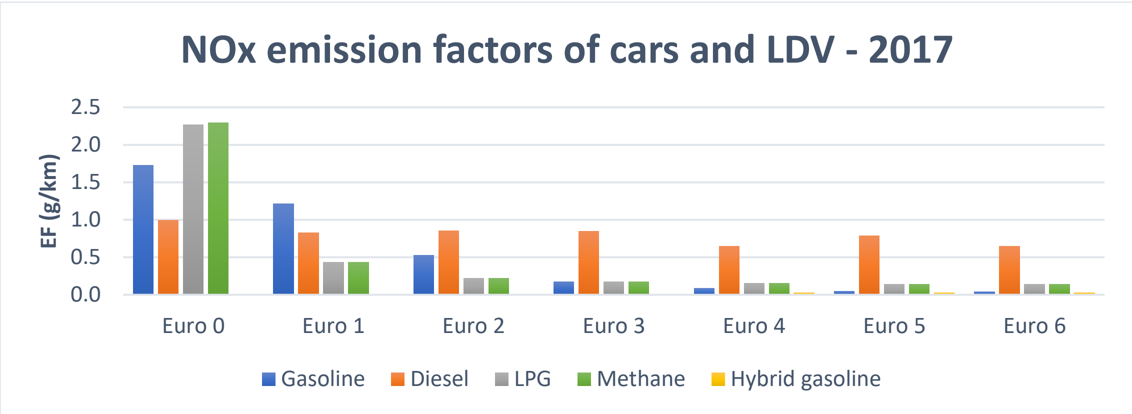

Figure 5-1: Emission factors of vehicles with different fuel, divided per Euro class.

A comparison between emission factors of gasoline and diesel vehicles of the INEMAR scenario and those of the compliant scenario, shows the effect of the evolution of emissions regulations. Looking at *Figures 5-2 and 5-3* it is evident the different behaviour between gasoline and diesel vehicles, with the introduction of new Euro classes.

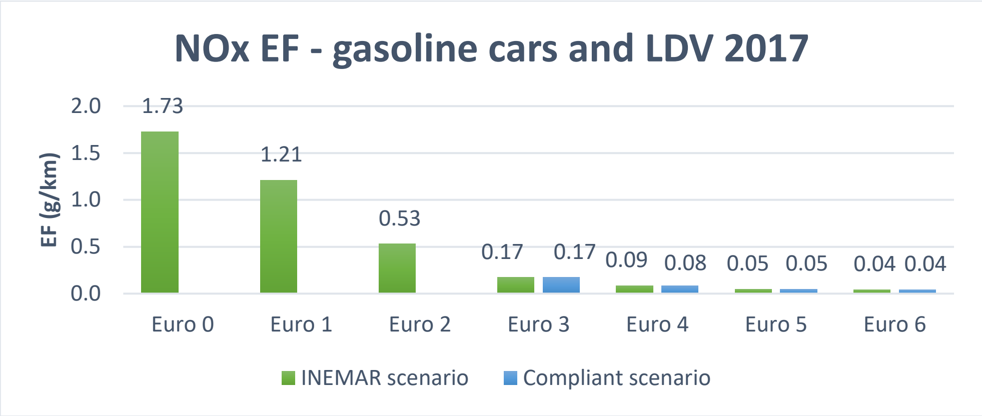

Figure 5-2: Comparison of NO_X emission factors of the INEMAR scenario and the compliant scenario for gasoline vehicles divided by Euro class.

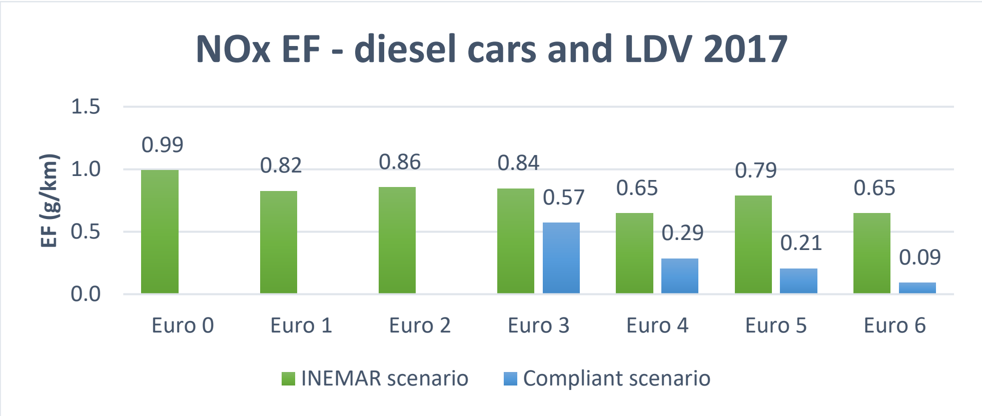

Figure 5-3: Comparison of NO_X emission factors of the INEMAR scenario and the compliant scenario for diesel vehicles divided by Euro class

Before the introduction of the Euro 3 legislation in 2000, NOx emissions were limited as the sum of NO_X and total hydrocarbons THC, and, therefore, for those cases we do not have a comparison with limits.

Considering vehicles from Euro 3 to Euro 6, we can see that for gasoline vehicles real data and the compliant scenario follow the same trend, decreasing according to the type approval evolution. Diesel vehicles, on the other hand, show a less regular trend not complying with what is expected from the relevant legislation.

We can see that for diesel vehicles, emission factors of the compliant scenario are higher than the corresponding emission factors of the gasoline vehicles, though this difference decreases for more modern Euro 5 and Euro 6.

The product between emission factors and the distance travelled by each vehicle category allows to calculate the mass of pollutant emitted. *Figure 5-5 and 5-6* show NO_X emission produced respectively by gasoline and diesel vehicles, expressed in tonnes, grouped by the Euro classes. As seen for the emission factors, while gasoline vehicles follow the evolution of regulations, diesel vehicles are far from it. The mass of NO_X emitted by gasoline-powered vehicles is one order of magnitude lower than for diesel-powered vehicles, due to the lower emission factor. Looking at these data with Euro class detail, we can see this trend from Euro 3 to Euro 6 vehicles, while for older vehicles, which represent only a small part of the fleet in 2017, gasoline emits more NO_X.

Diesel vehicles emission data in *Figure 5-5* show that despite EF for vehicles from Euro 0 to Euro 2 is the highest, they give just a small contribution to total NO_X emissions. This is due to the low number of vehicles of these categories still circulating. On the contrary, NO_X emitted from diesel vehicles increases from Euro 3 to Euro 5, with a small decrease for Euro 6. This last reduction is due to the fact that Euro 6 vehicles were introduced in 2015, so there was not enough time for a renovation of the circulating fleet. As a result, the number of diesel Euro 6 in 2017 was about half of the number of Euro 5.

The effect of the renovation of the vehicular fleet is observable also with a comparison between NO_X emission data of diesel vehicles of the same Euro class, circulating in 2017 (*Fig.5-5*) and 2014 (*Fig. 5-6)*.

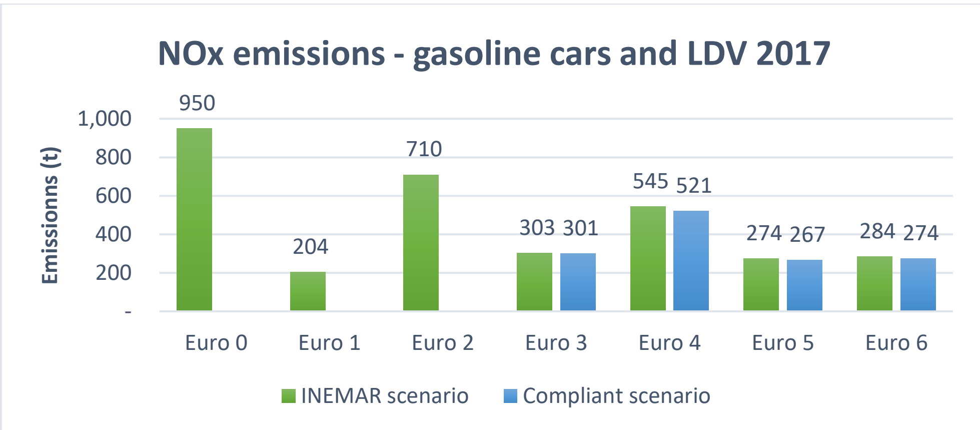

Figure 5-4: Comparison of the total NO_X mass emitted in 2017 by gasoline powered passenger cars and light duty vehicles in the two scenarios analysed. Emissions are expressed in tonnes and grouped by Euro class.

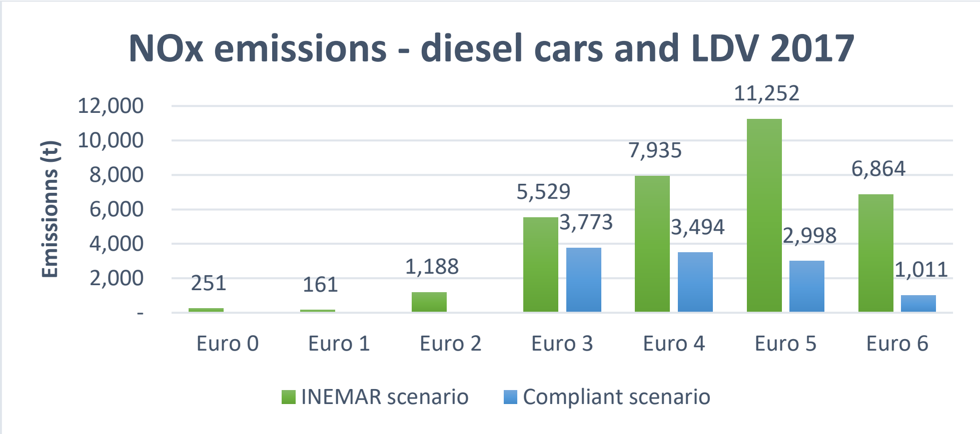

Figure 5-5: Comparison of the total NO_X mass emitted in 2017 by diesel powered passenger cars and light duty vehicles in the two scenarios analysed. Emissions are expressed in tonnes and grouped by Euro class.

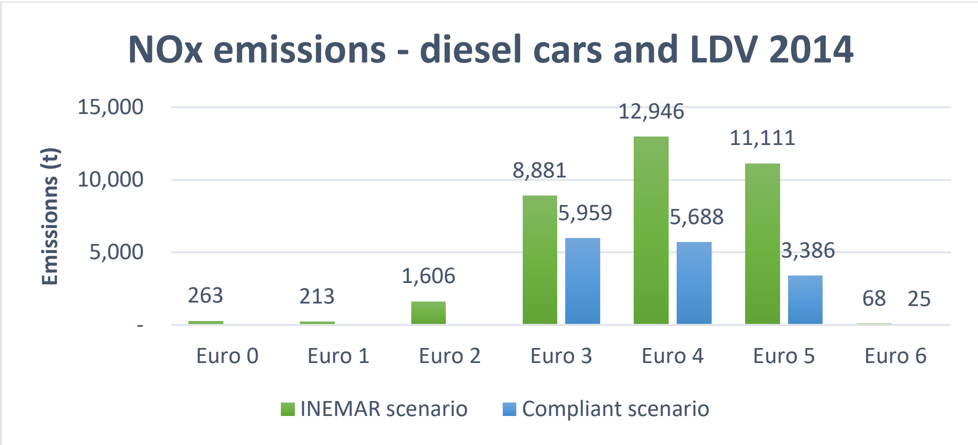

Figure 5-6: Comparison of the total NO_X mass emitted in 2014 by diesel powered passenger cars and light duty vehicles in the two scenarios analysed. Emissions are expressed in tonnes and grouped by Euro class

From 2014 to 2017 NO_X emissions of Euro 3 and Euro 4 vehicles decrease, due to the simultaneous decrease in vehicle numbers. NO_X emissions, on the other hand, remain stable for Euro 5 and increase for Euro 6 vehicles, whose representation in the fleet in 2014 was almost non-existent.

Among the diesel vehicle fleet, we can distinguish the contribution of passenger cars and light duty vehicles in 2017. We find that they both follow the same trend among the evolution of Euro regulation, and, despite passenger cars having lower emission factors, they generate about double of the amount of NO_X with respect to diesel light duty vehicles. The reason is the higher number of circulating passenger cars travelling longer distances, that are for LDV approx. four times those for passenger cars.

An overall comparison between real road traffic emission data of the INEMAR scenario and the compliant scenario shows that under the compliant scenario, reduction in NO_X

emitted is much more significant than for other pollutants, with a reduction by 36.6%, followed by the reduction in CO by 10.9%, as illustrated in *Table 5-1*. We do not find any variation in PM10, even if the projection of the scenario generates its reduction from exhaust emissions. The reason is that PM10 is for the 65% composed of wear emissions, that does not vary in the compliant scenario.

While reductions in NO_X are almost totally attributed to passenger cars and light duty vehicles, with only the 0.3% of the total reduction attributed to motorcycles, for CO half of the reduction is attributed to passenger cars and light duty vehicles and the other half to mopeds and motorcycles.

Pollutant	Emissions (t)		Total reduction
	INEMAR scenario	Compliant scenario	
NOx	56787	36005	-36.6%
CO	83169	74078	-10.9%
PM10	4072	4072	0%
VOC	18004	17909	-0.5%
NMHC	16866	16770	-0.6%

Table 5-1: Pollutant emissions from road traffic in the INEMAR scenario and resultant reduction due to the hypothesis of the compliant scenario.

Comparing these data with total emissions in Lombardy from all activities, the reduction of NO_X emissions due to the application of the compliant scenario becomes 18.6%, while reductions of CO becomes the 4%.

Looking at NO_X data with municipal detail it is possible to identify which areas are more susceptible to a variation in vehicle emissions. The map of Lombardy in *Figure 5-6* shows the differences in emission referred to each municipality, expressed in t/km^2, between the INEMAR and the compliant scenario.

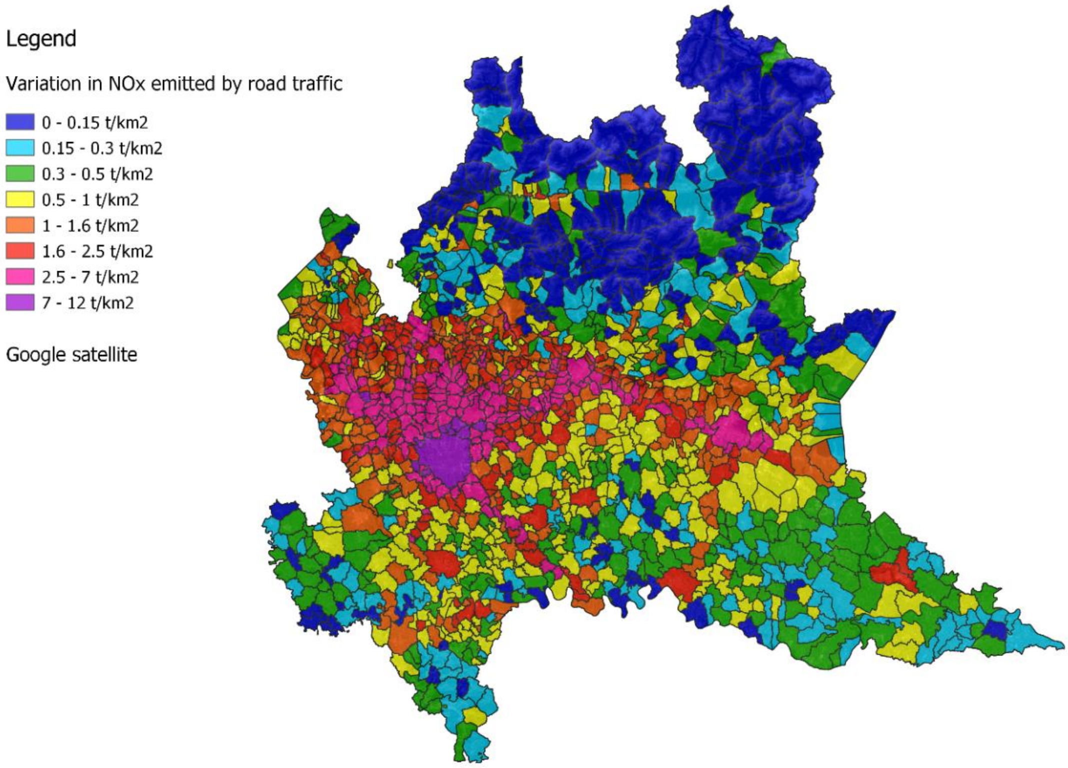

Figure 5-7: Map of differences of annual average NOx emissions from road traffic between the INEMAR scenario and the compliant scenario, with municipal detail.

It is clearly visible that the area of the metropolitan city of Milan and the area close to the principal motorways connected to the city, e.g. A4 and A1, present higher differences in NO_X emissions between the two scenarios than the rest of the region, while the mountainous area in the north of the region displays no signs of change. This distribution of improvements in NO_X emissions obtained with the compliant scenario is due to the urbanized area that has higher vehicular traffic, but it is also dependent on the assumptions made for the vehicular fleet. We consider the composition of the vehicular fleet to be homogeneous across the region; distinction are made for vehicles of different ages: the travelled distance decreases with the age of the vehicle and more modern vehicles spend more kilometres on motorways than older (Caserini, 2011). These assumptions result in a higher percentage of kilometres spent in linear traffic for modern vehicles. All these considerations contribute to generate exceedances of the limits even bigger in areas with intense linear traffic, since Euro 5 and Euro 6 vehicles are those exceeding limits the most.

6

CONCENTRATION SCENARIO

6.1. ARIA Regional modelling system

The ARIA Regional™ modelling system, developed by Arianet srl, is applied by the Environmental Monitoring Sector of ARPA Lombardia, in combination with fixed measurement data, to perform simulations of air quality.

The three-dimensional Eulerian model FARM is the core of the system, while other components allow the user to prepare needed input data of FARM (*Figure 6-1*). FARM is a Chemical Transport Model (CTM) that accounts for chemical conversion processes for primary and secondary pollutants, and transport and dispersion of atmospheric pollutants caused by the wind and by atmospheric mixing.

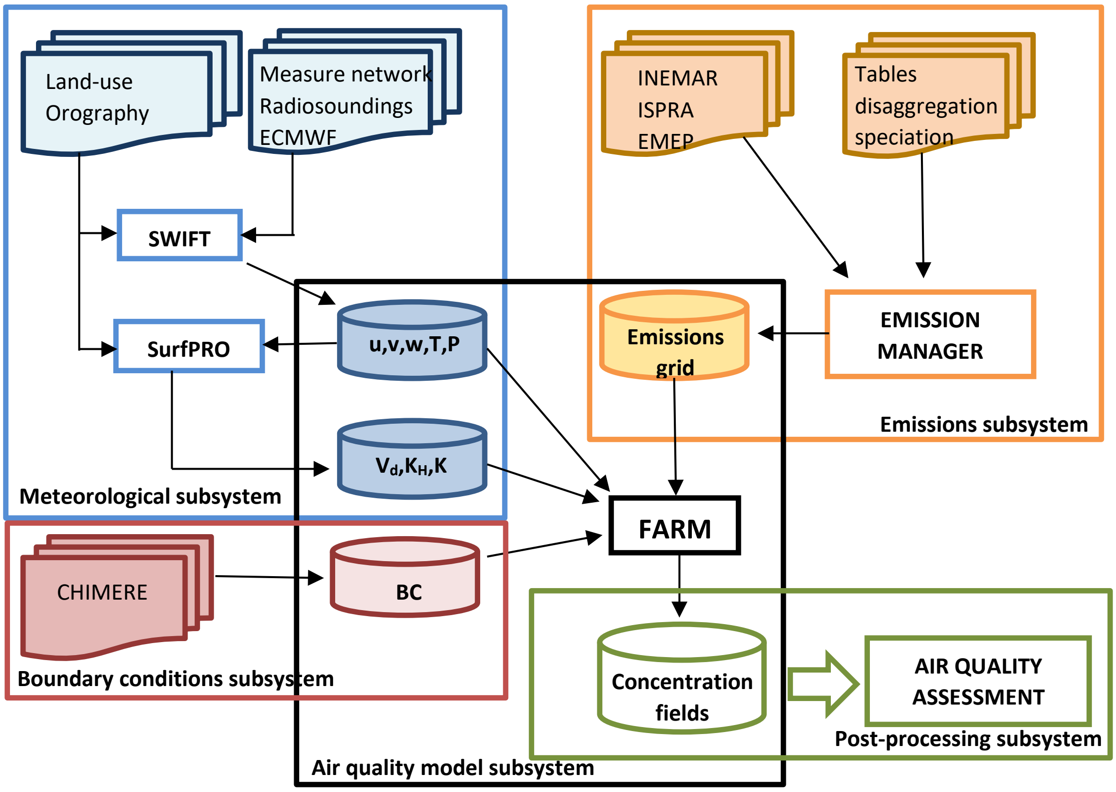

Figure 6-1: Modelling system ARIA Regional scheme (ARPA, 2018)

Others component of the system are:

- a meteorological driver.
- a diagnostic model for the reconstruction of wind fields, temperature, and humidity (SWIFT).
- a turbulence and deposition pre-processor (SurfPro).
- an emission pre-processing system (EMMA - ARIANET).
- initial and boundary conditions pre-processors, allowing to prepare 3D input for the current set of species starting from a set of observations present in the regional database for air quality and modelled continental data by CHIMERE model.
- processors for the organization of data from the air quality network and their interpolation to fields produced by the CTM model (ArpMeas).

6.1.1. Input data

The modelling system operates on a domain that includes the entire Lombardy (*Figure 6-2*). It extends for 236x244 km^2, with a resolution of 4x4 km^2 and 13 vertical levels extended from 10 to about 6000 m of altitude.

In order to reconstruct the emission input, we use INEMAR 2017 database, for emissions relating to the Lombard territory (version under public review), the dataset of the LIFE Prepair project referred to 2014 (www.lifeprepair.eu) for emissions relating to surrounding regions, and the dataset EMEP 2012 for Switzerland.

In the present study the production of the emission input required a detailed implementation for both scenarios, since it is the first time that the INEMAR 2017 database is used in a model simulation, while the other input data do not vary from other previous simulations.

The preparation of the emission model requires a spatial and temporal data disaggregation and the speciation of aggregated indicators, carried out through the pre-processing system Emission Manager (EMMA) (http://doc.aria-net.it/EmissionManager).

The starting input database of Emission Manager is composed of:

- a reference classification scheme adopted to identify all the emitting activities of interest (SNAP nomenclature by the EEA).
- emission data from the mentioned inventories, associated to point, line and area sources.
- geographic information describing the geometry of complex sources or to be used for space disaggregation of emission data.
- time modulation data, to describe the typical behaviour of the emitting sources when the emissions are coming from an inventory on e.g. yearly basis.

The generation of an emissions input for the FARM model by EMMA commands is organized in two consecutive phases: the pre-processing time-independent part (i.e.: speciation of aggregated indicators and their space disaggregation) that runs only once, and the time-dependent part, that manages essentially time modulation operations and the final generation of input files for FARM model. The time-dependent part runs at each time period. The temporal disaggregation of annual emission data is achieved by considering monthly, daily, and hourly modulations.

The speciation of NMVOCs and total PM, required by the photochemical model, is obtained through profiles related to each emission activity we have updated.

The meteorological data used for the realization of the meteorological files are related to the year 2017. The system directly interfaces with the ARPA Lombardia database, which collects data from air quality and meteorological-hydrological networks. The meteorological input is realised by correlating data collected on an hourly basis from a subset of stations of local networks and Linate's fine radio-soundings, to the fields produced by the European Centre for Medium-Range Weather Forecast (ECMWF), using the mass-consistent Swift model. The turbulence parameters atmospheric and pollutant deposition rates are then estimated with the SurfPRO processor.

The boundary and initial conditions are derived from the daily processing provided by the system Prev’air (CHIMERE at continental scale).

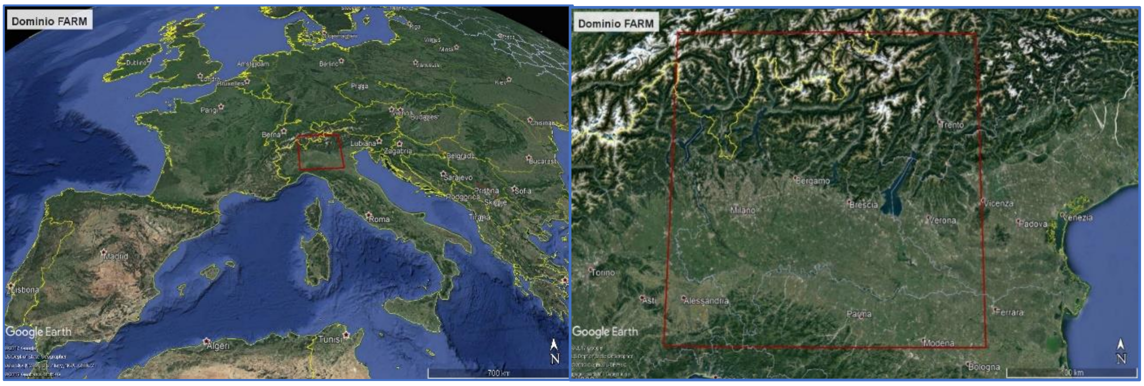

Figure 6-2: Domain of the modelling simulations (ARPA, 2018)

Results

We evaluate the results of modelling by comparing hourly based concentration data of the cells of the grid with data measured by monitoring stations at the same coordinates and at the same time.

For this study the data fusion process, obtained by interpolation between simulated fields and measures thanks to the Successive Correction Method (SCM) algorithm, is not carried out because it cannot be applied to the compliant scenario. The modelled data were, therefore, applied by the concentration differential (6.1), calculated between the concentration values of the two scenarios at the location of each monitoring station.

$$\Delta = \frac{C_{compliant} - C_{INEMAR}}{C_{INEMAR}} \qquad (6.1)$$

The calculated differential is multiplied by the data measured by the monitoring station to obtain the corresponding value under the compliant scenario.

The stations of the Lombardy air quality network are chosen based on their classification, geographical distribution and completeness of the data series. We focus the attention on ozone (O_3), dioxide nitrogen (NO_2) and particulate matter (PM10 and PM2.5) as these are the pollutants that present exceedances of legal limits on the regional territory.

6.1.2. Model validation

The model validation reported is produced like the annual report Air Quality Modelling Assessment (VMQA – Valutazione Modellistica della Qualità dell'Aria) which is performed every year by the air quality modelling and inventories unit of the Environmental Monitoring Sector of ARPA Lombardia (https://www.arpalombardia.it/Pages/Aria/Modellistica.aspx).

The performance of the model must be evaluated considering the uncertainties in model outputs. The model validation is based on data from the INEMAR scenario modelled for the year 2017.

Compliance with data quality goals is assessed through the evaluation of statistical indicators reported in the specialized literature and technical reports of the European community: Pearson correlation coefficient (R), Normalized Mean Bias (NMB), Normalized Mean Standard Deviation (NMSD), Root Mean Square Error (RMSE), Index of Agreement (IOA), Mean Fractional Bias (MFB), and Mean Fractional Error (MFE) (Thunis, Georgieva, & Pederzoli, 2011). They have been calculated for each measuring station and pollutant. Their mathematical definition and the resulting values are shown in the summary tables in Appendix B(a-f).

Figure 6-3 presents the scatter plot of pollutants concentrations measured at the stations and those extracted from the simulation performed for the year 2017 at the corresponding cell. Each point refers to a single station on different mediation periods. The dashed lines delimit the interval containing good quality data. Its range is between ± 50% for the annual average PM10 and PM2.5 particulates, and it is ± 30% for the annual average NO_2, the maximum daily values for NO_2 and O_3, and at the daily maximum of the eight hours moving average of O_3.

For all monitored pollutants, the performance of the model in representing the measured data is lower for those monitoring stations situated in areas strongly influenced by local emission sources. The reason for this effect stands in the base structure of the model. Specifically, the model provides estimated average concentrations computed on cells of 16 km^2, while monitoring stations provide punctual data. Such a large extension of the cells was required given the computational cost of the simulation with the available hardware and given the uncertainty regarding the spatial allocation of emissions.

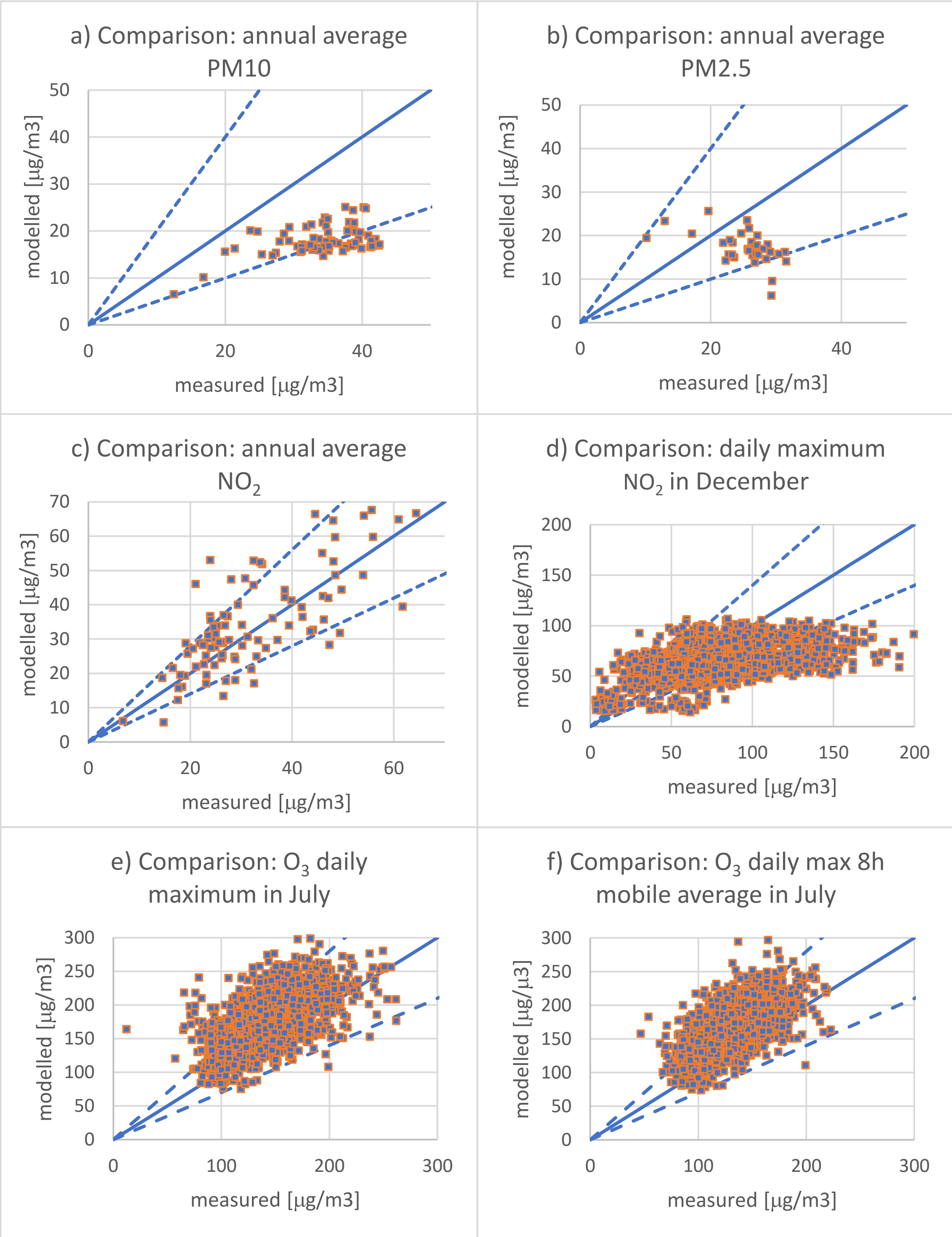

Figure 6-3: Dispersion diagrams of annual average and daily maximums pollutants concentrations for each monitoring station.

The model tends to underestimate the daily and annual average concentration of particulate matter. However, the model provides for both PM10 and PM2.5 higher values located below the range (*Figures 6-3(a) and 6-3(b)*). This behaviour is more evident for PM10 data and can be in part attributed to the lack of consideration of the resuspended fraction in the model.

For a large number of monitoring stations, the data quality objective for NO_2 is not satisfied. The annual average of simulated nitrogen dioxide varies widely between different monitoring stations. The model tends to overestimate lower values and to underestimate higher values, in particular peaks *Figure 6-3(d)*. Currently some modifications to the modeling system are under development to improve performances for this pollutant, also including increasing the density of the calculation grid.

The comparison between the estimated and measured daily maximum values of ozone both absolute and relative to the average mobile over eight hours shows a general tendency of the model to overestimate the concentration of this pollutant (*Figures 6-3(e) and 6-3(f)*).

6.2. Impact on pollutants concentration

To evaluate the impact of the compliant scenario on air quality, we choose to focus the attention on the pollutants more affected by the high variation of NOx emissions, which are ozone, nitrogen dioxide and fine particulate, which correspond to the pollutants more frequently exceeding the regulation limits and goals. Concentration data generated with the model are balanced with data measured by monitoring stations at the same coordinate. As mentioned above, the model we use has a resolution of 4x4 km^2. Therefore, concentrations are uniform in each cell of the grid, while peak values may probably show higher local improvements.

6.2.1. Nitrogen dioxide

Limit for the protection of human health

Under the compliant scenario, the estimation of the average annual NO_2 concentration over the whole Lombardy region falls by 16.1%. On a total of 93 stations monitoring NO_2 concentration, the number of monitoring stations registering values exceeding the limits decreases from 23 to 8. These 15 stations are located in the Milan agglomeration and the highly industrialized plane (zone A), and almost all of them are urban stations; they are split between the traffic UT, the background UB, and the suburban background SB category. The monitoring station still registering an annual NO2 concentration value above the limit are all traffic urban UT except for one suburban background SB.

Figures from 6-4 to 6-6 show the comparison between the annual average concentrations measured at the monitoring stations and estimated at the same sites under the compliant scenario. Numerical data are reported in *Table 6-3*.

It is visible a general decrease of NO_2 concentration values throughout the region, with the annual average estimated values for the provinces of Milan (MI) and Monza e Brianza (MB), falling below the annual limit for the protection of human health of 40 µg/m^3. Under the compliant scenario, the annual average NO_2 concentration measured in all areas falls below the limit. The limit of 200 µg/m^3 on an hourly basis, regulating the exposition of the population to very high concentrations of NO_2 for a short period of time, is exceeded just for few hours, less than eighteen in the whole 2017, even in measured data.

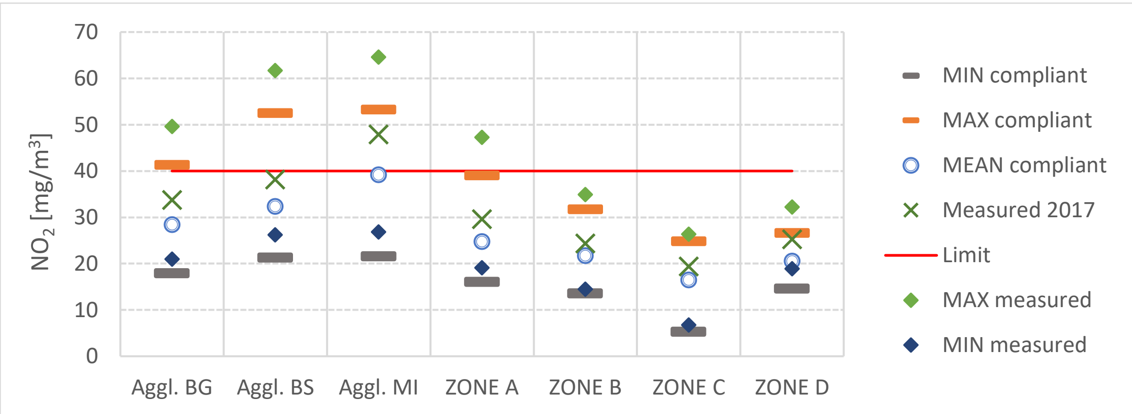

Figure 6-4: Projection of the annual average NO_2 concentration and its variability (min-max range), under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by areas.

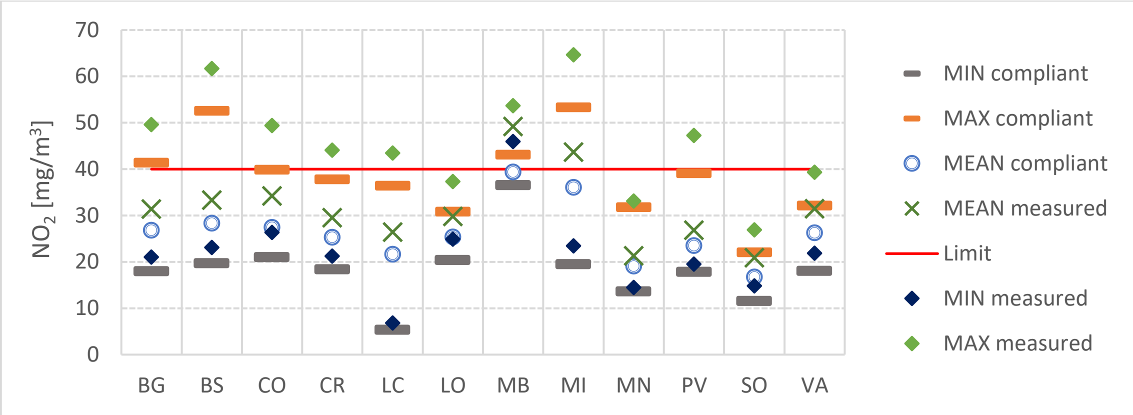

Figure 6-5: Projection of the annual average NO_2 concentration and its variability, under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by provinces.

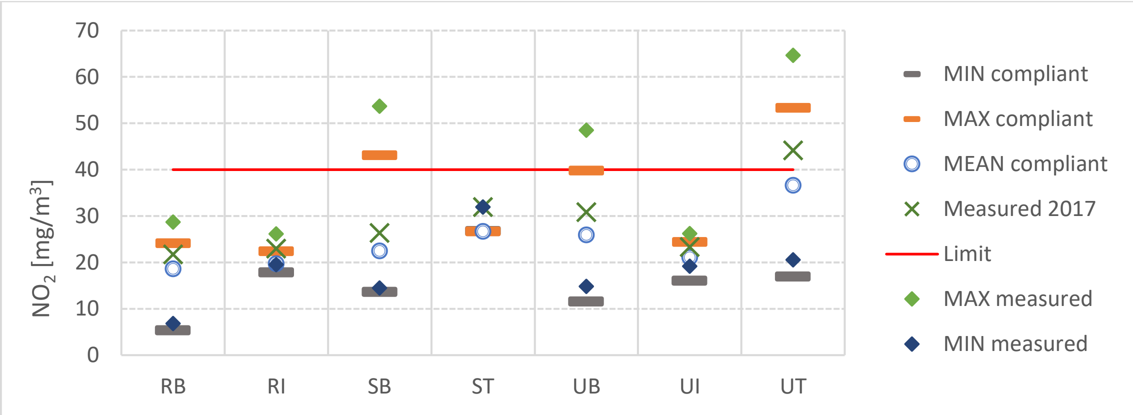

Figure 6-6: Projection of the annual average NO_2 concentration and its variability, under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by monitoring station category (UT = Urban Traffic; UB = Urban Background; UI = Urban Industrial; ST = Suburban Traffic; SB = Suburban Background; SI = Suburban Industrial; RB = Rural Industrial; RI = Rural Industrial monitoring station).

Concentration data grouped by category of monitoring stations, show that, as expected, the higher concentration is observed in traffic monitoring stations of urban areas. Traffic stations are those coincident with cells of the model grid that include principal roads from the Lombardy road network and are shown in *Figure 4-1*. This data shows that in areas with high NO_X emissions, so with higher NO_2 concentration, road traffic gives a large contribution.

NO$_2$ - 2017 measured and estimated data						
	Estimated			Measured		
Provinces	Annual average minimum	Annual average maximum	Annual mean	Annual average minimum	Annual average maximum	Annual mean
BG	18	41	27	21	50	31
BS	20	53	28	23	62	33
CO	21	40	27	26	49	34
CR	18	38	25	21	44	30
LC	5	36	22	7	43	26
LO	20	31	25	25	37	30
MB	36	43	39	46	54	49
MI	19	53	36	23	65	44
MN	14	32	19	14	33	21
PV	18	39	24	20	47	27
SO	12	22	17	15	27	21
VA	18	32	26	22	39	31

Table 6-1: Numerical data of the projection of NO_2 concentration and its variability, under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by provinces.

The spatial distribution of improvements in air quality under the compliant scenario is shown in *Figure 6-7*. Significant reductions of the annual average NO_2 concentration are identified in the area mostly interested by linear traffic conditions, which is also the area with the highest NO_2 concentrations measured by the monitoring stations. Therefore, the area with the highest reduction is the Milan agglomeration and the principal motorways South and East of it. A significant reduction is also observed in all the highly urbanized plane and in the rural plane, in which a higher improvement bordering the main roads and motorways is observable. Conversely, almost no difference is observed in the northern mountainous area, while it is registered for the valley floors of zone D.

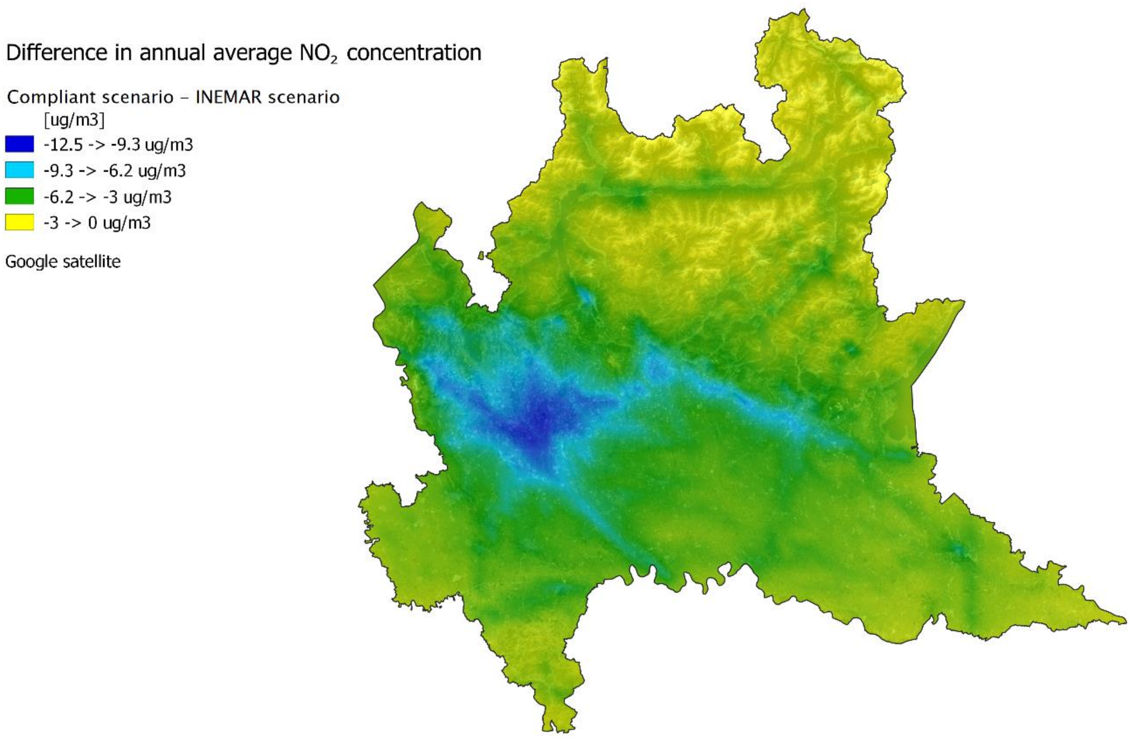

Figure 6-7: Map of the variation of annual average NO_2 concentration (µg/m^3) between the compliant scenario and the INEMAR scenario

6.2.2. Ozone

For ozone, the projection of the scenario generates an increase of the regional average by +2.5%. This parameter is highly variable in time and space; in the following, we evaluate the effect on parameters regulated by EU legislation.

Target value for the protection of human health

In Lombardy ozone concentration registers high values all around the region, and none of the 53 stations monitoring O_3 concentrations, measures values within the target of 120 µg/m^3. Indeed, in 2017 the number of days exceeding the target is at least four times the maximum acceptable (25 per year). With the projections estimated for the compliant scenario, all the monitoring station for ozone would still register a number of exceedances above the target value. Numerical data grouped by provinces are reported in *Table 6-2*.

For this pollutant, the projection of the scenario generates a regional average increase of +3%, with different results in different areas of the region. Ozone exceedances increase in the most urbanized area especially nearby urban traffic (UT) stations, where the estimated reduction of NO_X emissions attributed to road transport and therefore the reduction of NO_2 concentration, is the highest. The NO_X reduction interferes in the reaction of O_3 destruction carried out by NO, contributing to the ozone accumulation. In the mountainous area (zone C) and valley floors (zone D), instead, a reduction of ozone target value exceedances is estimated, respectively by 24% and 13% of the value registered in the named areas. The described trend is observable in the graphs in *Figures from 6-8 to 6-10*. In Sondrio province (SO) road traffic gives low contribution to the production of ozone precursors, for this reason ozone production is NO_X limited. For this reason, even a small reduction in NO_X concentration strongly influences the ozone production.

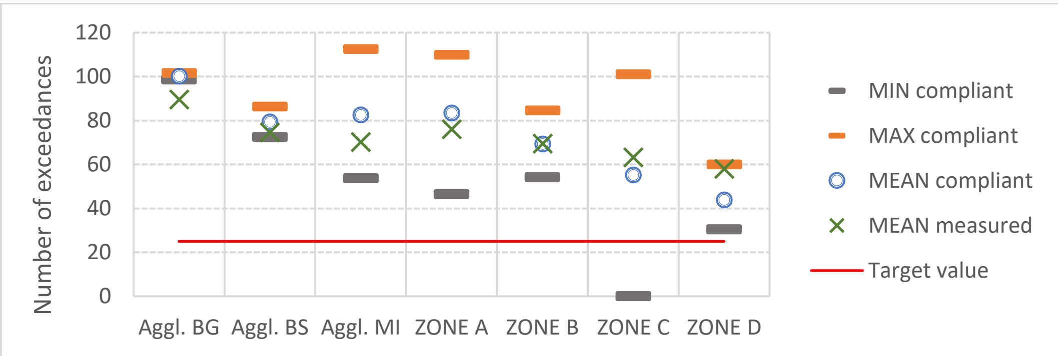

Figure 6-8: Projection of the annual average number of days of target value exceedances, calculated as the maximum on 8h moving average, under the compliant scenario. Data collected in the monitoring stations of the air quality monitoring network, grouped by areas.

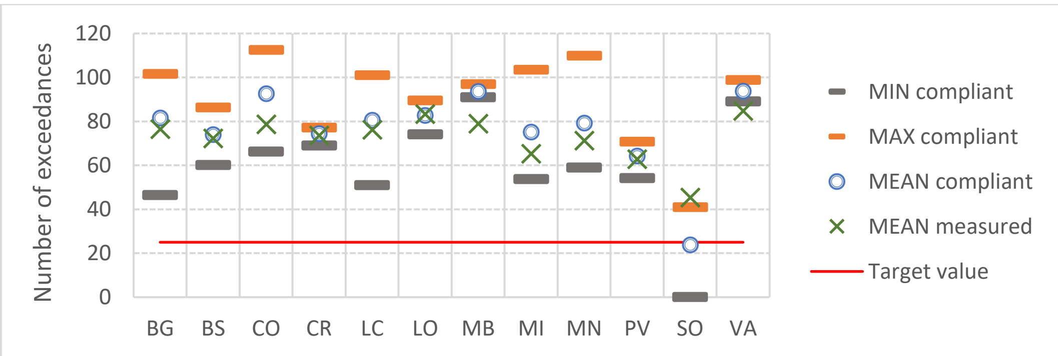

Figure 6-9: Projection of the annual average number of days of target value exceedances as the maximum on 8h moving average under the compliant scenario. Data collected in the monitoring stations of the air quality monitoring network, grouped by provinces.

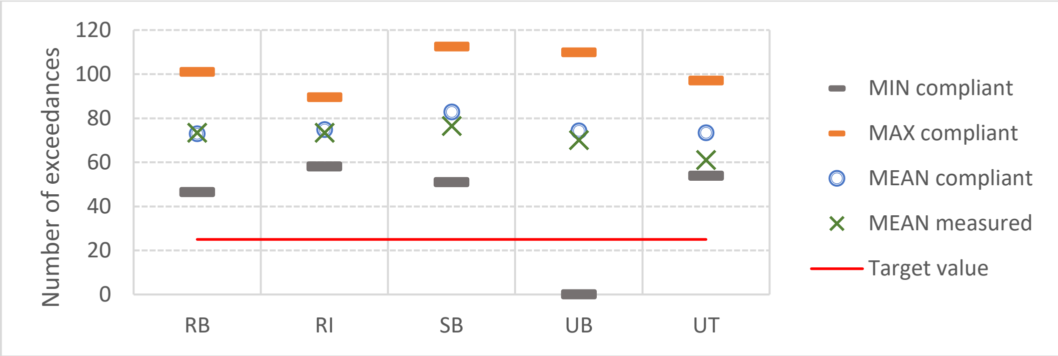

Figure 6-10: Projection of the annual average number of days of target value exceedances, as the maximum on 8h moving average, under the compliant scenario. Data collected in the monitoring stations of the air quality monitoring network, grouped by monitoring station category (UT = Urban Traffic; UB = Urban Background; UI = Urban Industrial; ST = Suburban Traffic; SB = Suburban Background; SI = Suburban Industrial; RB = Rural Industrial; RI = Rural Industrial monitoring station).

O_3 max mobile average on 8h - 2017 measured and estimated data						
	Estimated			Measured		
Provinces	Annual average minimum	Annual average maximum	Annual mean	Annual average minimum	Annual average maximum	Annual mean
BG	46	102	82	43	90	77
BS	60	86	74	62	82	72
CO	66	113	93	57	91	79
CR	69	77	74	71	76	74
LC	51	101	81	58	101	76
LO	74	90	83	73	90	83
MB	91	97	94	78	80	79
MI	54	104	75	43	86	65
MN	59	110	79	58	78	71
PV	54	71	64	52	72	63
SO	0	41	24	24	59	45
VA	89	99	94	80	91	85

Table 6-2: Projection of the annual average number of days of target value exceedances for ozone (120 µg/m³), calculated as the maximum on 8h moving average, under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by provinces.

In the map reported in *Figure 6-11* it is visible the spatial distribution of the variation in the annual number of ozone exceedances. As we have seen above in the graphs in *Figures from 6-8 to 6-10* the urbanized areas show an increase. Even if is not perceivable with the average of the zone B, the rural south-east part of the region shows a very slight decrease of approx. 0.2%. On the other hand, a reduction is registered in the pre-Alps area, which is particularly high in the mountainous area in the north of the region. Significant reductions of ozone exceedances are registered around the valley floor of Sondrio province as mentioned above.

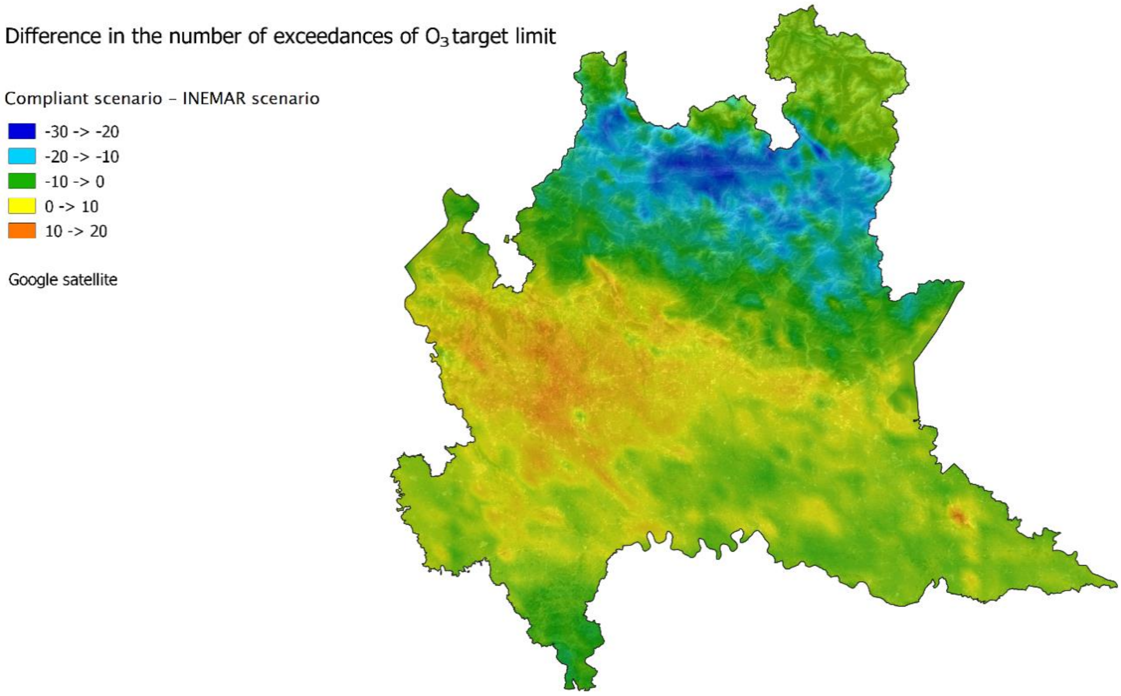

Figure 6-11: Map of the variation of number of exceedances of 120 µg/m³, calculated on the 8h moving average, between compliant and INEMAR scenarios.

Target limit for the protection of vegetation

AOT40 is an excess indicator for the protection of vegetation (Accumulated Ozone exposure over a Threshold of 40 ppb). Its target value is 18,000 µg/m³·h and it is calculated as the sum of the differences between hourly ozone concentration and 40 ppb (80 µg/m³), for each hour between 8.00 AM and 8.00 PM when the concentration exceeds 40 ppb, from the 1st May to the 31st July, averaged over five years.

Estimated values of AOT40 show that, as for the ozone indicator for the protection of human health, the compliant scenario produces a regional average slight increase of the AOT40 levels (+1%). As shown in *Figure 6-12*, the compliant scenario generates increasing values in the urban agglomerations and in the highly urbanised plain (zone B). They span from +12% in the agglomeration of Milan, +7% in the agglomeration of Bergamo, +1% in the agglomeration of Brescia, and +2% in the zone B. These quantities are in the orders of few tenths of µg/m³ compared to the regional average value.

Figures from 6-12 to 6-14, show the variation obtained by the compliant scenario in all the different areas of the region: even if variations in the AOT40 absolute values do constitute only a small fraction of the observed values, they are not negligible. In the regional map in *Figure 6-15* we can see that, under the compliant scenario, the rural area of the Po valley and the mountainous area in the north of the region benefit from an exposure to lower concentrations of ozone. A peak of reduction is estimated again in the valley of Sondrio.

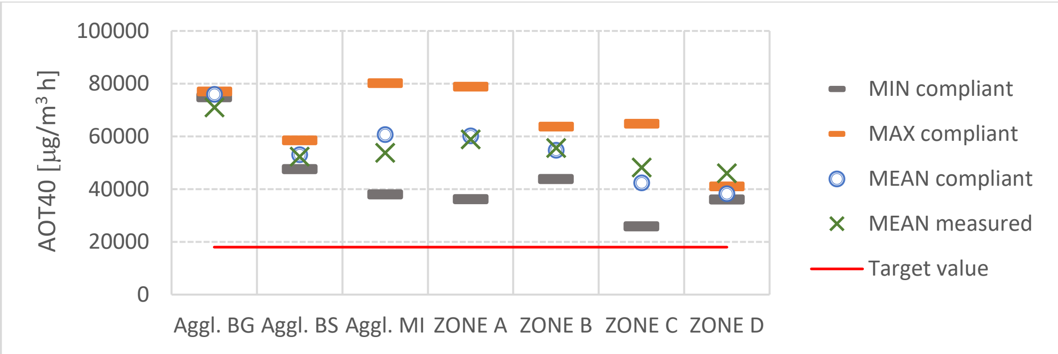

Figure 6-12: Projection of average AOT40 (µg/m³·h) under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by areas.

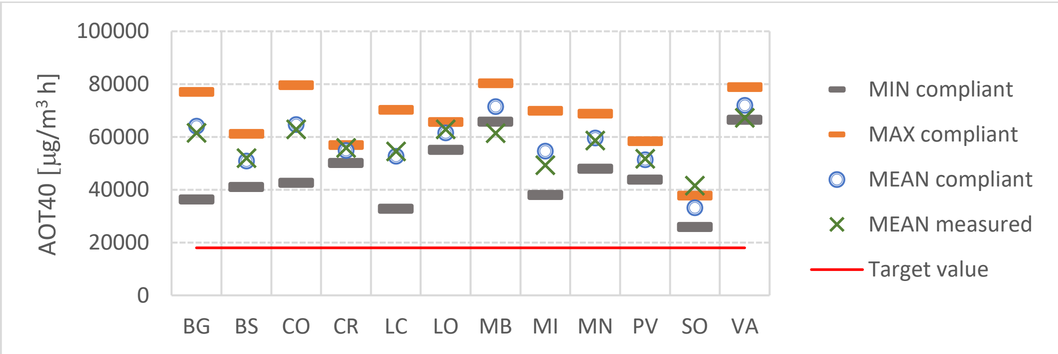

Figure 6-13: Projection of average AOT40 (µg/m³·h) under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by provinces.

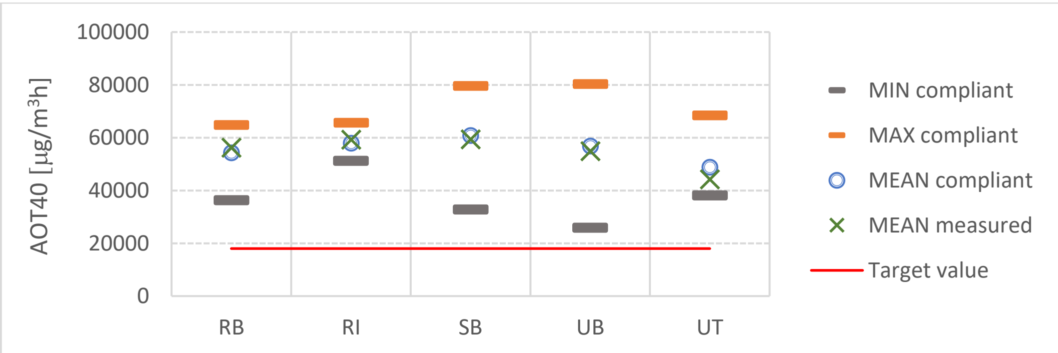

Figure 6-14: Projection of average AOT40 (µg/m³·h) under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by monitoring station category (UT = Urban Traffic; UB = Urban Background; UI = Urban Industrial; ST = Suburban Traffic; SB = Suburban Background; SI = Suburban Industrial; RB = Rural Industrial; RI = Rural Industrial monitoring station).

AOT40 - 2017 measured and estimated data						
	Estimated			Measured		
Provinces	Annual average minimum	Annual average maximum	Annual mean	Annual average minimum	Annual average maximum	Annual mean
BG	36,231	77,126	64,152	35,253	71,283	61,509
BS	41,034	61,181	50,855	46,082	63,061	52,010
CO	42,647	79,641	64,750	40,963	76,137	62,859
CR	50,054	56,955	54,938	51,774	58,640	55,823
LC	32,786	70,226	52,758	37,754	71,949	54,489
LO	55,088	65,712	61,519	55,979	66,764	62,895
MB	65,743	80,288	71,482	56,361	67,304	61,391
MI	38,033	69,928	54,597	30,830	65,052	49,265
MN	47,871	68,801	59,669	47,914	63,182	58,612
PV	43,780	58,375	51,377	42,582	59,303	51,769
SO	25,875	37,829	33,238	32,623	46,783	41,546
VA	66,438	78,879	72,006	63,703	74,234	67,233

Table 6-3: Projection of the annual average AOT40, under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by provinces.

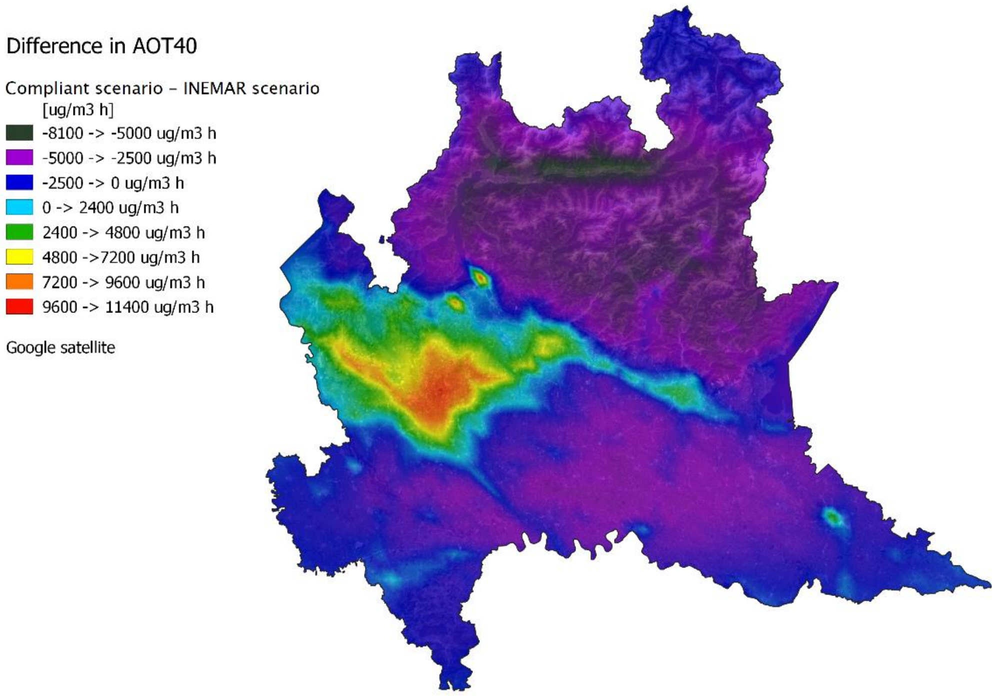

Figure 6-15: Map of the variation of annual average AOT40, between compliant and INEMAR scenarios.

Ozone information and alarm thresholds.

For the protection of human health, the Legislative Decree 155/2010 also sets an information threshold of 180 µg/m^3 and an alarm threshold of 240 µg/m^3, both as hourly average concentration. These limits are intended to identify peaks of concentrations in short periods and to protect people from short-period exposure to elevated O_3 concentrations.

Due to the importance of these parameters for human health, we decide to monitor the variations obtained applying the compliant scenario on an hourly basis. Under the modelled scenario, the number of hours the O_3 information threshold is exceeded decreases by an average of 20% all over the region, with an increase only in the agglomeration of Milan, in particular in Monza e Brianza province (MB) (see in *Table 6-4*).

Hours of O_3 alert threshold exceedance are not registered all over the region, and, moreover, with the scenario a decreasing trend is estimated. Values are reported in *Table 6-5*.

O_3 information threshold - 2017 measured and estimated data						
	Estimated			Measured		
Provinces	Annual average minimum	Annual average maximum	Annual mean	Annual average minimum	Annual average maximum	Annual mean
BG	6	140	88	7	162	102
BS	26	48	38	48	72	58
CO	36	146	93	39	157	109
CR	13	35	24	20	50	36
LC	4	130	63	21	143	89
LO	8	25	18	13	39	30
MB	103	134	115	88	113	103
MI	-	104	24	-	113	26
MN	4	47	28	6	62	35
PV	4	15	9	6	27	14
SO	-	28	9	-	44	24
VA	79	98	87	89	106	96

Table 6-4: Projection of the number of hours of exceedance of O_3 information threshold, under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by provinces.

O_3 alarm threshold - 2017 measured and estimated data						
	Estimated			Measured		
Provinces	Annual average minimum	Annual average maximum	Annual mean	Annual average minimum	Annual average maximum	Annual mean
BG	-	8.4	4.2	-	11	4.5
BS	-	2.5	0.5	-	5	1.0
CO	-	2.9	1.3	-	7	3.3
CR	-	-	-	-	-	-
LC	-	3.6	1.3	-	5	1.7
LO	-	-	-	-	-	-
MB	2.4	8.0	5.5	4.0	6	4.7
MI	-	3.5	0.4	-	3	0.4
MN	-	-	-	-	-	-
PV	-	-	-	-	-	-
SO	-	-	-	-	-	-
VA	-	1.9	1.1	-	3	2.0

Table 6-5: Projection of the number of hours of exceedance of O3 alert threshold, under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by provinces.

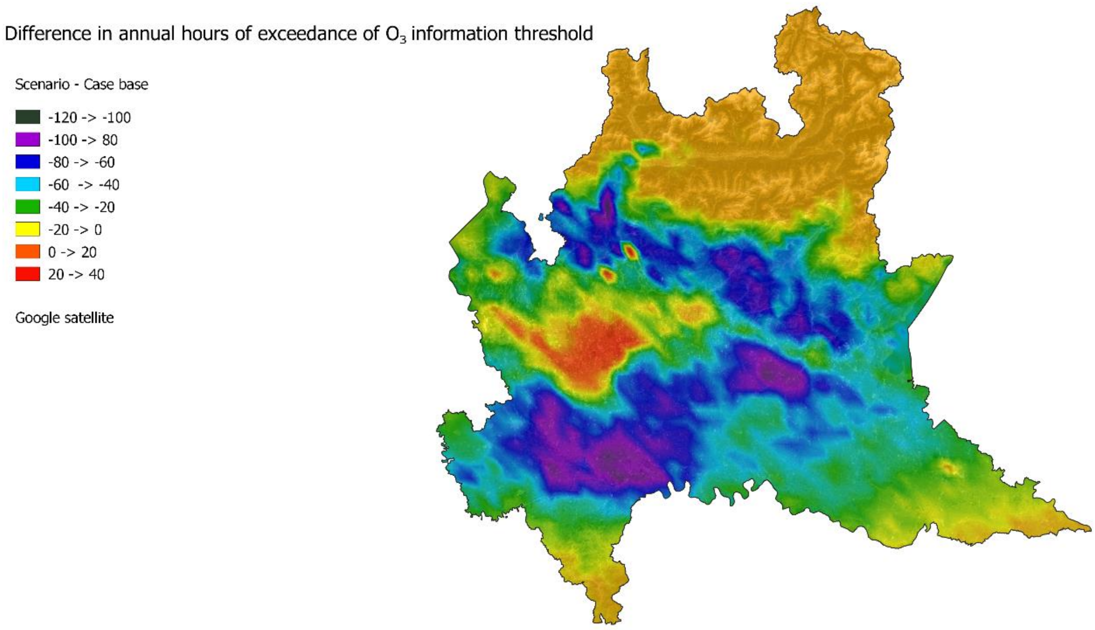

Figure 6-16: Map of the variation in the number of hours of exceedance of O_3 information threshold, between the compliant and INEMAR scenarios

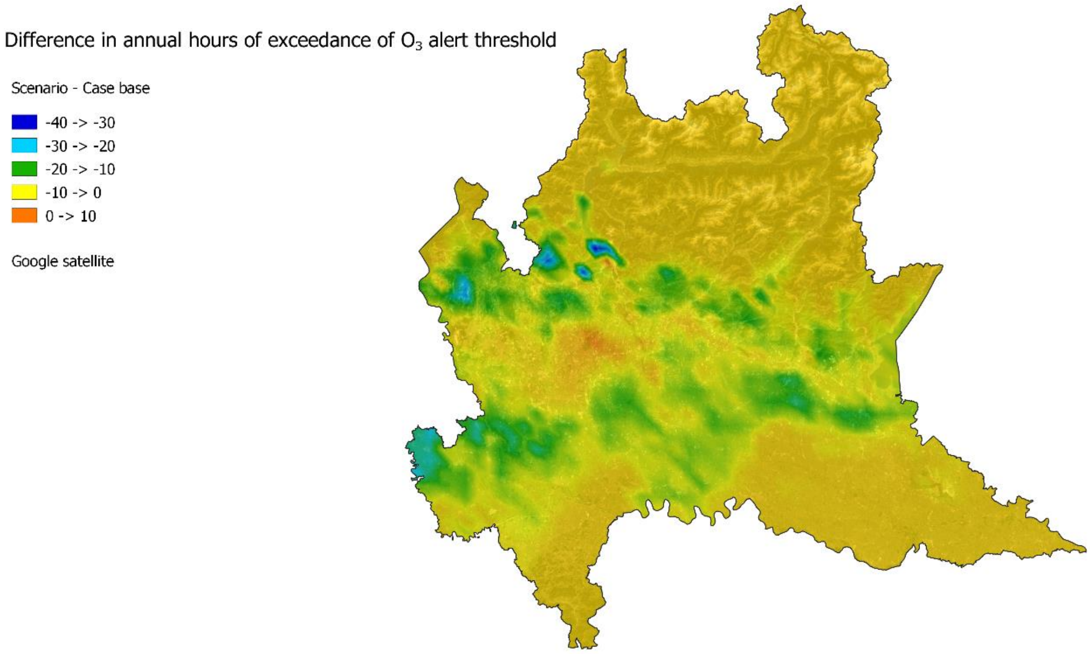

Figure 6-17: Map of the variation in the annual number of hours of exceedance of O_3 alert threshold between the compliant and INEMAR scenarios

6.2.3. Particulate matter

The applied compliant scenario generates for both PM10 and PM2.5 annual average a reduction of 0.8% regional average. As mentioned above, the limitation on vehicles emissions due to the applied scenario does not cause any variation of primary particulate matter emissions. Thus, the lower particulate matter concentration estimated is only due to the reduction of the secondary fraction because associated with the reduced emission of gaseous precursors from traffic.

PM10 annual average concentration, which is already below the limit of 40 µg/m^3, has a slight decrease, in orders of few tenths µg/m^3 , corresponding to -0.8%, more evident in the rural area of the Po valley, in the north mountainous area of Pre-Alps, and the valley floor of Sondrio. Numerical values are presented in *Table 6-6.*

PM10 - 2017 measured and estimated data						
	Estimated			Measured		
Provinces	Annual average minimum	Annual average maximum	Annual mean	Annual average minimum	Annual average maximum	Annual mean
BG	31.0	39.6	35.1	31	40	35.2
BS	32.1	42.4	36.4	32	43	36.6
CO	19.8	34.2	27.8	20	34	28.0
CR	37.3	41.6	40.2	38	42	40.5
LC	16.5	38.6	26.9	17	39	27.2
LO	34.8	41.0	36.8	35	41	37.2
MB	32.5	39.3	36.4	33	39	36.4
MI	29.3	61.2	39.0	29	61	39.0
MN	32.2	39.1	35.0	32	39	35.2
PV	31.0	40.9	35.0	31	41	35.1
SO	12.4	24.3	20.4	13	25	20.6
VA	28.2	34.6	30.5	28	35	30.5

Table 6-6: Projection of the number of daily PM10 exceedances data, under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by provinces

The variation of PM2.5 average concentration presents a similar pattern, but it does not respect the limit of 25 µg/m^3, except for the mountainous area. Numerical values are present in *Table 6-7*. Both maps in *Figure 6-18* and *6-19*, show a slight increase of particulate matter concentration in the agglomerated of Milan, which includes Milan and Monza e Brianza provinces. Less relevant changes are present in the area next to the boundary because pollutants concentration in there is influenced by those of the bordering regions, for which we have not simulated the emissions under the compliant scenario.

PM2.5 - 2017 measured and estimated data						
	Estimated			Measured		
Provinces	Annual average minimum	Annual average maximum	Annual mean	Annual average minimum	Annual average maximum	Annual mean
BG	22.6	28.7	24.8	23	29	24.8
BS	25.8	29.2	27.1	26	29	27.2
CO	26.7	26.7	26.7	27	27	26.9
CR	26.5	31.3	29.8	27	32	30.0
LC	12.8	25.5	18.4	13	26	18.6
LO	22.1	26.8	24.5	22	27	24.7
MB	29.5	29.5	29.5	29	29	29.4
MI	26.9	29.1	28.2	27	29	28.2
MN	25.5	27.8	26.9	26	28	27.0
PV	23.5	26.1	25.0	24	26	25.1
SO	10.0	19.5	14.7	10	20	14.9
VA	21.8	23.3	22.6	22	23	22.6

Table 6-7: Projection of the annual average PM2.5 concentration data, under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by provinces.

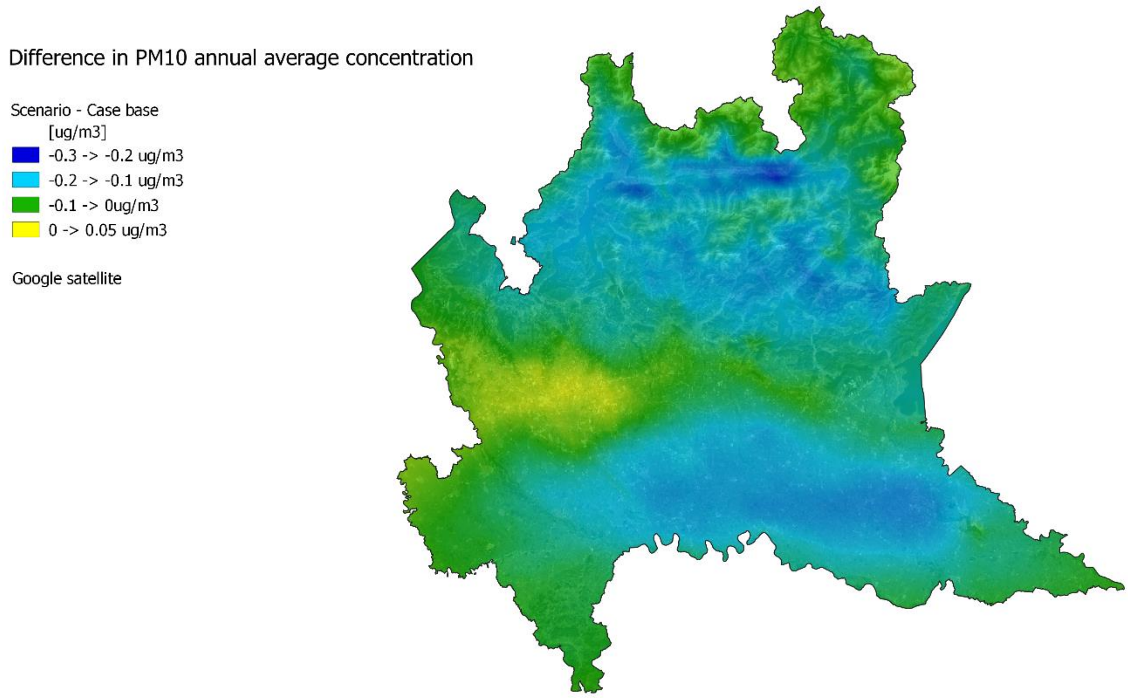

Figure 6-18: Map of the variation of PM10 annual average concentration data, between compliant and INEMAR scenarios

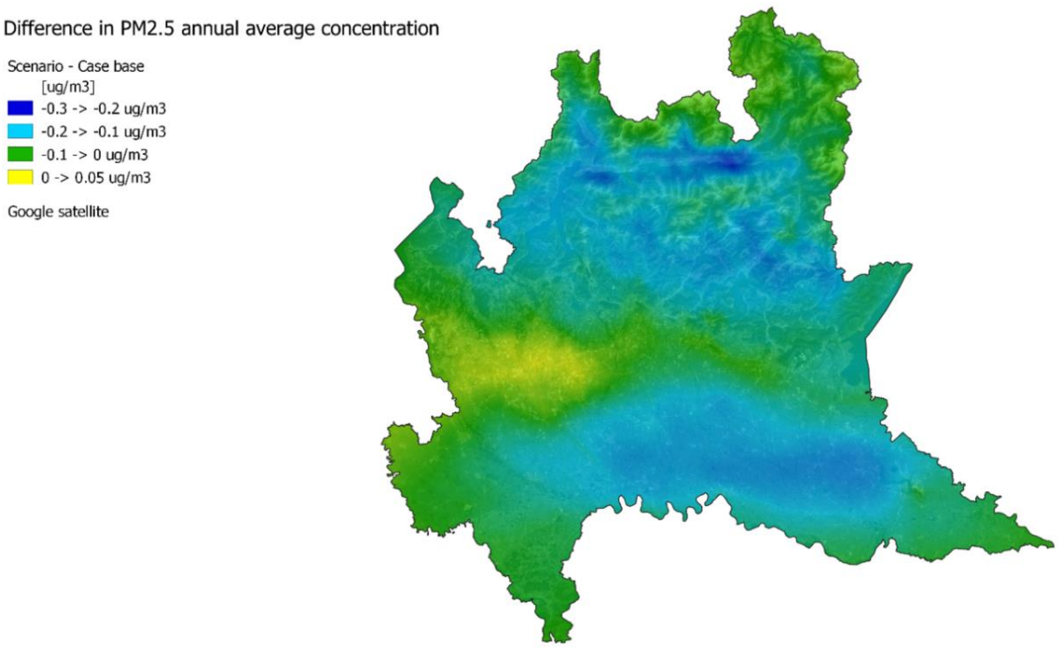

Figure 6-19: Map of the variation of PM2.5 annual average concentration data, between compliant and INEMAR scenarios

The average daily concentration of PM10 is above the limit value of 50 µg/m^3 for a large number of days and the projection of the scenario shows small variations in the number of these exceedances with some reduction in the rural area and some increase in urban and industrial area, in particular in Brescia province (*Figure 6-20*).

PM10 exceedances - 2017 measured and estimated data						
	Estimated			Measured		
Provinces	Annual average minimum	Annual average maximum	Annual mean	Annual average minimum	Annual average maximum	Annual mean
BG	46	93	70	14	93	71
BS	58	168	93	0	86	77
CO	14	68	48	60	90	45
CR	58	200	96	58	101	95
LC	0	65	14	20	101	42
LO	37	116	70	60	94	84
MB	75	103	90	87	104	85
MI	11	111	75	41	81	72
MN	42	88	59	32	100	74
PV	60	101	82	6	83	82
SO	0	20	14	72	103	14
VA	0	68	29	9	87	52

Table 6-8: Projection of the annual average PM10 concentration data, under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by provinces

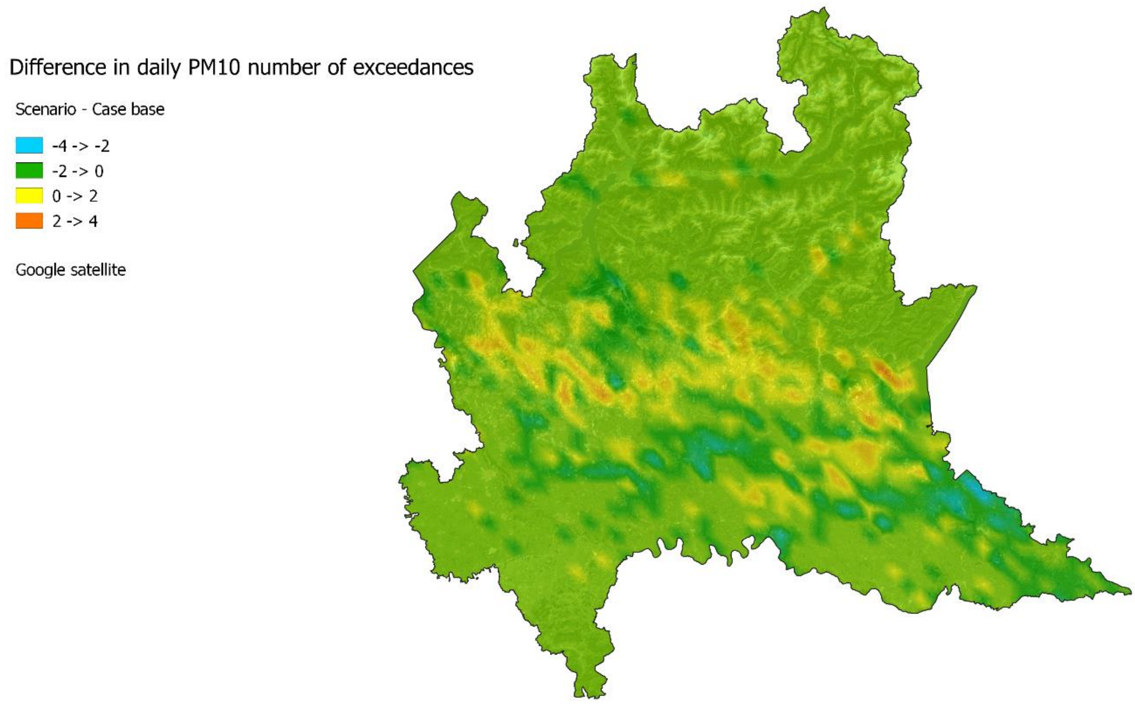

Figure 6-20: Map of the variation of the annual number of PM10 exceedances between compliant and INEMAR scenarios

Particulate matter composition

Under the compliant scenario the reduced emission of the gaseous precursors affects the PM mass composition.

According to model simulation for the INEMAR scenario (*Figure 3-9*), Carbon constitutes 40% of the mass of PM10 in Lombardy; 85% of such carbon is organic. However, variations of total carbon contribution among the different areas of the region are registered, with a peak of 60% in Sondrio province (zone D) and 34% in the rural Po valley (zone B). The secondary inorganic aerosol fraction is composed by sulphate (8%), nitrate (19%) and ammonium (7.5%) and these fractions are variable among different areas of the region too. Variations in particulate matter composition among the region, are due to the different activities generating it. In the mountainous area the main contribution to particulate matter production is due to non-industrial combustion (80% in Sondrio province), therefore particulate matter presents a higher content of carbon. The rural area (zone B) instead, has higher concentrations of SIA in air than the rest of the region.

The graph in *Figure 6-25* shows the variation of some components of particulate matter, caused by the applied scenario. On the average, it is visible a small reduction of nitrate (-0.4%) and ammonium (-0.1%) contribution, with an increase of organic carbon (+0.3%) and sulphate (+0.1%). Looking at SIA grouped by area in *Figure from 6-21 to 6-23*, it results that for sulphate, despite the average increase all over the region, in the mountainous area it is estimated an opposite trend, with a very slight decrease. In this area is also estimated a higher decrease of ammonium and nitrate compared to the regional average. The urban area of Milan registers the higher increase of sulphate, but it has the lower reduction of NH_4 and NO_3. This result is visible in the maps in *Figure from 6-21 to 6-23*.

SO_2 emissions have significantly decreased during the last decades, leading to year-round low concentrations recordings, so it is of major interest to understand the potential PM concentration reduction reachable through NO_X and ammonia emission limitation policies (Angelino et al., 2013).

The spatial distribution of the reduction in the sum of nitrate and ammonium is visible in the map in *Figure 6-25*. The areas more interested in this reduction are the rural area in the south part of the region and the mountainous area in the north. As mentioned above, these areas have different characteristics in terms of emission of particulate matter and so in terms of composition of the secondary particulate matter itself. They represent respectively the areas with the highest and the lowest concentration of ammonium nitrate NH_4NO_3.

As the main precursors of this pollutant are nitrogen oxides NO_X and ammonia NH_4, we can individuate a distinction between the rural and urban areas as the NO_X limited and NH_4 limited areas in NH_4NO_3 production, respectively. Indeed, the reduction of ammonium nitrate obtained applying the scenario, limits the production of ammonium nitrate in the NO_X limited rural area, while does not affect its production in the most urbanized area. The northern mountainous area has instead limited amounts of both nitrogen oxides and ammonia, so the reduction of one of the two reactants inhibits ammonium nitrate formation reaction. In this area the contribution to particulate matter reduction is estimated as reduction in all its components, also including the organic carbon.

The registered increase of sulphate amount is not due to an increase in sulphur emissions, but it can be due to the increase of hydroxyl radicals HO generated by the reduction of NO_X. HO reacting with VOC and SO_2, promotes the formation of secondary organic aerosol SOA and SO_4^{2-} (Angelino, et al., 2013).

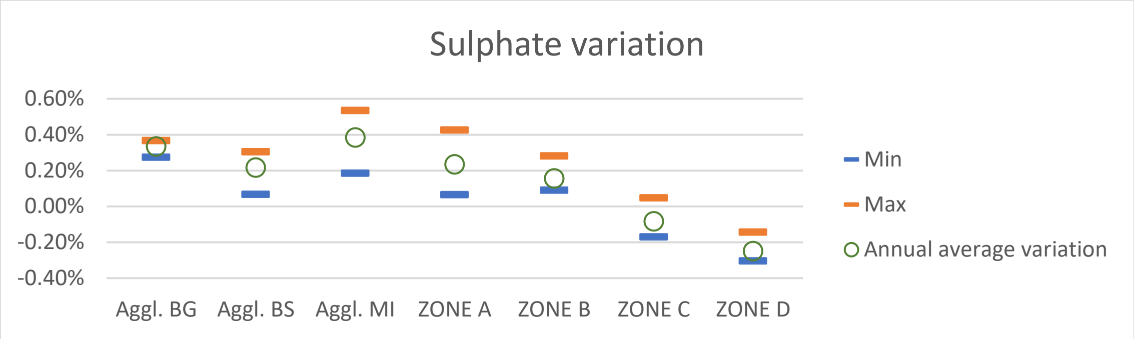

Figure 6-21: Graph representing percentage variation of sulphate composing PM10, under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by area.

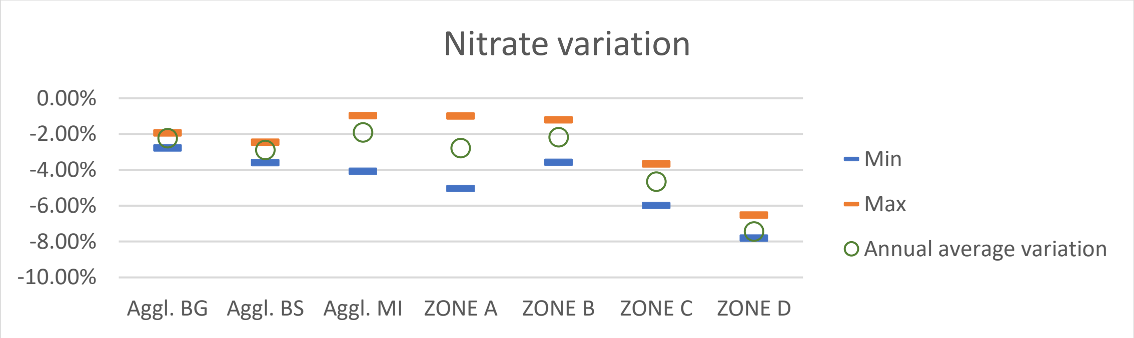

Figure 6-22: Graph representing percentage variation of nitrate composing PM10, under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by area.

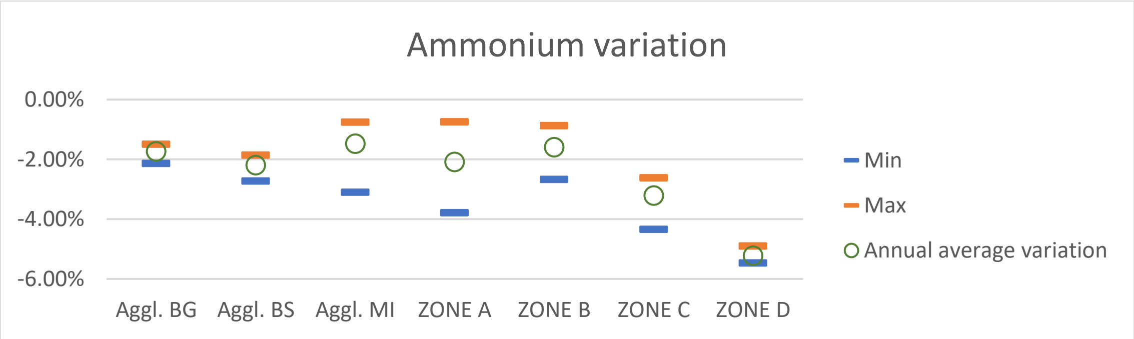

Figure 6-23: Graph representing percentage variation ammonium composing PM10, under the compliant scenario, in the monitoring stations of the air quality monitoring network, grouped by area.

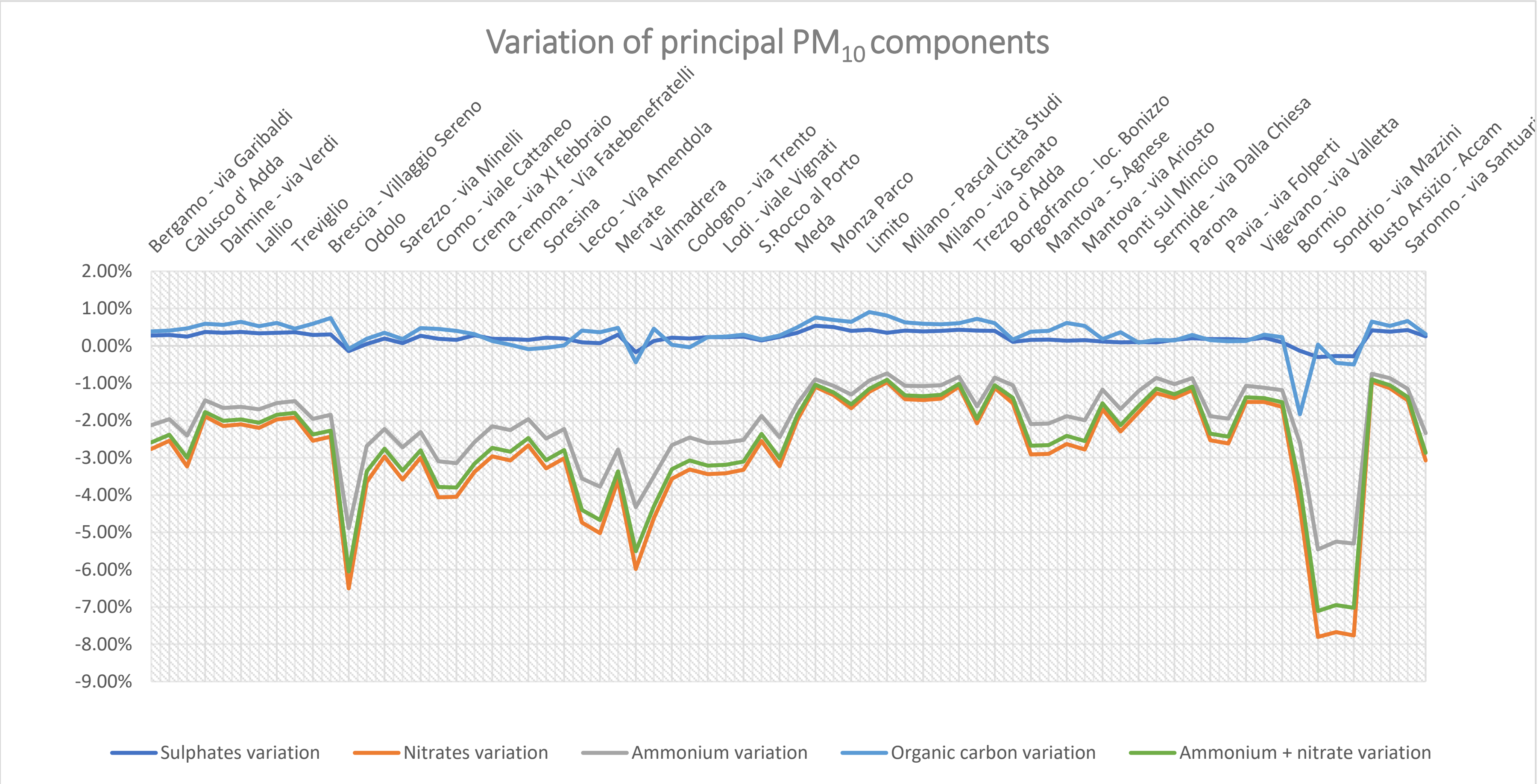

Figure 6-24: Graph of PM10 components percentage variation, under the compliant scenario, in the monitoring stations of the air quality monitoring network. Components represented are organic carbon, sulphate (SO_4), nitrate (NO_3), and ammonium (NH_4).

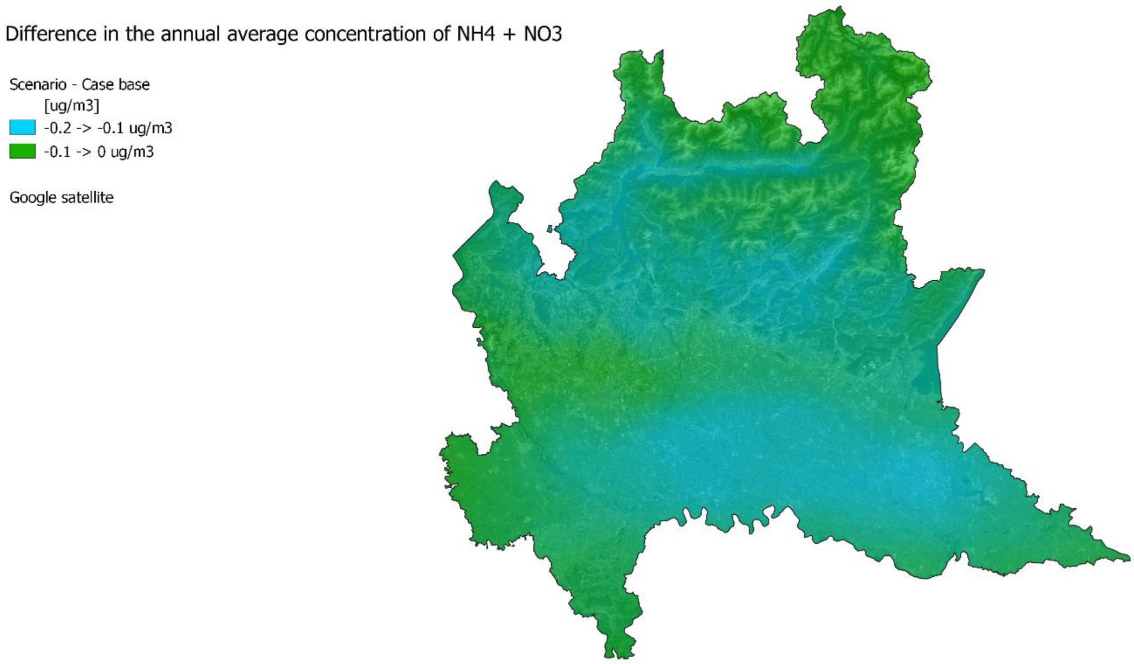

Figure 6-25: Map of the variation of NH_4+NO_3 annual average concentration data between the compliant and the INEMAR scenarios

7

CONCLUSIONS

This study assessed the impact on air quality in Lombardy of the excess of pollutant emissions from passenger cars and light duty vehicles compared with EU type approval limits.

The road transport sector contributes in particular to the production of pollutants such as nitrogen oxides, particulate matter, and ozone. For this reason, the evaluation of air quality is focused on these pollutants, their limits and target values.

Compliant emission scenario

This study examines the vehicular fraction composed of passenger cars, light duty vehicles, mopeds, and motorcycles, for which the limit is expressed as mass of pollutant per unit distance travelled. Heavy duty vehicles and buses are not included, since emission limit for this vehicle category is expressed in mass of pollutant per unit of power supplied by the engine (g/kWh) and for this reason they are affected by an additional degree of uncertainty. Further studies can be carried out for this category.

Comparisons between emission factors of light vehicles from the INEMAR inventory of Lombardy and the EU limit values for NO_X, CO, PM10, VOC, and NMVOC, reveal that in 2017 the non-compliance of light vehicles emissions with EU type approval limits generated significant excess of NO_X emissions and this excess was almost totally due to diesel passenger cars and light duty vehicles. The surplus of NO_X accounts for the 36.6% of the total NO_X emitted by the road traffic that corresponds to 18.6% of the total NO_X emitted by all activities in Lombardy. These excess emissions are differently distributed across the territory and are mainly due to the more recent Euro 5 and Euro 6 vehicles. The more urbanized area and the area adjacent to principal motorways register higher reductions than the rest of the region due to its high traffic density. The other pollutants also show excess emissions, even if in lower amounts. CO exceeds the limit by a factor of 10% but only half of this quantity is due to cars and LDV while the other half is produced by motorcycles. VOC and NMVOC exceed the limit by a factor of 0.5% and 0.6% respectively. Primary PM10 generated by combustion, instead, exceeds the limit only by a very small factor that becomes negligible when added together with evaporative and wear emissions. For all these pollutants the excess emission becomes negligible when compared with the total pollutant emitted by all sectors in the region.

Effect on air quality

Modelling air quality under the compliant scenario, we find variations in the ambient concentration levels for the most concerning pollutants in Lombardy, that are NO_2, O_3, and PM10 show different behaviour.

The consistent reduction of NO_X emissions generates 16% reduction in the average annual concentration of NO_2 that is more relevant in the urban agglomeration of Milan and lower in the rest of the region. The number of monitoring stations measuring an average annual NO_2 value above the limit decreases with the scenario from 23 to 8. The remaining stations still registering an annual average above the limit for this pollutant are urban traffic stations for the most. All of the areas in which the region is divided register an average annual concentration below the limit.

Ozone annual average concentration increases by 2.5%, resulting in an increase of the exceedances of the limit for human health (+3%) and AOT40 for the protection of vegetation (+1%). Therefore, exceedances of alarm and information thresholds are reduced. The ozone concentration increases in high NO_X emitting areas and decreases in areas with less NO_X production. This reduction is evident especially in the mountainous area and the valley of Sondrio, the areas in Lombardy the areas where NO_X is less produced. PM10 and PM2.5 average concentration is reduced by 0.8%. PM10 shows a variation in the fine SIA fraction concentration, which is reduced in the rural and mountainous areas. A deeper analysis of the SIA fraction shows as the variation is driven by the variation of NH_4NO_3 which is influenced by the concentration of ammonia, produced in high quantities in the rural area.

A comparison with EU limits and target values shows that the compliant scenario allows to achieve the limit value for the annual average concentration of NO_2 in all the areas under exam.

The compliant scenario reveals how excesses in NO_X emissions due to passenger cars and light duty vehicles, affect air quality contributing to the noncompliance with air quality limits and target values required by the European regulation.

7.1. Further research

This study is based on emission data concerning passenger cars, light duty vehicles, mopeds, and motorcycles. Given the large contribution that heavy duty vehicles and buses give to the overall diesel vehicle fleet, it could be interesting to evaluate a study concerning the contribution given by the latter.

Further considerations can be done starting from the results obtained on the effect that the excess emissions of these pollutants have on health and on the environment. More than 60,000 premature deaths have been associated with the current PM2.5 and ozone concentrations in Italy in 2016 (EEA, 2019). Due to its large population and high share of diesel cars in the national fleet, Italy is the country in Europe with the highest number of premature deaths attributed to PM2.5 and ozone induced from light vehicles (Jonson et al., 2017). It would therefore important, as a follow up study to use the current to estimate the contribution that excess emissions generated by the diesel fleet circulating in Lombardy give to the number of premature deaths, thus estimating the damage in terms of human lives.

Finally, the behaviour of ozone and secondary particulate matter are noteworthy. Further investigations with more detailed considerations including thermodynamics and kinetics of the chemical reactions could be done.

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APPENDIX A

List of monitoring stations.

Station ID	Zone	Monitoring station	Province	Type	NO_X	O_3	PM10	PM2.5
584	Agglomeration of Bergamo	Bergamo - via Garibaldi	BG	UT	X		X	
583	Agglomeration of Bergamo	Bergamo - via Meucci	BG	UF	X	X	X	X
1269	Agglomeration of Bergamo	Dalmine - via Verdi	BG	UT	X		X	X
595	Agglomeration of Bergamo	Filago - via Don Milani	BG	UF	X		X	
597	Agglomeration of Bergamo	Lallio	BG	UT	X		X	
596	Agglomeration of Bergamo	Osio Sotto	BG	SF	X	X	X	
592	Agglomeration of Bergamo	Treviglio	BG	UT	X		X	X
649	Agglomeration of Brescia	Brescia - Broletto	BS	UT	X	X	X	X
652	Agglomeration of Brescia	Brescia - via Turati	BS	UT	X			
669	Agglomeration of Brescia	Brescia - Villaggio Sereno	BS	UF	X	X	X	X
661	Agglomeration of Brescia	Rezzato	BS	SI	X		X	
654	Agglomeration of Brescia	Sarezzo - via Minelli	BS	UF	X		X	
558	Agglomeration of Milan	Busto Arsizio - Accam	VA	SF	X	X	X	
565	Agglomeration of Milan	Cantù - via Meucci	CO	SF	X	X	X	
529	Agglomeration of Milan	Cinisello Balsamo	MI	UT	X			
561	Agglomeration of Milan	Como - viale Cattaneo	CO	UT	X	X	X	X
544	Agglomeration of Milan	Cormano	MI	UF	X	X		
531	Agglomeration of Milan	Limito	MI	UF	X	X	X	
542	Agglomeration of Milan	Meda	MB	UT	X	X	X	
576	Agglomeration of Milan	Merate	LC	UT	X	X	X	X
705	Agglomeration of Milan	Milano - Pascal Città Studi	MI	UF	X	X	X	X
528	Agglomeration of Milan	Milano - Verziere	MI	UT	X	X	X	
548	Agglomeration of Milan	Milano - via Senato	MI	RF			X	X
539	Agglomeration of Milan	Milano - viale Liguria	MI	UT	X			
674	Agglomeration of Milan	Monza - via Machiavelli	MB	UF	X	X	X	X
1374	Agglomeration of Milan	Monza Parco	MB	SF	X	X	X	
514	Agglomeration of Milan	Rho - via Statuto	MI	UF	X			
554	Agglomeration of Milan	Saronno - via Santuario	VA	UF	X	X	X	X
504	Agglomeration of Milan	Sesto S.Giovanni	MI	UT				
551	Zone A	Arconate (aria)	MI	SF	X	X		

685	Zone A	Calusco d' Adda	BG	SF	X	X	X	X
609	Zone A	Casirate d`Adda	BG	RF	X	X	X	X
690	Zone A	Casoni - AGIP	PV	UT		X	X	
683	Zone A	Cassano d'Adda 2 - Via Milano	MI	UT	X		X	
627	Zone A	Cremona - p.zza Cadorna	CR	UT	X		X	X
677	Zone A	Cremona - Via Fatebenefratelli	CR	UF	X	X	X	X
1303	Zone A	Cremona - via Gerre Borghi	CR	RF	X		X	
564	Zone A	Erba - via Battisti	CO	UF	X	X	X	
687	Zone A	Ferno	VA	UF	X	X	X	
574	Zone A	Lecco - Via Amendola	LC	UT	X		X	
706	Zone A	Lecco - Via Sora	LC	UF	X	X	X	X
1265	Zone A	Lodi - S. Alberto	LO	UF	X	X	X	X
600	Zone A	Lodi - viale Vignati	LO	UT	X		X	X
657	Zone A	Lonato	BS	UF	X	X		
546	Zone A	Magenta	MI	UF	X	X	X	
664	Zone A	Mantova - p.zza Gramsci	MN	UT	X		X	
670	Zone A	Mantova - S.Agnese	MN	UF	X	X	X	X
671	Zone A	Mantova - Tridolino	MN	RI	X		X	
663	Zone A	Mantova - via Ariosto	MN	UI	X		X	
601	Zone A	Montanaso	LO	RI	X	X	X	
643	Zone A	Pavia - p.zza Minerva	PV	UT	X		X	
642	Zone A	Pavia - via Folperti	PV	UF	X	X	X	X
516	Zone A	Robecchetto	MI	SF	X		X	
606	Zone A	S.Giuliano Milanese	MI	UT	X			
1297	Zone A	Spinadesco	CR	RI	X	X	X	X
604	Zone A	Tavazzano	LO	SF	X		X	
513	Zone A	Trezzo d`Adda	MI	SF	X	X	X	
517	Zone A	Turbigo	MI	UF	X		X	
679	Zone A	Valmadrera	LC	SF	X	X	X	
560	Zone A	Varese - via Copelli	VA	UT	X		X	X
552	Zone A	Varese - Vidoletti	VA	UF	X	X		
709	Zone A	Vigevano - via Valletta	PV	UF	X		X	
1266	Zone B	Bertonico	LO	RF	X	X	X	
697	Zone B	Borgofranco - loc. Bonizzo	MN	SF	X		X	X
608	Zone B	Codogno - via Trento	LO	UT	X		X	
672	Zone B	Cornale (Voghera Energia)	PV	RF	X	X		X
626	Zone B	Corte de Cortesi	CR	RF	X	X		
629	Zone B	Crema - via XI febbraio	CR	SF	X	X	X	
682	Zone B	Ferrera Erbognone - ENI	PV	RI	X	X		
656	Zone B	Gambara	BS	RF	X	X		
696	Zone B	Monzambano - campo sportivo	MN	SF	X			

707	Zone B	Mortara	PV	UF	X	X		X
545	Zone B	Motta Visconti (aria)	MI	SF	X	X		
701	Zone B	Ostiglia - via Colombo	MN	UF	X		X	
708	Zone B	Parona	PV	UI	X		X	
695	Zone B	Ponti sul Mincio	MN	SF	X	X	X	X
598	Zone B	S.Rocco al Porto	LO	SF	X		X	
693	Zone B	Sannazzaro de' Burgondi - AGIP	PV	UI	X		X	X
703	Zone B	Schivenoglia	MN	RF	X	X	X	X
704	Zone B	Sermide - via Dalla Chiesa	MN	SF	X		X	
633	Zone B	Soresina	CR	ST	X		X	X
665	Zone B	Viadana	MN	UF	X	X		
673	Zone B	Voghera - via Pozzoni	PV	UF	X	X	X	
571	Zone C	Bormio	SO	UF	X	X	X	X
573	Zone C	Colico	LC	SF	X	X		
681	Zone C	Moggio	LC	RF	X	X	X	X
659	Zone C	Odolo	BS	SF	X		X	
1274	Zone C	Perledo	LC	RF	X	X		
588	Zone C	Tavernola Bergamasca	BG	SI	X			
655	Zone D	Darfo (aria)	BS	SF	X	X	X	X
572	Zone D	Morbegno - via Cortivacci	SO	UF	X	X	X	
569	Zone D	Sondrio - via Mazzini	SO	UT	X		X	
1264	Zone D	Sondrio - via Paribelli	SO	UF	X		X	X

Legend:

UT = Urban Traffic monitoring station

UB = Urban Background monitoring station

UI = Urban Industrial monitoring station

ST = Suburban Traffic monitoring station

SB = Suburban Background monitoring station

SI = Suburban Industrial monitoring station

RB = Rural Industrial monitoring station

RI = Rural Industrial monitoring station

APPENDIX B

a) Statistical indicators used to quantify model performance

Statistical indicators reported in the specialized literature and technical reports of the European community (Thunis, Georgieva, & Pederzoli, 2011). N represents the number of data, O_i and M_i are the observed and simulated concentration at the time interval i.

Pearson (correlation coefficient)	$R = \frac{\sum_{i=1}^{N}(M_i - \bar{M})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{N}(M_i - \bar{M})^2}\sqrt{\sum_{i=1}^{N}(O_i - \bar{O})^2}}$
Normalized Mean Bias	$NMB = \frac{BIAS}{\bar{O}} = \frac{\bar{M} - \bar{O}}{\bar{O}}$
Normalized Mean Standard Deviation	$NMSD = \frac{\sigma_M - \sigma_O}{\sigma_O}$ where: $\sigma_O = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - \bar{O})^2}$ $\sigma_M = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - \bar{M})^2}$
Root Mean Square Error	$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - M_i)^2}$
Systematic RMSE	$RMSE_S = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\widehat{M}_i - O_i)^2}$
Unsystematic RMSE	$RMSE_U = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - \widehat{M}_i)^2}$
Index of Agreement	$IOA = 1 - \frac{N \cdot RMSE^2}{\sum_{i=1}^{N}(\lvert M_i - \bar{O}\rvert + \lvert O_i - \bar{O}\rvert)^2}$
Mean Fractional Bias	$MFB = \frac{1}{N}\sum_{i=1}^{N}\frac{M_i - O_i}{\left(\frac{M_i + O_i}{2}\right)}$

Mean Fractional Error	$MFE = \frac{1}{N}\sum_{i=1}^{N}\frac{\lvert M_i - O_i\rvert}{\left(\frac{M_i + O_i}{2}\right)}$

Pearson Coefficient (R): it measures the strength and sign of the linear correlation between an observed and simulated value; it takes values in [-1, 1], a value of 0 denotes no linear correlation between the variables. 1 denote perfect alignment of the time series.

Normalized Mean Bias (NMB): it measures the under or over estimation of the model with respect to the observed data; it is symmetric and a-dimensional; its optimal value is 1.

Normalized Mean Standard Deviation (NMSD): it measures the spread of the model predictions; it is also symmetric and a-dimensional; its optimal value is 0.

Root Mean Square Error (RMSE): provides a measure of the size of the average discrepancies between modelled and observed values. It is symmetric, non-negative, and has the dimensions of the variable of interest; its optimal value is 0.

Systematic e Unsystematic RMSE (RMSEs e RMSEu): in a good model the systematic component of the RMSE should be lower than the unsystematic component. Since RMSE2=RMSEs2+RMSEu2, a good model should be characterised by an RMSEs close to 0 and a RMSEu close to the RMSE.

Index of Agreement (IoA): an estimate of how much the model captures the fluctuations of the observed data with respect to the average. Its optimal value is 1.

Mean Fractional Bias (MFB): denotes the tendency of the model to over or under estimating. It's symmetric, dimensionless, with values in [-2,2], and optimal value 0. A good model (at an urban or regional scale) should be characterised by |MFB|<0.6 and R>0.4. The model is considered excellent if we find that |MFB|<0.3 and R≥0.5, simultaneously.

Mean Fractional Error (MFE): also denotes the tendency of the model to over or under estimating. However, it does not depend on the absolute values of the variables (simullated or observed) and gives equal weight to the two types of data: the denominator is the sum of the estimated and observed values. Values must fall in [0,2], with optimal value 0.

b) Statistical indicators used to quantify model performance for PM10 daily average.

Performance parameters relating to the calculated average daily concentration values.

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
BG	Bergamo - via Garibaldi	UT	0.59	-0.42	-0.48	29.12	26.23	12.65	0.53	-0.5	0.62
BG	Bergamo - via Meucci	UB	0.64	-0.34	-0.38	23.45	19.77	12.61	0.59	-0.39	0.52
BG	Calusco d' Adda	SB	0.68	-0.45	-0.49	22.81	21.02	8.86	0.53	-0.54	0.63
BG	Casirate d`Adda	RB	0.64	-0.5	-0.53	28.61	27.03	9.38	0.49	-0.62	0.65
BG	Dalmine - via Verdi	UT	0.71	-0.37	-0.38	20.73	18.14	10.03	0.58	-0.43	0.5
BG	Filago - via Don Milani	UB	0.72	-0.44	-0.51	24.9	23.16	9.14	0.56	-0.49	0.55
BG	Lallio	UT	0.67	-0.35	-0.4	22.78	19.74	11.37	0.56	-0.4	0.53
BG	Osio Sotto	SB	0.64	-0.35	-0.42	21.37	18.65	10.43	0.57	-0.39	0.49
BG	Treviglio	UT	0.71	-0.46	-0.52	26.17	24.64	8.82	0.53	-0.55	0.59
BS	Brescia - Broletto	UT	0.7	-0.55	-0.6	29.19	28.18	7.61	0.49	-0.7	0.71
BS	Brescia - Villaggio Sereno	UB	0.75	-0.48	-0.51	25.96	24.65	8.14	0.52	-0.59	0.6
BS	Darfo (aria)	SB	0.66	-0.44	-0.32	21.21	18.56	10.27	0.51	-0.6	0.67
BS	Odolo	SB	0.7	-0.47	-0.43	23.28	21.33	9.33	0.52	-0.63	0.66
BS	Rezzato	SI	0.65	-0.61	-0.62	35.7	34.58	8.87	0.47	-0.77	0.84
BS	Sarezzo - via Minelli	UB	0.61	-0.47	-0.5	25.43	23.36	10.05	0.54	-0.6	0.65
CO	Cantù - via Meucci	SB	0.66	-0.29	-0.38	20.03	16.57	11.25	0.6	-0.29	0.52
CO	Como - viale Cattaneo	UT	0.68	-0.57	-0.63	29.63	28.66	7.52	0.49	-0.71	0.77
CO	Erba - via Battisti	UB	0.65	-0.23	-0.37	14.09	11.29	8.43	0.58	-0.2	0.54
CR	Crema - via XI febbraio	SB	0.6	-0.54	-0.57	30.17	28.79	9.02	0.49	-0.67	0.7
CR	Cremona - p.zza Cadorna	UT	0.64	-0.53	-0.59	31.18	29.88	8.91	0.5	-0.65	0.68
CR	Cremona - Via Fatebenefratelli	UB	0.68	-0.55	-0.58	30.85	29.78	8.05	0.48	-0.71	0.72
CR	Cremona - via Gerre Borghi	RB	0.63	-0.57	-0.56	27.89	26.81	7.69	0.43	-0.75	0.78
CR	Soresina	ST	0.58	-0.6	-0.57	32.3	31.18	8.43	0.43	-0.82	0.83

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
CR	Spinadesco	RI	0.61	-0.59	-0.6	32.07	31.06	7.99	0.45	-0.79	0.8
LC	Lecco - Via Amendola	UT	0.59	-0.44	-0.6	24.19	22.79	8.11	0.53	-0.42	0.6
LC	Lecco - Via Sora	UB	0.53	-0.4	-0.57	21.82	20.21	8.23	0.52	-0.36	0.57
LC	Merate	UT	0.7	-0.56	-0.58	30.75	29.51	8.64	0.49	-0.74	0.75
LC	Moggio	RB	0.07	-0.39	-0.49	14.88	13.51	6.24	0.39	-0.31	0.75
LC	Valmadrera	SB	0.64	-0.45	-0.63	24.77	23.55	7.68	0.55	-0.42	0.57
LO	Bertonico	RB	0.56	-0.55	-0.61	27.78	26.71	7.64	0.48	-0.64	0.72
LO	Codogno - via Trento	UT	0.61	-0.55	-0.59	29.51	28.31	8.33	0.49	-0.67	0.69
LO	Lodi - S. Alberto	UB	0.59	-0.5	-0.55	25.68	24.27	8.39	0.51	-0.59	0.62
LO	Lodi - viale Vignati	UT	0.5	-0.57	-0.62	33.58	32.31	9.15	0.47	-0.71	0.73
LO	Montanaso	RI	0.6	-0.51	-0.58	27.31	26.02	8.29	0.51	-0.58	0.63
LO	S.Rocco al Porto	SB	0.63	-0.52	-0.58	26.96	25.73	8.05	0.5	-0.62	0.68
LO	Tavazzano	SB	0.55	-0.55	-0.61	30.74	29.54	8.51	0.48	-0.68	0.7
MB	Meda	UT	0.73	-0.33	-0.41	23.85	20.74	11.78	0.63	-0.35	0.48
MB	Monza - via Machiavelli	UB	0.73	-0.43	-0.54	26.89	25.29	9.14	0.54	-0.47	0.55
MB	Monza Parco	SB	0.71	-0.32	-0.51	22.32	20.27	9.34	0.6	-0.22	0.49
MI	Cassano d'Adda 2 - Via Milano	UT	0.77	-0.52	-0.76	40.04	39.44	6.91	0.4	-0.63	0.63
MI	Limito	UB	0.63	-0.45	-0.56	28.98	27.17	10.08	0.54	-0.47	0.58
MI	Magenta	UB	0.71	-0.5	-0.61	26.66	25.71	7.05	0.52	-0.57	0.61
MI	Milano - Pascal Città Studi	UB	0.74	-0.38	-0.53	26.1	24.34	9.42	0.58	-0.36	0.46
MI	Milano - Verziere	UT	0.69	-0.37	-0.51	24.65	22.71	9.59	0.57	-0.38	0.46
MI	Milano - via Senato	UT	0.73	-0.39	-0.51	25.34	23.59	9.25	0.57	-0.4	0.47
MI	Robecchetto	SB	0.69	-0.52	-0.63	28.95	27.97	7.47	0.52	-0.56	0.67
MI	Trezzo d`Adda	SB	0.67	-0.4	-0.53	22.5	20.76	8.68	0.56	-0.4	0.54
MI	Turbigo	UB	0.69	-0.47	-0.56	23.29	22.01	7.61	0.53	-0.51	0.62
MN	Borgofranco - loc. Bonizzo	SB	0.63	-0.53	-0.55	26.45	25.13	8.25	0.48	-0.65	0.72
MN	Mantova - p.zza Gramsci	UT	0.63	-0.56	-0.66	32.65	31.7	7.82	0.5	-0.65	0.69

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
MN	Mantova - S.Agnese	UB	0.65	-0.52	-0.63	29.13	28.12	7.6	0.51	-0.59	0.64
MN	Mantova - Tridolino	RI	0.6	-0.53	-0.62	28.69	27.5	8.18	0.5	-0.61	0.67
MN	Mantova - via Ariosto	UI	0.65	-0.51	-0.58	26.5	25.3	7.88	0.51	-0.6	0.64
MN	Ostiglia - via Colombo	UB	0.66	-0.51	-0.58	25.69	24.46	7.85	0.53	-0.62	0.66
MN	Ponti sul Mincio	SB	0.66	-0.53	-0.55	26.44	25.04	8.49	0.52	-0.65	0.69
MN	Schivenoglia	RB	0.5	-0.58	-0.57	29.43	28.11	8.72	0.43	-0.79	0.81
MN	Sermide - via Dalla Chiesa	SB	0.7	-0.44	-0.52	23.44	21.83	8.54	0.54	-0.48	0.6
PV	Casoni - AGIP	RB	0.5	-0.49	-0.6	25.2	23.93	7.9	0.5	-0.46	0.67
PV	Parona	UI	0.63	-0.51	-0.63	27.03	26.06	7.18	0.52	-0.56	0.61
PV	Pavia - p.zza Minerva	UT	0.61	-0.6	-0.61	31.43	30.53	7.47	0.44	-0.8	0.8
PV	Pavia - via Folperti	UB	0.59	-0.51	-0.62	27.37	26.28	7.65	0.52	-0.53	0.62
PV	Sannazzaro de' Burgondi - AGIP	UI	0.54	-0.5	-0.61	25.75	24.61	7.58	0.51	-0.55	0.61
PV	Vigevano - via Valletta	UB	0.61	-0.59	-0.68	33.28	32.51	7.12	0.48	-0.71	0.74
PV	Voghera - via Pozzoni	UB	0.53	-0.49	-0.59	25.24	23.87	8.2	0.52	-0.56	0.61
SO	Bormio	UB	0.53	-0.48	-0.63	9.2	8.84	2.55	0.44	-0.48	0.67
SO	Morbegno - via Cortivacci	UB	0.62	-0.24	-0.19	13.04	9	9.44	0.59	-0.29	0.53
SO	Sondrio - via Mazzini	UT	0.7	-0.15	0.04	12.89	5.53	11.64	0.64	-0.24	0.5
SO	Sondrio - via Paribelli	UB	0.75	-0.19	0.07	12.13	5.68	10.72	0.67	-0.31	0.46
VA	Busto Arsizio - Accam	SB	0.63	-0.36	-0.47	19.16	17.15	8.54	0.55	-0.34	0.53
VA	Ferno	UB	0.68	-0.45	-0.51	22.24	20.64	8.28	0.53	-0.51	0.64
VA	Saronno - via Santuario	UB	0.66	-0.4	-0.51	25.1	23.01	10.03	0.54	-0.4	0.58
VA	Varese - via Copelli	UT	0.62	-0.31	-0.37	19.38	16.08	10.82	0.58	-0.35	0.53

c) Statistical indicators used to quantify model performance for PM2.5 daily average.

Performance parameters relating to the calculated average daily concentration values.

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
BG	Bergamo - via Meucci	UB	0.67	-0.18	-0.26	16.96	12.02	11.96	0.65	-0.17	0.44
BG	Calusco d' Adda	SB	0.68	-0.29	-0.41	15.93	13.52	8.42	0.61	-0.26	0.51
BG	Casirate d`Adda	RB	0.75	-0.18	-0.32	12.43	9.63	7.86	0.66	-0.13	0.38
BG	Dalmine - via Verdi	UT	0.73	-0.28	-0.39	17.89	15.08	9.63	0.64	-0.29	0.43
BG	Treviglio	UT	0.7	-0.17	-0.33	13.5	10.37	8.64	0.67	-0.12	0.36
BS	Brescia - Broletto	UT	0.75	-0.4	-0.56	19.71	18.49	6.83	0.61	-0.36	0.46
BS	Brescia - Villaggio Sereno	UB	0.78	-0.36	-0.43	17.18	15.48	7.45	0.62	-0.36	0.45
BS	Darfo (aria)	SB	0.67	-0.3	-0.34	17.53	14.21	10.27	0.63	-0.32	0.52
CO	Como - viale Cattaneo	UT	0.7	-0.48	-0.56	21.39	20.17	7.12	0.55	-0.56	0.63
CR	Cremona - p.zza Cadorna	UT	0.7	-0.33	-0.53	19.82	18.15	7.96	0.61	-0.18	0.46
CR	Cremona - Via Fatebenefratelli	UB	0.71	-0.44	-0.52	21.61	20.28	7.46	0.56	-0.47	0.54
CR	Soresina	ST	0.61	-0.49	-0.52	22.6	21.2	7.83	0.52	-0.57	0.62
CR	Spinadesco	RI	0.67	-0.48	-0.55	22.35	21.11	7.34	0.54	-0.52	0.59
LC	Lecco - Via Sora	UB	0.59	-0.16	-0.49	15.18	13.12	7.64	0.57	0.02	0.51
LC	Merate	UT	0.73	-0.38	-0.48	18.8	16.98	8.07	0.62	-0.38	0.49
LC	Moggio	RB	0.14	-0.26	-0.39	11.29	9.61	5.93	0.38	-0.15	0.69
LO	Lodi - S. Alberto	UB	0.64	-0.38	-0.48	18.23	16.49	7.77	0.59	-0.38	0.46
LO	Lodi - viale Vignati	UT	0.69	-0.24	-0.48	15.45	13.55	7.42	0.61	-0.1	0.45
MB	Monza - via Machiavelli	UB	0.79	-0.3	-0.46	17.74	15.92	7.83	0.64	-0.23	0.41
MI	Milano - Pascal Città Studi	UB	0.76	-0.2	-0.4	15.9	13.36	8.62	0.67	-0.11	0.35
MI	Milano - via Senato	UT	0.76	-0.13	-0.45	16.74	14.38	8.57	0.66	0.05	0.39
MI	Sesto S.Giovanni	UT	0.75	-0.09	-0.42	16.61	13.8	9.24	0.65	0.06	0.39
MN	Borgofranco - loc. Bonizzo	SB	0.67	-0.39	-0.52	19.23	17.62	7.7	0.59	-0.28	0.54

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
MN	Mantova - S.Agnese	UB	0.67	-0.42	-0.6	22.2	21.02	7.14	0.59	-0.36	0.48
MN	Ponti sul Mincio	SB	0.68	-0.45	-0.49	20.33	18.67	8.05	0.58	-0.51	0.56
MN	Schivenoglia	RB	0.69	-0.46	-0.49	18.67	17.31	7	0.54	-0.54	0.6
PV	Cornale (Voghera Energia)	RB	0.63	-0.45	-0.55	19.71	18.45	6.93	0.55	-0.47	0.56
PV	Mortara	UB	0.68	-0.34	-0.57	18.26	17.02	6.61	0.59	-0.19	0.47
PV	Pavia - via Folperti	UB	0.63	-0.39	-0.52	17.99	16.56	7.03	0.55	-0.32	0.54
PV	Sannazzaro de' Burgondi - AGIP	UI	0.63	-0.35	-0.57	17.79	16.54	6.55	0.57	-0.21	0.49
SO	Bormio	UB	0.51	-0.39	-0.56	6.9	6.44	2.48	0.44	-0.35	0.61
SO	Sondrio - via Paribelli	UB	0.81	0	0.15	9.45	0.9	9.41	0.72	-0.08	0.38
VA	Saronno - via Santuario	UB	0.71	-0.13	-0.43	16.75	13.92	9.32	0.64	0.08	0.51
VA	Varese - via Copelli	UT	0.65	-0.16	-0.26	14.28	10.03	10.16	0.63	-0.13	0.47

d) Statistical indicators used to quantify model performance for NO_2 daily average.

Performance parameters relating to the calculated average daily concentration values.

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
BG	Bergamo - via Garibaldi	UT	0.64	-0.1	-0.25	14.49	10.36	10.13	0.56	-0.08	0.24
BG	Bergamo - via Meucci	UB	0.65	0.41	-0.28	19.32	16.38	10.24	0.46	0.45	0.5
BG	Calusco d' Adda	SB	0.51	1.24	-0.33	32.03	30.71	9.1	0.29	0.86	0.87
BG	Casirate d`Adda	RB	0.49	0.34	0.1	17.65	11.22	13.62	0.45	0.31	0.44
BG	Dalmine - via Verdi	UT	0.64	0.63	-0.17	24.16	21.64	10.74	0.38	0.55	0.56
BG	Filago - via Don Milani	UB	0.61	1.2	0.07	27.81	25.43	11.26	0.29	0.82	0.83
BG	Lallio	UT	0.61	0.55	-0.23	22.91	20.4	10.43	0.4	0.51	0.53
BG	Osio Sotto	SB	0.6	0.54	-0.09	21.04	17.96	10.96	0.39	0.48	0.49
BG	Tavernola Bergamasca	SI	0.6	0.41	-0.27	15.32	12.99	8.12	0.43	0.43	0.5
BG	Treviglio	UT	0.79	0	-0.13	11.36	5.74	9.8	0.72	0.02	0.23
BS	Brescia - Broletto	UT	0.55	0.03	-0.01	13.65	6.59	11.95	0.56	0.04	0.27
BS	Brescia - via Turati	UT	0.54	-0.36	0.04	26.02	22.94	12.28	0.33	-0.47	0.48
BS	Brescia - Villaggio Sereno	UB	0.48	0.55	-0.25	24.07	21.16	11.47	0.35	0.49	0.53
BS	Darfo (aria)	SB	0.87	-0.45	-0.27	16.46	15.6	5.25	0.47	-0.66	0.67
BS	Gambara	RB	0.69	-0.37	-0.03	14.72	11.52	9.16	0.52	-0.57	0.62
BS	Lonato	UB	0.85	0.09	0.13	7.88	2.12	7.59	0.75	0.06	0.23
BS	Odolo	SB	0.69	0.24	-0.17	13.8	9.2	10.29	0.59	0.26	0.39
BS	Rezzato	SI	0.79	-0.03	0.08	8.69	2.01	8.45	0.71	-0.06	0.27
BS	Sarezzo - via Minelli	UB	0.83	-0.17	-0.09	10.12	6.24	7.97	0.72	-0.2	0.31
CO	Cantù - via Meucci	SB	0.83	0.26	-0.01	11.43	7.57	8.56	0.65	0.29	0.34
CO	Como - viale Cattaneo	UT	0.72	-0.35	-0.33	22.49	20.41	9.45	0.47	-0.44	0.47
CO	Erba - via Battisti	UB	0.87	-0.05	-0.28	9.54	6.96	6.52	0.75	0.04	0.25
CR	Corte de Cortesi	RB	0.69	-0.16	0.25	10.2	3.92	9.42	0.61	-0.28	0.47

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
CR	Crema - via XI febbraio	SB	0.81	-0.02	0.09	9.06	1.72	8.9	0.71	-0.05	0.26
CR	Cremona - p.zza Cadorna	UT	0.74	0.13	0.22	10.57	3.94	9.81	0.64	0.09	0.26
CR	Cremona - Via Fatebenefratelli	UB	0.69	-0.25	-0.06	16.09	12.27	10.41	0.5	-0.32	0.4
CR	Cremona - via Gerre Borghi	RB	0.76	-0.07	0.36	9.44	1.74	9.28	0.65	-0.18	0.37
CR	Soresina	ST	0.83	-0.33	-0.12	14.07	11.56	8.02	0.61	-0.51	0.54
CR	Spinadesco	RI	0.76	0.03	0.2	8.68	1.1	8.61	0.67	-0.07	0.38
LC	Colico	SB	0.87	-0.49	-0.4	15.26	14.64	4.31	0.49	-0.67	0.69
LC	Lecco - Via Amendola	UT	0.7	-0.13	-0.31	13.55	10.4	8.69	0.56	-0.08	0.31
LC	Lecco - Via Sora	UB	0.86	0.34	-0.28	12.47	10.74	6.34	0.57	0.44	0.49
LC	Merate	UT	0.67	-0.26	-0.29	18.64	15.32	10.62	0.53	-0.27	0.4
LC	Moggio	RB	0.18	-0.1	0.52	4.71	2.11	4.21	0.34	-0.22	0.57
LC	Perledo	RB	0.57	-0.3	-0.23	9.97	7.7	6.33	0.52	-0.35	0.52
LC	Valmadrera	SB	0.82	0.33	-0.28	12.33	10.15	7	0.57	0.44	0.52
LO	Bertonico	RB	0.78	0.11	0.01	9.11	3.92	8.22	0.67	0.1	0.29
LO	Codogno - via Trento	UT	0.68	-0.2	0.1	13.15	7.64	10.7	0.57	-0.29	0.41
LO	Lodi - S. Alberto	UB	0.81	-0.11	-0.1	11.03	5.98	9.27	0.72	-0.13	0.27
LO	Lodi - viale Vignati	UT	0.76	-0.24	-0.06	14.28	10.15	10.04	0.59	-0.33	0.4
LO	Montanaso	RI	0.79	0.12	0.58	10.48	4	9.69	0.64	0.01	0.33
LO	S.Rocco al Porto	SB	0.69	0.12	0.24	10.61	3.41	10.05	0.61	0.07	0.33
LO	Tavazzano	SB	0.78	0.14	0.22	10.56	3.55	9.95	0.67	0.09	0.32
MB	Meda	UT	0.8	-0.07	-0.54	21.6	19.73	8.79	0.59	0.11	0.39
MB	Monza - via Machiavelli	UB	0.67	0.1	-0.43	19.88	16.37	11.28	0.53	0.19	0.35
MB	Monza Parco	SB	0.73	-0.08	-0.41	17.85	14.59	10.28	0.57	0.01	0.32
MI	Arconate (aria)	SB	0.77	0.52	0.01	16.33	12.88	10.04	0.54	0.5	0.53
MI	Cassano d'Adda 2 - Via Milano	UT	0.68	-0.22	-0.09	16.91	12.09	11.82	0.52	-0.28	0.4
MI	Cinisello Balsamo	UT	0.55	0.07	-0.37	17.89	13.84	11.34	0.5	0.1	0.23
MI	Cormano	UB	0.55	0.23	-0.48	24.13	21.1	11.71	0.43	0.31	0.42

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
MI	Limito	UB	0.57	0.07	-0.22	19.5	12.81	14.7	0.54	0.1	0.32
MI	Magenta	UB	0.77	-0.06	-0.25	12.71	8.52	9.43	0.67	-0.03	0.24
MI	Milano - Pascal Città Studi	UB	0.61	0.49	-0.4	28.83	26.17	12.1	0.42	0.49	0.53
MI	Milano - Verziere	UT	0.62	0.34	-0.4	24.64	21.76	11.56	0.44	0.38	0.43
MI	Milano - via Senato	UT	0.57	0.22	-0.3	20.42	16.57	11.93	0.48	0.24	0.3
MI	Milano - viale Liguria	UT	0.59	0.06	-0.39	19.1	14.92	11.92	0.54	0.11	0.26
MI	Milano - viale Marche	UT	0.51	0.03	-0.4	19.76	15.58	12.15	0.47	0.07	0.24
MI	Motta Visconti (aria)	SB	0.77	-0.13	-0.06	10.7	5.54	9.15	0.68	-0.18	0.34
MI	Rho - via Statuto	UB	0.66	0.2	-0.41	19.7	16.6	10.61	0.5	0.27	0.37
MI	Robecchetto	SB	0.76	0.25	-0.11	13.11	8.37	10.09	0.63	0.29	0.4
MI	S.Giuliano Milanese	UT	0.67	-0.1	-0.21	16.26	10.79	12.16	0.6	-0.09	0.28
MI	Sesto S.Giovanni	UT	0.32	0.21	-0.31	22.25	18.11	12.93	0.37	0.23	0.32
MI	Trezzo d`Adda	SB	0.73	0.8	-0.16	21.88	19.65	9.62	0.4	0.72	0.74
MI	Turbigo	UB	0.83	0.28	-0.1	11.29	7.73	8.23	0.66	0.36	0.42
MN	Borgofranco - loc. Bonizzo	SB	0.8	0.28	0.23	7.34	4.06	6.11	0.61	0.25	0.37
MN	Mantova - p.zza Gramsci	UT	0.79	0.32	0.4	9.8	6.61	7.24	0.58	0.27	0.3
MN	Mantova - S.Agnese	UB	0.85	0.07	-0.29	9.31	6.88	6.27	0.69	0.18	0.3
MN	Mantova - Tridolino	RI	0.71	-0.07	0.25	9.55	2.15	9.3	0.63	-0.13	0.34
MN	Mantova - via Ariosto	UI	0.84	0.51	0.24	11.91	9.73	6.87	0.53	0.45	0.45
MN	Monzambano - campo sportivo	SB	0.84	0.29	0.15	7.91	4.76	6.32	0.66	0.3	0.38
MN	Ostiglia - via Colombo	UB	0.77	-0.13	-0.07	7.95	4.03	6.85	0.69	-0.16	0.35
MN	Ponti sul Mincio	SB	0.75	0.27	-0.09	10.84	7.29	8.02	0.59	0.3	0.37
MN	Schivenoglia	RB	0.81	-0.12	0.04	6.99	2.79	6.41	0.71	-0.2	0.37
MN	Sermide - via Dalla Chiesa	SB	0.84	0.08	0.09	6.03	1.66	5.8	0.74	0.07	0.23
MN	Viadana	UB	0.83	-0.25	-0.09	12.67	9.32	8.58	0.67	-0.37	0.41
PV	Cornale (Voghera Energia)	RB	0.85	0	0.08	6.55	0.89	6.49	0.77	-0.03	0.23
PV	Ferrera Erbognone - ENI	RI	0.74	0.32	0.02	10.86	6.82	8.45	0.62	0.31	0.38

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
PV	Mortara	UB	0.82	0.48	0.36	15.25	11.63	9.86	0.56	0.38	0.41
PV	Parona	UI	0.66	0.36	0.02	15.96	10.22	12.26	0.54	0.33	0.46
PV	Pavia - p.zza Minerva	UT	0.74	-0.39	-0.19	21.89	19.76	9.42	0.43	-0.53	0.54
PV	Pavia - via Folperti	UB	0.9	-0.07	-0.24	8.98	6.42	6.28	0.78	-0.01	0.23
PV	Sannazzaro de' Burgondi - AGIP	UI	0.07	0.3	-0.51	25.29	19.49	16.12	0.2	0.43	0.66
PV	Vigevano - via Valletta	UB	0.77	0.11	0.28	10.26	2.76	9.88	0.66	0.04	0.33
PV	Voghera - via Pozzoni	UB	0.82	0.27	0.08	9.92	6.11	7.82	0.66	0.26	0.33
SO	Bormio	UB	0.73	-0.62	-0.62	11.33	11.1	2.27	0.42	-0.87	0.88
SO	Morbegno - via Cortivacci	UB	0.87	-0.06	0	7.03	2.08	6.72	0.79	-0.1	0.32
SO	Sondrio - via Mazzini	UT	0.89	-0.35	-0.13	11.86	10.12	6.18	0.65	-0.54	0.56
SO	Sondrio - via Paribelli	UB	0.88	-0.26	-0.03	8.92	6.37	6.24	0.72	-0.4	0.45
VA	Busto Arsizio - Accam	SB	0.62	0.38	0.03	16.76	12.12	11.58	0.48	0.36	0.44
VA	Ferno	UB	0.74	0.69	-0.2	22.34	20.31	9.3	0.39	0.61	0.63
VA	Saronno - via Santuario	UB	0.84	0.15	-0.23	12.24	8.97	8.33	0.67	0.21	0.28
VA	Varese - via Copelli	UT	0.74	-0.13	-0.07	11.26	6.79	8.98	0.63	-0.15	0.25
VA	Varese - Vidoletti	UB	0.72	0.33	-0.07	12.51	8.49	9.19	0.56	0.34	0.42

e) Statistical indicators used to quantify model performance for NO_2 daily maximum.

Performance parameters relating to the calculated maximum daily concentration values.

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
BG	Bergamo - via Garibaldi	UT	0.04	0.05	-0.26	28.77	22.23	18.26	0.29	0.07	0.29
BG	Bergamo - via Meucci	UB	0.09	0.42	-0.38	42.86	38.05	19.73	0.3	0.42	0.54
BG	Calusco d' Adda	SB	0.09	0.8	-0.4	43.21	40.6	14.79	0.32	0.65	0.68
BG	Casirate d`Adda	RB	0.31	0.35	-0.14	27.06	21.11	16.93	0.36	0.34	0.46
BG	Dalmine - via Verdi	UT	-0.07	0.54	-0.29	47.61	42.96	20.52	0.26	0.48	0.56
BG	Filago - via Don Milani	UB	0.08	1.27	-0.05	49.92	46.61	17.87	0.24	0.82	0.83
BG	Lallio	UT	-0.1	0.54	-0.23	46.18	41.6	20.05	0.26	0.46	0.53
BG	Osio Sotto	SB	0.12	0.49	-0.22	38.27	33.74	18.06	0.29	0.43	0.48
BG	Tavernola Bergamasca	SI	0.06	0.14	-0.49	27.25	24.01	12.89	0.27	0.22	0.43
BG	Treviglio	UT	0.57	-0.05	-0.33	23.68	17.62	15.82	0.55	-0.01	0.29
BS	Brescia - Broletto	UT	0.06	-0.09	-0.5	36.86	32.56	17.28	0.34	-0.04	0.34
BS	Brescia - via Turati	UT	0.27	-0.38	-0.31	49.75	46.71	17.12	0.31	-0.47	0.49
BS	Brescia - Villaggio Sereno	UB	0.04	0.39	-0.36	41.49	36.78	19.2	0.23	0.38	0.5
BS	Darfo (aria)	SB	0.75	-0.5	-0.35	31.98	30.54	9.49	0.4	-0.69	0.7
BS	Gambara	RB	0.6	-0.36	-0.03	21.93	16.91	13.96	0.48	-0.52	0.59
BS	Lonato	UB	0.69	-0.03	0.03	14.22	5.28	13.2	0.64	-0.04	0.26
BS	Odolo	SB	0.53	0.13	-0.35	22.57	17.4	14.38	0.51	0.2	0.38
BS	Rezzato	SI	0.48	-0.06	0	16.81	8.71	14.38	0.53	-0.06	0.29
BS	Sarezzo - via Minelli	UB	0.77	-0.14	-0.1	14.74	9.18	11.53	0.65	-0.16	0.27
CO	Cantù - via Meucci	SB	0.62	0.22	-0.16	20.4	14.67	14.18	0.53	0.25	0.35
CO	Como - viale Cattaneo	UT	0.38	-0.27	-0.34	35.28	30.98	16.88	0.39	-0.31	0.38
CO	Erba - via Battisti	UB	0.68	0.05	-0.39	19.94	15.68	12.32	0.58	0.16	0.37
CR	Corte de Cortesi	RB	0.42	-0.25	0.21	20.83	12.45	16.7	0.48	-0.37	0.53

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
CR	Crema - via XI febbraio	SB	0.62	-0.15	-0.23	19.68	14.41	13.4	0.53	-0.15	0.31
CR	Cremona - p.zza Cadorna	UT	0.53	0.06	-0.12	18.87	11.03	15.31	0.52	0.08	0.27
CR	Cremona - Via Fatebenefratelli	UB	0.46	-0.28	-0.38	32.85	28.99	15.45	0.42	-0.31	0.39
CR	Cremona - via Gerre Borghi	RB	0.46	-0.14	0.27	20.27	9.18	18.07	0.49	-0.22	0.41
CR	Soresina	ST	0.6	-0.4	-0.23	29.22	25.24	14.72	0.44	-0.57	0.6
CR	Spinadesco	RI	0.44	0.05	0.34	18.58	6.16	17.53	0.48	-0.02	0.45
LC	Colico	SB	0.73	-0.49	-0.34	26.9	25.29	9.17	0.42	-0.68	0.7
LC	Lecco - Via Amendola	UT	0.3	-0.22	-0.34	29.15	24.86	15.22	0.38	-0.21	0.34
LC	Lecco - Via Sora	UB	0.66	0.2	-0.27	19.05	14.48	12.38	0.55	0.26	0.36
LC	Merate	UT	0.37	-0.29	-0.4	37.66	33.32	17.55	0.4	-0.31	0.42
LC	Moggio	RB	0.38	-0.03	0.05	8.83	4.65	7.51	0.48	-0.08	0.46
LC	Perledo	RB	0.4	-0.42	-0.26	21.91	19.01	10.89	0.39	-0.54	0.66
LC	Valmadrera	SB	0.66	0.28	-0.34	21.4	17.65	12.1	0.52	0.36	0.46
LO	Bertonico	RB	0.55	0.14	0.11	16.56	8.34	14.31	0.53	0.13	0.3
LO	Codogno - via Trento	UT	0.42	-0.31	-0.35	32.81	28.37	16.48	0.41	-0.37	0.47
LO	Lodi - S. Alberto	UB	0.55	-0.21	-0.34	27	22.02	15.62	0.51	-0.2	0.36
LO	Lodi - viale Vignati	UT	0.39	-0.32	-0.38	36.36	31.89	17.47	0.42	-0.37	0.46
LO	Montanaso	RI	0.52	0.09	0.34	18.05	5.66	17.14	0.54	0.04	0.33
LO	S.Rocco al Porto	SB	0.29	-0.03	0.07	22.86	12.61	19.07	0.4	-0.04	0.38
LO	Tavazzano	SB	0.48	0.02	0	20.01	10	17.33	0.52	0.02	0.35
MB	Meda	UT	0.3	-0.04	-0.61	43.44	39.68	17.68	0.33	0.12	0.5
MB	Monza - via Machiavelli	UB	0.03	0.25	-0.39	43.74	37.87	21.89	0.26	0.29	0.46
MB	Monza Parco	SB	0.24	0.04	-0.46	34.72	29.24	18.72	0.33	0.11	0.36
MI	Arconate (aria)	SB	0.39	0.63	-0.02	35.56	28.93	20.68	0.39	0.54	0.59
MI	Cassano d'Adda 2 - Via Milano	UT	0.4	-0.19	-0.28	30.03	23.84	18.26	0.43	-0.2	0.35
MI	Cinisello Balsamo	UT	-0.03	0.06	-0.34	42.29	34.71	24.16	0.27	0.09	0.33
MI	Cormano	UB	-0.15	0.14	-0.43	49.69	43.71	23.63	0.2	0.19	0.44

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
MI	Limito	UB	0.15	0.15	-0.19	37.34	27.94	24.77	0.32	0.17	0.37
MI	Magenta	UB	0.31	-0.1	-0.38	29.8	24.13	17.49	0.4	-0.06	0.32
MI	Milano - Pascal Città Studi	UB	-0.02	0.4	-0.34	53.26	47.1	24.86	0.26	0.39	0.5
MI	Milano - Verziere	UT	-0.12	0.39	-0.31	50.17	44.55	23.07	0.24	0.37	0.49
MI	Milano - via Senato	UT	-0.22	0.37	-0.11	47.5	41.23	23.59	0.22	0.33	0.42
MI	Milano - viale Liguria	UT	0	-0.03	-0.49	45.06	39.41	21.85	0.28	0.02	0.34
MI	Milano - viale Marche	UT	-0.06	0.12	-0.34	44.23	36.97	24.28	0.24	0.14	0.34
MI	Motta Visconti (aria)	SB	0.61	-0.15	-0.2	20.46	14.13	14.8	0.57	-0.16	0.36
MI	Rho - via Statuto	UB	0.1	0.11	-0.39	38.68	32.22	21.4	0.29	0.16	0.38
MI	Robecchetto	SB	0.32	0.23	-0.18	27.24	19.9	18.6	0.42	0.25	0.45
MI	S.Giuliano Milanese	UT	0.37	-0.09	-0.37	32.81	26.1	19.88	0.43	-0.05	0.31
MI	Sesto S.Giovanni	UT	0.14	0.21	-0.26	38.76	31.16	23.05	0.32	0.22	0.33
MI	Trezzo d`Adda	SB	0.36	0.03	-0.41	29.06	23.45	17.16	0.4	0.09	0.33
MI	Turbigo	UB	0.48	0.29	-0.17	24.45	18.04	16.5	0.48	0.32	0.44
MN	Borgofranco - loc. Bonizzo	SB	0.62	0.1	0.18	11.93	4.22	11.16	0.58	0.09	0.35
MN	Mantova - p.zza Gramsci	UT	0.56	0.21	0.11	16.9	9.48	13.99	0.51	0.19	0.31
MN	Mantova - S.Agnese	UB	0.69	0.01	-0.26	17.4	11.68	12.9	0.6	0.07	0.29
MN	Mantova - Tridolino	RI	0.34	-0.25	-0.18	26.97	20.89	17.06	0.42	-0.29	0.46
MN	Mantova - via Ariosto	UI	0.69	0.4	0.06	19.38	14.45	12.91	0.51	0.38	0.41
MN	Monzambano - campo sportivo	SB	0.58	0.03	-0.16	15.64	9.34	12.54	0.59	0.08	0.35
MN	Ostiglia - via Colombo	UB	0.55	-0.23	-0.17	17.91	12.67	12.66	0.56	-0.28	0.45
MN	Ponti sul Mincio	SB	0.51	0.16	-0.35	19.94	15.64	12.37	0.47	0.22	0.36
MN	Schivenoglia	RB	0.67	-0.17	0.09	12.85	6.22	11.24	0.61	-0.25	0.42
MN	Sermide - via Dalla Chiesa	SB	0.74	-0.09	0	11.02	4.87	9.89	0.67	-0.12	0.29
MN	Viadana	UB	0.65	-0.38	-0.36	33.14	29.56	14.98	0.5	-0.48	0.52
PV	Cornale (Voghera Energia)	RB	0.6	-0.01	0.08	14.19	5.26	13.18	0.61	-0.02	0.29
PV	Ferrera Erbognone - ENI	RI	0.54	0.26	0.06	20.12	11.67	16.39	0.54	0.23	0.4

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
PV	Mortara	UB	0.67	0.35	0.14	21.53	14.94	15.5	0.52	0.31	0.37
PV	Parona	UI	0.46	0.22	-0.15	24.86	17.02	18.12	0.46	0.23	0.42
PV	Pavia - p.zza Minerva	UT	0.49	-0.42	-0.43	43.25	40.7	14.63	0.38	-0.52	0.55
PV	Pavia - via Folperti	UB	0.72	-0.09	-0.3	17.69	13.01	11.99	0.63	-0.05	0.27
PV	Sannazzaro de' Burgondi - AGIP	UI	-0.37	0.97	-0.1	49.53	37	32.93	0.11	0.71	0.9
PV	Vigevano - via Valletta	UB	0.57	0.01	-0.05	18.37	9.09	15.96	0.58	0	0.33
PV	Voghera - via Pozzoni	UB	0.51	0.11	-0.16	19.29	12.31	14.85	0.53	0.14	0.33
SO	Bormio	UB	0.74	-0.65	-0.65	25.34	24.94	4.48	0.43	-0.91	0.93
SO	Morbegno - via Cortivacci	UB	0.79	0	-0.26	11.78	7.88	8.76	0.67	0.09	0.3
SO	Sondrio - via Mazzini	UT	0.77	-0.32	-0.14	20.42	16.46	12.08	0.6	-0.42	0.46
SO	Sondrio - via Paribelli	UB	0.77	-0.22	0.01	15.32	9.76	11.81	0.67	-0.3	0.37
VA	Busto Arsizio - Accam	SB	0.28	0.33	-0.18	30.24	24.2	18.13	0.34	0.32	0.43
VA	Ferno	UB	0.01	0.68	-0.16	46.76	41.7	21.16	0.27	0.56	0.62
VA	Saronno - via Santuario	UB	0.51	0.06	-0.31	23.82	17.36	16.31	0.49	0.1	0.28
VA	Varese - via Copelli	UT	0.42	-0.06	-0.16	19.84	12.93	15.05	0.45	-0.06	0.25
VA	Varese - Vidoletti	UB	0.64	0.26	-0.29	21.48	16.84	13.33	0.51	0.31	0.41

f) Statistical indicators used to quantify model performance for O_3 daily maximum.

Performance parameters relating to the calculated maximum daily concentration values.

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
BG	Bergamo - via Meucci	UB	0.87	-0.05	0.09	29.96	5.26	29.49	0.76	-0.09	0.32
BG	Calusco d' Adda	SB	0.88	-0.14	0.04	30.16	14.27	26.57	0.74	-0.22	0.37
BG	Casirate d`Adda	RB	0.86	0.3	0.36	40	24.61	31.53	0.66	0.29	0.43
BG	Osio Sotto	SB	0.88	0.02	0.11	30.04	2.15	29.96	0.77	0.04	0.35
BS	Brescia - Villaggio Sereno	UB	0.86	0.06	0.15	30.33	5.21	29.88	0.76	0.06	0.35
BS	Darfo (aria)	SB	0.79	0.18	0.04	35.43	17.07	31.05	0.68	0.22	0.37
BS	Gambara	RB	0.88	0.21	0.04	31.53	18.87	25.26	0.73	0.27	0.35
BS	Lonato	UB	0.86	0.26	0.2	36.5	20.61	30.12	0.69	0.24	0.38
BS	Sarezzo - via Minelli	UB	0.87	0.23	0.11	33.96	19.04	28.12	0.71	0.26	0.36
CO	Cantù - via Meucci	SB	0.86	0.01	0.18	32.72	1.01	32.7	0.73	-0.03	0.33
CO	Como - viale Cattaneo	UT	0.84	0.15	0.23	33.77	13.11	31.12	0.71	0.15	0.31
CO	Erba - via Battisti	UB	0.84	0.01	0.16	31.24	1.38	31.21	0.72	-0.02	0.29
CR	Corte de Cortesi	RB	0.87	0.22	0.15	33.08	19.46	26.75	0.71	0.26	0.36
CR	Crema - via XI febbraio	SB	0.88	0.18	0.2	33.08	15.64	29.15	0.74	0.21	0.36
CR	Cremona - Via Fatebenefratelli	UB	0.89	0.18	0.12	30.19	15.01	26.19	0.75	0.2	0.35
CR	Spinadesco	RI	0.89	0.19	0.14	31.17	17.2	25.99	0.73	0.21	0.32
LC	Colico	SB	0.77	0.12	0.08	31.58	12.44	29.03	0.66	0.13	0.31
LC	Lecco - Via Sora	UB	0.79	0.07	0.47	46.34	10.49	45.14	0.66	-0.03	0.36
LC	Merate	UT	0.86	0.17	0.18	34.38	14.28	31.27	0.72	0.19	0.37
LC	Moggio	RB	0.8	-0.09	0.29	30.5	9.99	28.82	0.63	-0.15	0.27
LC	Perledo	RB	0.77	0.05	0.22	35.64	5.77	35.17	0.65	0.01	0.3
LC	Valmadrera	SB	0.81	0.09	0.35	40.14	9.5	39	0.67	0.04	0.36
LO	Bertonico	RB	0.85	0.12	0.17	32.55	11.36	30.5	0.74	0.14	0.33

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
LO	Lodi - S. Alberto	UB	0.88	0.2	0.22	33.55	17.66	28.53	0.74	0.21	0.35
LO	Montanaso	RI	0.88	0.14	0.22	32.34	13.35	29.46	0.74	0.14	0.32
MB	Meda	UT	0.9	0.09	0.1	29.21	7.78	28.15	0.78	0.1	0.32
MB	Monza - via Machiavelli	UB	0.89	0	0.1	28.97	1.5	28.93	0.77	-0.02	0.35
MB	Monza Parco	SB	0.89	0.08	0.11	28.89	6.61	28.12	0.77	0.11	0.37
MI	Arconate (aria)	SB	0.88	0.11	0.23	31.46	11.36	29.34	0.74	0.11	0.33
MI	Cormano	UB	0.88	0.09	0.23	30.15	8.56	28.91	0.76	0.06	0.35
MI	Limito	UB	0.89	0.3	0.34	38.89	24.89	29.88	0.71	0.28	0.41
MI	Magenta	UB	0.88	0.21	0.29	35.23	18.86	29.76	0.73	0.22	0.36
MI	Milano - Pascal Città Studi	UB	0.9	0.03	0.19	27.07	3.81	26.8	0.78	-0.02	0.36
MI	Milano - Verziere	UT	0.88	0.16	0.3	30.94	14.24	27.47	0.74	0.12	0.36
MI	Motta Visconti (aria)	SB	0.86	0.25	0.36	39.02	23.27	31.32	0.68	0.22	0.35
MI	Trezzo d`Adda	SB	0.88	0.07	0.17	30.55	6.39	29.87	0.75	0.05	0.34
MN	Mantova - S.Agnese	UB	0.91	0.17	0.17	29.13	16.39	24.08	0.75	0.2	0.3
MN	Ponti sul Mincio	SB	0.87	0.07	0.11	26.72	6.9	25.81	0.76	0.08	0.27
MN	Schivenoglia	RB	0.9	0.11	0	22.96	11.41	19.92	0.78	0.17	0.26
MN	Viadana	UB	0.88	0.21	0.15	29.89	18.27	23.66	0.72	0.23	0.32
PV	Casoni - AGIP	RB	0.85	0.16	0.29	34.17	15.34	30.53	0.71	0.14	0.31
PV	Cornale (Voghera Energia)	RB	0.88	0.16	0.16	29.59	14.62	25.73	0.73	0.18	0.3
PV	Ferrera Erbognone - ENI	RI	0.87	0.16	0.29	32.86	15.79	28.82	0.72	0.15	0.3
PV	Mortara	UB	0.85	0.14	0.32	34.8	13.86	31.92	0.72	0.1	0.33
PV	Pavia - via Folperti	UB	0.88	0.26	0.17	35.71	21.88	28.22	0.71	0.3	0.4
PV	Voghera - via Pozzoni	UB	0.88	0.18	0.16	28.67	15.3	24.25	0.73	0.2	0.31
SO	Bormio	UB	0.66	-0.16	-0.15	22.95	17.91	14.35	0.47	-0.18	0.24
SO	Morbegno - via Cortivacci	UB	0.79	0.01	-0.04	26.99	9.95	25.09	0.69	0.01	0.27
SO	Sondrio - via Paribelli	UB	0.8	0.03	-0.15	25.4	13.45	21.55	0.7	0.09	0.28
VA	Busto Arsizio - Accam	SB	0.88	0.07	0.15	30.13	7.08	29.29	0.76	0.07	0.31

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
VA	Ferno	UB	0.87	-0.01	0.16	29.2	1.53	29.16	0.75	-0.05	0.32
VA	Saronno - via Santuario	UB	0.88	0.06	0.14	29.52	5.53	29	0.76	0.09	0.35
VA	Varese - Vidoletti	UB	0.81	0.01	0.27	35.28	1.63	35.24	0.68	-0.04	0.32

g) Statistical indicators used to quantify model performance for O_3 daily maximum mobile average on 8h.

Performance parameters relating to the calculated daily maximum mobile average on 8h.

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
BG	Bergamo - via Meucci	UB	0.91	-0.05	0.06	23.78	4.88	23.27	0.8	-0.09	0.32
BG	Calusco d' Adda	SB	0.9	-0.22	-0.01	29.39	19.52	21.97	0.73	-0.34	0.43
BG	Casirate d`Adda	RB	0.91	0.3	0.37	33.31	22.55	24.52	0.7	0.28	0.41
BG	Osio Sotto	SB	0.91	0	0.12	24.58	1.01	24.56	0.8	0	0.33
BS	Brescia - Villaggio Sereno	UB	0.9	0.03	0.1	24.61	2.44	24.49	0.8	0.04	0.36
BS	Darfo (aria)	SB	0.83	0.24	0.03	32.77	18.8	26.84	0.68	0.31	0.43
BS	Gambara	RB	0.91	0.22	0.03	27.48	17.68	21.04	0.76	0.3	0.35
BS	Lonato	UB	0.88	0.24	0.16	31.08	17.17	25.91	0.72	0.25	0.38
BS	Sarezzo - via Minelli	UB	0.9	0.28	0.13	31.9	20.33	24.58	0.72	0.32	0.4
CO	Cantù - via Meucci	SB	0.89	0.01	0.16	27.17	1.5	27.13	0.76	-0.03	0.32
CO	Como - viale Cattaneo	UT	0.87	0.2	0.26	31.04	15.21	27.06	0.71	0.19	0.34
CO	Erba - via Battisti	UB	0.88	0	0.12	25.52	0.56	25.51	0.76	-0.02	0.28
CR	Corte de Cortesi	RB	0.9	0.25	0.17	30.25	19.43	23.18	0.73	0.29	0.38
CR	Crema - via XI febbraio	SB	0.91	0.19	0.17	27.86	14.37	23.87	0.77	0.25	0.37
CR	Cremona - Via Fatebenefratelli	UB	0.92	0.19	0.11	25.61	13.74	21.61	0.78	0.23	0.35

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
CR	Spinadesco	RI	0.92	0.2	0.14	27.05	16.18	21.68	0.76	0.24	0.34
LC	Colico	SB	0.82	0.15	0.03	27.87	13.29	24.5	0.68	0.2	0.34
LC	Lecco - Via Sora	UB	0.83	0.06	0.39	38.66	9.4	37.5	0.7	-0.03	0.36
LC	Merate	UT	0.89	0.21	0.2	30.35	14.72	26.54	0.74	0.24	0.4
LC	Moggio	RB	0.8	-0.12	0.28	29.52	13.38	26.31	0.61	-0.19	0.29
LC	Perledo	RB	0.79	0.06	0.2	31.35	5.52	30.86	0.67	0.02	0.3
LC	Valmadrera	SB	0.85	0.07	0.28	32.93	6.95	32.19	0.71	0.03	0.35
LO	Bertonico	RB	0.9	0.11	0.14	25.26	9.3	23.49	0.78	0.13	0.31
LO	Lodi - S. Alberto	UB	0.91	0.2	0.19	28.03	15.63	23.27	0.77	0.23	0.35
LO	Montanaso	RI	0.92	0.14	0.18	26.26	11.84	23.44	0.78	0.15	0.32
MB	Meda	UT	0.92	0.08	0.11	24.42	6.49	23.54	0.8	0.08	0.32
MB	Monza - via Machiavelli	UB	0.91	-0.02	0.08	23.99	1.62	23.94	0.8	-0.06	0.33
MB	Monza Parco	SB	0.91	0.05	0.11	24.55	4.11	24.2	0.79	0.06	0.39
MI	Arconate (aria)	SB	0.9	0.1	0.22	26.97	9	25.42	0.77	0.09	0.33
MI	Cormano	UB	0.91	0.05	0.17	23.02	4.73	22.53	0.81	-0.01	0.35
MI	Limito	UB	0.91	0.27	0.3	31.95	19.98	24.93	0.75	0.25	0.4
MI	Magenta	UB	0.91	0.19	0.24	28.44	15.14	24.08	0.77	0.23	0.36
MI	Milano - Pascal Città Studi	UB	0.93	-0.03	0.11	20.89	2.63	20.72	0.83	-0.11	0.34
MI	Milano - Verziere	UT	0.92	0.1	0.25	23.16	9.53	21.11	0.79	0.02	0.34
MI	Motta Visconti (aria)	SB	0.88	0.24	0.38	33.99	20.7	26.96	0.7	0.19	0.35
MI	Trezzo d`Adda	SB	0.91	0.06	0.16	25.15	5.43	24.56	0.79	0.05	0.34
MN	Mantova - S.Agnese	UB	0.93	0.14	0.1	22.27	11.74	18.92	0.8	0.2	0.28
MN	Ponti sul Mincio	SB	0.91	0.07	0.06	21.71	5.76	20.93	0.8	0.09	0.27
MN	Schivenoglia	RB	0.92	0.12	-0.02	20.17	10.42	17.27	0.8	0.19	0.28
MN	Viadana	UB	0.91	0.23	0.13	26.82	17.42	20.39	0.74	0.26	0.34
PV	Casoni - AGIP	RB	0.87	0.14	0.27	28.37	12.08	25.67	0.74	0.11	0.3
PV	Cornale (Voghera Energia)	RB	0.9	0.16	0.16	24.96	12.57	21.56	0.76	0.18	0.3

Province	Monitoring station name	Category	Pearson	NMB	NMSD	RMSE	RMSEs	RMSEu	IoA	MFB	MFE
PV	Ferrera Erbognone - ENI	RI	0.88	0.16	0.27	28.22	13.59	24.73	0.75	0.15	0.31
PV	Mortara	UB	0.89	0.09	0.27	27.61	9.85	25.79	0.77	0.03	0.32
PV	Pavia - via Folperti	UB	0.91	0.26	0.18	30.55	19.48	23.53	0.74	0.32	0.4
PV	Voghera - via Pozzoni	UB	0.91	0.17	0.14	23.8	12.77	20.08	0.77	0.2	0.32
SO	Bormio	UB	0.71	-0.15	-0.19	20.96	16.11	13.41	0.53	-0.15	0.23
SO	Morbegno - via Cortivacci	UB	0.82	0.02	0.01	24.3	7.15	23.22	0.71	0.01	0.28
SO	Sondrio - via Paribelli	UB	0.86	0.1	-0.17	23.67	14.52	18.69	0.73	0.22	0.34
VA	Busto Arsizio - Accam	SB	0.91	0.06	0.13	24.94	5.36	24.36	0.79	0.05	0.32
VA	Ferno	UB	0.9	-0.05	0.13	24.14	4.39	23.74	0.78	-0.11	0.32
VA	Saronno - via Santuario	UB	0.91	0.05	0.13	24.69	3.93	24.38	0.8	0.09	0.36
VA	Varese - Vidoletti	UB	0.84	0.01	0.22	30.01	1.35	29.98	0.71	-0.03	0.33