Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Analysis of the lockdown effects due to the COVID-19 on air pollution in Brescia (Lombardy)

Elza Bontempi a, Claudio Carnevale b,*, Antonella Cornelio a, Marialuisa Volta b, Alessandra Zanoletti a

a INSTM and Chemistry for Technologies Laboratory, Department of Mechanical and Industrial Engineering, University of Brescia, via Branze 38, 25123 Brescia, Italy
b Department of Mechanical and Industrial Engineering, University of Brescia, via Branze 38, 25123 Brescia, Italy

ARTICLE INFO

Keywords:
COVID-19
Lockdown
Environmental pollution
PM10
Nitrogen oxides
Air quality
Air pollution

ABSTRACT

SARS-CoV-2 virus (COVID-19) pandemic has impacted several countries, with also some differences at local levels. When lockdown restrictions were imposed, the concentrations of some air pollutants were reduced, as reported in some other cities in the world. This was often considered a positive by-product of the pandemic. However, often literature reporting the connection of air quality (AQ) and lockdown, suffers of limited and incomplete data analysis, not considering, for example, some confounding factors.

This work presents a methodology, and the results of its application, to assess the impact of pandemic restrictions on AQ (in particular nitrogen oxides, NO2 and particulate matter, PM10) in spring 2020 in Brescia, located in one of the most affected areas in terms of virus diffusion and in one of the most polluted areas in Europe (Po Valley, Italy).

In particular, the proposed methodology integrates data and AQ modelling simulations to distinguish between the changes in the PM10 and NO2 pollutants concentration that occurred due to the restriction measures and due to other factors, like spatial-temporal characteristics (for example the seasonality), meteorological factors, and governmental actions that were introduced in the past to improve the air quality.

Results show that NO2 is strongly dependent to traffic emission. On the contrary, although the expected decrease in PM10 concentrations, the results highlight that the reduction of transport emission would not help to avoid severe air pollution, due to the other pollution sources that contribute to its origin.

The results presented for the first time in this work are of particular interest because they may be used as a basis to investigate in more details the sources that can impact on the air quality in Brescia, with the aim to propose effective measures able to reduce it.

1. Introduction

Despite the introduction in 2015 of Sustainable Development Goals (SDGs), with an emphasis to reach sustainable cities targets before 2030, nowadays air pollution is one of the biggest problems to face in several areas (Longhurst et al., 2018) (World Health Organization, 2021). Among the different air pollutants, greatest concern is devoted to particulate matter (PM) and nitrogen oxides (NOx) (Domingo and Rovira, 2020).

In the last decades, in Europe strong efforts have been performed to reduce the concentrations of these pollutants. These efforts range from the introduction of suitable emission control technologies, definition of new strategies, solicitation, and promotion of behavioral changes and they allow to reach some (even limited in some areas) improvement (Zanoletti et al., 2021).

Nevertheless, some areas in Europe still have strong problems in terms of PM10 and NOx levels; in particular, Northern Italy is one of the most critical regions in this situation (Carnevale et al., 2010) (European Environment Agency (EEA), 2020).

In the last months, great concern has triggered the COVID-19 epidemic that spread in Italy starting from the end of February 2020 (Anand et al., 2021). Apart the sanitary adopted approach to face the pandemic, restriction measures were imposed to limit the virus diffusion among population (Bontempi, 2021). In particular, the imposed
most of articles examining the impacts of COVID-19 on air pollution environment and the pandemic (Shakil et al., 2020) have reported that, area (Etchie et al., 2021). The weather conditions, and the local characteristic of the investigated stations to propose robust and reliable conclusions (Jakob et al., 2021). These pitfalls make very difficult to perform a reliable evaluation of the lockdown impact on air pollution by means of only a simple comparison of the investigated pollutants concentrations in 2020 with the levels of previous period, even if considered in the very same locations.

The aim of this work is to evaluate the effect of the lockdown limitations on PM$_{10}$ and NO$_2$ concentration in the Brescia urban area, considering the possible contribution of confounding factors, such as meteorological parameters. This area has been selected for two main reasons: a) Brescia has very high PM$_{10}$ and NO$_2$ concentrations in nominal situations (Carnevale et al., 2020); b) this area suffered from a strong impact of COVID-19 pandemic, leading to very active participation of the population to the lockdown limitations (De Angelis et al., 2021). Finally, this area was never still investigated in terms of lockdown connected air change, and the results of this study may be interesting also in the frame of the discussion about a possible role of PM in SARS-CoV-2 transmission (Bontempi and Coccia, 2021). For this aim, models able to distinguish the air quality changes due to confounding factors from the ones obtained because of the lockdown restriction measures are used. Indeed, some works have highlighted that incomplete correction for meteorological factors may lead to biased results (Menut et al., 2020). Nevertheless, modelling gives some methodological tools able to overcome these issues, and in particular to take into account the peculiarities of the area under study, for example:

1. The specific characteristics (meteorology, orography, population and emission density, industrialization level) of the area under study.
2. The impact on the pollutant formation and accumulation phenomena of both short term (local activity emissions, meteorology) and long term (structural emission reductions) dynamics.
3. The impact of strong unpredictable and daily changing drivers (meteorology).

Table 1

| Group | Wind speed (m/s) | Rainfall (mm/day) |
|-------|-----------------|------------------|
| G1    | >2 m/s          | >3 mm/day        |
| G2    | >2 m/s          | <3 mm/day        |
| G3    | <2 m/s          | >3 mm/day        |
| G4    | <2 m/s          | <3 mm/day        |

lockdown rules limited the people movement, with the aim to reduce social interactions. These stringent measures led to an almost total blockage of traffic and the closure of schools, offices, and factories as well as the prohibition to carry out any outdoor human activity. The progressive adoption of these measures produced a fast and impressive modification of the human activities, with the consequence to produce a change of the typical conditions of pollutants emission.

This gives the researchers (and the political authorities) a unique opportunity to evaluate the impact of emission control strategies (even if related to a limited range of activities) on air quality.

Indeed, several studies have been performed comparing the pollutant concentrations before and during the COVID-19 pandemic (Liu et al., 2020) (Dutheil et al., 2020). However, in several of these works, based only on preliminary data analysis, a generalized decline in anthropogenic air pollution has been reported in almost all the nations where lockdown was applied with a generalized conclusion about the positive effect of traffic limitation on pollutants reduction (Collivignarelli et al., 2020) (Liu et al., 2020) (Dutheil et al., 2020). These considerations were generally deduced by comparing the pollutants concentrations before and during the COVID-19 pandemic, with a lack of a more comprehensive comparison with complete long-term historical data, to better support the conclusions.

Only few papers have evaluated the lockdown effects while accounting for factors, like seasonality, air quality improvement trends, the weather conditions, and the local characteristic of the investigated area (Etchie et al., 2021).

Some interesting review papers investigating the nexus between environment and the pandemic (Shakil et al., 2020) have reported that, most of articles examining the impacts of COVID-19 on air pollution were based on explorative analyses, with several methodological limitations to propose robust and reliable conclusions (Jakob et al., 2021).

It is a matter of fact that what in principle seems a quite simple problem hides many pitfalls related (but not limited) to:

1. ARMA/ARX analysis to try to discriminate the impact of meteorology on the results (Camelletti, 2020), even if the limited number of available data and the strong peculiarity of the situation make a daily study very difficult.
2. A set of modelling simulation over Europe (Menut et al., 2020).
3. Time series analysis (seasonality and trend) in order to consider the impact of the long-term emission changes.
4. Classification method to grants to evaluate data observed in similar meteorological situations.
Fig. 2. Trend and detrended series of PM$_{10}$ mean monthly concentration time series [μg/m$^3$]. Data were shown for the Broletto station (urban traffic).

Fig. 3. Comparison of PM$_{10}$ daily mean concentration [μg/m$^3$] in 2020 with respect to the period 2016–2019, for Villaggio Sereno station (urban background).
5. Source-apportionment analysis as a benchmark to explain the results, the similarity, and differences among the different pollutant responses to the lockdown limitations.

2. Materials and methods

2.1. Study area

In this paper, the study has been focused on the Brescia city, located in the east side of Lombardy region, in the Po Valley, known to be one of the most polluted areas in Europe because of its geographical position and morphological conformation which favor the accumulation and stagnation of pollutants (European Environment Agency (EEA), 2019) and the high emission levels of the area. In fact, Brescia is the second most populated city of Lombardy, after Milan, and the third industrial area in Italy. The strong industrialization, the high traffic flows and the large presence of farms contribute negatively to the air quality in this area (European Environment Agency (EEA), 2019).

2.2. Data and methods

2.2.1. Available data

From February 23rd to March 8th 2020, lockdown measures were adopted in some areas of Northern Italy, limiting the movement of people, then from March 9th to June 2nd 2020 national lockdown was extended to all Italy. In order to evaluate the impact of COVID-19 restrictions, the analysis have been performed taking into account both lockdown and no-lockdown days and years with and without the

---

Fig. 4. Comparison of PM$_{10}$ daily mean concentration [µg/m$^3$] in 2020 with respect to the period 2016-2019, for Broletto Station (urban traffic).

Fig. 5. Comparison of NO$_2$ daily mean concentration [µg/m$^3$] in 2020 with respect to the period 2016-2019, for Villaggio Sereno station (urban background).
Fig. 6. Comparison of NO$_2$ daily mean concentration [μg/m$^3$] in 2020 with respect to the period 2016–2019, for Broletto station (urban traffic).

Fig. 7. Comparison of PM$_{10}$ mean concentration [μg/m$^3$] in lockdown and no lockdown period for 2020 and 2016–2019, for Broletto and Villaggio Sereno stations.
Fig. 8. Comparison of NO$_2$ mean concentration [$\mu$g/m$^3$] in lockdown and no lockdown period for 2020 and 2016–2019, for Broletto and Villaggio Sereno stations.

Fig. 9. Average PM$_{10}$ concentrations [$\mu$g/m$^3$] in the 4 selected meteorological classes. Comparison between 2020 and 2016–19. Broletto station (urban traffic).
Fig. 10. Average PM$_{10}$ concentrations [μg/m$^3$] in the 4 selected meteorological classes. Comparison between 2020 and 2016–19. Villaggio Sereno station (urban background).

Fig. 11. Average NO$_2$ concentrations [μg/m$^3$] in the 4 selected meteorological classes. Comparison between 2020 and 2016–19. Broletto station (urban traffic).
Fig. 12. Average NO$_2$ concentrations [µg/m$^3$] in the 4 selected meteorological classes. Comparison between 2020 and 2016–19. Villaggio Sereno station (urban background).

Fig. 13. Trend and detrend of PM$_{10}$ mean Monthly concentration time series [µg/m$^3$]. Villaggio Sereno station (urban background).
restrictions. For this reason, the selected period of analysis ranges from January 1, 2016 to July 31, 2020.

All the measured data needed by the analysis, are collected for the 2 monitoring stations of Villaggio Sereno (urban background) and Broletto (urban traffic) measuring both hourly data of NO\textsubscript{2} and daily mean concentration of PM\textsubscript{10}.

To evaluate the impact of meteorology, data about wind speed and rainfall have been collected in two stations of regional monitoring network (Ziziola and Pastori).

The locations of the monitoring stations used in this works are shown in Fig. 1.

The data have been collected from the Regional Authority network (ARPA Lombardia, 2021).

2.2.2. Accounting for meteorology impact

In order to take into account the impact of the meteorological conditions, with the aim to compare 2020 and the 2016–2019 period, a classification of the daily situation based on meteorological conditions have been performed. In this work the impact of wind speed and rainfall has been considered. The area under study is placed in the Po Valley and so it is characterized by a huge number of wind calm situations and relatively poor rainfall. Because in this work the air quality considerations are performed in terms of daily mean, the hourly data measured from the ARPA monitoring network have been aggregated on a daily basis, computing the daily average wind speed and the total cumulative rainfall. Each day is then classified in one of the 4 group in Table 1 on the basis of two thresholds (2 m/s for wind speed and 3 mm/d for rainfall) in order to consider the situation where in the area under study the day is “rainy” or “windy”. After that classification, the mean values over the 4 groups have been computed for the period 2016–2019 and the 2020. This procedure allows us to evaluate the impact of the lockdown compacting the measured data in the same meteorological conditions but it did not allow to fully evaluate the impact of the meteorology on the pollutant concentration like for example machine learning detrending procedure (Ryan et al., 2021).

2.2.3. Concentration trend analysis

In order to take into account the impact on the concentrations of the structural emission reduction occurred in the area under study and its surroundings in the period 2016–2020, a trend analysis has been performed.

In particular, for each considered station \(s\) and pollutant \(p\) the (linear) monthly trend \(T_{p,s}\) has been estimated for the period 2016–2019 by means of least-square approach and then extrapolated for the 2020 months (Fig. 2). Finally, the detrended series \(D_{p,s}\) can be calculated as in Equation (1):

![Fig. 14. Analysis of the Monthly mean over the detrend series of PM\textsubscript{10} concentrations [\(\mu g/m^3\)]. Broletto Station (urban traffic).](image)
\[ D_{p,s}(m) = C_{p,s}(m) - T_{p,s}(m) \]  

where:

- \( m \) is the time (in month) from January 2016;
- \( C_{p,s}(m) \) is the average concentration measured in station \( s \) for pollutant \( p \).

The detrended monthly series include all the seasonal and not known phenomena once the impact of the emission reduction is excluded (Fig. 2). This analysis allows to understand the relationships between the linear trend and the average concentration for each year and to evaluate the (potential) discrepancies in this relationship for 2020. Strong differences between the detrended series for a certain month in different years means that some phenomena, not related to the structural change defined by the trend, occurs in that period.

### 2.2.4. Source-apportionment analysis

The analyses have been supported by the results of a source-apportionment exercise performed over the domain under study by means of CAMx open source model (CAMx, 2014).

CAMx is a Eulerian chemical transport model allowing to take into account the main phenomena involved in the formation and accumulation of primary and secondary pollutant in atmosphere. In the configuration used in this work, CAMx implements the Carbon Bond CB05 (Yarwood et al., 2005) mechanism, considering 156 reactions for 51 gaseous species. The chemistry is accounted by the EBI (Hertel et al., 1993) numerical solver. Secondary organic particle formation is driven by SOAP module (Strader et al., 1998) while the inorganic thermodynamic module is ISORROPIA (Nenes et al., 1999).

CAMx implements two different modules for PM (PSAT) and ozone (OSAT) source apportionment (Yarwood et al., 2004), both based on the tracer methodology. The module objective is to trace the dynamic of the emission of ozone and PM precursors to evaluate the fraction of the concentration of these two pollutants due to different emission sources selected by the user. The use of the tracer methodology allows the modules to consider chemical transformations, transport, diffusion and deposition. More details about the modules and an application of the model can be found in (Carnevale et al., 2020).

### 3. Results and discussion

The evaluation of the lockdown effects on air quality has been performed by comparing PM\(_{10}\) and NO\(_2\) concentrations measured in the metropolitan area of Brescia for the years ranging from 2016 to 2020. For each pollutant, the daily mean time series, the impact of

![Graph](image_url)
meteorology, and the impact of the emission trend on the analysis have been considered for the two monitoring stations of Broletto (urban, traffic) and Villaggio Sereno (urban, background).

3.1. Daily averages and extremes comparison

Fig. 3 and Fig. 4 present maximum, minimum, and average calculated values for the PM$_{10}$ daily mean concentration for the period January–July of the years 2016–2019 on the two selected stations. These values are compared to the PM daily mean concentrations for the same period of 2020. Some extraordinary events, in particular Saharan dust intrusion phenomena (Copernicus - European Commission, 2020), produced some spike events, that can be highlighted at the day March 28th of 2020, when a decrease in PM$_{10}$ daily mean concentration is not evident.

Fig. 5 and Fig. 6 show the time series comparison for NO$_2$. A large impact of the lockdown restrictions can be highlighted in this case. In fact, the daily mean concentration value for 2020 in the period March–May is almost always under the minimum value for the period 2016–2019. Such behavior is something that can be expected due to the high impact of traffic emissions on NO$_2$ concentrations, and the strong emission reductions that have been achieved during the lockdown for this activity.

Despite the reduction in emission sources during lockdown period (March 8th – June 2nd), that allowed to reach a significant reduction of NO$_x$ emissions, Figs. 3 and 4 show that the PM levels did not have a similar trend, even if the resulting concentrations are comparable to the minimum values measured in the previous years. The daily PM average value in March 2020, as exception of some peaks (March 28th-29th) (Copernicus - European Commission, 2020), is lower than the daily average of PM in March 2016–2019. In particular, the reduction in March 2020 compared to the March average of four previous years is about 30% for PM$_{10}$. However, in April 2020 the concentrations of airborne PM are not very different from the daily average in April 2016–2019, with a reduction about 14% for PM$_{10}$.

The strong lockdown restriction measures (blockage for traffic and the closure of schools, offices, and factories) have determined a fast variation in the human activities, changing their impact on air quality. In particular, ARPA Lombardia report highlighted that in the strong lockdown period (March/April 2020) a decrease in atmospheric

![Fig. 16. Trend and detrend of NO$_2$ mean Monthly concentration time series [µg/m$^3$]. Broletto station (urban traffic).](image-url)
emissions of about 28% for nitrogen oxides (for which the decrease in traffic flows was particularly important) and about 11% for primary PM$_{10}$ was estimated. This observation was reported not only for Brescia, but also for several other European cities, and were attributed to different reasons (Sokhi et al., 2021).

In order to better highlight the different impacts that lockdown had on PM$_{10}$ and NO$_2$, Fig. 7 and Fig. 8 show the boxplot of the daily mean concentration measured for PM$_{10}$ and NO$_2$ respectively for lockdown and no lockdown periods compared with the same periods for the 2016–2019 years. First of all, the two figures show how the two periods present very different concentrations for both the pollutant even for the years 2016–2019, due to the intrinsic seasonality of the formation and accumulation phenomena of PM$_{10}$ and NO$_2$. Nevertheless, in order to try to evaluate the impact of the lockdown on the two pollutants, a possible way consists in comparing the same periods of the 2020. In this sense, Fig. 7 confirms how for PM$_{10}$ the impact results very limited in terms of median but stronger in terms of 75th percentile (from 35 μg/m$^3$ to 27 μg/m$^3$ for Broletto station and from 39 μg/m$^3$ to 31 μg/m$^3$ for Villaggio Sereno) and maximum. The impact is stronger for NO$_2$ (Fig. 8). In this case, the median drops from 32 μg/m$^3$ to 17 μg/m$^3$ for Broletto and from 27 μg/m$^3$ to 14 μg/m$^3$ for Villaggio Sereno, with a difference close to 50%, leading to measured values that in the lockdown period of 2020 have median lower than the 25th percentile of the data of the same period for the years 2016–2019. A similar behavior is shown also by the 75th percentile of the 2020 lockdown period with respect to the maximum of the same period 2016–2019. From this first analysis it seems that the lockdown had an impact on NO$_2$ mean and peak concentrations and on the PM$_{10}$ peaks. However, before to provide final conclusions about the lockdown role in the pollutant reduction, it is mandatory to consider the contribution of meteorological and/or long-term phenomena. This will be discussed in the next sections.

3.2. The meteorology impact

As stated in section 2, the area under study is often characterized by low wind and poor rainfall, leading to meteorological conditions favouring the formation and accumulation of pollutant. According to the methodology, all the days in the period between March 9th (starting of the “strong” lockdown restrictions) and the beginning of June (end of the restrictions) for the years 2016–2020 have been grouped in 4 different meteorological groups, on the basis of thresholds of 2 m/s and 3 mm/day defined in section 2 for windspeed and rainfall respectively. Figs. 9–12 show the impact of the lockdown on the PM$_{10}$ and NO$_2$ concentrations for each group in terms of boxplot. For PM$_{10}$ (Figs. 9 and 10), the impact in terms of median of the concentration reduction is negligible for both the station of Broletto and Villaggio Sereno when the
wind is over the considered threshold of 2 m/s and while the differences in terms of 75th percentile are around 5 μg/m³. This behavior suggests that in these days the impact of favorable meteorology is dominant in comparison to the impact of the emission reductions. In the absence of wind, the lockdown effect is slightly more consistent, in particular in the traffic station of Broletto, reaching 10 μg/m³ in terms of median in the case with poor rainfall. The evaluation of the 75th percentile in this case is particularly interesting because for the Broletto station the third quartile of the data in 2020 is lower than the median of the data in the 2016–2019 suggesting a strong reduction of the high concentrations.

For NO₂, the median concentration for 2020 is always lower than that of the year 2016–2019 for the days with “similar” meteorology (in terms of wind speed and total rainfall), and the impact seems more intense in absence of favorable meteorological conditions (i.e. for days when there is low wind and poor rainfall), with differences around 20 μg/m³. Also in this case, a strong impact on 75th percentile can be highlighted (15–25 μg/m³).

In particular for NO₂, the case windspeed <2 m/s and rainfall >2 mm/day shows a peculiar behavior, but ts has to be stressed as in the area under study the days with rainfall higher than 3 mm are relatively few (28 in the period January–June 2020).

3.3. The structural emission reductions impact

In the last decade, a strong emission reduction has been achieved, due to the application of suitable emission control technologies and strategies, that can be considered the effect of the Europe’s clean air policy directives (European Council, 2013) and the Lombardy Region Air Quality plan (Regione Lombardia, 2020). This may have caused a decreasing trend in the pollutant concentrations, in the investigated area. In order to discriminate the effect of the lockdown from the effect of this structural emission reduction a trend analysis has been performed.

The analysis highlights a consistent decreasing trend in PM₁₀ concentration in the period 2016–2020, with a reduction close to the 10 μg/m³ (more than 2 μg/m³ per year), reported in Figs. 2 and 13. In order to evaluate the impact of the lockdown, the detrended time series have been analyzed. In particular, the analysis presented in Fig. 14 and Fig. 15 allows comparing the impact of monthly mean once the contribution of the trend (considered as due to all the long-term phenomena like
structural emission control strategies) has been excluded. The detrended series take therefore into account seasonality (causing the value to be both over and under the trend in different months). For these reasons, a value of the detrended series for a certain period of a certain year strongly different from the others highlights that a critical event happened. As shown in Figs. 14 and 15 for PM$_{10}$, the detrended series monthly mean in 2020 has a behavior that is comparable with the average of the 2016–2019 both in lockdown (March–May) and not lockdown period, showing a limited impact of the lockdown restrictions on PM$_{10}$ concentration.

On the other hand, for NO$_2$ the impact of the lockdown strategies is still strong if the long-term trend role is removed (Figs. 16–19). The detrended series monthly mean analysis shows how for both the stations the first months (January and February) of 2020 are characterized by value comparable (and greater) the average of the period 2016–2019, while starting from March the differences in the two series are stronger. In particular, the case of March must be stressed since usually the detrended series assumes a value greater than zero (i.e. the monthly average is higher than the trend) but this is not the case for 2020 for both the considered stations. This means that a non-predictable/critical event (pandemic restrictions) occurred, and that the level of the impact is so high to change the seasonality of the series for that year.

3.4. Source-apportionment analysis

The source-apportionment analysis performed with the CAMx model allows justify the detected differences in the PM$_{10}$ and NO$_2$ concentrations due to the lockdown. As stated in section 2, source-apportionment analysis allows to evaluate the impact of different emission sources on the pollutant concentration in atmosphere. The analysis has been performed starting from the results of the simulation for the whole Northern Italy (540 × 360km$^2$, Fig. 20), with a resolution of 6 × 6 km$^2$. The simulation has been performed for the year 2011, considered as a standard year in terms of wind speed and rainfall phenomena and for this reason comparable in terms of source-apportionment to the average situation. More details about the validation and the source-apportionment results can be found in (Carnevale et al., 2018) and (Carnevale et al., 2022).

Fig. 21 shows the results of the source-apportionment analysis performed over the Brescia area. The results highlight how the total of PM$_{10}$ concentration is due to a series of causes (agriculture, domestic heating, industrial processes, and road transport); then not only to the traffic.

![Graph showing detrended series monthly mean](image-url)
emissions heavily impacted by the lockdown (ARPA Lombardia, 2020). These results can help in explaining, the lack of average decrease of PM concentrations, that should correspond to the reduced emissions, since the strong secondary inorganic fraction of this pollutant and on the high availability of ammonia emissions, leading to the formation of ammonium nitrates and ammonium sulphates and on not reduced emission of primary fraction coming from domestic heating (Carnevale et al., 2018; Scotto et al., 2021; Lonati et al., 2008). For these reasons, a strong PM$_{10}$ reduction cannot be expected in this area without the reduction of agriculture and domestic heating (ARPA Lombardia, 2019). This result is in accord with a recently published review paper (Adam et al., 2021) reporting that during lockdown the complex and nonlinear behavior of secondary aerosols can be considered the origin of small change in PM concentration, in several countries.

On the other hand, for the NO$_2$ concentrations, the road traffic emission assumes a dominant role on the formation and accumulation of NO$_2$ in atmosphere, so the lockdown restrictions, allowing to strongly reduce the vehicle circulation, can be the origin of a strong reduction of NO$_2$ concentrations.

4. Conclusions

In this work, the evaluation of the impact of the lockdown restrictions caused by the first wave of COVID-19 pandemic on the nitrogen oxides (NO$_2$) and particulate matter (PM$_{10}$) concentrations is presented. The work is based on both data monitored by a portion of the Regional Authority network and modelling systems results. The analysis has been performed for the Brescia metropolitan area in Lombardy, which is generally affected by high levels of pollutants during both summer and winter.

The results show that, considering the estimated pollutants concentration reduction trends due to the implementation of the air quality policies in the area and in the whole Po Valley, the lockdown impact on NO$_2$ reduction is extremely clear and results considerable. Nevertheless, a meteorology analysis shows that it is higher in strong accumulation conditions (low wind speed and no rain period). On the contrary, the measured PM$_{10}$ concentrations result almost in accord with the values reported on the same period for the last 4 years. Finally, the causes of the detected differences between NO$_2$ and PM$_{10}$ behavior have been investigated through a source-apportionment modelling technique. The results of this analysis show that emissions due to road transport are responsible to the formation of more than the 50% of the NO$_2$. 

Fig. 20. Simulation domain used for the source-apportionment procedure.
concentration, while the formation of PM$_{10}$ in atmosphere depends on a larger number of emission sources like road transport, residential heating, agriculture, and industrial processes. Then, it is possible to conclude that lockdown restrictions, that essentially affect the urban mobility, have a limited effect on PM$_{10}$ reduction. This highlights the importance to adopt more effective measures to reduce PM, in conventional situations (not in lockdown period), as it was shown that the simple traffic limitation is not enough to ensure an improvement in PM concentration in Brescia especially when meteorology is unfavorable. This work may be used as a basis to investigate in more details the sources that can impact on the air quality in this city, and to propose effective new measures able to reduce it. Future studies may be devoted to accounting for confounding meteorological factors in the used model. For example, machine learning approaches may be proposed to evaluate time series of air pollutants based on a long-term range (several years). This may help to really evaluate the effects of a single emission source change.

**Author contributions**

Conceptualization, M.V., E.B., C.C.; methodology, C.C., M.V.; formal analysis, C.C., M.V.; data curation, A.C., A.Z., C.C.; writing original draft preparation, E.B., A.C., A.Z., C.C., M.V.; writing—review and editing, M.V., E.B.; visualization, A.C., A.Z.; supervision, M.V.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**References**

Adam, M.G., Tran, P.T.M., Balasubramanian, R., 2021. Air quality changes in cities during the COVID-19 lockdown: a critical review. Atmos. Res. 264.

Anand, U., Cabreros, C., Mal, J., Ballesteros, F., Sillanpää, M., Tripathi, V., Bontempi, E., 2021. Novel coronavirus disease 2019 (COVID-19) pandemic: from transmission to control with an interdisciplinary vision. Environ. Res. 197.

ARPA Lombardia, 2019. Progetto Ammoniaca : Relazione Finale Triennio 2017–2019, ARPA Lombardia, 2020. Emissioni in Lombardia Durante l’Emergenza COVID-19, pp. 1-27.

ARPA Lombardia, 2021. Aria-ARPA Lombardia [WWW Document]. URL. https://www.arpalombardia.it/Pages/Aria/qualita-aria.aspx. (Accessed 25 October 2021).

Bontempi, E., 2021. The europe second wave of COVID-19 infection and the Italy “strange” situation. Environ. Res. 193, 110476.

Bontempi, E., Coccia, M., 2021. International trade as critical parameter of COVID-19 spread that outclasses demographic, economic, environmental, and pollution factors. Environ. Res. 201, 111514.

Cameletti, M., 2020. The Effect of Corona Virus Lockdown on Air Pollution: Evidence from the City of Brescia in Lombardia Region (Italy), vol. 239. Atmospheric Environment.

CAMx, 2014. CAMx A Multi-scale Photochemical Modeling System for Gas and Particulate Air Pollution [WWW Document]. URL. https://www.camx.com/.

Carnevale, C., Pisoni, E., Volta, M., 2010. A non-linear analysis to detect the origin of PM10 concentrations in Northern Italy. Sci. Total Environ. 409, 182-191.

Carnevale, C., De Angelis, E., Finzi, G., Pedrazzani, A., Turrini, E.M., Volta, M., 2018. A non linear model approach to define priority for air quality control. IFAC-PapersOnLine 51 (13).

Carnevale, C., De Angelis, E., Tagliani, F.L., Turrini, E., Volta, M., 2020. A short-term air quality control for pm10 levels. Electron 9, 1–17.

Cameletti, M., Sangiorgi, L., De Angelis, E., Mansini, R., Volta, M., 2022. A system of systems for the optimal allocation of pollutant monitoring sensors. IEEE Syst. J. https://doi.org/10.1109/JSYST.2021.3132454.

Collivignarelli, M.C., Abbà, A., Bertanza, G., Pedrazzani, R., Ricciardi, P., Carnevale Miino, M., 2020. Lockdown for CoViD-2019 in Milan: What are the effects on air quality? Sci. Total Environ. 732.

Copernicus - European Commission, 2020. Desert Dust Strikes Southern Europe [WWW Document]. URL. https://atmosphere.copernicus.eu/desert-dust-strikes-southern-europe. (Accessed 28 October 2021).

De Angelis, E., Renzetti, S., Volta, M., Donato, F., Calza, S., Placidi, D., Lucchini, R.G., Rota, M., 2021. COVID-19 incidence and mortality in Lombardy, Italy: an ecological study on the role of air pollution, meteorological factors, demographic and socioeconomic variables. Environ. Res. 195, 110777.

Domingo, J.I., Rovira, J., 2020. Effects of air pollutants on the transmission and severity of respiratory viral infections. Environ. Res. 187, 106650.
