Proceedings of the 19th Conference on Computer Science and Intelligence Systems (FedCSIS) pp. 713–718 DOI: 10.15439/2024F838 ISSN 2300-5963 ACSIS, Vol. 39

Dynamic Relationship Between Population Densities and Air Quality in the Four Largest Norwegian Cities

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***Abstract*—Air pollution is a significant cause of health problems and disease worldwide. Considering the rapid urbanisation at a global scale in recent decades, resulting in more and more people in urban areas, cities deserve special attention in this regard. In this paper, we use air quality measurement data from 2010 to 2023 in the four largest Norwegian cities (Oslo, Bergen, Trondheim, and Stavanger) and correlate it with the evolution of population densities for the same period. The empirical analysis focuses on nitrogen dioxides (NO2) and particular matter (PM2.5 and PM10) as critical pollutants in urban areas to verify whether their concentrations are affected by the increase in population densities for individual municipalities. In addition, we also correlate the data on air pollutants with different natural indicators such as temperature, air pressure, humidity, wind, and the rate of motorisation in the cities of interest.**

I. Introduction

SINCE the rise of sustainability concerns in the 1970s, the focus on the negative impact of cities on the environment is growing gradually and air pollution is considered a major one. A comparative study between 20 cases in various European countries by [8] demonstrates that air pollution levels in Norway are similar to the other Scandinavian countries but lower than in southern Europe. The Norwegian Institute of Public Health (NIPH) confirms this statement in its annual health report from 2018 [18]. The institute documents that the air pollution levels in Norway have been relatively stable over the last decade, as the levels of key pollutants particulate matter (PM) and nitrogen dioxide (NO2), have been even slightly declining.

However, it seems crucial to measure the extent of the negative anthropogenic factors of urban development and concentrations of activities on the accumulation of hazardous air pollutants within this discussion. Recent studies, including [11] and [3], emphasise this negative correlation, respectively, in the context of China and Germany. In Norway NIPH also outlines that the concentration of pollutants, such as PM and NO2 varies considerably between urban areas and elsewhere in the country. There may also be significant variations within each town and densely populated area, depending on traffic and other emissions [18]. This is a fundamentally critical question considering the health, economic, and environmental impact that air pollution has, defining the latter as an essential determinant of the quality of life [3]. Examples of behaviours that contribute to air pollution include driving vehicles that emit pollutants, idling engines, burning fossil fuels for heating and energy, and engaging in activities that produce emissions like industrial processes and releasing harmful chemicals into the air [5].

On the other hand, it is crucial to recognise that denser urban environments can provide more effective use of resources such as space, energy, and raw materials. Denser cities require less space, saving valuable peri-urban lands instead of providing environmental services and agricultural goods. By reducing travel distances and enhancing connectivity through (a combination of) public transport, cycling, or walking, it is possible to reduce fossil fuel use significantly. More compact buildings also require less energy for cooling and heating [15]. Moreover, dense urban environments provide the conditions to reduce and improve supply chain coordination [13], leading to a better logistic distribution of goods [1]. Consequently, denser built environments can reduce CO2 emissions, resulting in densification as a practical approach to guiding sustainable urban development [14].

Motivated by this somewhat twofold impact of urban densities, we address the relationship between population densities and concentration of air pollutants in the context of the four largest cities in Norway, i.e., Oslo, Bergen, Trondheim, and Stavanger. This goal defines the main research question of this study: What is the correlation between the population density's dynamics and the concentration of air pollutants within the four largest Norwegian cities?

By exploring this question, we aim to outline the correlation between the concentration of people, respectively, human activities and air quality. Therefore, we also make a modest attempt to compare the correlation between air pollution and population densities with the correlation between air pollution and other geographic-meteorological factors, such

The work is supported by the National Scientific Fund of Bulgaria under the grant DFNI KP-06-N52/5.

as wind speed, temperature, humidity, atmospheric pressure, precipitation, and sun irradiation (sunshine hours).

II. Air quality monitoring and norms regarding specific pollutants

Measurements of air emissions are critical for epidemiology and air quality control. Traditionally, concentrations of air emissions have been measured by air monitoring stations with standard equipment, allowing for highly reliable results. Although recently there is a scientific concern about the limitations of this, ground-based air pollution observations have limitations in terms of assessing personal exposure to pollution, this traditional approach possesses strong capacities in estimating the extent of air pollution on a city and municipal level [21], [12]. Thus, data collected by stationary monitoring stations in Norwegian cities fit the purpose of the study.

A. Hazardous pollutants of interest

Air pollution consists of a range of different substances, depending on the source. However, three of them, i.e., PM, NO2 and ozone (O3), are considered to be the most critical air-polluting components in urban areas that cause problems, disease, and death in this part of the world [4]. This study focuses on the former two – PM and NO2. PM air pollution is a suspended combination of solid and liquid particles that vary in quantity, size, shape, surface area, chemical composition, solubility, and origin. Total Suspended Particles (TSPs) have a trimodal distribution in the ambient air, including coarse particles, fine particles, and ultrafine particles [20]. PM size-selective sampling refers to collecting particles below, above, or within a defined aerodynamic range of sizes, which is commonly chosen to be relevant to inhalation, deposition, causes, or toxicity [6]. Particle size is generally described in terms of a 50 per cent cut point at a specific aerodynamic diameter (such as 2.5 or 10 μm) and the slope of the sampling effectiveness curve because samplers are incapable of accurate size distinction. In terms of establishing guidelines or standards for acceptable levels of ambient PM pollution, public health policy has primarily focused on indicators of fine particles (PM2.5), inhalable or thoracic particles (PM10), and thoracic coarse particles (between PM10 and PM2.5) [9], [19]. Nitrogen Dioxide (NO2) is another pollutant, part of a group of reactive gases known as oxides of nitrogen or nitrogen oxides (NOx). Other nitrogen oxides include nitrous acid and nitric acid. NO2 is used as the indicator for the larger group of nitrogen oxides [7]. In cities, NO2 primarily accumulates in the air from internal combustion engines burning fossil fuels, i.e., motor vehicles, power plants, and offroad equipment [4]. Exposures to NO2 over a short period can aggravate respiratory diseases, particularly asthma, leading to respiratory symptoms (such as coughing, wheezing or difficulty breathing), hospital admissions and visits to emergency rooms. Longer exposures to elevated concentrations of NO2 may contribute to the development of asthma and potentially increase susceptibility to respiratory infections. People with asthma and children and the elderly are generally at greater risk for the health effects of NO2 [9], [19].

B. Norms regarding specific air pollutants

Although providing a solid background regarding limiting air pollution in urban and rural areas, WHO guidelines can be considered practical recommendations without mandatory character. On the other hand, in Europe, the EU Air Quality Directive represents legislation that every EU member must follow. The most noticeable difference is that there is no limit for daily limits for PM2.5 in the EU Air Quality Directive. In Norway, however, there are implemented limit values for each of the pollutants of interest, based on a long-term national ambition for local air quality. These goals are set to the same level for each city as air quality criteria for PM (annual mean) and NO2 (annual mean). These criteria are established so that most of the population in the country is effectively protected against harmful effects if they are exceeded [18]. Based on newer knowledge about the health effects of PM by NIPH, the criteria for air quality concerning PM10, PM2.5, and NO2 was revised and set to lower limits in 2014 [17], [16]. The current limits for the pollutants of interest in Norwegian cities are as follows: for PM10 [max: 25 $\mu g/m^3$, target: 20 $\mu g/m^3$]; for PM2.5 [max: 15 $\mu g/m^3$, target: 8 $\mu g/m^3$; for NO2 [max, annual mean: 40 $\mu g/m^3$, max, hourly value: 200 $\mu g/m^3$].

III. Methodology

The method applied in this study is a quantitative approach to explore the relationships of interest regarding the concentration of air pollutants. This section describes the various aspects of the method, including the origin of the utilised datasets, their specifics and the approach through which correlations of interest are estimated.

A. Data

1) Air quality data: Regarding the emissions data of PM10, PM2.5, and NO2, we use the annual mean values from 2010 to 2023. These datasets are extracted from the Central database for local air quality (SDB) and collected by the Norwegian Institute for Air Research (NILU). These stations are representative of NILU and stationary, as there are a different number of measurement stations located in the four cities. However, they are positioned in strategic locations to record air pollution in key areas, lying on streets and transport axes, or dispersed throughout cities. These variables are added to our regressions as dependent variables correlated with the weather, and density indicators.

2) Population densities: Population density (POPd) is a well-established indicator in urban planning, and its use is documented in the works of notable researchers, such as [22], [23], [10], among others. The measurement focuses on estimating the number of people per spatial unit. It is predominantly calculated in people per hectare and in "gross densities," as in the case of this study. The dynamics of the variables are calculated for the period 2010-2023 for the municipalities of interest, based on the census data publicly provided by the

Norwegian Statistics Bureau (SSB). The specific estimations are calculated through the following formula:

$$POPdx = POPx/Ax \quad (1)$$

where:
POP = total population
A = base land area (in hectares)
x = area of aggregation (the municipalities of Oslo, Bergen, Trondheim, and Stavanger)

3) Weather data: As argued in the previous section, the ambient concentrations of emissions tend to be affected crucially by the specific weather conditions in each context [2]. Thus, although not representing the primary research direction of interest for this study, we still use weather variables to generate basic linear regressions with each one of them. The measurements we include are the annual means of temperature (°C), atmospheric pressure (hPa), humidity levels, wind speed (m/s), average precipitation (mm), average precipitation days ($\geq$ 1.0 mm), and average sunshine hours. For the first four indicators, we use the collected data for 2023 by all stations, which we use for extraction of emissions data, for the precipitation data, we use the aggregated data of NILU for the specific cities for the period of 1991-2023, and for the average sunshine hours, we employ the data for the period 2016-2023.

B. Correlation analysis

The last step of the data processing consists of performing statistical correlations between the concentration of air pollutants and population densities for the four case studies. This activity is realised through a series of correlation analyses (Pearson's correlation coefficient). The measure represents a practical statistical approach to exploring the relationship between two variables based on their values' standard deviation. This defines it as a normalised bivariate measurement whose value is always between -1 and 1.

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad (2)$$

where:
r = correlation coefficient
xi = values of the x-variable in a sample
$\bar{x}$ = mean of the values of the x-variable
yi = values of the y-variable in a sample
$\bar{y}$ = mean of the values of the y-variable

Based on these estimations, we explore the relationships of interest by executing the correlations between the annual mean of each pollutant and the population density for the respective year for the period 2010-2023, excluding two correlations for which data is not available. This provides 42 correlations based on which basic regression analysis is elaborated. As a last verification activity to compare the influence of the population densities with the impact of weather indicators on air pollution, additional regressions are also executed. They correlate the extracted weather data (annual mean average) with the mean yearly average for the concentration of air pollutants (2010-2023) for the respective cities.

IV. Results

The following section presents the generated outcomes from the undertaken data processing and discusses the empirical assumptions that can be drafted based on them.

A. Case studies

Before presenting the results from the data processing and the executed correlations, it is required to present a brief description of the examined cases. This is an essential element that allows us to interpret our results more rigorously. As a part of the case description, we include:

- The number and locations of the stationary sensors of NILU, based on which the data regarding air pollution is collected;
- The aggregated weather data for each city;
- The dynamic of the population density of its municipality for the period of 2010-2023.

1) Oslo: Oslo is the most carefully monitored case of the four examined as the capital and most populous city in Norway. NILU has 14 positioned stations all around Oslo's municipality, from where data is permanently collected. Oslo is also a specific case since it is the only one of the four major Norwegian cities not on its west coast. Thus, it is characterised as the case with the least average annual mean of humidity, precipitation, and wind but the city with the most sunshine hours annually. The municipality of Oslo is also the most densely populated one in Norway and, therefore, in between all of the four examined cases with a density of 54 people per hectare in 2023, see Table I. Since 2010 we can observe a gradual increase in the population density of approx. 2% each year. Exclusions are observed in 2011 and 2013 when there is a more significant increase and in 2017, 2021, and 2023 when there is no increase.

2) Bergen: Bergen is the second-most populous city in Norway. The emissions and weather data for Bergen are collected through five stations located all around the municipality. Regarding weather specifics, it is worth outlining that Bergen is by far the rainiest city of the examined cases. Its annual mean for average precipitation is double the one of Stavanger and triples the value of Oslo and Trondheim. This condition respectively reflects on the highest humidity and lowest sunshine hours from the examined cases. Although being the second-most populous city in Norway, the municipality of Bergen is characterised by lower population density numbers (with 30 people per hectare in 2023) even with respect to Stavanger and Trondheim. Since 2010 we can indicate a state of stagnation due to the stable number. Looking at the numbers, we can observe two rapid jumps of the density indicator in 2013 and 2020, but this is due to administrative changes resulting in a reduction in the municipality's area. Such restructuring events affect air pollution data records, as monitoring stations within added or removed municipal territories are included or excluded from the aggregated data.

TABLE I
POPULATION DENSITIES (INHABITANTS PER HECTARE) FOR THE FOUR LARGEST MUNICIPALITIES IN NORWAY, 2010-2023

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
OSLO POPd	42	44	45	47	48	49	50	50	51	52	53	53	54	54
OSLO +/-	-	+4.6%	+2.2%	+4.3%	+2.1%	+2.0%	+2.0%	-	+2.0%	+1.9%	+1.9%	-	+1.9%	-
BERGEN POPd	23	23	23	27	27	28	28	28	28	28	30	30	30	30
BERGEN +/-	-	-	-	+14.8%	-	+3.6%	-	-	-	-	+6.7%	-	-	-
TRONDHEIM POPd	25	25	26	30	30	30	30	31	31	31	32	33	33	34
TRONDHEIM +/-	-	-	+3.8%	+13.3%	-	-	-	-	-	-	+3.1%	+3.1%	-	+3.1%
STAVANGER POPd	26	27	27	31	30	31	31	31	31	31	17 (31)	17	17	17
STAVANGER +/-	-	+3.7%	-	+27.0%	-3.2%	+3.2%	-	-	-	-	-45.1% (-)	-	-	-

3) Trondheim: Trondheim is the most northern city of all examined cases, and its population is lower than Bergen's. NILU collects the climate data in the municipality via four permanent stations. Despite its geographic location to the north and on the coast, Trondheim has specific topographic conditions that result in lower humidity, wind, and precipitation compared to all other cases on the west coast. The municipality of Trondheim represents the second-most dense case from the ones examined in this study, with a density of 34 people per hectare for 2023. Looking holistically at the number, we can state that they illustrate a minor increase, as the only rigid one (in 2013) is due to administrative restructuring of the municipal borders.

4) Stavanger: Stavanger is a comparable city with Trondheim in terms of population size but weather-wise with Bergen. However, the degree of precipitation is still significantly lower than the one recorded in Bergen. Apart from this, it is worth mentioning that Stavanger is the warmest and the windiest city of all examined cases. In Stavanger, the weather and air pollution data are collected by four stations positioned within the municipality. By looking at the population densities dynamic we can argue that the case of Stavanger represents a state close to stagnation with fluctuating values. Similar to the case of Bergen, the two dramatic changes in the number (in 2013 and 2020) are due to administrative restructuring. However, the latter results in a significant decrease in the population density to 17 people per hectare. This is due to the incorporation of two low-dense populated municipalities within the administrative body of Stavanger.

B. Air quality

As section 2 presents in greater detail, there are different values to assess air quality levels. However, due to health effects and the Norwegian policies in this study, we focus on NO2, PM2.5 and PM10 as hazardous air pollutants. In this sub-section, the dynamics of their annual means (average annual concentrations from 2010 to 2023 are presented.

1) Nitrogen dioxide (NO2): Table II illustrates the dynamic development of the annual means throughout the period of interest for all cases. By examining the data, we can identify the apparent trend of reducing the emission of NO2 in all of the examined cases in the last decade. This trend is even more evident after 2016 when the values for the instances of Oslo and Bergen had been fluctuating. From a contemporary perspective, the levels for NO2 do not exceed the standard max, namely, an annual mean of 40 $\mu g/m^3$.

2) PM10: The next pollutant of interest examined is PM10, as Table III shows its changes for the previous decade. Concerning the concentrations of this air pollutant, there is also a general tendency to reduce its emissions in Norwegian cities. A positive fact is that since 2016 all of the studied cities have managed to maintain an annual mean with the normative limit of 25 $\mu g/m^3$. However, in the case of Oslo, it seems that the levels of PM10 are being kept the same for almost the whole period, very close to the indicated limit. In the last years, a particularly impressive improvement in reducing the concentration of this air pollutant is documented in Stavanger.

Concerning PM2.5 concentrations, it can be claimed that the implemented measures to keep the levels below annual means of 15 $\mu g/m^3$ have proven to be successful, as an exceeding of this limit is not observed for the last decade (Table IV). There is a general decline in emissions, though, in the case of Oslo, this seems harder to state since the value has been fluctuating. This is the only city in which the target of 8 $\mu g/m^3$ has not been achieved yet.

C. Air pollution and weather-based variables

In addition to the primary relationship of interest between population densities and air pollution, we also explored the relationship between the latter and the weather-based variables we retrieved from the publicly available sources. This was motivated by the literature review presented in section 2.2 and the ambition of how influential the weather conditions are compared to a socio-demographic factor such as population density. Tab;e VI illustrates the results of the run regression models for available weather data as the highlighted value indicates r^2 and the italic number below represents Pearson's coefficient (r) for each correlation, see Table V.

The presented results indicate some interesting notions with respect to estimated correlations. To simplify them, we can identify whether factors with a homogenous (although not equal) impact on all of the pollutants and weather factors significantly stronger on a particular contaminant. The former group seems to include temperature, atmospheric pressure, and humidity. The latter two weather conditions have a strong negative correlation with all pollutants, meaning the greater

TABLE II
THE ANNUAL MEAN (AVERAGE ANNUAL CONCENTRATIONS) OF NO2 ($\mu g/m^3$) FOR CITIES OF INTEREST FROM 2010 TO 2023

City	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Oslo	62	54	60	61	50	51	56	41	40	39	33	32	29	29
Bergen	55	38	43	41	42	38	41	35	36	32	24	27	24	24
Trondheim	52	46	40	37	35	32	33	28	31	29	22	24	21	19
Stavanger	-	52	45	44	41	37	33	32	28	25	22	27	21	21

TABLE III
THE ANNUAL MEAN (AVERAGE ANNUAL CONCENTRATIONS) OF PM10 ($\mu g/m^3$) FOR CASE STUDIES FROM 2010 TO 2023

City	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Oslo	24	22	21	27	25	24	24	22	24	22	23	32	29	29
Bergen	26	-	18	22	19	16	17	14	17	14	15	27	24	24
Trondheim	28	30	29	24	22	16	13	14	17	14	14	24	21	19
Stavanger	29	27	26	28	24	28	22	13	14	13	16	27	21	21

TABLE IV
THE ANNUAL MEAN (AVERAGE ANNUAL CONCENTRATIONS) OF PM2.5 ($\mu g/m^3$) FOR CASE STUDIES FROM 2010 TO 2023

City	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Oslo	14	14	12	15	11	9	10	9	12	9	12	9	9	7
Bergen	14	9	9	9	9	8	8	7	7	7	8	8	7	7
Trondheim	11	10	10	10	10	7	6	5	7	6	8	7	6	6
Stavanger	12	10	8	10	10	10	10	8	9	9	8	10	7	7

TABLE V
CORRELATIONS BETWEEN POPD AND AIR POLLUTANTS

Correlations	**NO2** ($\mu g/m^3$)	**PM2.5** ($\mu g/m^3$)	**PM10** ($\mu g/m^3$)
Pearson's r	0.38	0.42	0.18
r-square (r^2)	0.14	0.18	0.03
Coefficient of covariance (CV)	0.43	0.10	0.01
p-value (standard error)	< 0.01	0.013	0.26

their values are, the lower the concentration of air pollutants will be. However, the average temperature does not seem to influence the concentrations of NO2, PM2.5, and PM10.

The weather factors, such as precipitation, sunshine hours, and wind, seem to affect the three pollutants differently. For instance, the level of precipitation (both in terms of the average mean of absolute value or as an average number of high precipitation days – above 1.0 mm) influence to a greater extent the concentrations of PM10. A little lower but still in a moderate and negative direction, the precipitation impacts PM2.5 and NO2. On the contrary, the wind speed has a stronger negative correlation with the concentration of NO2, a minor impact on PM2.5 and an insignificant correlation with PM10. Lastly, we can outline the significant impact that sunshine hours have on the concentration of PM10; the data suggest a more moderate effect on PM2.5 and a minor one on NO2.

D. Discussion

After presenting the generated outcomes from the undertaken data processing, we can outline some specific empirical assumptions. First of all, it is essential to address the main research question of whether there is a correlation between population densities and air pollution in the examined case, i.e., the municipalities of the four largest Norwegian cities. The processed data suggests a positive correlation, but this does not seem highly influential compared with other geographic-meteorological factors. Furthermore, an assumption that we might make is that the positive impact of population density on air quality seems to decrease with time. Based on the examined cases, there are minor increases in population density figures for Bergen, Trondheim, and Stavanger (excluding 2020) and notable growth of the variable in the case of Oslo. However, looking at the concentration of the observed air pollutants, there are strong tendencies of reduction. This trend demonstrates that the policies for reducing air pollution by promoting electric cars (and vehicles) in Norway and fossil-fuel-free modes of transport in cities are somewhat successful.

The second significant outcome from the executed study is that specific weather conditions seem to be much more influential to air pollution than the density of people and activities within the explored context. The annual mean of the average temperature is the only weather-based factor estimated with lower significance to air pollution than population densities in the examined cases. Variables such as atmospheric pressure, humidity, precipitation, and sunshine hours demonstrate strong correlations to at least one of the pollutants of interest. The former two have a strong negative correlation with all of NO2, PM10 and PM2.5. At the same time, precipitation and sunshine hours predominantly influence the two examined

TABLE VI
RESULTS OF THE RUN REGRESSION MODELS FOR AVAILABLE WEATHER DATA AS THE HIGHLIGHTED VALUE INDICATES R2 AND THE ITALIC NUMBER BELOW REPRESENTS PEARSON'S FOR EACH CORRELATION

	Temperature	**Atmospheric Pressure**	**Humidity**	**Wind**	**Precipitation annually**	**Precipitation days**	**Sunshine hours**
NO2	0.01 (-0.08)	0.95 (-0.97)	0.81 (-0.9)	0.39 (-0.62)	0.06 (-0.24)	0.39 (-0.63)	0.15 (0.39)
PM2.5	0.02 (0.15)	0.83 (-0.91)	0.78 (-0.88)	0.13 (-0.35)	0.16 (-0.39)	0.52 (-0.72)	0.39 (0.55)
PM10	0 (0.02)	0.48 (-0.69)	0.63 (-0.8)	0.04 (-0.21)	0.63 (-0.8)	0.82 (-0.9)	0.78 (0.89)

variants of PM, respectively, negatively (for precipitation) and positively (for sunshine hours).

V. CONCLUSION AND FUTURE RESEARCH

The applied method promotes a simplistic, straightforward approach to combine different types of data, such as weather monitoring parameters, geo-database, and census data. We have succeeded in comparing the impact of various factors upon the same variable, i.e., concentration of air pollutants, demonstrating to us the higher relevance of certain geographic-meteorological factors on air quality compared to population densities. However, the latter's positive correlation still suggests exploring avenues of further research regarding this finding. As a potential subsequent endeavour in this direction, we see more elaborated regression models to integrate both types of factors in a single equation.

Elaborating further on this line of thought, a potent idea can be to look at additional traffic data, and electrical vehicle adoption in these municipalities as well as changes in means of transportation throughout the years. Socio-economic variables (anthropogenic factors) that impact the concentration of air pollutants. This would be a worthwhile effort to develop a more holistic understanding of the human impact on air quality in the cases of interest. Interesting explorations could incorporate aspects such as car ownership per capita, the percentage of electric cars, and the degree of use of other mobility modes.

Lastly, the technical aspect of the data collection can be improved by incorporating an additional number of monitoring stations to effectively document the air pollution emissions in two of the cases. Potential possibilities to enhance this are the employment of low-cost sensors and mobile monitoring stations. When combined with the official monitoring stations and model calculations, air quality data would eventually offer a high spatial resolution for in-depth research of particular cases, e.g., municipality, city, neighbourhood, etc.

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