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Maciej Mikulski, Paweł Drożdżel, and Sławomir Tarkowski*

Reduction of transport-related air pollution. A case study based on the impact of the COVID-19 pandemic on the level of NO_x emissions in the city of Krakow

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Abstract: This article describes the impact of limiting human mobility related to the COVID-19 pandemic on the level of air pollution related to transport. The city of Krakow and the emission level of nitrogen oxides (NO_x) were used as a case study. This article describes the air quality monitoring system in Krakow and the measurement results from the measurement station at Krasinskiego Avenue. The average values of the pollution level in April 2018–2020 were compared. For the selected range of data, a significance test was performed, which resulted in no grounds for rejecting the hypothesis of the equality of the mean levels of nitrogen oxides concentrations in the spring. The analysis takes into account the average monthly temperatures in the discussed years.

Keywords: air pollution, transportation, COVID-19 pandemic

1 Introduction

At the beginning of March 2020, the first case of infection with the SARS-CoV-2 virus was recorded in Poland. The following days and months brought new realities of social life that all people and the entire Polish economy had to face. Due to the COVID-19 pandemic, schools have been closed, border controls have been reintroduced and

international flights have been suspended. Lockdown has started. April 2020 was special – the largest restrictions during the COVID-19 pandemic were maintained throughout the month, under the slogan “stay at home,” and Poles had to come to terms with spending Easter in a limited group. Schools and universities, shopping centers, cultural and sports centers were closed. Employees of many companies worked remotely. These limitations resulted from the introduced regulations [1]. The lockdown affected all areas of the economy and caused a significant reduction in the mobility of society. On the streets of cities, the traffic of vehicles and the number of people decreased significantly.

Air pollution is caused by industrial plants, transport, and heating devices used in households [2–5]. Among the pollutants emitted to the atmosphere, nitrogen oxides (NO_x) can be indicated as characteristic of transport and conventional propulsion sources. This is due to the combustion process in the cylinder chamber. The conditions of vehicle operation in urban areas [6–8] and relatively frequent engine starts (compared to the operation of vehicles outside urban agglomerations) can be indicated as favoring the occurrence of this pollution. The mobility limitation related to the COVID-19 pandemic in its initial phase (“hard lockdown”) in Poland was a good time to investigate the impact of transport on air pollution. In scientific publications [9–15], the impact of pandemic restrictions on noise reduction has been observed. It seems logical that if the intensity of traffic decreased (due to lockdown) then NO_x emissions will decrease as well. The aim of the study was to analyze numerical data for a city, whose location favors the accumulation of pollution. The study [16] analyzed the effect of the Olympic-year policy package on the level of air pollution. Local air pollution has been reduced by enforcing traffic restrictions. This conclusion [16] concerned a city with a large area and large number of inhabitants. This article covers a city much smaller than Beijing. The city of Krakow was selected

* **Corresponding author: Sławomir Tarkowski**, Department of Automotive Vehicles, Faculty of Mechanical Engineering, Lublin University of Technology, Lublin, Poland, e-mail: s.tarkowski@pollub.pl

Maciej Mikulski: Krakow Public Transport Authority, Krakow, Poland, e-mail: mmikulski@ztp.krakow.pl, kontakt@maciejmikulski.pl

Paweł Drożdżel: Department of Sustainable Transport and Powertrains, Faculty of Mechanical Engineering, Lublin University of Technology, Lublin, Poland, e-mail: p.drozdzdel@pollub.pl

as the case study. An important aspect of the analysis carried out in this study is the adoption of such a methodology as to reduce the error associated with emissions related to the use of heating devices in households.

Krakow is one of the largest cities in Poland (approximately 760,000 inhabitants) and is located in the southern part of the country. Due to its geographic location and topography, it is particularly exposed to smog. The city is located at an altitude of 187 m above sea level, up to 384 m above sea level and is located in the Vistula valley – the largest river in Poland. On the north and south sides of the city, there are elevations of the terrain, which impede air circulation and ventilation of pollutants. In Krakow, about 120 days a year are known as “windless” days, and the wind speed often does not exceed 2 m/s [17]. Krakow is an important administrative, scientific, business, and cultural center. The city has a well-developed air quality monitoring infrastructure, and the solutions introduced to reduce pollutant emissions (especially from households) allow Krakow to be defined as the Polish leader in this field. For many years, the city has been reimbursing some of the costs related to the replacement of coal-fired stoves, conducts educational campaigns, introduces appropriate law, and develops low-emission public transport. In order to reduce the error related to emissions from heating appliances in households, the analysis compared the results for one selected month, taking into account the weather conditions influencing the demand for thermal power.

2 Transport-related air pollution

It is estimated that up to 30% of Europeans living in urban areas are exposed to air pollution that exceeds allowable concentrations and EU quality standards [18,19]. The air condition and visibility in smog conditions on one of the streets of Krakow are shown in Figure 1. The picture shown in Figure 1 was taken at night to show the pollution level clearly. There is no doubt that actions related to the reduction of pollutant emissions are needed. In the field of transport, such measures are, for example, replacing the public transport fleet with electric and hybrid vehicles, introducing discounts for low-emission car owners, and reducing road traffic in city centers to a minimum – while promoting and favoring “active” mobility. Public transport also uses means of transport where the emission of pollutants depends on the type of fuel [20–22].

The largest share in the emission related to transport is [2,18,23] carbon dioxide (CO_2), carbon monoxide (CO),

Figure 1: Dietla street in Krakow, during the smog. Source: own materials.

nitrogen oxides (NO_x), non-metallic volatile organic compounds and solid particles. The pollutants, the significant emitter of which is transport, also include methane (CH_4), nitrous oxide (N_2O), sulfur dioxide (SO_2) and lead (Pb). The combustion of liquid fuels in motor vehicles may also affect the formation of ground-level ozone, and moving vehicles cause emissions with abrasion of tires, brakes, and road surfaces. There is also “secondary dusting,” consisting in the lifting of dust already existing on the road [18,24]. This article focuses primarily on the analysis of changes in the concentration of nitrogen oxides (NO_x) in the air. This pollutant component is typical of emissions related to the operation of internal combustion engines and at the same time has a small share in the pollution related to energy and industrial activities.

3 Analysis of data from the air quality monitoring system

The monitoring of air quality in Krakow is carried out by the Provincial Inspectorate for Environmental Protection. In April 2020, eight air pollution measurement stations were located in the city [25]. The concentration of nitrogen oxides (NO_x) was measured in four of them. For the analysis in this article, the station on Krasinski Avenue was selected (Figure 2). It is a station located on one of the main communication routes in Krakow. Krasinski Avenue is a north–south transit artery along the so-called Alley of the Three Hangers. For this communication section (as for others located in Krakow), there were no available data on the number of vehicles on the road. On the

Figure 2: Location of Krasinski Avenue within the city of Krakow [26].

other hand, there are data on the general traffic intensity in terms of its changes during the lockdown and for the entire city [23]. The measuring station located on Aleja Krasinskiego collects data on air pollution related to road traffic, which makes it possible to observe and analyze any changes in transport emissions.

Measurements of average daily concentrations of nitrogen oxides in a selected station in April 2018–2020 were analyzed. Figure 3 presents their results, comparing the maximum and minimum levels for the following

days. The lowest level of the average daily concentration of nitrogen oxides was recorded on April 13, 2020. It had a value of $28 \mu\text{g}/\text{m}^3$, the highest level was recorded on April 4, 2018. It had a value of $296 \mu\text{g}/\text{m}^3$. Then, the measurement results from the entire analyzed period were compared and the 20 lowest and 20 highest daily mean values were selected from them. Their total number in individual years is presented in Table 1. For 2020, there are no events among the 20 highest average daily concentrations, as well as a large share of days with the lowest

Figure 3: Average daily concentration of NO_x in the air in Krakow on Krasinski Avenue in April 2018–2020. Source: own study based on data from ref. [25].

Table 1: Summary of 20 days with the lowest and highest average daily concentration of NO_x in the air in Krakow (on Krasinskiego Avenue), broken down by year

Year	Number of days	
	With the lowest concentration	With the highest concentration
2018	1	8
2019	4	12
2020	15	0
Sum	20	20

Source: Own study based on data from ref. [25].

concentration (75% of them occurred in April 2020). The difference is much clearer when you compare 10 days with the best air quality. There are eight of them for 2020, and one for 2018 and 2019. Fluctuations in the level of emissions and the achieved minimum values on individual days in April, in the compared years, may be related to non-working days and holidays. It can be seen, for example, that on selected days of 2019, the level of pollutant emissions was lower than the level of emissions registered on the same days in April 2020. The period of Easter in April 2019 fell on the 21st and 22nd of the month. The traffic and communication needs of the inhabitants at that time were small. Regardless of these circumstances, it can be seen that the absolute drops in the pollution value on the selected days of April 2018 or 2019 are higher than the absolute increases in pollution on the selected days of April 2020.

Figure 4 compares the average monthly and average daily minimum and maximum value of NO_x concentration for April in the analyzed years. In any event, the

Figure 4: Comparison of average values, minimum and maximum of average-daily concentration of NO_x in the air in Krakow at Krasinskiego Avenue in April 2018–2020. Source: own study based on data from ref. [25].

lowest results were recorded in 2020. The highest average monthly value and the maximum average-daily emission were recorded in 2018. In the case of the days with the lowest value of the average-daily NO_x emission, 2019 was the least favorable. It should be noted that the maximum average-daily emission value in April 2020 (165 µg/m³) is lower than the monthly average for 2018 (181 µg/m³) and 2019 (171 µg/m³).

4 Comparison of the average level of pollutants

In order to compare the average levels of pollutants in the selected years, 3 significance tests were performed successively:

- (1) between 2018 and 2019,
- (2) between 2018 and 2020,
- (3) between 2019 and 2020.

In each case, a null hypothesis (H_0) was made such that the means are equal ($m_1 = m_2$). The alternative hypotheses (H_1) were as follows ($m_1 > m_2$):

- (1) the average for spring 2018 is higher than that for spring 2019,
- (2) the average for spring 2018 is higher than that for spring 2020,
- (3) the average for spring 2019 is higher than that for spring 2020.

Then, a statistical analysis was performed based on formula (1) [30]. The calculated Z value is a statistic that allows you to determine whether it is possible to reject the null hypothesis in favor of an alternative hypothesis (the Z value will be in the critical area) or to find that there are no grounds for rejecting it (the Z value will be within the acceptability area of the null hypothesis).

$$Z = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \quad (1)$$

where: $\bar{X}_n$ – arithmetic mean of the sample, S_n – standard deviation of the sample, n – sample size.

For the significance level of 0.01, the critical area was determined $< z_\alpha; +\infty$, where $z_\alpha = 2.33$ [30].

Comparing the averages calculated for 2018 and 2019, the value $Z_{18,19} = 0.73$ was obtained. Due to the fact that Z was not in the critical area, at the significance level of 0.01, there was no basis to reject the hypothesis of the equality of the average levels of nitrogen oxides

Table 2: Summary of significance test results

Comparison		Hypothesis	Significance test result – average concentration NO_x
m_1	m_2		
Spring of 2018	Spring of 2019	H_0	$m_1 = m_2$
Spring of 2018	Spring of 2020	H_1	$m_1 > m_2$
Spring of 2019	Spring of 2020	H_1	$m_1 > m_2$

concentration in spring 2018 and 2019. When comparing the averages calculated for 2018 and 2020, the highest result was obtained for statistics $Z_{18,20} = 7.77$. Its value was in the critical area. Therefore, it was found that with a 99% probability one can reject the null hypothesis of equality of the averages from 2018 and 2020 in favor of the alternative hypothesis that the average concentration of NO_x in Krakow in spring 2018 is higher than that in 2020. Compared to averages calculated for 2019 and 2020, the statistics result was $Z_{19,20} = 6.24$. It falls in the critical area and it is slightly lower than that in the case of the analysis conducted for 2018 and 2020 ($Z_{18,20}$). Therefore, at a significance level of 0.01, the hypothesis that the mean concentration of NO_x in the spring in 2019 and 2020 can be rejected in favor of the alternative hypothesis such that the mean for 2019 is higher. The results of all significance tests are summarized in Table 2.

The condition of the air quality, apart from other factors, is also influenced – directly and indirectly – by weather conditions, in particular the movements of air masses, humidity, and temperature [23]. For temperature, its indirect relationship with the level of pollutants emitted is best visible in the case of the so-called low emissions during the heating season: the lower the temperature, the greater the demand for heating houses, therefore the combustion in household stoves and the amount of harmful substances released into the atmosphere increases. A similar relationship may occur between the temperature and the level of emissions from transport, which may be related to the comfort of travel. The lower the

temperature, higher humidity, and more rainfall, theoretically people should choose to drive their own heated car than to walk, cycle, or use public transport and wait at stops. Increased road traffic may mean more transport pollution.

Bearing in mind the above, in order to complete the observations and analyzes, the average monthly temperatures in Krakow in the selected period of time (April 2018–2020) were analyzed, as well as the sum of precipitation and the number of days with rain. Their values are presented in Table 3.

Taking into account the values of average temperatures in April 2018–2020, theoretically the best conditions for using public transport and means of transport – other than motor vehicles – were April 2018. The least favorable in this respect was April 2020. Taking into account the sum of rainfall and the number of days when it occurred, April 2020 should be considered the most favorable in this regard, and the least April 2019. The analysis of the NO_x emission level in the analyzed period shows no relationship between air pollution and the average monthly temperature in the whole analyzed period. Much more complex is the impact of rainfall and the inhabitant's behavior. While the sum of rainfall in 2020 was the smallest – which in a sense could explain the reduction of NO_x emissions – it is worth paying attention to the comparison of 2018 and 2019. In April 2019, the average daily amount of rainfall (on the days on which it was recorded) was much higher than that in April 2018. Despite this – as shown by the statistical analysis – the average concentrations of NO_x in the air were at a similar level (Table 2). This prompts us to conduct further, extended research taking this aspect into account. The lowest average temperature value recorded for the analyzed period in April 2020 indicates that the demand for heating power in households was not lower than in 2018–2019. Thus, the NO_x emission level at that time was not lower. The actual reduction in its level can be associated mainly with the lockdown and the resulting limitation of the mobility of inhabitants. The weather conditions in April 2020 were not conducive to reduce the level of transport pollution, but it decreased compared to previous years.

Table 3: Average temperature, rainfall, and number of rainfall days in Krakow in April 2018–2020

Month	Average temperature (°C)	Rainfall (mm)	Rainfall days
April 2018	13.7	9.9	10
April 2019	10.0	72.3	8
April 2020	9.5	5.4	3

Source: own study based on data from ref. [4,5,27,28].

5 Recapitulation

According to data for the entire city, which were made available by the Department of the Municipal Traffic Engineer of the City of Krakow, during the lockdown in spring 2020, road traffic in the city decreased by 30% to even 70% [23]. The authors did not obtain more precise data on the traffic volume in selected points in Krakow, e.g. on Krasinskiego Avenue – where the level of air pollution was analyzed. The reduction in the number of vehicles on the road was clearly noticeable and was reflected in the amount of transport pollutants emitted into the atmosphere. The performed statistical analysis showed a decrease in the mean values of the concentration of nitrogen oxides during the restrictions related to the COVID pandemic. April 2018 and 2019 did not differ significantly in relation to the average level of NO_x concentration in the air. However, this cannot be said for 2020, when the average concentration of this pollutant was significantly lower than that in spring 2018 and 2019. In April 2020, the highest number of days with the cleanest air and the least with the most polluted air were registered in Krakow. This state of affairs was not related to the air temperature and the reduction of pollutant emissions from households, as April 2020 was the coldest in the analyzed period. Were it not for the limitations related to the COVID-19 pandemic, the inhabitants of Krakow would use private cars more often than public transport, bicycles, or other personal transport devices. There is a close relationship between air quality and the size of traffic flows. This confirms the desired direction of activities consisting in the development of low-emission or zero-emission means of transport. It is also appropriate to restrict passenger car traffic and to replace them with

public transport or active mobility. It is worth mentioning here that Polish cities (with a population of over 100,000) have relatively new tools to combat transport pollution. These are clean transport zones. They make it possible to designate areas that can only be entered by vehicles powered by electricity, hydrogen, or natural gas [29]. So far, only Krakow in the Kazimierz districts, as well as the Old Town, has used this option (Figure 5).

The need for further research on the impact of the size of road traffic flows on air pollution, both locally and globally, should be emphasized. The period of the COVID-19 pandemic should become a valuable lesson for the future and a knowledge base for further studies and implementations. In particular, units responsible for the organization of road traffic and the development of public transport should show interest in this regard.

Conflict of interest: The authors declare that they have no known conflict of interest or personal relationships that could have appeared to influence the work reported in this article.

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Figure 5: Marking of the clean transport zone in Krakow.

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