TRANSPORT PROBLEMS 2025 Volume 20 Issue 2
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2025.20.2.18

Keywords: traffic pollution; transport ecology; distribution of traffic pollution

Agata JAROŃ[1], Anna BORUCKA[2]*, Patrycja GUZANEK[3]

UAV-BASED STATISTICAL ANALYSIS OF SEASONAL TRAFFIC POLLUTANT DIFFUSION: A CASE STUDY OF POLAND'S A4 HIGHWAY

Summary. Road transport is a significant source of pollution, accounting for up to 25% in the EU. Traffic pollution resulting from the movement of vehicles harms human health. Therefore, it is important to understand the process of spreading harmful substances from the source of their formation. This article presents an original method for measuring pollution in the roadside area for a key road in the Silesian Voivodeship. The focus was on determining the mathematical dependencies related to the diffusion of pollutants from the selected road section. The determined correlations may contribute to the implementation of traffic route projects, which can reduce air pollution. A key innovation of this study is the use of an unmanned aerial vehicle equipped with air quality sensors to perform spatial pollution measurements near a highway. This method enables a high-resolution, three-dimensional assessment of pollutant dispersion, which is then compared to conventional point-based data from the Chief Inspectorate of Environmental Protection (GIOŚ). This novel approach not only improves measurement coverage but also provides new insights for air quality modeling and environmental planning.

1. INTRODUCTION

Traffic pollution caused by car traffic is a significant threat to the environment and human health. [1]. Traffic causes excessive exhaust emissions, which include particulate matter (PM) and gases such as oxides of carbon, nitrogen, sulfur, heavy metals, benzo(a)pyrene, and PM_{10}, $PM_{2.5}$, PM_1 [2].

Reaction mechanisms that occur during so-called "traffic pollution" are known to contribute to hazardous phenomena such as smog, especially in large urban areas and under suitable weather conditions. According to data from the National Center for Balancing and Emission Management (KOBIZE), carbon and nitrogen oxides account for the largest share of emissions for road transportation. According to data as of 2021, the total annual emissions were 295,640 tons and 188,910 tons. The demonstrated emissions are 11.73% and 31.94% of the total emissions [3].

In contrast, within the EU, according to a report by the European Environment Agency [3], the exhaust systems of motor vehicles primarily release nitrogen oxides and carbon oxides, with percentages of approximately 43% and 31%, respectively. Another important element of concern is PM2.5 and PM10, which, together with substances of organic origin, have a share of 11% and 4%, respectively [3]. PM is particularly dangerous to humans. PM dust can penetrate the bloodstream due to its small diameter, which contributes to poor health and even earlier deaths from cardiovascular and respiratory diseases.

As shown by the European Environment Agency, about 25% of all emissions of harmful substances are generated by transportation, 71.7% of which come from automobile transport [4]. Data

[1] Military University of Technology; gen. Kaliskiego 2, 00-902 Warsaw, Poland; e-mail: agata.jaron@wat.edu.pl; orcid.org/0000-0001-5054-061X
[2] Military University of Technology; gen. Kaliskiego 2, 00-902 Warsaw, Poland; e-mail: anna.borucka@wat.edu.pl; orcid.org/0000-0002-7892-9640
[3] Military University of Technology; gen. Kaliskiego 2, 00-902 Warsaw, Poland; e-mail: patrycja.guzanek@student.wat.edu.pl; orcid.org/0000-0001-6650-7187
* Corresponding author. E-mail: agata.jaron@wat.edu.pl

made available by the European Environment Agency shows that 30% of the European population is exposed to harmful substances above the permissible level. In turn, 98% of Europeans are exposed to emissions considered harmful, according to the WHO [5]. In addition, harmful pollutants emitted from the combustion of fuels in automobile engines can also contribute to environmental acidification and the formation of ground-level ozone phenomenon.

Given the above, this study aims to analyze the diffusion of selected traffic pollutants in the context of distance from the linear source (road section) of their formation, which is the highway section under study. This research marks the first attempt to map traffic-related pollution across Poland using measurements obtained from an unmanned aerial vehicle (UAV) and to compare these findings with data collected by the stationary monitoring stations of the Chief Inspectorate of Environmental Protection (GIOŚ). This approach is distinguished by its innovative character, as this methodology has not previously been applied in the context of analyzing traffic-related pollution in Poland. The study not only facilitated the collection of detailed data on pollutant distribution but also evaluated the potential of UAV technology for monitoring air quality in areas heavily impacted by road traffic. This novel approach paves the way for advancements in modeling and assessing the environmental impact of transport, providing tools to support monitoring efforts, spatial planning, and environmental policy-making.

2. GROUNDS AND LITERATURE REVIEW

The sources of air pollutants emitted by traffic are primarily the products of fuel combustion in automobile engines, in which dangerous compounds are released through the exhaust system. The second source is non-exhaust emissions, by which harmful substances are released through other means, such as the friction of tires against the road surface, wear and tear of vehicle system components (e.g., discs and brake pads), and refueling losses, among others [6]. In the case of pollutants from internal combustion engines, total emissions depend on extensive and intensive factors. The extensive factor is the number and average annual mileage of vehicles in a particular category. The intensive factor is the structure of the vehicle, taking into account its purpose, conventional size, and technical characteristics, including its emission characteristics [**Błąd! Nie można odnaleźć źródła odwołania.**, 8].

Along with the civilization progress, the number of vehicles is increasing, which translates into increasingly serious traffic pollution problems. Currently, research on road transport pollutants is thriving. With the above in mind, it is essential to understand the spatiotemporal propagation of traffic-related pollutants and develop solutions to mitigate air pollution. As stated by the author in [7], there are two approaches to studying how traffic-related pollutants propagate. These include the deterministic model and field measurements. The deterministic model is based on the use of computational fluid dynamics, which allows the patterns of pollutants to be reproduced under different conditions and the diffusion processes to be reproduced. The conducted research allows us to understand the vertical profile of pollutants in urban streets for different infrastructure layouts (bridges, structures, etc.) and under various weather conditions [10]. The actual conditions of pollutant diffusion are much more complex compared to simulated conditions. To measure vertical profiles, researchers used towers [11] and balloons [12], but the most popular method is drones [13]. The small size and ease of operation means that drones can reach virtually any location. Drones can take measurements over short distances and are relatively inexpensive [14]. Drones are widely used to study pollution distribution profiles. In [15], the authors studied profiles under different topographic conditions, while in [16], they measured pollutant concentrations near highways using UAVs specifically. Measurements of profiles near roads with residential infrastructure were the subject of a study in [17]. An interesting method of measurement involved placing mobile sensors in vehicles. The study revealed that in Hong Kong, the highest levels of pollution during rush hour occur at tunnel entrances and congestion points [18]. The authors also concluded that pollution from regional transportation is a major contributor to high pollution episodes. In Texas, researchers also placed air pollution monitoring equipment on a vehicle and studied the temporal and spatial distribution of traffic pollution on sections of urban roads and highways [19]. In Seoul, the authors surveyed roadside areas using a miniaturized portable particle counter [20]. This allowed them to capture many points with higher concentrations of pollutants. Based on a land use regression model, they predicted the distribution of urban particle concentrations. In [21], Belkacem et al. used a mobile spectrometer to study the distribution of nanoparticle dispersion at the height at which pedestrians breathe in roadside areas. Measurements were also conducted at three distances from the road (6.60, 30, and 100 miles). The influence of weather and traffic conditions was discussed. The research was conducted in urban areas. The elevation profile of pollutants near the road was also studied in [22], where a roadside high-rise building was used to take samples from the first and last floors. The differences in concentration and composition of PM and volatile organic compounds at each level were analyzed. The use of roadside high-rise buildings to study the pollution profile was also described by the authors in [23], where equipment was set up to measure PM2.5, NO2, benzene, and toluene at different heights. The authors discuss correlations related to their emissions and traffic. Setting up sensors on different floors in a high-rise building allows height profiles to be obtained, but as the study shows, much better measurement dynamics can be obtained using a UAV system.

Numerous papers have been published on the diffusion of air pollutants at different heights related to traffic. These studies have focused on numerical modeling using various measurement techniques and determining correlations for emissions under different traffic volumes or weather conditions. Relatively few studies have presented empirical research that illustrates the dispersion of harmful particles from their source of emission through spatial mapping while providing comparative references to measurements from the Chief Inspectorate of Environmental Protection (GIOŚ). This study addresses this research gap by responding to a key research question: Are there significant differences in the concentration of harmful substances depending on the distance from their emission source? Additionally, the study examines the impact of seasonal conditions by comparing results from the warm period (characterized by high air temperatures) with those from the cold period (characterized by low air temperatures).

3. CHARACTERISTICS OF THE RESEARCH OBJECT

The study object is a fragment of Poland's key road infrastructure, a section of the A4 highway in the city of Katowice (Poland). The indicated section of the road is traveled by approximately 200,000 vehicles daily. This place is the most congested road of the Silesian agglomeration. The highway is a two-lane road located on the outskirts of the city. In addition, the choice of this section was influenced by the fact that the National Air Pollution Monitoring station is located nearby, allowing for comparisons of the research results with those from a stationary station. The present paper builds on the research described in [24], which focused on the quarterly measurement of air pollution from a linear source (road section) of pollution, taking into account the varying seasons of the year. The measurements were carried out using a UAV platform equipped with a laser detector of air pollutants such as PM2.5, PM1, PM10, SO2, NxOy, and O3. This sensor features a GPS that enables the accurate determination of the measurement location, including altitude, latitude, and height above sea level. The platform, including the mounted sensor, is shown in Fig. 1.

Earlier studies conducted by the authors, as described in [24], focused on demonstrating the feasibility of graphically presenting pollutant distribution profiles in the form of maps. Their continuation aims to test whether there are significant differences in the diffusion of pollutants depending on the distance from the linear source of pollution (road section). Taking into account the available literature on similar topics, it was noted that the greatest dispersion of pollutants from the road oscillates within 50–100 m from the source, and therefore, such an area was studied. Additionally, a limitation was the nearby field infrastructure, which was located approximately 50 m from the road, preventing UAV flight. Therefore, the focus was solely on this area, and no attempt was made for the long-term determination of spatial fading. Field measurements were conducted in a rectangular area of approximately one hectare adjacent to the road to assess the distribution of pollution in the immediate vicinity of the road. Measurements were conducted taking into account the alternation of seasons in two periods: cool (autumn and winter) and warm (spring and summer). The results of the measurements were evaluated, and changes in the concentration of selected pollutants were studied for both cool and warm periods, depending on the distance and height from the road. The following study scheme was adopted:

1. Preparing databases and evaluating collected observations.
2. Testing for conformity to normal distribution in groups using the Lilliefors test.
3. Determining whether the distribution of individual pollutants varies according to the study period using the Kruskal-Wallis test.
4. Verifying whether there are correlations between emissions and distance from the road for the cool and warm periods by calculating Pearson's correlation coefficient.
5. Evaluating the statistical significance of the obtained results.
6. Drawing conclusions.

Fig. 1. Measurement platform with a sensor during flight operation

4. MATERIALS AND METHODS

4.1. Preparation of databases and evaluation of observations

Considering the speed of the UAV and its ability to record results, the measurement was carried out with an accuracy of one meter, both vertically and horizontally. The drone flight lasted one hour, and more than 4,000 observations were collected for a given altitude, latitude, and height above sea level. The results obtained using cartographic interpolation and previously described in [24] were plotted on a terrain map. This allowed us to depict the actual contaminants present in the field. The obtained maps allowed a preliminary verification and evaluation of the existing distribution of pollutants. As a result of pollutant mapping, it was noted that for three substances (SO2, NxOy, and O3), the concentration level in each plane was practically constant. Due to a lack of variability, the indicated pollutants were excluded from further investigation, and the other three pollutants presented in the paper were analyzed and evaluated.

4.2. Verification of the distribution of traffic pollution according to the study period

The observations used in the study refer to two measurement periods: July (warm period) and January (cool period). In July, during field flights, the temperature on measurement day was 28°C, and the humidity was 45%. In January, during field flights, the temperature was 3°C, and the humidity was 23%.

The first stage involved verifying that the distribution of individual pollutants differed across the test period. To select an appropriate test, the conformity of the distribution in the groups separated by the season variable (warm and cool periods) to a normal distribution was first evaluated. The Lilliefors test was used for this purpose. Table 1 shows the results of this test.

The Kruskal-Wallis test was used due to the lack of compliance of the distribution in the groups with the normal distribution. At the significance level of $0<\alpha<1$, the following working hypothesis

(H0) was formulated: the distributions in the groups are identical, or the differences in the distributions are insignificant. The alternative hypothesis (H1) is as follows: the distributions in the groups differ significantly. The results of the Kruskal-Wallis test are presented in Table 2.

Table 1

Lilliefors test results

Pollution	The value of the test statistic D_n	p-value
Cool period		
PM_1	0.052	$< 2.2 \cdot 10^{-16}$
$PM_{2.5}$	0.053	$< 2.2 \cdot 10^{-16}$
PM_{10}	0.044	$< 1.78 \cdot 10^{-12}$
Warm period		
PM_1	0.158	$< 2.2 \cdot 10^{-16}$
$PM_{2.5}$	0.119	$< 2.2 \cdot 10^{-16}$
PM_{10}	0.096	$< 2.2 \cdot 10^{-16}$

Table 2

Kruskal-Wallis test results for individual pollutants

Pollution	χ^2	p-value
PM_1	4547	$< 2.2 \cdot 10^{-16}$
$PM_{2.5}$	4546.5	$< 2.2 \cdot 10^{-16}$
PM_{10}	4546.2	$< 2.2 \cdot 10^{-16}$

As the test results show, the distributions differ significantly depending on the study period. This is confirmed by the correlations shown in the following figures. Box-and-whisker plots of the distribution of PM concentrations are shown in Figs. 1–3.

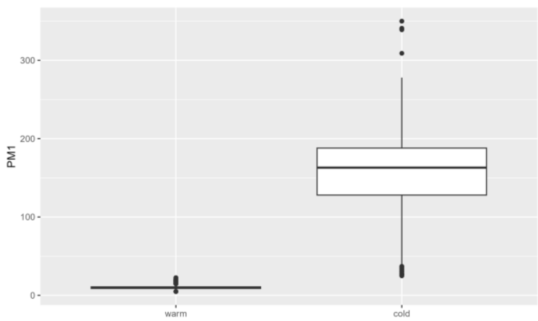

Fig. 2. PM_1 distribution for two periods

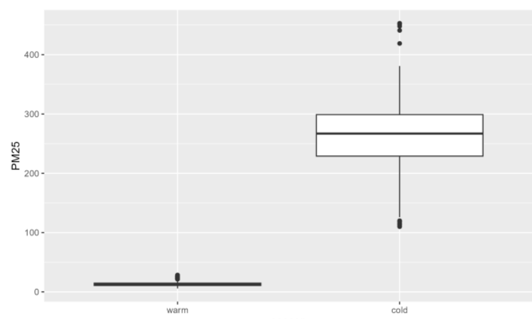

Fig. 3. $PM_{2.5}$ distribution for two periods

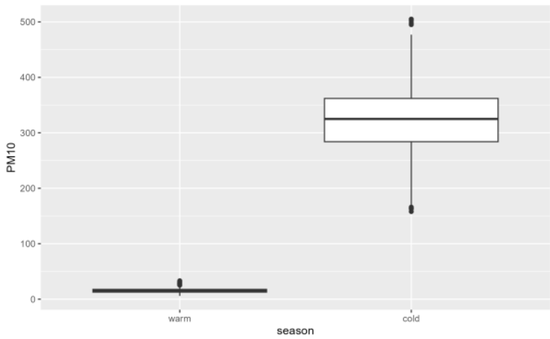

Fig. 4. PM_{10} distribution for two periods

The first stage of the study showed that emissions in the two observed periods differed significantly. Therefore, the following part of this paper investigates the relationships in the distribution of traffic pollutants for two separate periods.

4.3. Verification of the distribution of traffic pollutants for warm and cool periods

Pearson's correlation coefficient was used to test whether there were significant relationships between the concentrations of individual traffic pollutants and distance from the emission source.

In this part of the study, the correlation coefficient between the concentration of air pollutants and the distance from the road was determined, and it was verified whether the determined correlation was statistically significant. The results are presented in Table 3.

Based on the adopted significance level and the evaluation of results in Table 4, for the warm period, only one p-value (for PM1) was less than the adopted significance level, and for the cool period, all of them were. Therefore, for these cases, there is no basis for accepting the null hypothesis. The value of the correlation coefficient is significantly different from zero. A graphical presentation of the distributions of pollutants as a function of distance from the road, along with the plotted line of fit for the warm period, is shown in Fig. 5. For the cool period, the distributions are presented in Figs. 6–8. The peak observed at a distance of approximately 12 m from the road in the presented figures corresponds to the moment of landing and takeoff of the drone during the measurements. The drone had a limited battery life, and during one raid, the battery had to be replaced three times.

Table 3

The values of the correlation coefficients between the study variables and the test statistic

Pollution	Correlation coefficient	The value of the test statistic	p-value
Warm period			
PM_1	-0.064	-3.255	0.001
$PM_{2.5}$	-0.092	-4.728	$2.394 \cdot 10^{-6}$
PM_{10}	-0.091	-4.639	$3.664 \cdot 10^{-6}$
Cool period			
PM_1	0.054	3.259	0.001
$PM_{2.5}$	0.022	1.305	0.192
PM_{10}	0.019	1.136	0.256

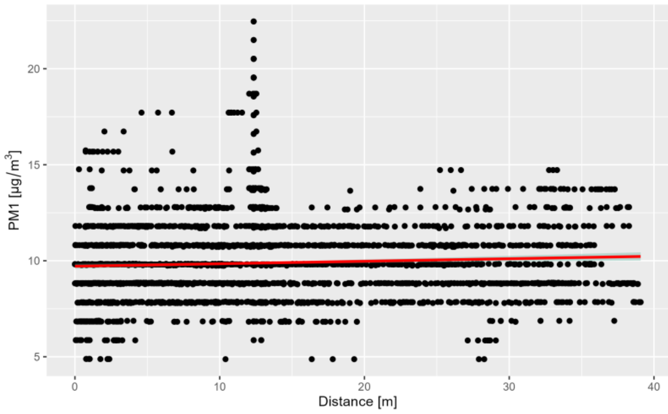

Fig. 5. PM_1 concentration with increasing distance from the road – warm period

Fig. 5 shows a suspended PM in the air. For this dust, the value of the correlation coefficient was statistically significant. The correlation has a positive sign (i.e., the concentration value increases with increasing distance). The concentration of the pollutant under study changes in the range of 5–15 ppm. An interesting situation is shown in Fig. 6 concerning the distribution of PM_1 for the cold period. Compared with Fig. 5 and Table 3, the p-values indicate that the correlation occurring is statistically significant. However, unlike Figs. 5, 6 does not show clear ordered bands. The explanation for this is the difference in humidity on the day of measurements, which was twice as low during the cold season. When there are a greater number of suspended water droplets in the air, this promotes the uniform settling of very fine solid contaminants in the air rather than their dispersion in space, as is the case with lower humidity. A similar phenomenon was noted by the authors in [7] and is related to the homogenization of the particle in a humid environment. This situation is also confirmed, in contrast to the warm period, by the distribution of $PM_{2.5}$ and PM10 dust pollutants (Figs. 7 and 8), for which the distributions presented are very similar. Similar conclusions were reached by the authors in [25].

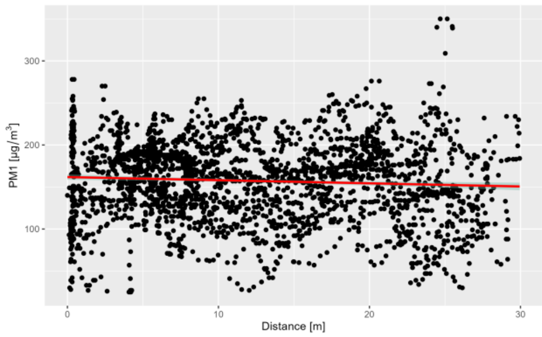

Fig. 6. PM_1 concentration with increasing distance from the road - cool period

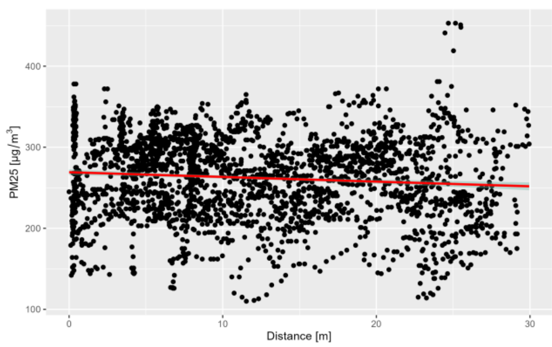

Fig. 7. $PM_{2.5}$ concentration with increasing distance from the road – cool period

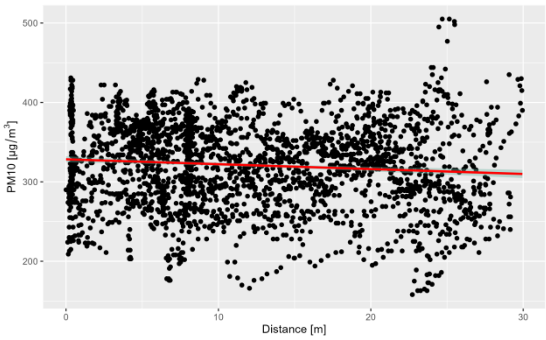

Fig. 8. PM_{10} – concentration with increasing distance from the road – cool period

As shown in Figs. 6–8, the concentration distribution for the cold period reveals that the concentrations of PM1, PM2.5, and PM10 vary between 25 and 350 ppm, 80 and 480 ppm, and 80 and 500 ppm, respectively. The p-values for all the pollutants mentioned in this period show that the value of the correlation coefficient is statistically significant. In addition, the correlation coefficient has a negative sign, which means that as the distance increases, the concentration decreases.

5. DISCUSSION

The first stage of the study investigated whether pollutant emissions differed between periods. For this purpose, the Lilliefors test was used. The findings show that distributions of traffic pollutants for the two studied periods differed significantly. The results of the test (Figs. 1-3) showed that the cold period is characterized by significantly higher emissions. This is likely because cars and trucks consume more fuel during the winter period, resulting in higher levels of emissions [25]. The next step was to verify whether there were significant changes in the distribution of concentrations depending on the distance from the emission source for each period independently. For PM_1 pollution during warm and cool periods and for $PM_{2.5}$ and PM_{10} emissions during cool periods, there were significant correlations between the change in concentration and distance from the road. In addition, the correlation occurring for PM_1 varies in sign for the periods studied. During the cool period, the concentration decreased with distance from the road; during the warm period, it increased. Similar conclusions were reached by the authors in [7, 26], who showed a linear horizontal distribution of particulate pollution [27-29].

6. COMPARISON OF MEASUREMENT METHODS: UAV AND GIOŚ

An innovative aspect of this study is the comparison of pollution concentration results obtained using an unmanned aerial vehicle (UAV) with measurement data from the Chief Inspectorate of Environmental Protection (GIOŚ) monitoring stations. As detailed in Section 3, the measurement site was selected deliberately and purposefully. The study area includes the location of a GIOŚ station, which served as a reference and verification point for the employed approach. The comparison of results enabled an evaluation of the consistency of data between the two measurement methods and an analysis of potential discrepancies in the recorded concentration values. This allowed us to estimate the accuracy of UAV measurements in the context of their application to spatial air pollution analysis.

Table 4 summarizes the averaged pollutant concentration values obtained from the two measurement methods, enabling a detailed comparison. These results demonstrate consistency between the two approaches and provide a basis for assessing potential differences arising from varying measurement conditions, such as location, measurement height, or the influence of atmospheric variables. Such a comparison offers valuable insights for the further development of air quality monitoring methods and the evaluation of their practical utility in environmental research.

Table 4

Comparison of Results from Two Measurement Methods

Type of Pollutant	UAV Measurement [µg/m³]	GIOŚ Measurement [µg/m³] (C6H6 = benzene; HCHO = formaldehyde)
cold period		
PM10	27.2	30.1
PM2.5	14.95	15.3
PM1	12.2	Not measured
SO2	0.095	Not measured
C6H6	0.006	Not measured
HCHO	0.024	Not measured
warm period		
PM10	180	200
PM2.5	127	141
PM1	12.2	Not measured
SO2	0.03	Not measured
C6H6	0.01	Not measured
HCHO	0.01	Not measured

Standard deviation values were calculated for UAV measurements to compare the measurement methods (Table 5).

The standard deviation values presented in Table 5 are low, indicating a minimal dispersion of values around the mean. This suggests high consistency in the UAV measurements. Finally, absolute and relative errors were determined for the average concentrations of specific pollutants. Error calculations were only possible for PM10 and PM2.5 due to the lack of measurements conducted by GIOŚ.

A comparison of the innovative UAV-based measurement method with the GIOŚ monitoring stations shows that the GIOŚ stations measure only two of the six pollutants under investigation. Additionally, the significant measurement error observed for the examined pollutants highlights a considerable discrepancy between point-based and spatial measurement approaches. Another advantage of the presented method is its capability to provide a graphical representation of the diffusion of selected pollutants. An example of such visualization is shown in Fig. 9.

Table 5

Standard Deviation

Pollutant	Standard Deviation
PM10	2.1
PM2.5	3.05
PM1	3.21
SO2	0.04
C6H6	0.04
HCHO	0.03

Absolute Error:

$$\Delta x = |x - x_0|$$

Relative Error:

$$\delta = \frac{|x - x_0|}{x} \cdot 100\%$$

This approach to the research problem provides broader knowledge and understanding of the mechanisms associated with the diffusion of traffic-related pollutants. Employing innovative measurement methods, such as the use of unmanned aerial vehicles (UAVs) and comparing the obtained results with traditional data from GIOŚ stations, makes it possible to determine the spatial distribution of pollutants and the factors influencing their movement with greater precision. This method accounts for environmental variability, including atmospheric conditions and seasonal temperature differences, which can significantly affect the dispersion of harmful particles. Moreover, studying the spread of pollutants in relation to their emission sources and the distance from these sources allows for the identification of areas with particularly high exposure risk. Understanding these processes is crucial not only from a scientific perspective but also in practical applications. The research findings can support efforts to improve air quality, such as efforts to optimize traffic systems, design green buffer zones, and implement policies to reduce transport emissions. In this way, this study contributes to the development of knowledge that can inform decision-making in environmental protection and public health.

Table 6

Values of Individual Errors for Traffic-Related Pollutants

Pollutant	Δx	δ [%]
PM10	051	7.2
PM2.5	0.62	6.5
PM1	-	-
SO2	-	-
C6H6	-	-
HCHO	-	-

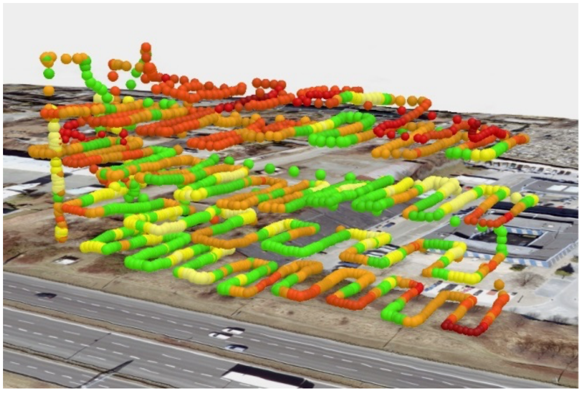

Fig. 9. Traffic-related pollution diffusion map

7. CONCLUSIONS

Transportation is a significant source of pollution within the EU, and harmful dust and gases harm human health. Therefore, this paper focused on taking field measurements and evaluating the existing environmental situation rather than employing a simulated model, as is often the case in previous studies.

The study used a UAV platform with a mounted laser sensor to measure six selected environmental pollutants. Of these, three pollutants were excluded during a preliminary evaluation of the collected information. Based on previous studies on the spread of traffic pollutants, a roadside adjacent area of one hectare within 50 meters of the emission source was studied.

This study aimed to verify the differences in traffic pollutant concentrations for the period when the air temperature is high (warm period) and low (cool period). In this case, the results of the tests allowed us to conclude that these differences are significant. More emissions occurred in the winter period.

In addition, the paper evaluates the diffusion of selected traffic pollutants in the context of distance from the linear source (road section) of their formation (the highway section studied). The field measurements showed that for PM_1 (cool and warm periods), $PM_{2.5}$, and PM_{10} (cool period), there were correlations between the change in concentration and the distance from the source of their emissions. In addition, for PM_1, there was an inverse relationship for the two periods studied. For the cool period, it is negative; for the warm period, it is positive. For $PM_{2.5}$ and PM_{10}, the statistical significance of the obtained results for the warm period was not confirmed. The indicated pollutants will be subjected to more detailed observation in a further research cycle.

This study, in addition to its mathematical description, demonstrated an innovative approach to measuring spatial pollution using unmanned aerial vehicles (UAVs). The relatively high measurement errors observed for GIOŚ stations, combined with the low standard deviation values, highlight significant discrepancies between point-based and spatial measurements. The latter provides a more comprehensive understanding of the ecological situation and can be visually represented through maps, offering a broader perspective on the environmental conditions under investigation.

Although this study provides valuable insights into pollutant diffusion near a major roadway, certain limitations should be acknowledged. First, measurements were limited to a 50-meter zone from the highway, primarily due to physical constraints in the field. This narrow range restricts the ability to assess the full spatial extent of pollutant dispersion, particularly at greater distances where different atmospheric behaviors may occur. Second, the research was conducted at a single location — a section of the A4 highway in Katowice — which, while representative of high-traffic urban infrastructure, may not reflect conditions in other urban, suburban, or rural areas. As such, the generalizability of the results to other settings is limited. Lastly, while seasonal variation was included, other influencing factors such as wind speed, direction, or traffic composition were not directly analyzed. Future studies should expand the spatial scope, include diverse locations, and incorporate more environmental variables to enhance the robustness and applicability of the findings.

In summary, each of the traffic pollutants differs in atomic mass, structure, size, and other properties, which translates into a different method of diffusion. Therefore, it is important to develop methods for creating a global air quality index so that any type of pollutant's impact on the environment near road infrastructure can be unified. The current research can be extended to compare measurement results for different seasons, which may result from changing seasons. Expanding the knowledge of this scope will enable a better understanding of the spatial distribution of traffic pollution, depending on atmospheric conditions. This will ultimately allow for the development of recommendations to protect the population against emissions of harmful substances, similar to the case of noise barriers on highways. Future research could extend measurements beyond 50 meters using hybrid UAV-balloon systems. These results support urban planning policies, such as implementing protective buffer zones within 50 meters of high-traffic roads.

References

1. Andrych-Zalewska, M. & Chłopek, Z. & Merkisz, J. & Pielecha, J. Research on the results of the WLTP procedure for a passenger vehicle. *Eksploatacja i Niezawodność - Maintenance and Reliability*. 2024. Vol. 26(1). No. 176112.
2. Žvirblis, T. & Hunicz, J. & Matijošius, J. et al. Improving diesel engine reliability using an optimal prognostic model to predict diesel engine emissions and performance using pure diesel and hydrogenated vegetable oil. *Eksploatacja i Niezawodność - Maintenance and Reliability*. 2023. Vol. 25(4). No. 174358.
3. *Krajowy bilans emisji SO_2, NOx, CO, NH3, NMLZO, pyłów, metali ciężkich i TZO za lata 1990 2021*. Available at: https://www.kobize.pl/uploads/materialy/Inwentaryzacje_krajowe/Krajowy_bilans_emisji.pdf. [In Polish: *National emission balance of SO_2, NOx, CO, NH3, NMVOCs, dust, heavy metals and POPs for the years 1990–2021*].
4. European Environment Agency (EEA). Available at: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-air-pollutants-8/transport-emissions-of-air-pollutants-4.

5. Jaroń, A. & Borucka, A. & Parczewski, R. Analysis of the impact of the COVID-19 pandemic on the value of CO_2 emissions from electricity generation. *Energies*. 2022. Vol. 15(13). No. 4541.
6. Sawczuk, W. & Merkisz-Guranowska, A. & Rilo Cañás, A. et al. New approach to brake pad wear modelling based on test stand friction-mechanical investigations. *Eksploatacja i Niezawodność - Maintenance and Reliability*. 2022. Vol. 24(3). No. 3. P. 419-426.
7. Zheng, T. & LI, B. & Bing, X. et al. Vertical and horizontal distributions of traffic-related pollutants beside an urban arterial road based on unmanned aerial vehicle observations. *Building and Environment*. 2021. Vol. 187. No. 107401.
8. Kozłowski, E. & Borucka, A. & Oleszczuk, P. & Leszczyński, N. Evaluation of readiness of the technical system using the semi-Markov model with selected sojourn time distributions. *Eksploatacja i Niezawodność – Maintenance and Reliability.* 2024. Vol. 26(4). DOI: 10.17531/ein/191545.
9. Andrych-Zalewska, M. & Chlopek, Z. & Pielecha, J. et al. Investigation of exhaust emissions from the gasoline engine of a light duty vehicle in the real driving emissions test. *Eksploatacja i Niezawodność - Maintenance and Reliability*. 2023. Vol. 25(2). No. 165880.
10. Fuller, C. & Brugge, D. & Williams, P.L. et al. Spengler estimation of ultrafine particle concentrations at near-highway residences using data from local and central monitors. *Atmos. Environ*. 2012. Vol. 57. No. 004. P. 257-265.
11. Sun, Y. & Du, W. & Wan, Q. et al. Real-time characterization of aerosol particle composition above the urban canopy in Beijing: insights into the interactions between the atmospheric boundary layer and aerosol chemistry. *Environ. Sci. Technol*. 2015. Vol. 49(19). No. 02373. P. 11340-11347.
12. Wang, D. & Huo, J. & Duan, Y. et al. Vertical distribution and transport of air pollutants during a regional haze event in eastern China: a tethered mega-balloon observation study. *Atmos. Environ*. 2021. Vol. 246. No. 118039.
13. Samad, A. & Alvarez, D. & Florez, I. et al. Concept of using an unmanned aerial vehicle (UAV) for 3D investigation of air quality in the atmosphere – example of measurements near a roadside. *Atmosphere*. 2022. Vol. 13. No. 663.
14. Lee, S. & Hwang, H. & Young, J. Vertical measurements of roadside air pollutants using a drone. *Atmospheric Pollution Research*. 2022. Vol. 13(12). No. 101609.
15. Kuuluvainen, H. & Poikkimäki, M. & Järvinen, A. et al. Vertical profiles of lung deposited surface area concentration of particulate matter measured with a drone in a street canyon. *Environ. Pollut*. 2018. Vol. 241. No. 100. P. 96-105.
16. Liu, X. & Shi, X. & He, X. et al. Vertical distribution characteristics of particulate matter beside an elevated expressway by unmanned aerial vehicle measurements. *Build. Environ*. 2021. Vol. 206. No. 108330.
17. Park, Y. Assessing personal exposure to traffic-related air pollution using individual travel-activity diary data and an on-road source air dispersion model. *Health & Place*. 2020. Vol. 63. No. 102351.
18. Wei, P. & Brimblecombe, P. & Yang, F. et al. Determination of local traffic emission and non-local background source contribution to on-road air pollution using fixed-route mobile air sensor network. *Environ. Pollut*. 2021. Vol. 290. No. 118055.
19. Miller, D. & Actkinson, B. & Padilla, L. et al. Characterizing elevated urban air pollutant spatial patterns with mobile monitoring in Houston. *Environ. Sci. Technol*. 2020. Vol. 54. No. 4. P. 2133-2142.
20. Lim, C.C. & Kim, H. & Vilcassim, M.J.R. et al. Mapping urban air quality using mobile sampling with low-cost sensors and machine learning in Seoul. *South Korea. Environ*. 2019. Vol. 131. No. 105022.
21. Belkacem, I. & Khardi, S. & Helali, A. et al. The influence of urban road traffic on nanoparticles: roadside measurements. *Atmos. Environ*. 2020. Vol. 242. No. 117786.
22. Pateraki, S. & Manousakas, M. & Bairachtari, K. et al. The traffic signature on the vertical PM profile: environmental and health risks within an urban roadside environment. *Sci. Total Environ*. 2019. Vol. 646. No. 289. P. 448-459.

23. Komnos, D. & Tsiakmakis, S. & Pavlovic, J. et al. Analysing the real-world fuel and energy consumption of conventional and electric cars in Europe. *Energy Conversion and Management*. 2022. Vol. 270. No. 116161.
24. Jaroń, A. & Borucka, A. & Deliś, P. & Sekrecka, A. An assessment of the possibility of using unmanned aerial vehicles to identify and map air pollution from infrastructure emissions. *Energies*. 2024. Vol. 17(3). No. 577.
25. Mikhailuta, S.V. & Taseiko, O.V. et al. Seasonal fluctuations in air pollution concentrations in the city of Krasnoyarsk. *Environ Monit Assess*. 2008. Vol. 149. No. 9. P. 329-341.
26. Li, B. & Cao, R. & He, H.D. et al. Three-dimensional diffusion patterns of traffic-related air pollutants on the roadside based on unmanned aerial vehicles monitoring. *Building and Environment*. 2022. Vol. 219. No. 109159.
27. Sang, T. & Zhu, K. & Shen, J. & Yang, L. An uncertain programming model for fixed charge transportation problem with item sampling rates. *Eksploatacja i Niezawodność – Maintenance and Reliability*. 2025. Vol. 27(1). DOI: 10.17531/ein/192165.
28. Furch, J. & Jelínek, J. Design of a tribotechnical diagnostics model for determining the technical condition of an internal combustion engine during its life cycle. *Eksploatacja i Niezawodność – Maintenance and Reliability*. 2022. Vol. 24(3). No. 5. P. 437-445.
29. Kosucki, A. & Szczepaniak, M. & Skowrońska, J. et al. Data-driven operational pressure estimation for hydraulic actuators fed by fixed displacement pump with variable speed. *Eksploatacja i Niezawodność – Maintenance and Reliability.* 2025. Vol. 27(1). DOI: https://doi.org/10.17531/ein/192758.
30. Oszczypała, M. & Ziółkowski, J. & Małachowski, J. Semi-Markov approach for reliability modelling of light utility vehicles. *Eksploatacja i Niezawodność – Maintenance and Reliability*. 2023. Vol. 25(2). No. 161859.

Received 16.12.2023; accepted in revised form 15.06.2025