

EVALUATION OF TRAFFIC-RELATED AIR POLLUTION (TRAP): THE CASE OF VILNIUS, LITHUANIA

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A b s t r a c t

Urban air pollution associated with traffic emissions remains an important environmental concern in rapidly developing urban areas. This study presents an indicative corridor-scale assessment of traffic-related air pollution (TRAP) in Vilnius, Lithuania, based on multi-site monitoring conducted between March and July 2023 across five major urban traffic corridors characterized by varying traffic intensity and urban morphology.

The study evaluated spatial and temporal variations in nitrogen oxides (NO_x), carbon monoxide (CO), PM_{2.5}, and PM₁₀ concentrations in relation to traffic activity and meteorological conditions. Descriptive statistics and Pearson correlation analysis were applied to examine relationships between traffic intensity, pollutant concentrations, and selected meteorological parameters.

The results demonstrated strong positive relationships between traffic volume and gaseous pollutants, particularly NO_x ($r = 0.72$) and CO ($r = 0.88$), indicating the dominant influence of vehicular emissions on short-term roadside air quality variability. PM_{2.5} and PM₁₀ exhibited comparatively weaker relationships with traffic intensity, suggesting additional influences from non-exhaust emissions, atmospheric dispersion, and regional background sources. Pollutant concentrations generally increased under higher traffic intensity conditions, further supporting the role of traffic activity in shaping urban roadside air quality patterns. Among the investigated sites, Konstitucijos Avenue and Ukmergės Street exhibited the highest pollutant levels.

Overall, the study provides locally grounded empirical evidence on TRAP patterns in a medium-sized Baltic city by integrating pollutant measurements, traffic observations, and meteorological data across multiple urban corridors. The findings may support future air quality management and sustainable urban mobility planning in Vilnius and comparable urban environments.

Keywords: traffic emissions, Vilnius, CO, NO_x, PM

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1. INTRODUCTION

Urban air pollution, particularly from traffic-related sources, is a pressing environmental and public health challenge in cities worldwide. According to the World Health Organization (WHO), ambient air pollution is estimated to cause approximately 4.2 million premature deaths worldwide each year [1]. Traffic-related air pollution (TRAP)—including nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM_{2.5} and PM₁₀)—is especially critical in densely populated urban areas where vehicle emissions are a dominant contributor. Numerous studies have demonstrated strong associations between TRAP and adverse health outcomes such as allergic diseases, respiratory infections, and cardiovascular conditions [2-7]. Beyond human health impacts, traffic emissions also contribute to climate change through the release of ozone precursors and black carbon, amplifying their environmental footprint [8-10].

In response to these risks, metropolitan areas worldwide have introduced measures such as congestion pricing, low-emission zones, and incentives for electric vehicles, many of which have shown promising results [8,11,12]. Increasingly, integrated methodological approaches—combining emission inventories, dispersion modeling, and real-time monitoring—are being used to better understand the spatiotemporal dynamics of TRAP [13,14]. Moreover, conceptual frameworks such as the Environmental Kuznets Curve (EKC) and Health Impact Assessments (HIA) have helped situate air quality challenges within broader socio-economic and policy contexts [15,16].

Despite these advances, the dynamics of traffic-related pollution in medium-sized post-socialist cities remain underexplored. Urban centers such as Vilnius, Lithuania—characterized by rapid motorization, urban sprawl, and legacies of centralized planning—face distinct air quality challenges that may not mirror those observed in megacities like London, Beijing, or Delhi [17-19]. Differences in urban morphology, vehicle ownership trends, and public transport infrastructure suggest that findings from larger metropolitan contexts may not be directly transferable [20-22].

In the Baltic and Eastern European region, although several studies have identified traffic as a key contributor to air pollution, comprehensive, site-specific assessments remain scarce [20,21]. Previous studies conducted in Lithuania and the broader Baltic region have increasingly highlighted the growing importance of traffic-related air pollution and its implications for urban sustainability and public health. Davtalab et al. [20] reported significant long-term spatial and temporal variations in PM_{2.5} and PM₁₀ concentrations across Lithuania, emphasizing the influence of both anthropogenic emissions and meteorological variability on particulate matter dynamics. Similarly, Peleckis et al. [23] demonstrated that increasing motorization rates and the persistence of aging vehicle fleets continue to contribute substantially to transport-related emissions in Lithuania and across the European Union.

More recent investigations have focused specifically on urban traffic emissions in Lithuanian cities. Kecorius et al. [24] conducted an integrated assessment of ultrafine particles (UFP) and equivalent black carbon (eBC) across six Lithuanian cities, including Vilnius, revealing substantial spatial differences associated with vehicle fleet composition, diesel prevalence, and traffic intensity. Their findings highlighted Vilnius as one of the cities with the highest traffic-related particle emissions in the country. In addition, Andriulė et al. [25] examined NO₂ and particulate pollution patterns in Klaipėda and demonstrated the combined influence of traffic activity, urban land use, and seasonal meteorological conditions on local air quality.

Despite these advances, detailed corridor-scale investigations of traffic-related air pollution in Vilnius remain limited, particularly studies that combine site-specific pollutant measurements with traffic observations and meteorological data. This limitation is especially relevant in medium-sized Baltic and Eastern European cities, where urban morphology, traffic patterns, and local background conditions may differ from those reported for larger metropolitan areas.

In this context, the present study provides a preliminary, data-driven assessment of traffic-related air pollution in Vilnius based on integrated pollutant measurements, traffic volume observations, and meteorological data collected between March and July 2023 across five representative urban traffic corridors. The study focuses on four key pollutants (NO_x , CO, $\text{PM}_{2.5}$, and PM_{10}) and aims to: (1) quantify their concentrations in high-traffic urban environments, (2) examine their relationships with traffic intensity and selected meteorological conditions, and (3) provide evidence relevant to traffic management and sustainable urban air quality planning in Vilnius.

Rather than proposing a new methodological framework, this study contributes locally grounded empirical evidence on traffic-related air pollution patterns in a medium-sized Baltic city. By linking roadside pollutant concentrations with traffic intensity and meteorological conditions across multiple urban corridors, the study aims to support future TRAP research and context-specific air quality management strategies in Vilnius and comparable urban environments.

2. MATERIALS AND METHODS

2.1. Study area

As shown in Fig. 1, Vilnius is the capital of Lithuania with a population of approximately 580,000 and a complex urban structure shaped by rapid post-independence development [26].

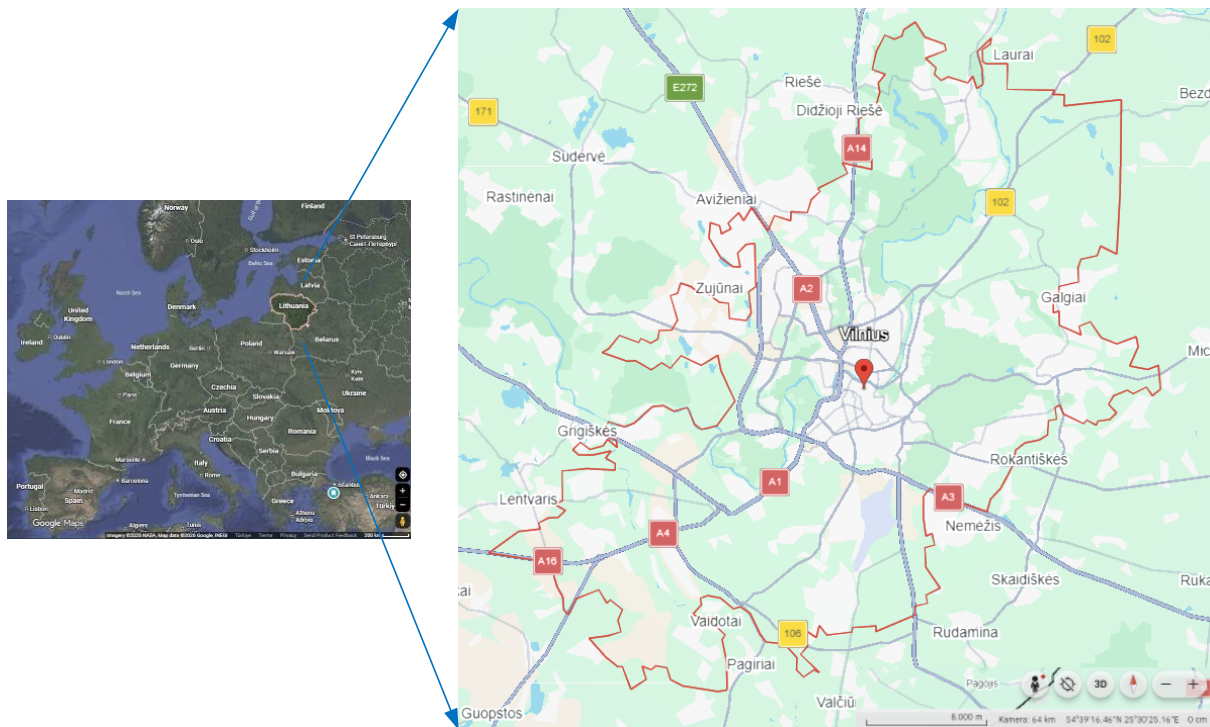


Fig. 1. The geographical location of Vilnius (source: Google Earth)

The city's location at the confluence of the Neris and Vilnia rivers, its hilly terrain, and frequent winter temperature inversions contribute to localized pollution accumulation [26,27].

2.2. Monitoring sites and equipment

Air quality data were collected from five major traffic corridors: Gediminas Avenue, Konstitucijos Avenue, Station Street, Ukmergės Street, and Žirmūnai Bridge. Each site was chosen based on traffic intensity, urban morphology, and pedestrian exposure potential [27-32]. These locations represent different urban traffic environments characterized by varying traffic density and built-up conditions.

The monitoring campaign focused on near-road measurements of NO_x , CO, $\text{PM}_{2.5}$, and PM_{10} concentrations during predefined traffic activity periods. Monitoring instruments were positioned adjacent to the selected traffic corridors in order to represent typical roadside urban exposure conditions and to capture localized traffic-related pollutant concentrations.

Measurements were conducted using portable urban air quality monitoring instruments provided during the field campaign. Preliminary data for this study were obtained from M. Arif Ghaznavi's master's thesis completed at Balikesir University in 2024 [33]. Since the study relied on previously collected field data, detailed technical specifications and quantitative uncertainty information for all monitoring instruments were not fully available in the thesis documentation. Therefore, the measurements should be interpreted as indicative roadside observations conducted following standard urban air quality monitoring practices. Basic operational consistency checks were performed during the monitoring campaign to maintain measurement consistency.

The monitoring sensors were positioned adjacent to the selected traffic corridors to represent typical near-road urban exposure conditions and to capture localized traffic-related pollutant concentrations.

Figure 2 presents the spatial distribution of the selected traffic-related air pollution monitoring locations across Vilnius, Lithuania. The monitoring sites were strategically positioned along major urban transport corridors characterized by varying traffic intensity, road geometry, and surrounding urban morphology. The selected locations represent different functional urban environments, including dense commercial districts, central transport hubs, arterial commuter roads, and bridge crossings. Their spatial distribution enables the assessment of both temporal and spatial variability in pollutant concentrations under differing traffic and meteorological conditions. In particular, the arrangement of the monitoring points provides a representative overview of key urban traffic emission hotspots within the city and supports the evaluation of localized pollutant accumulation patterns associated with major transportation corridors.

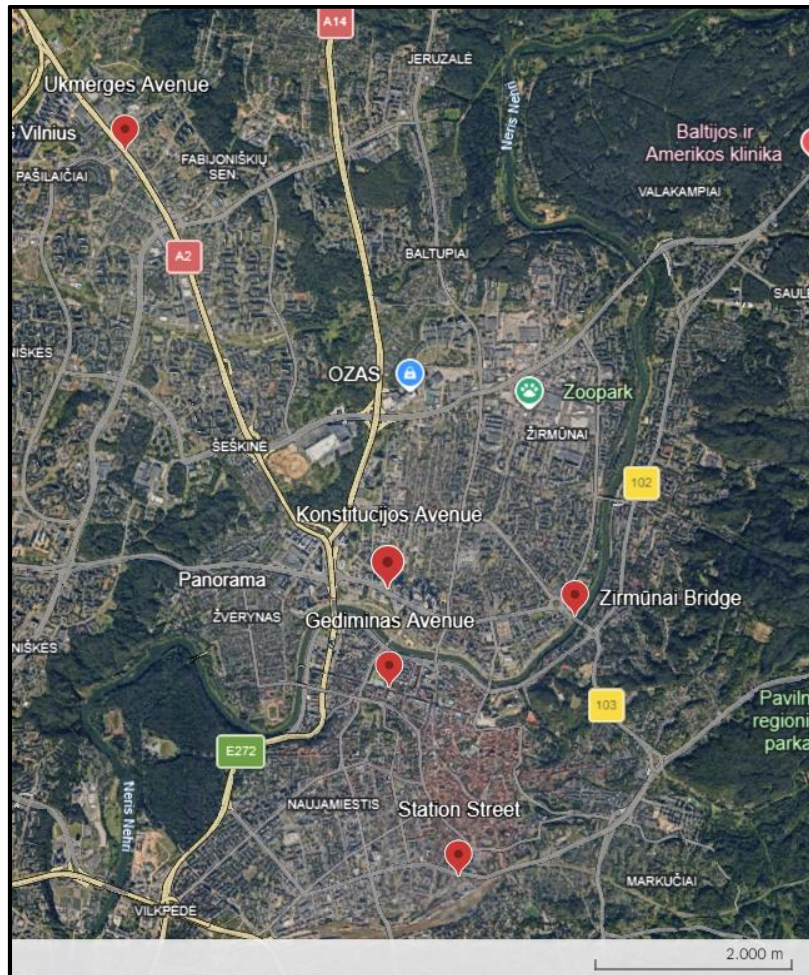


Fig 2. Spatial distribution of the traffic-related air pollution monitoring locations across major urban corridors in Vilnius, Lithuania. (source: Google Earth)

As presented in Fig. 2, Gediminas Avenue experiences intense vehicular and pedestrian activity during peak hours. Although certain sections are designated for pedestrian use, most parts of the avenue remain accessible to motorized traffic, frequently leading to congestion. The combination of high traffic density and a compact urban environment makes this corridor an important location for assessing the influence of traffic-related emissions on local air quality.

Konstitucijos Avenue skirts the northern bank of the Neris River, forming the spine of Vilnius's modern business district. This four-lane commuter artery is flanked by high-rise offices and commercial centers, creating intense rush-hour congestion. The combination of heavy traffic and tall buildings traps pollutants—particularly NO_x and PM_{10} —by limiting air circulation. As such, it serves as a critical site for assessing how dense urban corridors impact air quality.

Station Street serves Vilnius's central rail station, acting as a busy interchange for buses, taxis and private cars. Its two-lane, two-way layout often becomes congested—especially around taxi ranks and transit stops—leading to the buildup of vehicle emissions. Previous studies have shown that heavy public transport activity, traffic congestion, and limited road ventilation can significantly increase concentrations of NO_x , $\text{PM}_{2.5}$, and CO in urban transport hubs [20,25,28,30]. Monitoring at this location

is therefore important for evaluating the accumulation of traffic-related pollutants around major transit corridors.

Ukmerges Avenue stretches northwest from Vilnius's historic core toward surrounding suburbs and rural areas, serving as a key four-lane, two-way artery. Despite its capacity, morning inbound and evening outbound commuter flows routinely create bottlenecks, extending journey times and trapping exhaust. Research shows that the stop-and-go traffic—especially from diesel vehicles—drives up NO_x particulate concentrations, highlighting how suburban commuting feeds into urban air pollution. Continuous monitoring of this corridor is essential for tracing how outlying traffic patterns impact the city's air quality.

Žirmūnai Bridge links central Vilnius to the Žirmūnai district across the Neris River, serving as a vital two-lane, bidirectional commuter route. During morning and evening peaks, traffic slow-downs and stop-and-go flows routinely create bottlenecks, trapping exhaust emissions on the bridge. Limited air circulation over the river allows pollutants—especially from diesel vehicles—to concentrate, posing heightened exposure risks for nearby residents. As such, this crossing is a key site for examining how choke-points in urban mobility amplify local air pollution.

2.3. Traffic and meteorological data

To evaluate the influence of traffic intensity on roadside pollutant concentrations, measurements were organized according to predefined traffic activity periods. Peak traffic conditions were represented by morning (07:00–09:00) and evening (16:00–18:00) rush-hour intervals, while lower-traffic conditions were assessed during midday off-peak periods (11:00–13:00). In addition, continuous hourly observations were used to support temporal comparisons throughout the monitoring campaign. Where possible, vehicle classification data (light-duty vs. heavy-duty, diesel vs. petrol) were incorporated to differentiate emission profiles. Traffic counts were conducted through direct field observations by trained personnel and were cross-validated with available automated traffic data from the municipal transport authority. Although manual counting may introduce some uncertainty, the use of standardized time intervals and repeated observations ensured representative traffic estimates. Detailed vehicle classification data were not consistently available across all sites and are therefore considered a limitation of the study.

Meteorological data (temperature, humidity, wind speed, atmospheric pressure) were obtained at hourly resolution from the Lithuanian Hydrometeorological Service's main station, located approximately 3 km from the nearest sampling point [34]. This distance was considered suitable for representing broader meteorological conditions across the study area.

Analytical Methods

Three analytical tiers were applied:

1. Descriptive statistics (mean, median, standard deviation, range) for all pollutant concentrations across sites and time intervals.
2. Pearson correlation analysis between traffic volume, meteorological factors, and pollutant concentrations, with p-values reported for statistical significance at the 95% confidence level.
3. Comparative analysis of temporal differences (weekday vs. weekend; peak vs. off-peak) and spatial differences across the five sites.

The statistical analysis focused on descriptive statistics and Pearson correlation analysis to evaluate relationships between traffic activity, meteorological parameters, and pollutant concentrations. All analyses were conducted using IBM SPSS Statistics v26 [35].

3. RESULTS

Significant spatial variability emerged across the five monitoring locations (Table 1). Konstitucijos Avenue and Ukmergės Street had the highest mean concentrations of NO_x (21.6 and 20.1 $\mu\text{g}/\text{m}^3$) and CO (2.1 and 2.2 mg/m^3), while Station Street recorded the highest PM levels (PM_{10} : 1.2 $\mu\text{g}/\text{m}^3$, $\text{PM}_{2.5}$: 0.8 $\mu\text{g}/\text{m}^3$). Peak NO_x concentrations reached 112.3 $\mu\text{g}/\text{m}^3$ on Konstitucijos Avenue during weekday rush hours, and peak CO levels reached 1.89 mg/m^3 on Ukmergės Street in the evening.

The strong correlations observed between traffic volume and gaseous pollutants (Figure 3) further support the representativeness of the traffic-related observations used in this study. Higher traffic intensity was generally associated with increased NO_x and CO concentrations across the monitored urban corridors. In contrast, $\text{PM}_{2.5}$ and PM_{10} concentrations exhibited comparatively weaker responses to traffic intensity, suggesting the influence of non-exhaust emissions, atmospheric dispersion, regional background processes and secondary PM contribution. Pearson correlation coefficients (Figure 3) showed strong positive correlations between traffic volume and gaseous pollutants: CO ($r = 0.88$, $p < 0.01$) and NO_x ($r = 0.72$, $p < 0.01$). Particulate matter (PM_{10} $r = 0.32$, $p = 0.05$; $\text{PM}_{2.5}$ $r = 0.24$, $p = 0.08$) showed weaker associations, suggesting additional influences from non-traffic sources. While NO_x and CO are well-established indicators of traffic-related emissions, particulate matter ($\text{PM}_{2.5}$ and PM_{10}) originates from a broader range of sources. In addition to exhaust emissions, non-exhaust processes such as road dust resuspension, tire and brake wear contribute significantly to urban PM levels. Furthermore, domestic heating and other combustion activities may represent major sources, particularly in urban environments. The contribution of secondary particulate matter formation, resulting from atmospheric chemical processes, should also be considered, as it can account for a substantial fraction of PM under certain meteorological conditions. These factors help explain the weaker correlations observed between traffic volume and PM concentrations in this study.

To control for meteorological confounding, we conducted multiple regression analyses. Traffic volume remained the primary predictor of NO_x and CO levels ($p < 0.01$), while wind speed and humidity showed moderating effects, particularly for gaseous pollutants. Although temperature and humidity exhibited negative correlations with most pollutants, their relationships with particulate matter ($\text{PM}_{2.5}$ and PM_{10}) were weaker and not statistically significant.

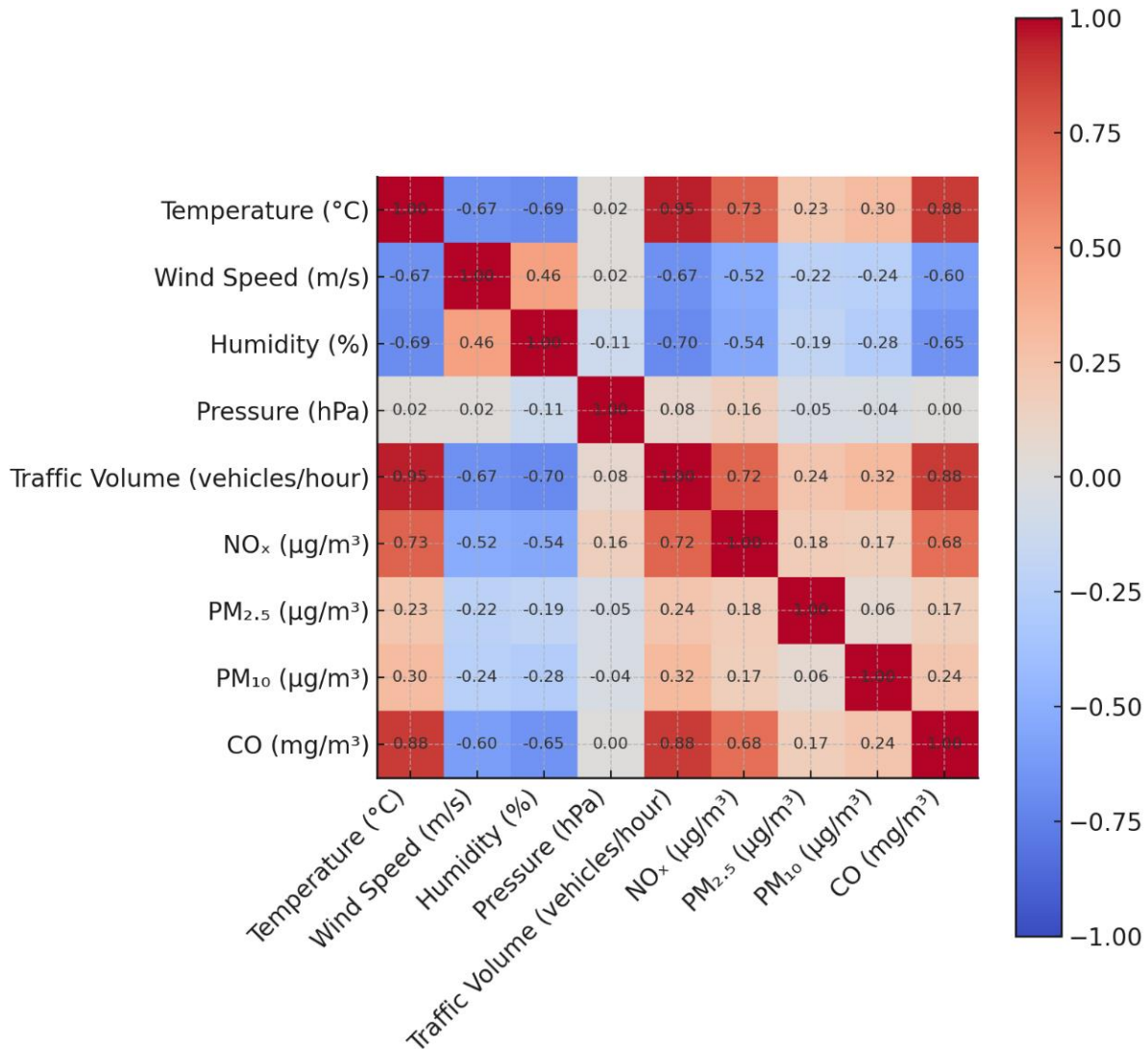


Fig 3. Heatmap of Pearson correlation coefficients between meteorological variables, traffic volume and pollutant concentrations

These coefficients confirm that rush hour vehicular activity drives peaks in combustion-related pollutants. In contrast, particulate matter (PM_{2.5} and PM₁₀) is influenced by a combination of sources. This weaker correlation can be explained by a combination of additional sources and processes, including non-exhaust traffic emissions (e.g., road dust resuspension, tire and brake wear), domestic heating, and secondary formation processes in the atmosphere.

Pearson correlation coefficients between traffic volume and meteorological parameters are also illustrated in Figure 3. Among meteorological drivers, traffic volume correlates most strongly and positively with temperature ($r = 0.95$), indicating that the hottest hours coincide with the heaviest commuter flows—and thus the highest emissions. Wind speed shows a strong negative relationship ($r = -0.67$), and humidity likewise is inversely linked ($r = -0.70$), suggesting that breezier, more humid

conditions both coincide with—and help enforce—lighter traffic and enhanced pollutant dispersion. Atmospheric pressure, however, registers almost no systematic effect on traffic volume ($r = 0.08$), implying that synoptic-scale pressure fluctuations did not critically influence local commuting patterns during the study period

Spatial patterns mirror the influence of traffic intensity and urban morphology. The relatively low $PM_{2.5}$ and PM_{10} concentrations observed across the monitoring sites (Table 1), together with their weaker correlation with traffic volume, suggest that particulate matter levels are not solely driven by direct vehicular emissions. Instead, they reflect a combination of influences, including non-exhaust sources such as road dust resuspension, tire and brake wear, as well as local urban conditions and atmospheric dispersion processes. Furthermore, secondary particulate formation may contribute to PM levels under specific meteorological conditions. The absence of detailed source apportionment limits the ability to quantify these contributions, representing an important area for future research. High-rise canyons like Konstitucijos Avenue showed higher NO_x and CO due to trapped emissions. Station Street’s high PM levels likely reflect combined effects of transit activity and limited air circulation.

Table 1. Mean pollutant concentrations from March to July 2023

Location	CO (mg/m ³)	NO _x (µg/m ³)	PM _{2.5} (µg/m ³)	PM ₁₀ (µg/m ³)
Gediminas Ave.	1.5 ± 0.3	15.6 ± 0.2	1.5 ± 0.2	2.3 ± 0.4
Konstitucijos Ave.	2.1 ± 0.4	21.6 ± 4.1	2.1 ± 0.3	3.2 ± 0.5
Station St.	0.8 ± 0.2	8.4 ± 1.9	0.8 ± 0.1	1.2 ± 0.2
Ukmergės St.	2.2 ± 0.5	20.1 ± 3.8	2.1 ± 0.3	3.3 ± 0.5
Zirmūnai Bridge	1.2 ± 0.3	11.9 ± 2.4	1.1 ± 0.2	1.8 ± 0.3

Konstitucijos Avenue and Ukmergės Street record the highest mean concentrations of all four pollutants, with CO averaging 2.1–2.2 mg/m³, NO_x at 20–22 µg/m³, PM_{2.5} around 2.1 µg/m³ and PM₁₀ near 3.2–3.3 µg/m³. These two corridors are both four lane commuter arteries lined with high rise offices, where rush hour congestion and reduced air circulation combine to trap exhaust and particulate emissions.

Gediminas Avenue occupies an intermediate position: CO at 1.5 mg/m³ and NO_x at 15.6 µg/m³ sit roughly 25–30 % below the peaks seen on Konstitucijos and Ukmergės, while PM_{2.5} (1.5 µg/m³) and PM₁₀ (2.3 µg/m³) are about 30 % lower. This reflects its mixed pedestrian-vehicle design, which affords slightly better dispersion than the fully trafficked boulevards.

Station Street shows the lowest pollutant burdens (CO 0.8 mg/m³, NO_x 8.4 µg/m³, PM_{2.5} 0.8 µg/m³, PM₁₀ 1.2 µg/m³). As the zone immediately surrounding the rail terminal, it benefits from more open geometry and frequent stop start flows that clear emissions quickly, despite high public-transport use.

Zirmūnai Bridge—though only a two lane crossing—yields moderate values (CO 1.2 mg/m³, NO_x 11.9 µg/m³, PM_{2.5} 1.1 µg/m³, PM₁₀ 1.8 µg/m³). Here the choke-point effect of the bridge deck over the river elevates concentrations above those on Station Street but remains below the busiest avenues.

Across all sites, the ratio of NO_x to CO suggests a strong contribution from diesel powered vehicles, while the relatively low PM_{2.5}/PM₁₀ ratios point to coarse road dust and tire wear as additional sources. Although average concentrations remain below most short term health thresholds, these means mask pronounced rush hour spikes and localized hotspots. From a policy standpoint, targeting emission controls and traffic flow improvements on Konstitucijos Avenue and Ukmergės Street would yield the

greatest air-quality benefits, while maintaining open geometries and green buffers could help reduce pollutant buildup on more constrained links like Zirmūnai Bridge.should be explained.

To further evaluate the influence of traffic intensity on roadside air pollution, Figure 4 presents the relationships between traffic volume and the average concentrations of NO_x , CO, $\text{PM}_{2.5}$, and PM_{10} measured across the monitored urban corridors in Vilnius.

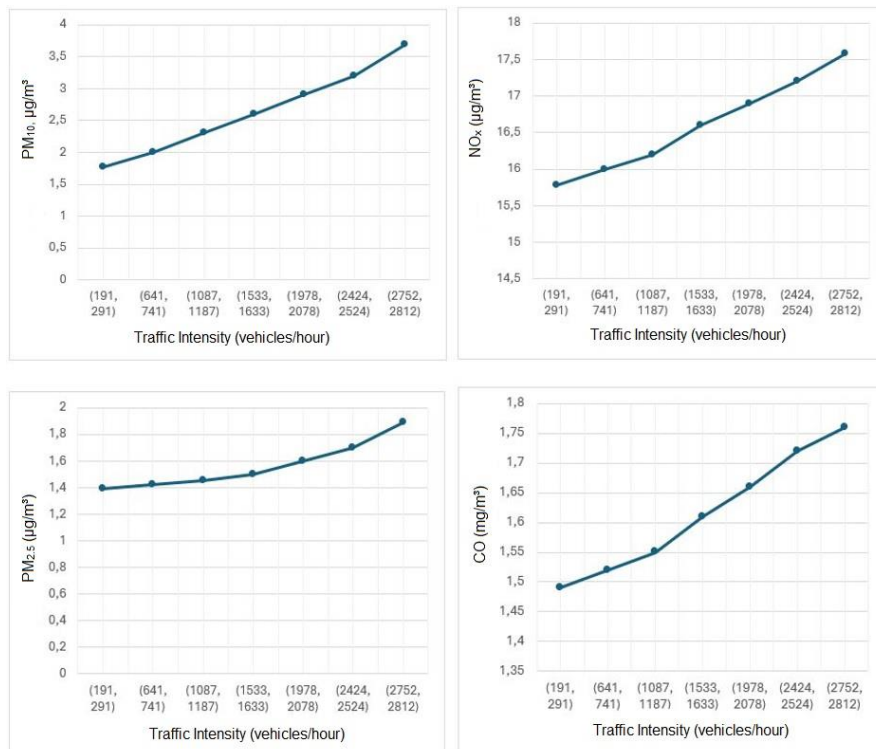


Fig. 4. Relationships between grouped traffic intensity intervals (vehicles/hour) and average concentrations of PM_{10} , NO_x , $\text{PM}_{2.5}$, and CO measured across the monitored urban corridors in Vilnius, Lithuania

Traffic intensity categories shown in Figure 4 represent grouped traffic volume intervals (vehicles/hour) derived from observed roadside traffic counts during the monitoring campaign. The strongest positive relationships were observed for NO_x and CO, which exhibited consistent increases under higher traffic volumes. This pattern strongly supports the dominant contribution of vehicular combustion emissions to gaseous pollutant concentrations in roadside urban environments.

$\text{PM}_{2.5}$ and PM_{10} concentrations also increased with traffic intensity, although the observed trends were comparatively weaker than those of NO_x and CO. This suggests that particulate matter concentrations were influenced not only by direct traffic emissions but also by additional urban and atmospheric factors.

The gradual increase in pollutant concentrations with traffic activity further supports the interpretation that traffic intensity plays a major role in short-term air quality variability within the investigated urban corridors. Nevertheless, the relatively moderate PM responses indicate that particulate pollution dynamics in Vilnius are governed by multiple interacting urban and meteorological factors.

It is important to distinguish between coarse (PM_{10}) and fine particulate matter ($\text{PM}_{2.5}$), as they often originate from different sources. PM_{10} is typically associated with non-exhaust emissions such as

road dust resuspension, tire and brake wear, whereas $PM_{2.5}$ is more closely linked to combustion processes and secondary formation mechanisms. The relatively low PM concentrations observed in this study may also be related to the limited availability of precursor gases required for secondary particle formation. While NO_x was analyzed, other key precursors such as ammonia (NH_3) were not included due to data limitations.

4. DISCUSSION

The results indicate that higher traffic intensity was generally associated with increased NO_x and CO concentrations across the monitored urban corridors in Vilnius, supporting the dominant role of vehicular emissions in short-term roadside gaseous pollution. This pattern is consistent with previous urban air quality studies that identify traffic activity as a major source of NO_x and CO in densely used transport corridors [8,36]. In contrast, $PM_{2.5}$ and PM_{10} exhibited comparatively weaker associations with traffic intensity, suggesting the additional influence of non-exhaust emissions, atmospheric dispersion, road dust resuspension, residential heating, and regional background sources.

Meteorological factors, particularly wind speed, also appeared to influence pollutant dispersion and short-term concentration variability within the investigated urban corridors. Meteorological conditions also likely affected the observed pollutant variability during the monitoring period. The campaign was conducted between March and July 2023, when Vilnius experienced typical late spring and early summer conditions characterized by generally low to moderate wind speeds and variable humidity. Under such conditions, lower wind speeds may have reduced pollutant dispersion, whereas higher wind speeds likely enhanced atmospheric mixing and dilution. However, more complex atmospheric processes such as stability, turbulence, and boundary-layer dynamics were not explicitly evaluated in this study and should be considered in future analyses [37,38]. These results mirror studies conducted in Scandinavian and Baltic contexts [28,39], where similar topographical constraints and seasonal inversion layers influence air quality outcomes.

The spatial differences observed among the monitored corridors further highlight the role of local urban form in shaping roadside air pollution patterns. Konstitucijos Avenue and Ukmergės Street consistently showed the highest pollutant levels, which may reflect the combined influence of heavy traffic activity and reduced air exchange in dense urban corridors bordered by high-rise buildings. By contrast, Station Street showed lower average NO_x and CO concentrations but comparatively distinct particulate behavior, possibly reflecting the influence of public transport activity, stop-and-go traffic conditions, and local ventilation characteristics around the transit hub [13]. These findings are broadly consistent with previous studies showing that urban morphology and traffic flow characteristics can strongly influence pollutant accumulation, even within medium-sized cities [28,39].

The relatively low $PM_{2.5}$ and PM_{10} concentrations observed in this study should be interpreted cautiously. First, the monitoring period covered spring and summer months, when residential heating emissions are limited and atmospheric dispersion conditions are generally more favorable than during winter. Second, the dataset represents indicative short-term roadside observations rather than long-term regulatory monitoring records. Finally, the absence of PM speciation or source apportionment prevents a more detailed separation of traffic-related and non-traffic particulate sources. For these reasons, the particulate matter results are best interpreted as corridor-scale observational evidence rather than as a complete characterization of PM sources in Vilnius.

From an applied perspective, the results suggest that traffic management and sustainable urban mobility measures may be particularly relevant in heavily trafficked corridors such as Konstitucijos Avenue and Ukmergės Street. Measures such as improving public transport attractiveness, reducing congestion, supporting active transport, and prioritizing cleaner vehicle fleets could help reduce

localized roadside pollution exposure. At the same time, the findings should be viewed as a preliminary empirical assessment rather than a direct basis for source-specific regulatory intervention, given the limited temporal coverage and the absence of detailed source apportionment.

Several limitations should be considered when interpreting the results. Monitoring was limited to March–July and therefore does not capture wintertime conditions, when residential heating and inversion episodes may substantially alter pollutant concentrations. Traffic counts were partly based on manual observations, which may introduce counting uncertainty. In addition, PM speciation and source apportionment were not conducted, meaning that the relative contributions of traffic and non-traffic sources could not be quantified directly. Construction activities and roadworks during the study period may also have influenced local particulate measurements at some sites. These limitations should be taken into account when generalizing the findings beyond the monitored period and locations.

5. CONCLUSION

This study provides an indicative, corridor-scale assessment of traffic-related air pollution (TRAP) in Vilnius, Lithuania, based on multi-site data collected from five high-traffic corridors between March and July 2023. The findings address the study’s main objectives and provide locally grounded empirical evidence on roadside air pollution patterns in a medium-sized Baltic city:

- Concentrations of key pollutants (NO_x , CO, $\text{PM}_{2.5}$, and PM_{10}) were quantified, with the highest values generally observed at Konstitucijos Avenue and Ukmergės Street.
- Strong positive correlations were identified between traffic volume and gaseous pollutants, particularly CO ($r = 0.88$) and NO_x ($r = 0.72$), while PM exhibited comparatively weaker associations with traffic intensity, suggesting additional influences from non-exhaust emissions, atmospheric dispersion, and regional background sources. Additional long-term measurements and source apportionment analyses would be valuable for confirming and further interpreting these observations.
- Spatial analysis indicated that urban morphology and reduced air circulation may contribute to localized pollutant accumulation within heavily trafficked corridors.
- From an applied perspective, the results support the relevance of targeted traffic management measures, improvements in public transport and cycling infrastructure, and the broader integration of sustainable urban mobility planning in pollution-prone parts of Vilnius.

Overall, the integrated framework adopted in this study—combining multi-site pollutant monitoring, traffic observations, meteorological data, and statistical correlation analysis—provides a useful empirical basis for future traffic-related air pollution studies in Vilnius and comparable medium-sized urban environments. At the same time, the study should be interpreted as an indicative and locally grounded assessment rather than a comprehensive source-apportionment analysis.

For future research, year-round monitoring would be valuable to capture seasonal variations, particularly during winter inversions. Health risk assessments using exposure-based approaches, together with PM source characterization and higher-resolution traffic and meteorological observations, would help provide a more comprehensive understanding of traffic-related air pollution dynamics in Vilnius.

Overall, reducing traffic-induced air pollution in Vilnius requires a multi-dimensional and data-informed approach integrating environmental management with sustainable urban mobility planning. In this context, the results presented here offer site-specific evidence that may support local authorities and urban planners in developing healthier and more livable urban environments.

Competing Interests

We declare that the authors have no competing interests as defined by the publisher, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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REFERENCES

1. WHO 2019. Ambient air pollution: Health impacts 2019. Geneva: World Health organization. <http://www.who.int/airpollution/ambient/health-impacts/en/>
2. Boogaard, H et al. 2022. Long-term exposure to traffic-related air pollution and selected health outcomes: A systematic review and meta-analysis. *Environment International* **164**, 107262.
3. Brunekreef, B and Holgate, ST 2002. Air pollution and health. *The Lancet* **360**(9341), 1233-42.
4. Khreis, H et al. 2020. Traffic-related air pollution: Emissions, human exposures, and health: An introduction. In: *Traffic-related air pollution*. Elsevier, 1-21.
5. Kumar, N, Kumar, S and Pandey, SP 2023. Traffic-Related Air Pollution and Associated Human Health Risk. Wiley Online Library.
6. Min K-D et al. 2020. Association between exposure to traffic-related air pollution and pediatric allergic diseases based on modeled air pollution concentrations and traffic measures in Seoul, Korea: a comparative analysis. *Environmental Health* **19**, 1-12.
7. Pope III, CA and Dockery, DW 2006. Health Effects of Fine Particulate Air Pollution: Lines that Connect. *Journal of the Air & Waste Management Association* **56**(6), 709-42.
8. Beevers, SD and Carslaw, DC 2005. The impact of congestion charging on vehicle emissions in London. *Atmospheric Environment* **39**(1), 1-5.
9. Solanki, N 2022. Air Matters: The Effect of Ozone and Traffic Related Air Pollution on the Airways. In: *Lung Health and the Exposome: How Environmental Factors Influence Lung Health*. Springer, 1-21.
10. Syed, M et al. 2023. Environmental factors and their impact on airway diseases: exploring air pollution, indoor and outdoor allergens, and climate change. *Current Pulmonology Reports* **12**(3), 162-70.
11. Figenbaum, E and Kolbenstvedt, M 2016. Learning from Norwegian battery electric and plug-in hybrid vehicle users. <https://www.toi.no/>
12. Fischer, PH et al. 2015. Air pollution and mortality in seven million adults: the Dutch Environmental Longitudinal Study (DUELS). *Environmental Health Perspectives* **123**(7), 697-704.
13. Snyder, EG et al. 2013. The Changing Paradigm of Air Pollution Monitoring. *Environmental Science & Technology* **47**(20), 11369-77.
14. Zhang, Y et al. 2022. Spatial effects of urban expansion on air pollution and eco-efficiency: Evidence from multisource remote sensing and statistical data in China. *Journal of Cleaner Production* **367**, 132973.
15. Cesaroni, G et al. 2013. Long-Term Exposure to Urban Air Pollution and Mortality in a Cohort of More than a Million Adults in Rome. *Environmental Health Perspectives* **121**(3), 324-31.

16. Grossman, GM and Krueger, AB 1995. Economic Growth and the Environment. *The Quarterly Journal of Economics* **110**(2), 353-77.
17. Badach, J, Dymnicka, M and Baranowski, A 2020. Urban Vegetation in Air Quality Management: A Review and Policy Framework. *Sustainability* **12**(3), 1258.
18. Cârlan, I et al. 2020. Mapping heat and traffic stress of urban park vegetation based on satellite imagery-A comparison of Bucharest, Romania and Leipzig, Germany. *Urban Ecosystems* **23**(2), 363-77.
19. Jumaah, M, Abdulrazzaq, Z and Abdul Majeed, A 2021. Role of green spaces and their impact on climate design and ecosystem efficiency. Earth and Environmental Science: IOP Publishing.
20. Davtalab, M, Byčenkienė, S and Bimbaitė, V 2023. Long-term spatial and temporal evaluation of the PM_{2.5} and PM₁₀ mass concentrations in Lithuania. *Atmospheric Pollution Research* **14**(12), 101951.
21. Dėdelė, A, Miškinytė, A and Česnakaitė, I 2019. Comparison of Measured and Modelled Traffic-Related Air Pollution in Urban Street Canyons. *Polish Journal of Environmental Studies* **28**(5).
22. Shkrey Fahim, MA and Visockienė, JS 2024. Air Pollution Sources And Their Impact On The Environment. *Science: Future of Lithuania/Mokslas: Lietuvos Ateitis* **16**.
23. Peleckis, K, Peleckienė, V and Peyravi, B 2025. Influence of transport air pollutants on climate change in EU: case of Lithuania. *Business: Theory and Practice* **26**(2), 277-86.
24. Kecorius, S et al. 2025. *Environmental Advances* **21**, 100661.
25. Andriulė, A et al. 2024. Air pollution in the port city of Lithuania: characteristics of the distribution of nitrogen dioxide and solid particles when assessing the demographic distribution of the population. *Sustainability* **16**(19), 8413.
26. Vilnius Population and Demographic Report 2022. <https://osp.stat.gov.lt/en>.
27. Green Spaces in Vilnius 2022. Their role in urban air quality. Lithuanian Ministry of Environment. <https://am.lrv.lt/en/>.
28. Bekesiene, S and Meidute-Kavaliauskiene, I 2022. Artificial Neural Networks for Modelling and Predicting Urban Air Pollutants: Case of Lithuania. *Sustainability* **14**(4), 2470.
29. Fahim, MAS and Visockienė, JS 2024. Air pollution sources and their impact on the environment. *Mokslas–Lietuvos ateitis/Science–Future of Lithuania* **16**.
30. Mažeika, M and Juodvalkis, D 2023. Analysis of Air Pollution Monitoring System in Lithuania. Champ: Springer International Publishing.
31. Urban Development Challenges 2020. Addressing traffic congestion in modern Vilnius. <https://vrsa.lt/en>.
32. Vitkauskaitė, A and Salytė, M 2023. Air quality investigation using functional data analysis methods. *Lietuvos matematikos rinkinys Lietuvos matematikų draugijos darbai Ser B* **64**, 36-53.
33. Ghaznavi MA 2025. Investigation Of Traffic-Caused Air Pollution: The Case Of Vilnius, Lithuania [MSc.]: Balikesir University. Balikesir, Turkey.
34. Lithuanian Hydrometeorological Service 2023. The Ministry of Environment <https://www.meteo.lt/en/>.
35. IBM SPSS 2019. IBM SPSS Statistics for Windows, version 26. Armonk, N.Y., USA: IBM Corp.
36. Cesaroni, G 2012. Health benefits of traffic-related air pollution reduction in different socioeconomic groups: the effect of low-emission zoning in Rome. *Occupational and Environmental Medicine* **69**(2), 133-9.
37. Oke, TR 1984. Methods in urban climatology. *Applied Climatology* **14**(18), 19-29.
38. Stull, RB 1988. Boundary layer clouds: An introduction to boundary layer meteorology: Springer.
39. Davulienė, L et al. 2021. Long-term air pollution trend analysis in the South-eastern Baltic region, 1981–2017. *Atmospheric Research* **247**, 105191.