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Air Quality in Urban Mobility Hubs: An Analysis of Particulate Matter in Underground Transport Spaces

Michal Loman [1], Veronika Harantová [2,*] and Saša Milojević [3]

[1] Department of Road and Urban Transport, Faculty of Operation and Economics of Transport and Communications, University of Zilina, 010 26 Žilina, Slovakia
[2] Department of Quantitative Methods and Economic Informatics, Faculty of Operation and Economics of Transport and Communications, University of Zilina, 010 26 Žilina, Slovakia
[3] Department for Motor Vehicles and Motors, Faculty of Engineering, University of Kragujevac, 34000 Kragujevac, Serbia; sasa.milojevic@kg.ac.rs
* Correspondence: harantova@uniza.sk

Abstract

Enclosed transport environments are becoming an integral part of compact urban structures; however, their air quality is monitored less systematically than that of the outdoor urban environment. This study evaluates particulate matter concentrations (PM_1, $PM_{2.5}$, PM_{10}) in two urban microenvironments in Banská Bystrica (Slovakia): an underground parking garage (representing private urban mobility) and an underground bus station (representing public transport). Continuous measurements using an enviDUST monitoring device were analysed in relation to occupancy rates and transport intensity. The results showed a dominance of the PM_{10} fraction in both environments, suggesting the importance of non-exhaust sources and dust resuspension in enclosed urban transport spaces. In the parking facility, the immediate relationship between occupancy and PM concentrations was weak; however, a time lag effect was observed, indicating particle accumulation. The bus station exhibited higher average concentrations (PM_1: 8.67; $PM_{2.5}$: 14.12; PM_{10}: 34.12 μg/m^3), while peak levels during nighttime highlighted the critical role of air stagnation and ventilation regimes. The study emphasizes the need to perceive such transport nodes as semi-public urban spaces requiring the integration of intelligent air quality management within sustainable urban development.

Keywords: particulate matter (PM_1; $PM_{2.5}$; PM_{10}); urban transport microenvironments; underground parking; bus station; air quality monitoring; urban mobility

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1. Introduction

Air pollution represents one of the most pressing environmental challenges of our time, carrying extensive negative impacts on human health and ecosystems [1]. Within urban environments, transport, industry, and energy production constitute the primary drivers of ambient degradation. The combustion of fossil fuels releases an array of harmful substances, including nitrogen oxides (NO_x), carbon monoxide (CO), sulfur dioxide (SO_2), particulate matter (PM), and volatile organic compounds (VOC). These pollutants actively contribute to photochemical smog formation, acid rain, and global climate change [2].

Measurement and Interpretation of Emissions

Accurate quantification of emissions from road transport is a fundamental prerequisite for reliable predictive air quality models in urban agglomerations and for the valid evaluation of policy and planning measures [3]. Therefore, generating comprehensive real-time empirical datasets is essential.

A variety of methodological approaches are applied, including portable emission measurement systems (PEMS), remote sensing techniques, stationary roadside monitoring, and experimental studies conducted in tunnel environments [4,5].

The interpretation of measured pollutant concentrations in street canyons is influenced by a complex synergy of dynamic factors [6]. Key determinants include traffic-related parameters such as flow intensity, fleet composition, and driving cycle characteristics (speed profiles, acceleration, and road gradient) [7]. The microscale dispersion of pollutants is governed not only by local meteorological conditions and urban morphology (e.g., vegetation, built structures), but also by turbulence generated by the kinetic energy of moving vehicles [8,9].

Enclosed transport microenvironments

Recent research has increasingly focused on air quality and human exposure in enclosed transport microenvironments. A comprehensive review of transport-related environments highlighted that particulate matter concentrations in confined transport spaces can substantially exceed recommended air quality levels, making them important exposure settings for daily commuters and transport users [10]. Studies conducted in underground transport facilities further demonstrated that PM exposure is strongly influenced by ventilation regimes, airflow patterns, and passenger movement within enclosed spaces [11]. Similarly, investigations of subway stations showed that the design of environmental control and ventilation systems significantly affects $PM_{2.5}$ and PM_{10} concentrations, with reductions of up to 50% reported under optimized ventilation conditions [12]. In underground parking facilities, pollutant accumulation has been directly linked to ventilation performance, emphasizing the importance of airflow design for limiting the build-up of traffic-related emissions [13]. Elevated particulate matter concentrations have also been reported in closed parking environments, where prolonged exposure may increase potential health risks for users and employees [14]. Together, these findings demonstrate the importance of assessing air quality in enclosed transport spaces and support the need for further investigation of particulate matter dynamics in underground mobility hubs.

Specific Characteristics of Underground Garages and Urban Measures

The global increase in motorization, particularly evident in Asian megacities, has led to extensive development of underground parking infrastructure. Research supports the hypothesis that the limited volumetric capacity of these spaces facilitates the accumulation of transport-related emissions, which represent a primary source of VOCs with high carcinogenic and toxic potential. Even short-term exposure may affect neurological, respiratory, hepatic, renal, and reproductive systems. Therefore, the integration of efficient ventilation and air filtration systems is critical in underground facilities [15].

Although direct restrictions on access to underground garages based on Euro standards are not commonly enforced globally, several European cities—including Munich, Frankfurt, Augsburg, Vienna, and cities in the UK and Denmark—have implemented low-emission zones (LEZs) requiring environmental certification [16]. Progressive cities such as London apply policies to reduce parking capacity in city centres in order to encourage modal shifts toward walking and cycling. In Germany, regulatory frameworks link housing units to parking provision while simultaneously requiring bicycle infrastructure. Sweden adopts a flexible parking policy and actively promotes car-sharing to reduce overall private vehicle use [17].

Empirical studies consistently demonstrate that pollutant concentrations, including PM, are significantly higher in enclosed parking facilities than in the open urban atmo-

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sphere. This phenomenon is attributed to high vehicle turnover, increased emissions during cold-start phases, and specific microclimatic conditions. For instance, research conducted at the University of Minnesota showed that carbon monoxide and nitrogen oxide concentrations peak at exit zones of underground garages due to thermal instability during vehicle warm-up [18].

A key mitigation strategy is the modal shift from private car use toward public transport. Bus transport systems enable higher occupancy rates, significantly reducing emissions per passenger [19].

Air Quality Research in Underground Parking Facilities

The analysis of microclimatic conditions in underground parking garages (UPG) is currently based on the integration of two main methodological pillars: numerical simulations (primarily CFD models) and in situ measurements under real operating conditions [20]. Advanced simulations have described particle dispersion mechanisms under natural airflow conditions penetrating through access ramps [21] and quantified exposure risks during short-term emission peaks [22].

Published studies consistently indicate excessive concentrations of particulate matter in UPGs resulting from emission accumulation and limited air exchange. These works emphasize significant health risks associated with exposure, particularly to $PM_{2.5}$ and ultrafine particles (UFP). Hanif et al. identified critical mass concentrations of UFP in hospital parking garages containing toxic elements and polycyclic aromatic hydrocarbons (PAHs), with high deposition rates in lung tissue [23].

Further studies examined the contribution of tyre wear particles to $PM_{2.5}$ and confirmed that indoor concentrations in UPGs systematically exceed outdoor background levels, particularly in zones with stagnant air [24]. Research conducted in Chinese urban environments found a direct positive correlation between PM concentrations and traffic volume [25]. Field measurements revealed frequent exceedance of air quality standards, especially near entry/exit zones and areas with insufficient ventilation [26]. Additional studies reported nanoparticle concentrations exceeding 80,000 particles/cm^3, approximately twice the reference levels [27]. This body of research clearly indicates that underground parking garages represent high-risk microenvironments characterized by elevated concentrations of particulate pollutants driven by vehicle emissions and suboptimal ventilation conditions.

In this study, experimental monitoring of particulate air pollution was conducted in the specific microenvironment of an underground parking facility at the shopping centre. The primary objective was to obtain relevant empirical data on the temporal and spatial distribution of PM concentrations and to analyse their correlation with traffic intensity.

Based on the obtained results, a methodological framework for comprehensive air quality assessment in enclosed urban transport environments was developed. The findings revealed that peak concentrations occur mainly during evening hours and, paradoxically, during periods of decreasing vehicle numbers, indicating a dominant influence of cold-start emissions during vehicle departure.

Finally, targeted mitigation measures aimed at optimizing indoor environmental quality were proposed. These include the implementation of real-time monitoring sensor networks, dynamic public information systems, and technological solutions to reduce dust resuspension. These measures are designed as low-cost, easily implementable, and fully sustainable solutions within the context of modern urban infrastructure.

The aim of this study was to assess particulate matter concentrations (PM_1, $PM_{2.5}$, and PM_{10}) in two enclosed urban transport microenvironments in Banská Bystrica, Slovakia: an underground parking facility and an underground bus station. The study further aimed to analyse the relationship between transport activity and PM concentrations, compare

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exposure conditions between private and public transport environments, and identify factors influencing particulate matter accumulation in enclosed transport spaces.

2. Materials and Methods

Particulate matter represents one of the key parameters for assessing air quality, particularly in urban and industrially burdened environments.

2.1. Monitoring Equipment

For the purposes of this research, an enviDUST sensor was (Figure 1) unit used for continuous monitoring of airborne particulate matter concentrations. The device enables real-time measurement of aerosol particles in the fractions PM_1, $PM_{2.5}$, and PM_{10}. The $PM_{2.5}$ and PM_{10} concentrations shown in the figures were compared with the air-quality categories used by the Slovak Hydrometeorological Institute. According to this classification, concentrations below 14 µg/m^3 for $PM_{2.5}$ and below 20 µg/m^3 for PM_{10} correspond to the "very good" air-quality category. These thresholds were used only as a reference framework to facilitate the interpretation of measured values. Since SHMÚ categories were developed primarily for ambient outdoor air quality assessment, their application to enclosed and semi-enclosed transport environments should be interpreted with caution and does not represent a direct regulatory standard for indoor air quality.

The measurement core consists of a high-quality optical sensor by Plantower, operating on the principle of light scattering. This method allows for the detection of both mass and number concentrations of particles within an effective range of 0–500 µg/m^3 for $PM_{2.5}$ and PM_{10} fractions. The measurement device is calibrated through comparison with a reference or equivalent certified monitoring instrument, ensuring high reliability and accuracy of the collected data.

Calibration was performed during the testing phase in cooperation with reference monitoring stations of the Slovak Hydrometeorological Institute. Data transmission is carried out online via GSM and GPS technologies, enabling remote monitoring and precise geolocation of measurements [28]. Technical parameters of the measuring unit, as well as the device itself and its application, are presented in Table 1 and Figure 1.

Table 1. Technical parameters of the EnviDUST measuring set [28].

Parameter	Value/Description
Measurement principle	Optical scattering of laser beams (scattering)
Measured quantities (simultaneous)	PM_1, $PM_{2.5}$, PM_{10}—mass and number concentration of particles (multiple size channels)
Dust sensor manufacturer	Plantower
Measuring range (mass conc.)	0–500 µg/m^3
Interval	30 s (standard); can be set individually as needed
Power supply	230 V/0.11 A input; 5 V/5 A output (internal switched power supply, max. power 25 W)
Operating temperature	−15 °C to +40 °C
Housing	Polycarbonate, non-flammable, self-extinguishing, IP44 protection
Control unit	Integrated with GSM and GPS support (online data transfer)

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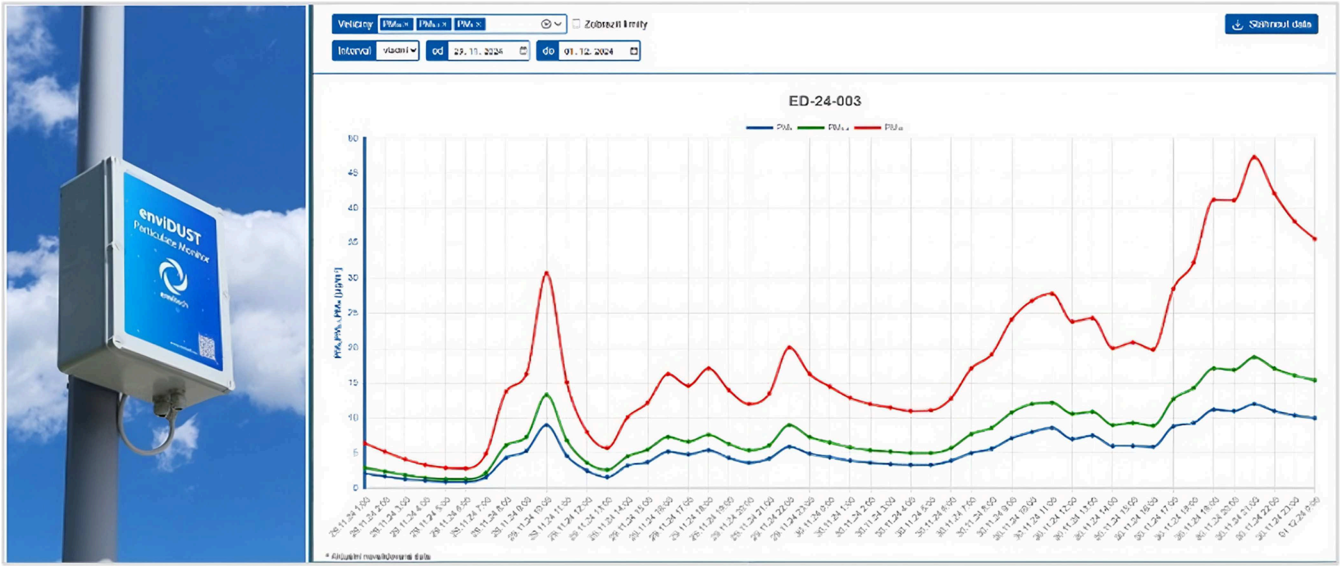

Figure 1. EnviDUST measuring device and SmartEnvi web application [29].

2.2. Study Area and Monitoring Methodology

The measurement of particulate matter concentrations was carried out at two selected locations in the city of Banská Bystrica, which are characterized by enclosed spaces with limited ventilation and a frequent presence of both pedestrians and vehicles:

- underground parking facility of a shopping centre,
- underground bus station (Figure 2).

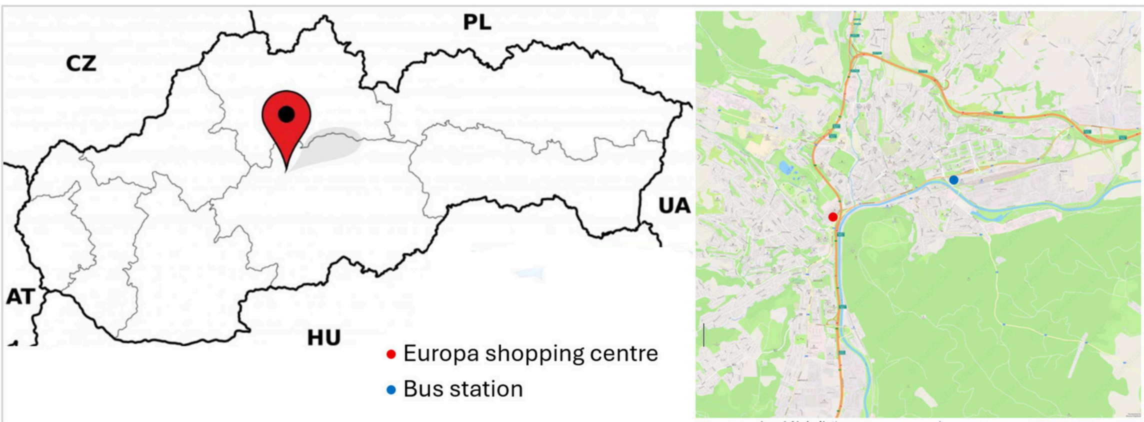

Figure 2. Geographical location of the monitored sites in Banská Bystrica (Slovakia): Europa Shopping Centre underground parking facility (red) and underground bus station (blue).

These specific nodes, where individual automobile traffic intersects with urban public transport, were selected due to the increased presence of people in the immediate vicinity of vehicles powered by internal combustion engines, which creates the potential for elevated concentrations of air pollutants, including particulate matter (PM_1, $PM_{2.5}$, PM_{10}).

To ensure the representativeness of the monitored data, continuous PM monitoring was conducted during clearly defined monitoring campaigns. In the underground parking facility, measurements were performed at two locations. Measurement Point 1 (MP1) was monitored from 29 November 2025 to 7 December 2025, while Measurement Point 2 (MP2) was monitored from 9 December 2025 to 14 December 2025. Monitoring at the underground bus station was conducted from 1 March 2026 to 27 March 2026. The measurements at the parking facility and the bus station were not conducted simultaneously; therefore, the

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comparison between the two environments should be interpreted as a comparison of representative urban transport microenvironments rather than an assessment under identical temporal conditions. All measurements were recorded continuously and subsequently aggregated into hourly averages for statistical analysis. Prior to processing, the datasets were checked for consistency and quality control, and only valid measurement records were included in the final evaluation. Any incomplete or invalid observations were excluded from the analysis and no gap-filling procedures were applied. Outdoor background PM concentrations, meteorological parameters (temperature and relative humidity), and detailed HVAC operational records were not monitored during the measurement campaigns.

An enviDUST sensor unit was used for the measurements, operating on the principle of optical light scattering of a laser beam. The device enables simultaneous monitoring of both mass and number concentrations of PM_1, $PM_{2.5}$, and PM_{10} particles. The measuring unit was installed at a height of 1.5 m above the floor level, corresponding to the average human breathing zone. This configuration ensured that the recorded values reflect realistic human exposure to air pollutants in the given environment.

During the entire measurement period, the number of vehicles present in the monitored area (entries, exits, and stationary vehicles) was recorded simultaneously. This information was used to correlate particulate matter concentrations with traffic intensity, allowing for an assessment of the direct impact of vehicle movement on air quality. In the underground parking facility, occupancy data were available in hourly intervals through the parking management system, while at the bus station, transport intensity was evaluated using hourly bus departure frequencies derived from official timetables.

2.2.1. Measurement Setup in the Underground Parking Facility

Air quality monitoring and pollutant exposure assessment were conducted in the underground parking facility of the urban multifunctional complex Europa Shopping Center (Europa SC) in Banská Bystrica (Slovakia). The facility represents a key element of urban infrastructure characterized by high traffic intensity. The parking facility, with a total capacity of 245 spaces, is structured into several visually distinct sectors.

Public operating hours are defined from 7:00 to 21:30, with vehicle entry restricted after 21:00. Vehicle ingress and egress are controlled by an automated ticketing system, which also serves as a primary data source for continuous monitoring of traffic flow. The dynamic distribution of vehicles within the interior is managed by electronic information panels installed at entrances and along main corridors, providing real-time information on sector occupancy in conjunction with ultrasonic sensors positioned above each parking space.

For the purposes of experimental measurement, two fixed measuring points (Measuring Points—MP1 and MP2) were strategically selected in the immediate vicinity of the two main entrances to the parking structure. This spatial configuration was chosen to enable a comparative analysis of varying levels of anthropogenic load resulting from differences in traffic intensity. The spatial location of the measuring devices within the floor plan of the underground parking facility is presented in Figure 3, while the visual characteristics of the actual environment are illustrated in Figure 4.

Experimental Setup and PM Monitoring

Continuous PM monitoring was conducted at two measurement locations in the underground parking facility. MP1 was monitored from 29 November 2025 to 7 December 2025 and MP2 from 9 December 2025 to 14 December 2025. Low-cost enviDUST sensor units were used for data acquisition.

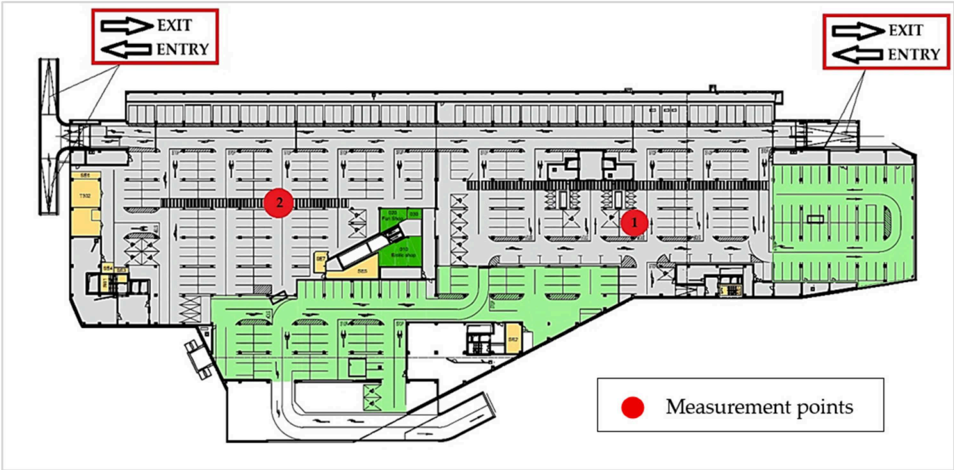

Figure 3. Layout of the underground parking facility showing the locations of measurement points MP1 and MP2.

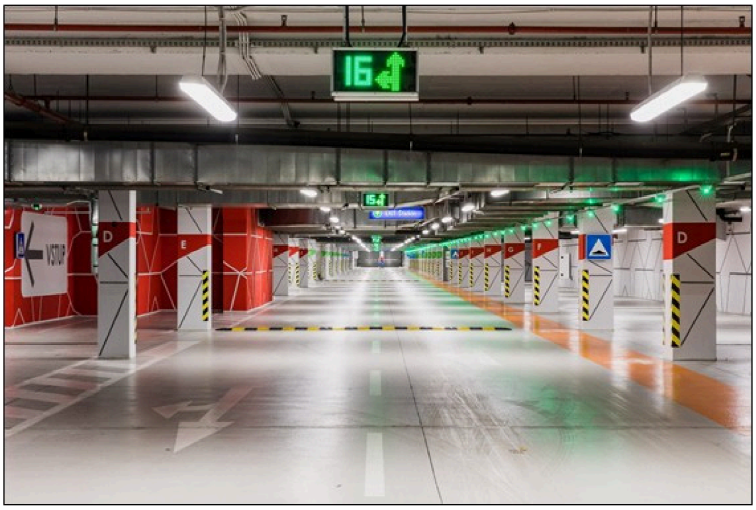

Figure 4. A real look into the underground parking lot.

The devices were fixed at a height of 1.5 m above floor level. This height strictly represents the human breathing zone, which is critical for the valid assessment of inhalation exposure and associated environmental risks for individuals present in the monitored space. From the perspective of operational safety and protection of the instrumentation against mechanical damage, the power supply and data cabling were routed discreetly along the ceiling structure, while the sensor inlet probe was vertically extended into the defined exposure zone.

Traffic Volume and Occupancy Data

In parallel with environmental monitoring, data on parking occupancy were collected. Anonymized datasets were provided by the management of Europa SC for the entire monitoring period. Data on vehicle frequency and occupancy within the facility were exported at hourly intervals (1-h interval), enabling precise temporal synchronization (time-matching) with environmental data obtained from the enviDUST sensor units.

The resulting time series were used as an independent variable to identify correlations between traffic intensity (a proxy indicator of emissions from exhaust gases and mechanical wear) and fluctuations in PM concentrations. The overall occupancy distribution profile of the parking facility over the entire monitoring period is visualized in Figure 5, where the horizontal dashed line represents the maximum capacity of the facility (N = 245 spaces).

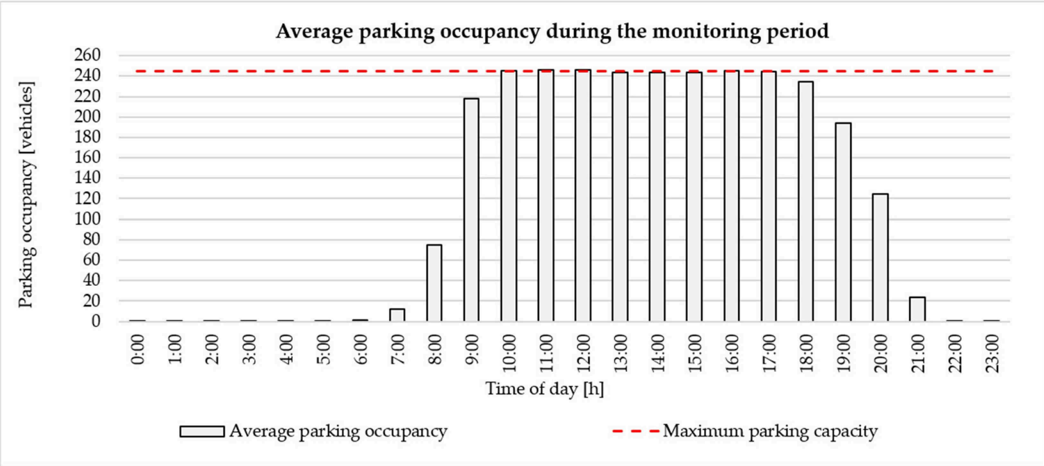

Figure 5. Average hourly parking occupancy during the monitoring period in the underground parking facility. The dashed line indicates the maximum parking capacity (245 vehicles).

The analysis of the obtained empirical data demonstrated a high degree of temporal homogeneity and periodicity. Throughout the entire monitoring period, including weekends, parking occupancy exhibited a highly consistent diurnal pattern. For this reason, it was methodologically justified to analyze the dataset as a unified time series without distinguishing between weekdays and weekends, as the level of parking capacity utilization showed equivalent values regardless of the day of the week.

This specific phenomenon is primarily determined by the limited capacity of the parking facility (245 spaces), which remained consistently saturated during operating hours. The temporal profile (Figure 5) indicates a rapid increase in vehicle numbers during the morning hours (between 7:00 and 9:00), approaching the maximum capacity (approximately 100%). This is followed by a steady-state phase, during which the parking facility remains nearly fully occupied until approximately 18:00. This circadian pattern exhibited minimal standard deviation over the entire two-week monitoring period.

In contrast, the decrease in occupancy during the late afternoon and evening hours (after 17:00–18:00) displayed different kinetics. While the morning accumulation of vehicles is linear, rapid, and highly consistent, the evening clearance of the parking facility is characterized by greater stochastic variability and lower dynamics. This asymmetric behavior (steep morning increase vs. gradual evening decline) indicates that, whereas arrivals are highly time-synchronized (e.g., due to working hours or opening times), departures are distributed more asynchronously, reflecting individual behavioral patterns. The high-stability capacity utilization profile provides a robust methodological basis for subsequent modeling and interpretation of causal relationships between traffic dynamics and indoor air quality within the given microenvironment.

2.2.2. Measurement Setup in an Underground Bus Station

The second phase of experimental measurements was conducted in a specific microclimatic environment of the bus station. This transport hub is directly integrated into the urban structure of the city, being located within the underground premises of the Terminal commercial and transport center. It thus represents a typical urban environment with semi-enclosed architecture, where intense accumulation of traffic-related emissions occurs alongside limited dispersion of air pollutants.

In contrast to conventional underground parking facilities, this space exhibits a different operational regime and dynamic profile. The dominant source of anthropogenic emissions is not individual automobile traffic, but rather vehicles of public transport and regional/long-distance bus services, which are predominantly powered by diesel engines with a distinct emission profile.

The station area consists of multiple platforms organized within a one-way traffic system. From the perspective of urban ecology and air quality assessment, this location is critical: it concentrates a high density of traffic within short time intervals while simultaneously accommodating large numbers of people (passengers and staff), thereby increasing the risk of inhalation exposure in the urban environment (the real visual context of the hub is documented in Figure 6).

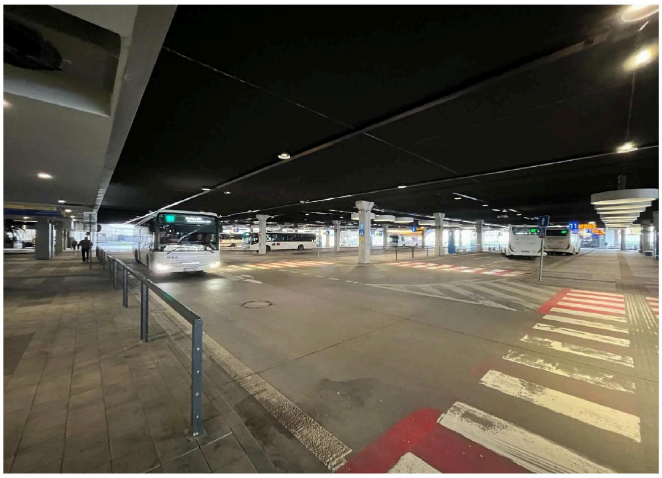

Figure 6. Underground bus station.

Monitoring System and Measurement Configuration

The monitoring station was strategically positioned at platform No. 19 (primarily designated for long-distance bus services (Figure 7)).

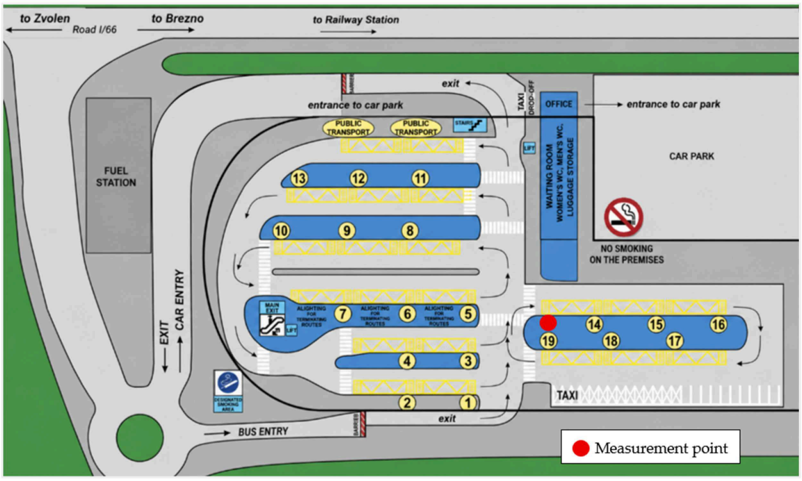

Figure 7. Layout of the underground bus station showing the location of the measurement point.

This micro-location exhibits specific aerodynamic characteristics—it is partially separated from the main airflow, with significantly limited natural ventilation. The selection of this site enabled detailed monitoring of local pollutant accumulation processes (i.e., a street canyon effect under indoor conditions) associated with specific vehicle maneuvers (engine start-up, idling, and braking).

Analysis of Urban Mobility Intensity

To quantify traffic activity within the monitored urban environment, precise data on service frequency were processed based on official public transport timetables (Figure 8).

This parameter served as the primary operational indicator for subsequent correlation analysis with the measured concentrations of suspended particulate matter (PM).

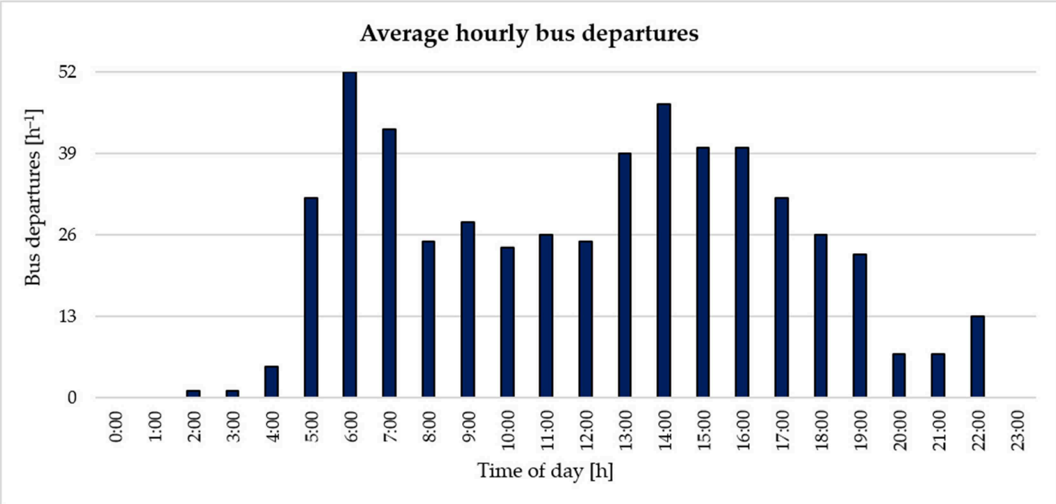

Figure 8. Average hourly number of bus departures at the monitored bus station.

From the perspective of temporal variability, urban mobility exhibits a characteristic bimodal peak pattern:

- Morning peak (06:00): Maximum intensity reaching 52 departures per hour.
- Afternoon peak (14:00): Secondary increase in operational activity associated with the end of working hours and school schedules.
- Nighttime period: Minimal to negligible traffic-related emissions (serving as baseline/background values).

The methodology of mathematical–statistical evaluation was based on the comparison of temporal trends in hourly concentrations of PM_1, $PM_{2.5}$, and PM_{10} with fluctuations in traffic intensity. The main objective was to verify the causal relationship between service frequency and the level of air pollution in a confined urban environment.

The evaluation was conducted on two levels:

Normative comparison: Measured values of $PM_{2.5}$, and PM_{10} were compared with reference air quality indices (AQI).

Specific analysis of the submicron fraction: Separate assessment of the ultrafine fraction PM_1, which is considered a particulate fraction of particular health concern due to its ability to penetrate deeply into the respiratory tract.

2.3. Data Processing and Statistical Analysis

The measured data were subsequently processed using statistical methods, with the following parameters evaluated:

- average concentrations of PM_1, $PM_{2.5}$, and PM_{10},
- maximum and minimum values,
- temporal trends,
- dependence of concentrations on the number of vehicles present.

Hourly PM concentrations were aggregated and analysed using descriptive statistical methods. The final dataset consisted of approximately 216 hourly observations for MP1, 144 hourly observations for MP2, and 648 hourly observations for the underground bus station. Average, maximum and minimum concentrations were calculated for PM_1, $PM_{2.5}$, and PM_{10}. Pearson correlation analysis, linear regression and time-lag analysis were used to evaluate the relationship between transport intensity and PM concentrations.

Comparative analyses were subsequently performed between monitoring locations and transport microenvironments. Average hourly profiles from MP1 and MP2 (24 paired hourly observations) were compared using paired *t*-tests to assess differences between monitoring locations.

Because the analysed variables represent hourly time-series observations, temporal autocorrelation may be present and should be considered when interpreting the reported correlation and regression coefficients.

The results provide an objective assessment of particulate air pollution levels in enclosed transport environments with human presence and serve as a basis for proposing appropriate measures aimed at improving microclimatic conditions and protecting public health.

3. Results

This section presents the results of PM monitoring conducted in the underground parking facility and the underground bus station. The results are organised according to the monitored transport microenvironments and are subsequently compared to identify similarities and differences in particulate matter dynamics.

3.1. Monitoring Subsystem: Underground Parking Facility

Analysis of Measurement Point No. 1 (MP1)

Based on continuous 14-day monitoring, average hourly concentrations of suspended particulate matter fractions PM_1, $PM_{2.5}$, and PM_{10} were calculated for measurement point No. 1 (MP1). These environmental indicators were temporally compared with the average hourly occupancy of the parking facility, enabling identification of the influence of diurnal variability in individual automobile transport intensity on air quality in a confined urban environment.

In terms of daily mobility dynamics (Figure 9), parking occupancy reached its lowest levels during nighttime and early morning hours. A significant increase in the number of parked vehicles occurred with the onset of the morning urban logistics cycle at approximately 07:00, with maximum capacity reached between 09:00 and 10:00. This high occupancy level remained stable throughout the daytime period.

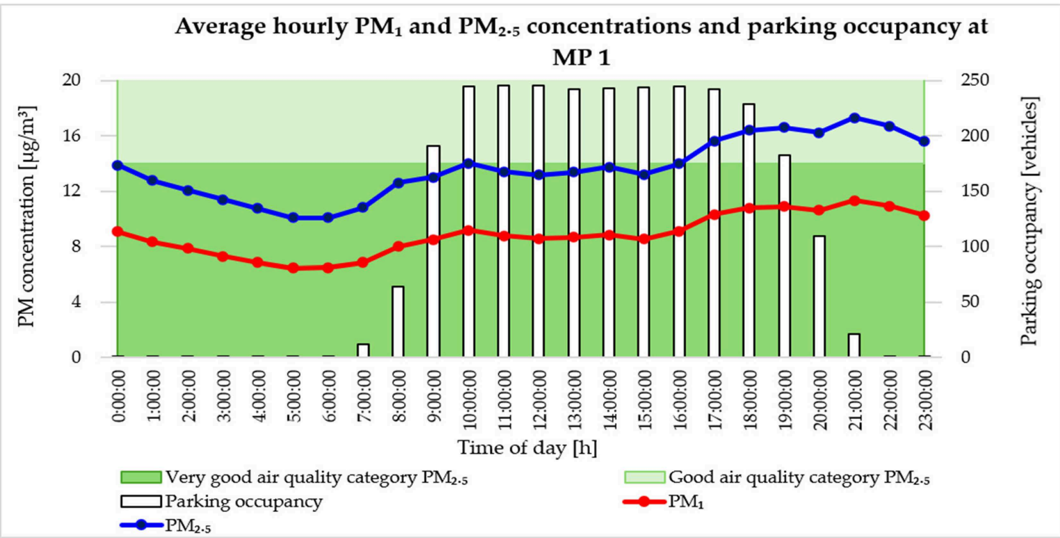

Figure 9. Average hourly PM_1 and $PM_{2.5}$ concentrations and parking occupancy during the monitoring period at measurement point MP1.

Average concentrations of the fine fraction $PM_{2.5}$ ranged from 10 μg/m^3 to 17 μg/m^3. Minimum values correlated with low morning activity, while gradual accumulation of aerosols occurred during the operational daytime period, with peaks in the afternoon and evening. A similar trend was observed for the submicron fraction PM_1 (6 to 11 μg/m^3).

This pattern may indicate the influence of vehicle operation processes (cold starts, exhaust emissions during maneuvering) and mechanically induced air turbulence caused by vehicle movement.

The profile of average concentrations of the coarse fraction PM_{10} (Figure 10) showed significantly higher absolute values compared to fine fractions. This phenomenon is determined by the mechanical origin of this fraction in urban environments, where non-exhaust traffic emissions dominate—particularly tire wear, brake abrasion, road surface degradation, and resuspension of settled dust induced by passing vehicles.

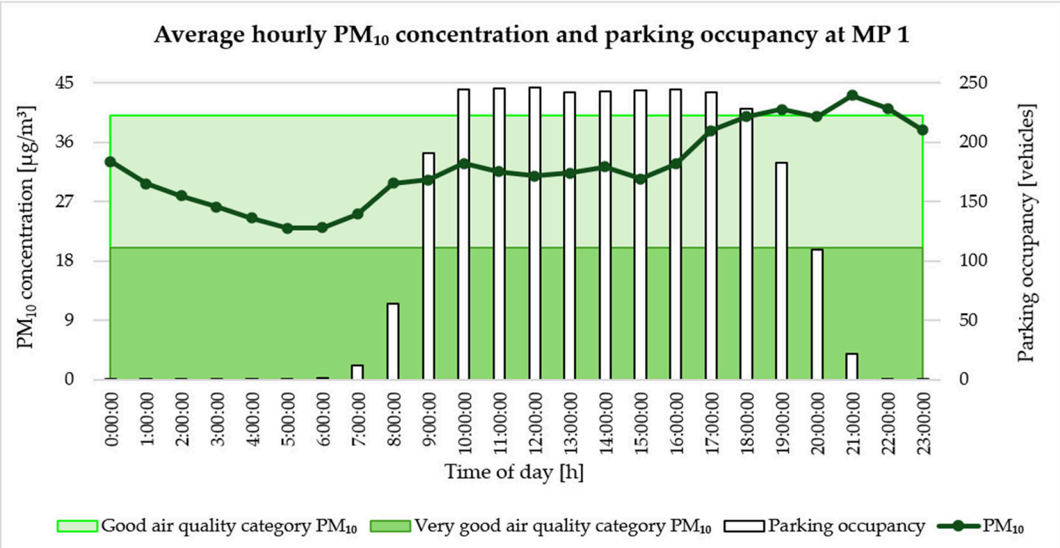

Figure 10. Average hourly PM_{10} concentration and parking occupancy during the monitoring period at measurement point MP1.

During nighttime and early morning periods, PM_{10} values ranged from 23 to 33 μg/m^3. During full daily operation, an increase was recorded, with afternoon and evening maxima reaching 40 to 44 μg/m^3. These elevated concentrations temporally correlated with periods of intensive vehicle departures, suggesting that PM_{10} emission and resuspension are primarily linked to kinetic activity and vehicle dynamics within the facility rather than static occupancy levels alone.

From an environmental perspective and in terms of assessing potential population exposure in an urban setting, air quality at MP1 can be considered relatively acceptable, as $PM_{2.5}$ values only marginally exceeded the "good" air quality range. However, given the occurrence of local pollution peaks during high-demand periods, mitigation measures are necessary, including intensified wet surface cleaning cycles to reduce resuspension and optimization of HVAC system management in relation to peak urban mobility periods.

Analysis of Measurement Point No. 2 (MP2)

An identical methodological approach was applied to data from measurement point No. 2 (MP2), located in a different morphological zone of the underground parking structure, in order to capture spatial heterogeneity in air pollution.

The occupancy profile (Figure 11) exhibited an almost identical pattern to MP1, with a morning increase starting at 08:00 and stable capacity saturation from 09:00 onward, followed by gradual emptying of the parking facility during late evening hours.

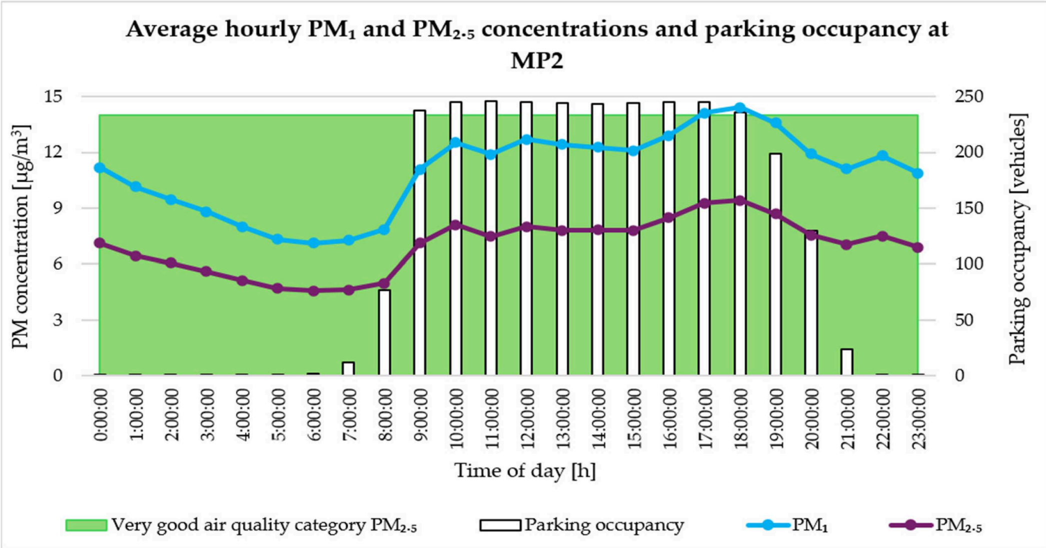

Figure 11. Average hourly PM_1 and $PM_{2.5}$ concentrations and parking occupancy during the monitoring period at measurement point MP2.

At MP2, $PM_{2.5}$ concentrations showed slightly lower amplitudes, ranging from 7 to 14.5 μg/m^3. A significant increase occurred after 09:00, with a peak during the afternoon traffic rush between 17:00 and 18:00. The submicron fraction PM_1 followed a similar trend, within the range of 4.5 to 9.5 μg/m^3. This progression suggests the cumulative effect of vehicle emissions during the day under conditions of limited air exchange.

Concentrations of coarse particulate matter PM_{10} (Figure 12) ranged from 16 μg/m^3 (morning minimum) to 34 μg/m^3 (afternoon maximum between 17:00 and 18:00).

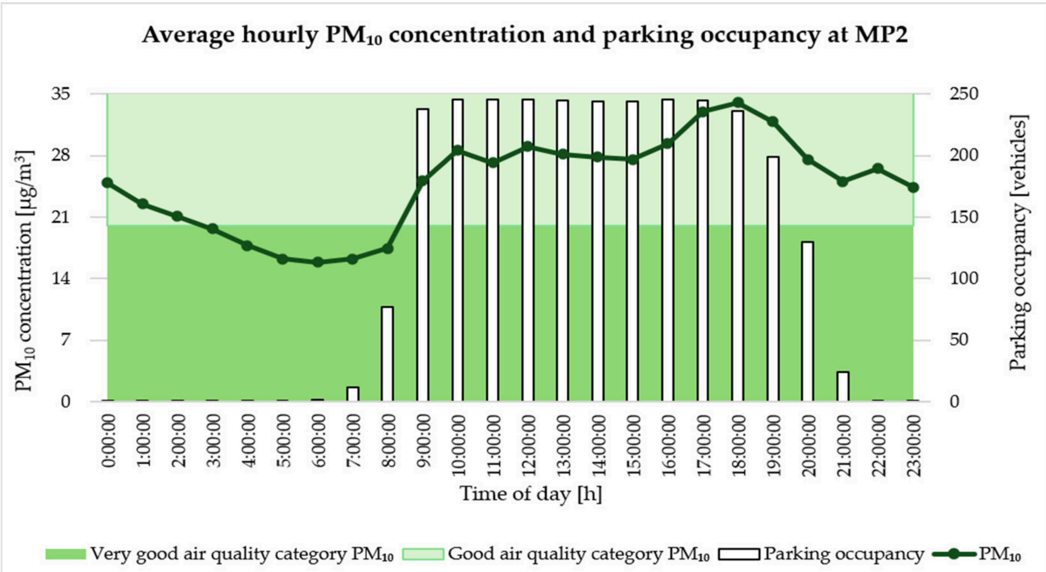

Figure 12. Average hourly PM_{10} concentration and parking occupancy during the monitoring period at measurement point MP2.

These results suggest a potential contribution of dust resuspension and mechanical wear of vehicle components during peak traffic activity was confirmed. Although pollution levels did not exceed critical limit values, periodic increases highlight the necessity of controlled mechanical ventilation during peak operation hours.

Spatiotemporal Comparison of Measurement Points in the Parking Facility

To accurately assess spatial variability in air quality within the monitored micro-urban subsystem, a comparison of integrated data from MP1 and MP2 was performed (Table 2).

Table 2. Comparison of average particulate matter concentrations between measurement points No. 1 and No. 2.

Fraction	Average MP1 [μg/m^3]	Average MP2 [μg/m^3]	Difference MP1—MP2 [μg/m^3]	Difference [%]	Correlation of Daily Profiles (r)
PM_1	8.85	7.01	1.84	26.3	0.777
$PM_{2.5}$	13.62	10.96	2.65	24.2	0.779
PM_{10}	32.29	24.87	7.41	29.8	0.744

The analysis showed that the MP1 micro-location was systematically more burdened across all monitored PM fractions. The most pronounced spatial discrepancy was observed for the coarse fraction PM_{10}, with an absolute difference of 7.41 μg/m^3 (29.8%). Fine fractions exhibited consistent increases at MP1 in the range of 24–26%.

Calculated Pearson correlation coefficients ($r \in \langle 0.744; 0.779 \rangle$) indicate a strong and statistically significant positive linear relationship between the daily profiles of both points. This suggests that both locations are subject to the same macro-operational regime of the parking facility; however, local micro-aerodynamic factors (e.g., proximity to entry routes, interior structural geometry, or local ventilation efficiency) significantly modify absolute pollution levels.

For deeper insight into temporal variability, data were segmented into four characteristic daily periods (Table 3).

Table 3. Comparison of average concentrations of PM_1, $PM_{2.5}$, and PM_{10} by time of day.

Time Period	PM_1 MP1 [μg/m^3]	PM_1 MP2 [μg/m^3]	$PM_{2.5}$ MP1 [μg/m^3]	$PM_{2.5}$ MP2 [μg/m^3]	PM_{10} MP1 [μg/m^3]	PM_{10} MP2 [μg/m^3]
0:00–6:00	7.48	5.66	11.57	8.87	26.76	19.72
7:00–10:00	8.13	6.21	12.60	9.69	29.48	21.85
11:00–16:00	8.75	7.91	13.48	12.38	31.52	28.18
17:00–23:00	10.73	8.05	16.35	12.56	40.07	28.92

Detailed segmentation reveals that emission maxima were concentrated in the evening interval (17:00–23:00), corresponding to periods of intensive vehicle departures in urban mobility systems (increased frequency of cold starts and acceleration during exit). This trend was most pronounced for PM_{10} at MP1, where the average value reached a peak of 40.07 μg/m^3.

An additional analytical step involved determining mass ratios between fractions (Table 4), which serve as indicators of pollution origin.

Table 4. Ratios of fine fractions relative to PM_{10} at measurement points.

Indicator	Measurement Point No. 1	Measurement Point No. 2
$PM_{2.5}/PM_{10}$	0.422	0.441
$PM_1/PM_{2.5}$	0.650	0.640
PM_1/PM_{10}	0.274	0.282

Low values of the $PM_{2.5}/PM_{10}$ ratio (0.422 and 0.441) clearly confirm the dominance of coarse particles in total mass concentration (more than 55% of particulate matter consists of particles larger than 2.5 μm). This finding is consistent with the hypothesis that the primary processes generating environmental burden in these nodes are mechanical interactions between tires and surfaces and the resuspension of settled dust.

To express total human exposure within this environment, integrated daily particulate exposure was calculated in units of [$\mu g/m^3 \cdot h$] (Table 5).

Table 5. Estimated daily particulate matter exposure at measurement points.

Fraction	MP1 [$\mu g/m^3 \cdot h$]	MP2 [$\mu g/m^3 \cdot h$]	Difference MP1–MP2 [$\mu g/m^3 \cdot h$]
PM_1	212.51	168.30	44.21
$PM_{2.5}$	326.78	263.07	63.71
PM_{10}	774.90	596.96	177.94

From the perspective of cumulative daily exposure, less favorable conditions at MP1 were again confirmed, with an excess exposure of 177.94 $\mu g/m^3 \cdot h$ for coarse particles. To verify the statistical significance of these differences, a paired *t*-test of average hourly profiles was conducted (Table 6).

Table 6. Paired comparison of average hourly profiles between measurement points.

Fraction	t-Value	*p*-Value	Interpretation
PM_1	9.23	<0.001	statistically significant difference
$PM_{2.5}$	8.95	<0.001	statistically significant difference
PM_{10}	8.87	<0.001	statistically significant difference

Extremely low *p*-values ($p < 0.001$) confirm that the observed spatial differences between MP1 and MP2 are highly statistically significant and result from systematic local microclimatic and operational factors within the parking structure.

This leads to a key urban and methodological conclusion: when assessing air quality in semi-enclosed transport systems, data collection from a single monitoring point is insufficient and non-representative.

3.2. Monitoring Subsystem: Underground Bus Station

Analysis of Pollution Dynamics and Its Link to Urban Transport

In the semi-enclosed interior of the Banská Bystrica bus station (an integrated transfer hub), average hourly concentrations of PM_1, $PM_{2.5}$ and PM_{10} were compared with a direct indicator of urban and regional bus transport performance—the number of vehicle departures per hour (h^{-1}).

The temporal profile of transport activity (Figure 13) suggests typical peak characteristics of urban mobility: a morning peak (06:00–08:00) and an afternoon shoulder peak (14:00–17:00), followed by nighttime decline.

Average hourly concentrations of fine particulate matter $PM_{2.5}$ ranged from 8 to 19 $\mu g/m^3$ while the PM_1 fraction ranged from 5 to 12 $\mu g/m^3$ However, analysis of the curves revealed an unexpected paradox characteristic of enclosed urban environments: minimum concentrations of fine particles were recorded between 13:00 and 15:00, a period with relatively high service frequency. In contrast, concentration maxima occurred during late evening and nighttime hours (21:00–23:00), when bus traffic intensity significantly declined.

This discrepancy suggests that concentrations of ultrafine particles in a covered terminal do not directly reflect instantaneous transport volume. One possible explanation is the influence of limited natural airflow and reduced mechanical ventilation intensity during evening hours.

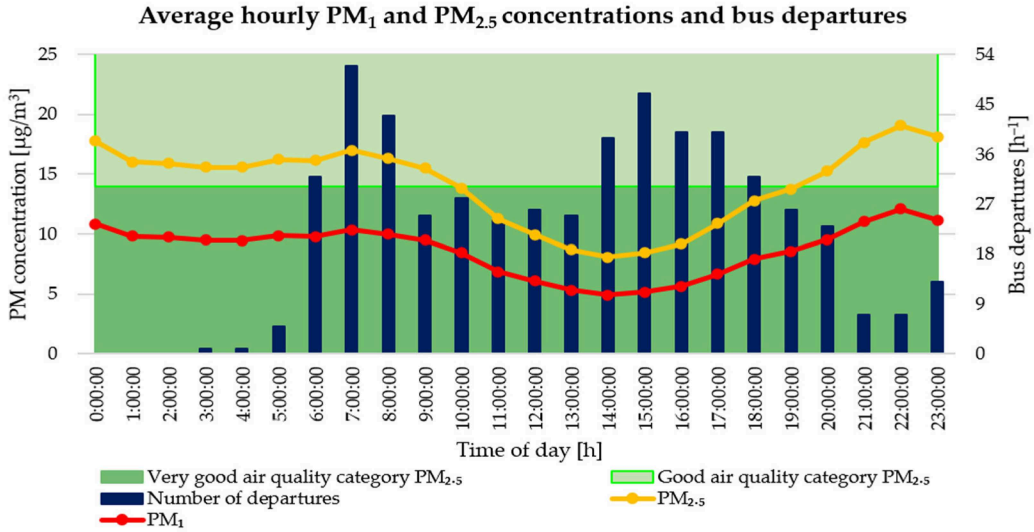

Figure 13. Average hourly PM_1 and $PM_{2.5}$ concentrations and bus departures during the monitoring period at the underground bus station.

Combined with the cumulative effects of diesel engine emissions throughout the day, this leads to the evening "retention" and accumulation of pollutants within the breathing zone of platforms.

The coarse particle fraction PM_{10} (Figure 14) showed generally higher concentration levels, ranging from 18 to 48 $\mu g/m^3$. Here as well, maxima were concentrated in the evening period (21:00–23:00), when values approached air quality threshold limits. Elevated concentrations were also detected in early morning hours, indicating the effects of initial engine start-up and resuspension of dust accumulated overnight.

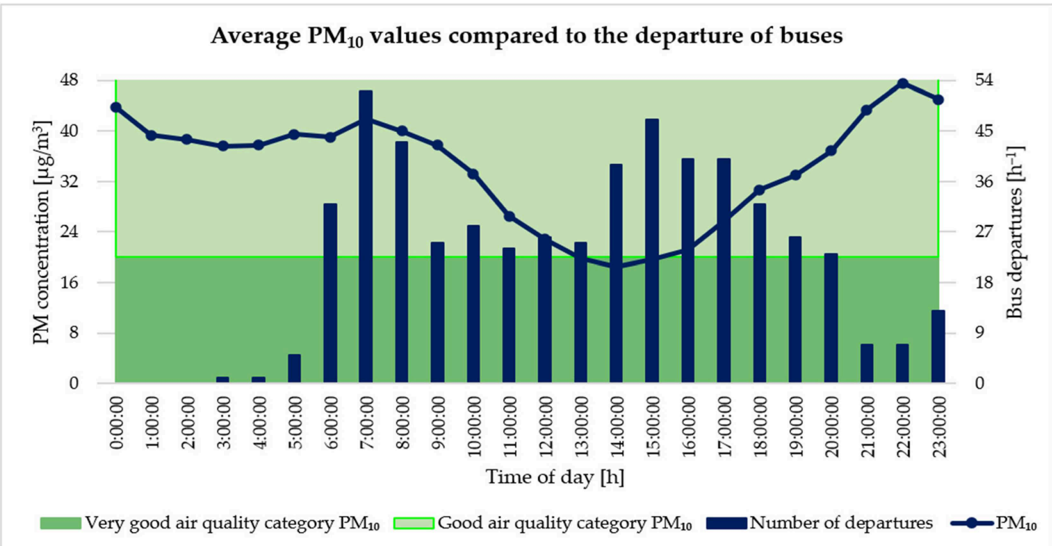

Figure 14. Average hourly PM_{10} concentration and bus departures during the monitoring period at the underground bus station.

These findings suggest that accurate modeling of air quality in enclosed public transport terminals should not rely solely on service frequency.

Operational factors such as bus idling duration at platforms, braking dynamics of heavy vehicles, and especially the ventilation design of the terminal play a crucial role.

Statistical Correlation and Regression Analysis

To verify and quantify the relationship between transport intensity and air pollution levels, Pearson correlation analysis and linear regression were applied (Table 7).

Table 7. Correlation and regression comparison of bus departures and PM concentrations.

Fraction	Pearson Correlation Coefficient (r)	Determination Coefficient R^2	*p*-Value	Regression Coefficient [μg/m³ per Bus]	Interpretation
PM_1	−0.549	0.302	0.005	−0.070	moderately strong negative relationship
$PM_{2.5}$	−0.551	0.303	0.005	−0.112	moderately strong negative relationship
PM_{10}	−0.545	0.297	0.006	−0.291	moderately strong negative relationship

The statistical analysis yielded a seemingly counterintuitive yet scientifically highly significant result: a moderately strong negative relationship ($r \approx -0.55$) was observed between the variables. Regression coefficients indicate that as the number of bus departures increases, particulate matter concentrations tend to decrease.

The coefficient of determination (R^2) suggests that approximately 30% of PM variability may be explained by the number of departures. Low *p*-values ($p < 0.01$) confirm the statistical significance of this relationship.

The negative slope of the regression may be explained by the fact that during peak operational periods—when vehicle movement generates a piston effect and forced ventilation operates at maximum efficiency—the interior is ventilated more effectively than during evening periods, when reduced ventilation leads to stagnation and aerosol accumulation.

To assess system inertia, a cross-correlation analysis with time lags of 1–3 h was conducted (Table 8).

Table 8. Correlation between PM concentrations and bus departures with time lag.

Fraction	No Lag (r)	Lag 1 h (r)	Lag 2 h (r)	Lag 3 h (r)
PM_1	−0.549	−0.464	−0.374	−0.311
$PM_{2.5}$	−0.551	−0.478	−0.402	−0.342
PM_{10}	−0.545	−0.471	−0.396	−0.338

Table 8 clearly shows that the strongest relationship occurs synchronously (without time lag). With increasing lag, correlation weakens, indicating the absence of a delayed transport effect and confirming that the station microclimate responds immediately to changes in ventilation regimes and interior aerodynamics.

Further segmentation by daily phases (Table 9) confirms the cumulative pollution hypothesis.

Table 9. Comparison of average PM concentrations by time period.

Time Period	PM_1 [μg/m³]	$PM_{2.5}$ [μg/m³]	PM_{10} [μg/m³]	Number of Departures [Bus/h]
0:00–5:00	9.86	16.18	39.43	1.17
6:00–9:00	9.91	16.23	39.65	38.00
10:00–16:00	6.05	9.91	23.10	32.71
17:00–23:00	9.56	15.35	37.43	21.14

The lowest pollution levels were observed during midday (10:00–16:00) despite high transport intensity, whereas nighttime and evening periods showed nearly double pollution levels at minimal transport activity. The absolute maximum was recorded at 22:00 PM_{10} = 47.50 μg/m^3 when only 7 buses per hour were operating. This highlights the critical importance of revising HVAC operational regimes in such urban nodes.

3.3. Comparative Study of Urban Subsystems: Underground Parking vs. Bus Station

The final synthesis focuses on inter-spatial comparison of two typologically distinct semi-enclosed transport nodes (Table 10 and Figure 15), both representing specific exposure risks for urban populations.

Table 10. Comparison of average particulate matter concentrations between underground parking and bus station.

Fraction	Underground Parking Facility MP1 a MP2 [μg/m^3]	Bus Station [μg/m^3]	Difference [μg/m^3]	Difference [%]
PM_1	7.93	8.67	0.74	9.3
$PM_{2.5}$	12.29	14.12	1.83	14.9
PM_{10}	28.58	34.12	5.54	19.4

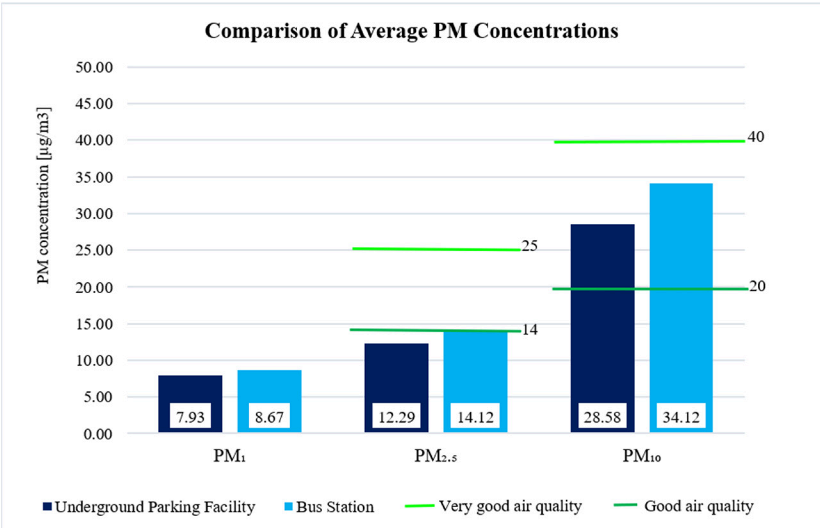

Figure 15. Graphical comparison of average PM concentrations between underground parking and bus station.

The comparative analysis clearly shows that the semi-enclosed environment of the bus station exhibits higher pollution levels across all particle size fractions. The average PM_{10} concentration was higher by 19.4%, while fine fractions $PM_{2.5}$ and PM_1 increased by 14.9% and 9.3%, respectively.

This significant difference reflects two primary factors typical of modern urban environments:

- Fleet emission characteristics: While underground parking facilities are predominantly used by passenger vehicles (with a higher share of gasoline engines and modern catalytic converters), bus stations serve heavy-duty diesel vehicles, which produce higher emissions of primary particulate matter and soot.
- Mechanical resuspension and vehicle kinetics: The greater mass and size of buses generate stronger turbulent airflows during movement and maneuvering, leading to more intensive resuspension of dust particles compared to passenger cars.

These findings provide important empirical evidence for urban planning and public health. They indicate that integrated transport hubs with semi-enclosed designs require a distinct approach to environmental risk management. Ventilation system design and operation must reflect cumulative daily pollution trends rather than instantaneous transport intensity alone. It should be emphasized that the two monitored environments differ substantially in their physical characteristics, including spatial geometry, ventilation configuration, vehicle fleet composition, operational regime, and user behaviour. Therefore, the presented comparison should be interpreted as a comparison of two specific urban transport microenvironments in Banská Bystrica rather than as a general comparison between all underground parking facilities and bus terminals. The observed differences may partially reflect site-specific conditions that cannot be directly generalized to other transport infrastructures.

4. Discussion

The results of the presented study demonstrate that enclosed and semi-covered transport nodes represent highly specific urban environments in which immission trajectories of suspended particulate matter (PM) are determined not only by transport intensity itself but also by fluid dynamics, ventilation aerodynamics, secondary resuspension of settled dust, and the spatial–structural configuration of infrastructure. These findings are of fundamental importance for sustainable urban development and human ecology, as underground parking facilities and semi-enclosed public transport terminals constitute structural pillars of the compact city concept. Although the integration of such facilities optimizes land use efficiency and strengthens intermodality, it simultaneously generates localized environmental "hotspots" associated with elevated inhalation exposure to traffic-related pollutants.

Within the underground parking facility, two monitoring points were analyzed in parallel. The average mass concentrations of PM_1, $PM_{2.5}$ and PM_{10} exhibited significant spatial variability and were consistently higher at measurement point No. 1. The most pronounced divergence was observed for the coarse fraction PM_{10}, where measurement point No. 1 reached an average concentration of 32.29 $\mu g/m^3$, while measurement point No. 2 recorded 24.87 $\mu g/m^3$. This discrepancy confirms the assumption that microclimatic air quality within a single underground facility is not homogeneous but is influenced by local micro-topography, vehicle movement trajectories, specific airflow circulation patterns, and the intensity of mechanical resuspension.

These partial conclusions are consistent with the model presented by Zhao et al. [30], which indicates that PM concentrations in naturally ventilated underground garages are primarily governed by traffic intensity and local ventilation. Similarly, Zhang et al. [25] demonstrated that indoor air quality in underground parking facilities is a nonlinear function of traffic periodicity, architectural morphology, building function, and air-exchange rates. Liu et al. [31] further emphasize that passively ventilated underground parking structures often suffer from insufficient air exchange, reducing the effectiveness of emission removal.

The crucial role of controlled ventilation is also confirmed by Oh et al. [32], who identified substantial differences in exposure to respirable particles and VOCs depending on HVAC system operation. These findings highlight that environmental conditions in underground parking structures are not determined exclusively by traffic volume but rather by the system's capacity to remove contaminated air masses. This theoretical framework is essential for interpreting the presented results, where spatial heterogeneity was directly observed within a single facility.

Analysis of Non-Exhaust Emissions and Temporal Accumulation

The dominance of the coarse fraction PM_{10} reflects current scientific understanding regarding the significant contribution of non-exhaust emissions from road transport. In the underground parking facility, PM_{10} constituted the majority of total particulate pollution, indicating the dominant role of mechanical processes—particularly road dust resuspension, brake wear, tire abrasion, and surface degradation.

The importance of non-exhaust sources in confined urban transport spaces is supported by Chae and Choi [33], whose findings confirm that emissions in enclosed traffic nodes cannot be attributed solely to combustion processes but must also consider mechanically induced turbulence.

Correlation analysis between parking occupancy and PM concentrations without time lag did not reveal a statistically significant linear relationship. Thus, static vehicle density alone cannot serve as a reliable predictor of air quality. It should be noted that the explanatory variables used in this study represent indirect indicators of emission activity rather than direct emission measurements. Previous studies have shown that PM concentrations in underground parking facilities are influenced not only by vehicle numbers but also by vehicle movements, cold starts, manoeuvring, braking processes, dust resuspension, and ventilation conditions. Similarly, in bus terminals, PM concentrations may be affected by vehicle idling, dwell time at platforms, bus type, engine technology, and terminal ventilation characteristics. Therefore, the observed relationships should be interpreted with caution, as additional operational variables may contribute to the variability of PM concentrations [30,34,35].

Stronger associations were detected after applying time-lag analysis, confirming the accumulation and persistence of airborne particles in semi-enclosed environments even after a reduction in emission activity. This phenomenon aligns with findings by Gonzalez et al. [18], who reported that indoor pollutant concentrations in garages can significantly exceed outdoor background levels due to cumulative operational effects.

Comparison of Individual Mobility and Public Transport Systems

In a comparative context, the semi-enclosed bus station exhibited consistently higher average concentrations across all PM fractions than the underground parking facility. Average concentrations reached 8.67 $\mu g/m^3$ for PM_1, 14.12 $\mu g/m^3$ for $PM_{2.5}$, and 34.12 $\mu g/m^3$ for PM_{10}. Compared to the integrated average of the parking facility, this represents increases of approximately 9% (PM_1), 15% ($PM_{2.5}$), and 19% (PM_{10}), respectively.

These differences clearly indicate that public transport nodes represent higher-risk exposure microenvironments. This is primarily due to the operation of heavy-duty diesel vehicles, increased frequency of transient engine phases (acceleration, braking, maneuvering), continuous turbulence caused by passenger movement, and limited macro-scale ventilation.

Parallel studies focused on transport terminals consistently confirm elevated health risks associated with PM exposure. Cheng et al. [33], in their monitoring of PM_{10}, $PM_{2.5}$, UFP, and CO_2 at interurban transfer hubs, highlighted high levels of acute passenger exposure. In a follow-up study, Cheng et al. [34] concluded that pollutant loads on platforms significantly exceed those in enclosed waiting areas and exhibit a direct dependence on bus flow dynamics. Nogueira et al. [35] further emphasize the serious public health implications (urban health) within terminals, as repeated transit and waiting increase the cumulative lifetime inhaled dose of particulate matter among urban populations. These findings are highly relevant to the present study, as the analyzed bus station functions as a multifunctional urban mobility node directly connected to a commercial center and railway infrastructure.

A paradoxical finding of this study is that PM concentrations at the bus station did not increase linearly with the current number of vehicle departures. Statistical analysis revealed a significant negative correlation between service frequency and concentrations of PM_1, $PM_{2.5}$ and PM_{10}. Maximum concentrations were primarily observed during evening and nighttime hours, when departure frequency was minimal. This indicates that the simple number of scheduled departures does not represent an independent explanatory variable for air quality modeling in such environments.

This nonlinear behavior reflects the synergistic influence of additional factors, including temporally variable ventilation efficiency, nocturnal stagnation of the boundary layer, continuous accumulation of fine particles, emissions from idling vehicles, and the specific placement of the sampling location. It should be noted that several mechanisms discussed in this section, including the effects of ventilation regimes, air stagnation, particulate matter resuspension, diesel engine emissions, and HVAC system operation, were not directly measured within the scope of this study. Their potential influence is inferred from the observed concentration patterns and supported by findings reported in previous studies. Therefore, these explanations should be interpreted as plausible mechanisms consistent with the available evidence rather than as direct causal relationships demonstrated by the collected data.

Implications for Urban Planning and Environmental Management

From the perspective of urban planning and architecture, these results reveal an important environmental duality. Although public transport is globally perceived as a pro-environmental solution that reduces overall carbon footprint and mitigates dependence on private automobile use, its spatially concentrated nodes may paradoxically deteriorate local micro-environmental quality [36]. Therefore, modernization and planning of urban transport infrastructure must no longer focus exclusively on technocratic parameters such as transport capacity, spatial accessibility, or transfer time optimization. Instead, environmental sustainability and indoor air quality in areas with high population turnover must become primary design criteria.

Mitigation of environmental risks and reduction of human exposure in semi-enclosed terminals require the implementation of multi-criteria technological, organizational, and urban planning measures. Wang et al. [37] demonstrated the mitigation potential of green infrastructure elements in capturing particulate matter at transit points. In underground or fully enclosed terminals, however, the integration of vegetation is spatially and technically constrained. Nevertheless, key strategies include strict architectural separation of conditioned waiting areas from emission corridors, the application of advanced aerodynamic airflow control systems, and technological measures to reduce dust resuspension. Contemporary urban research further explicitly links spatial configuration and stop density with macro-scale pollution distribution patterns in urban structures [38]. Optimization of these nodes thus represents an integral component of comprehensive environmental management in modern cities.

The importance of non-exhaust emissions in interpreting the obtained results is supported by a global scientific consensus identifying transport as a key source of particulate pollution. Thorpe and Harrison [39] define non-exhaust particles as a critical component of immission load, particularly in densely urbanized environments. Similarly, Zhang et al. [40] confirmed that mechanically generated emissions represent a dominant contribution to exceedances of particulate matter limits in large metropolitan areas. In the Central European context, these conclusions are supported by the empirical study of Jandačka et al. [41], who identified a significant contribution of non-exhaust sources in the confined environment of a road tunnel in Žilina. These findings are fully consistent with the results presented here, where the PM_{10} fraction was dominant in both types of analyzed transport environments.

In a broader urban context, the presented data align with the findings of Jafari et al. [42], who analyzed gaseous and particulate pollutants across various traffic-influenced urban exposure settings. Their results demonstrate that urban hotspots exhibit high immission variability depending on transport characteristics and spatial geometry. This supports the requirement that air quality monitoring should not be limited to macro-scale urban background stations but should also specifically target micro-environments with high human activity density.

This assertion is further supported by Rakowska et al. [43], who investigated the impact of traffic heterogeneity on pedestrian exposure in a typical street canyon. Their models confirm that pollutant concentrations in urban environments are determined not only by traffic volume but also by surrounding built structures and local microcirculation patterns. This directly explains why, in the present study, neither parking occupancy nor the number of bus departures provided a simple linear correlation with PM concentration dynamics.

Contribution to Research and Study Limitations

The primary contribution of the presented research lies in the comparative analysis of air quality across two fundamentally different urban transport microenvironments: an underground parking facility representing individual automobile use, and a semi-enclosed terminal representing public transport systems. Both facilities constitute integral components of contemporary urban mobility systems, particularly within the framework of sustainable compact cities, where transport infrastructure is vertically integrated into multifunctional urban developments.

The results indicate that such nodes can no longer be interpreted purely through a technocratic lens as utilitarian engineering structures. Instead, they must be understood as specific semi-public urban spaces in which air quality directly constrains the health index of the urban population.

The study also opens a broader discussion on the necessity of implementing intelligent environmental management systems within the Smart Cities paradigm. Continuous real-time monitoring of particulate matter (PM) in such environments should be cybernetically integrated with adaptive ventilation systems (demand-controlled ventilation), digital passenger information systems, and centralized urban environmental management platforms. Within the framework of smart governance, these localized data streams enable immediate optimization of HVAC systems, strategic planning of wet surface cleaning to reduce resuspension, regulation of unnecessary engine idling (anti-idling policies), and structural modifications of terminal layouts.

However, the study has several limitations. The empirical analysis was conducted at two specific locations within a single urban agglomeration, which limits the immediate generalization of the findings to the broader typology of underground and covered transport facilities without further validation. In addition, the two monitored environments differ substantially in terms of geometry, ventilation characteristics, vehicle fleet composition, operational regime, and user behaviour. Therefore, the observed differences should be interpreted within the context of the analysed case study rather than as universally applicable characteristics of underground parking facilities and bus stations.

The limitation of this study is the absence of simultaneous outdoor background PM measurements. Therefore, the contribution of ambient air pollution to the measured indoor concentrations could not be quantified. Moreover, the monitoring campaigns were conducted during different periods (November–December 2025 for the parking facility and March 2026 for the bus station), which may have introduced seasonal and meteorological differences (temperature and relative humidity), and detailed HVAC operational data were not monitored simultaneously with the indoor measurements. Consequently, the comparison should be interpreted as a comparison of representative transport microenvironments rather than measurements performed under identical environmental conditions. Another limitation of the study is that parking occupancy and bus departure frequency were used as surrogate indicators of transport activity. While these variables provide a useful measure of overall operational intensity, they do not fully represent the actual emission-generating processes occurring within the monitored environments. Factors such as vehicle manoeuvring, cold starts, braking, idling duration, vehicle fleet composition, and engine technology were not evaluated and may have influenced the measured PM concentrations. Moreover, the research was strictly limited to mass concentrations of PM_1, $PM_{2.5}$ and PM_{10}. Particle number concentration (PNC),UFP distribution, chemical and toxicological analyses (e.g., heavy metals and polycyclic aromatic hydrocarbons—PAHs), as well as gaseous pollutants (NO_x, CO, VOC), were not included in the measurements.

Future research should therefore focus on long-term monitoring campaigns covering different seasonal cycles, a wider range of transport infrastructure typologies, integration of real-world ventilation system performance data, detailed characterization of vehicle fleets, and simultaneous measurement of ambient urban background concentrations to accurately determine indoor–outdoor relationships. Several mechanisms discussed in this study, including the potential effects of ventilation, air stagnation, dust resuspension, and vehicle operating conditions, were not directly measured and are therefore interpreted as plausible explanations supported by previous studies rather than directly demonstrated causal relationships.

Such a comprehensive approach would enable the development of advanced predictive models to assess the interaction between urban transport infrastructure development and environmental health and safety.

5. Conclusions

This study provides an empirical analysis of the dynamics of suspended particulate matter PM_1, $PM_{2.5}$ and PM_{10} in two specific types of semi-enclosed transport infrastructure: an underground parking facility and a covered bus station. The measurement results confirmed that both evaluated microenvironments exhibit pronounced intra-day variability in air pollution, with the coarse fraction PM_{10} dominating in both cases. This finding indicates that mechanical processes associated with transport operations play a crucial role in these environments.

In the underground parking facility, spatial heterogeneity of pollution was demonstrated, whereby the monitoring point with limited air circulation showed significantly higher concentrations than the point located near ventilation zones. The most pronounced gradient was observed for the PM_{10} fraction, highlighting the key role of local dust resuspension induced by vehicle movement. Linear analysis confirmed that instantaneous parking occupancy is not a sufficient predictor for pollution modeling. Only the incorporation of a time-lag effect revealed the cumulative nature of emissions, where delayed ventilation system response leads to prolonged accumulation of pollutants in the indoor urban environment.

The covered bus station, as a critical urban transport node, exhibited higher average concentrations across all monitored fractions compared to the underground parking facility. Paradoxically, the frequency of bus departures did not show a direct linear relationship with pollution levels. The highest emission loads were identified during evening and nighttime hours, when service frequency was minimal. This phenomenon suggests that air quality in underground transport nodes is more strongly influenced by local microclimatic conditions—especially air mass stagnation, inadequate ventilation management, idling vehicle emissions at platforms, and continuous resuspension of settled particles.

From the perspective of sustainable urban development, these findings emphasize the urgent need to integrate air quality assessment directly into the architectural and technological design of transport infrastructure embedded within compact urban structures. Although underground parking facilities and covered terminals are essential components of modern mobility systems, they simultaneously function as high-risk exposure microenvironments for sensitive population groups (passengers, employees). Their design, operation, and environmental management must therefore incorporate advanced HVAC systems (forced ventilation), regular wet surface maintenance to mitigate resuspension, and strict regulation of engine operation.

The present study clearly supports the transformation of such nodes into intelligent transport infrastructure through the implementation of real-time air quality monitoring systems. Sensor networks integrated with automated ventilation control (based on real-time PM and CO_2 concentrations) and passenger information displays represent an effective Smart Cities solution. This proactive approach aligns the goals of efficient urban transport with the concept of Urban Health and provides a robust evidence base for environmentally sustainable urban planning and the development of healthy cities.

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References

1. Manisalidis, I.; Stavropoulou, E.; Stavropoulos, A.; Bezirtzoglou, E. Environmental and health impacts of air pollution: A review. *Front. Public Health* **2020**, *8*, 14. [CrossRef] [PubMed]
2. Odubo, T.C.; Kosoe, E.A. Sources of air pollutants: Impacts and solutions. In *Air Pollutants in the Context of One Health: Fundamentals, Sources, and Impacts*; Springer Nature: Cham, Switzerland, 2024; pp. 75–121.
3. Pisoni, E.; Christidis, P.; Thunis, P.; Trombetti, M. Evaluating the impact of "Sustainable Urban Mobility Plans" on urban background air quality. *J. Environ. Manag.* **2019**, *231*, 249–255. [CrossRef]
4. Mądziel, M. Vehicle emission models and traffic simulators: A review. *Energies* **2023**, *16*, 3941. [CrossRef]
5. Song, H.; Hwang, K.; Park, H.-S.; Park, Y.; Han, S.; Byun, M.; Kim, J.-J.; An, J.G.; Yim, U.H.; Choi, W. Estimating vehicular emission factors and vehicle-induced turbulence: Application of an air quality sensor array for continuous multipoint monitoring in a tunnel. *Atmos. Pollut. Res.* **2023**, *14*, 101799. [CrossRef]
6. Wu, C.L.; He, H.-D.; Song, R.-F.; Peng, Z.-R. Prediction of air pollutants on roadside of the elevated roads with combination of pollutants periodicity and deep learning method. *Build. Environ.* **2022**, *207*, 108436. [CrossRef]
7. Wang, X.; Yue, X.; Huang, J.; Li, S. Integrating traffic dynamics and emissions modeling: From classical approaches to data-driven futures. *Atmosphere* **2025**, *16*, 695. [CrossRef]
8. Liang, M.; Chao, Y.; Tu, Y.; Xu, T. Vehicle pollutant dispersion in the urban atmospheric environment: A review of mechanism, modeling, and application. *Atmosphere* **2023**, *14*, 279. [CrossRef]
9. Buccolieri, R.; Carlo, O.S.; Rivas, E.; Santiago, J.L.; Salizzoni, P.; Siddiqui, M.S. Obstacles influence on existing urban canyon ventilation and air pollutant concentration: A review of potential measures. *Build. Environ.* **2022**, *214*, 108905. [CrossRef]
10. Marinello, S.; Lolli, F.; Coruzzolo, A.M.; Gamberini, R. Exposure to Air Pollution in Transport Microenvironments. *Sustainability* **2023**, *15*, 11958. [CrossRef]

11. Liu, L.; Liu, H.; Ma, Y. Surrogate-Assisted Fine Particulate Matter Exposure Assessment in an Underground Subway Station. *Int. J. Environ. Res. Public Health* **2022**, *19*, 2295. [CrossRef] [PubMed]
12. Wang, X.; Xia, L.; Pei, F.; Wang, Z.; Liu, Y.; Chang, L.; Pan, S. The Characteristics of Particulate Matter in Different Subway Station Environmental Control Systems. *Heliyon* **2023**, *9*, e20116. [CrossRef] [PubMed]
13. Chu, C.-R.; Su, Z.-Y. Natural Ventilation Design for Underground Parking Garages. *Build. Environ.* **2023**, *227*, 109784. [CrossRef]
14. Chlebnikovas, A.; Jasevičius, R. Air Pollution with Fine Particles in Closed Parking and Theoretical Studies of the Interaction of Inhaled Particles in Respiratory Tract. *Buildings* **2022**, *12*, 1696. [CrossRef]
15. Zhang, L.; Wu, W.; Wang, J.; Wang, Y.; Zhang, Y.; Wang, N.; Yuan, S.; Li, J.; Xian, W.; Deng, L.; et al. VOCs pollution and respiratory exposure in commercial and residential underground parking garages. *Transp. Res. Part D Transp. Environ.* **2024**, *136*, 104472. [CrossRef]
16. Urban Access Regulations in Europe. München (Munich). Available online: https://urbanaccessregulations.eu/countries-mainmenu-147/germany-mainmenu-61/munchen (accessed on 29 March 2026).
17. Lower, A.; Szumilas, A. Parking policy as a tool of sustainable mobility-parking standards in poland vs. European experiences. *Sustainability* **2021**, *13*, 11330. [CrossRef]
18. Gonzalez, A.; Boies, A.; Swanson, J.; Kittelson, D. Measuring the air quality using low-cost air sensors in a parking garage at University of Minnesota, USA. *Int. J. Environ. Res. Public Health* **2022**, *19*, 15223. [CrossRef] [PubMed]
19. Zheng, J.; Huang, Z.; Zhou, X.; Scheuer, B.; Wang, H. Spatiotemporal analysis of CO_2 emissions and emission reduction potential of Beijing buses using smart card data. *Sustain. Cities Soc.* **2023**, *99*, 104976. [CrossRef]
20. Faramarzi, A.; Lee, J.; Stephens, B.; Heidarinejad, M. Assessing ventilation control strategies in underground parking garages. *Build. Simul.* **2021**, *14*, 701–720.
21. Raj, A.; Larsson, I.S.; Ljung, A.-L.; Forslund, T.; Andersson, R.; Sundström, J.; Lundström, T. Evaluating hydrogen gas transport in pipelines: Current state of numerical and experimental methodologies. *Int. J. Hydrogen Energy* **2024**, *67*, 136–149. [CrossRef]
22. Deng, B.; Chen, Y.; Duan, X.; Li, D.; Li, Q.; Tao, D.; Ran, J.; Hou, K. Dispersion behaviors of exhaust gases and nanoparticle of a passenger vehicle under simulated traffic light driving pattern. *Sci. Total Environ.* **2020**, *740*, 140090. [CrossRef] [PubMed]
23. Vaze, N.; Calderon, L.; Tsiodra, I.; Mihalopoulos, N.; Serhan, C.N.; Levy, B.D.; Demokritou, P. Assessment of the Physicochemical Properties of Ultrafine Particles (UFP) from Vehicular Emissions in a Commercial Parking Garage: Potential Health Implications. *Toxics* **2024**, *12*, 833. [CrossRef] [PubMed]
24. Chae, E.; Choi, S.S. Particulate matter ($PM_{2.5}$) concentrations and contributions of tire wear particles to $PM_{2.5}$ in an indoor parking garage: Comparison with outdoor environment and differences by sampling locations. *Heliyon* **2024**, *10*, e23140. [CrossRef]
25. Zhang, L.; Wang, J.; Hu, X.; Zhou, J.; Zhao, M.; Zhang, J.; Bo, Y.; Huang, Y.; Zhang, Y. VOCs and PM concentrations in underground parking garages of the commercial center and high-rise residential buildings. *Air Qual. Atmos. Health* **2021**, *14*, 1117–1131. [CrossRef]
26. Prachanurak, A.; Prachanurak, P. Influence of Meteorological factors and Distribution of Particulate Matter at Underground Parking. *J. Ind. Technol.* **2024**, *20*, 112–129.
27. Garcia-Gonzalez, H.; Domat, M.; Lopez-Pola, T.; Fernandez-Rubio, P.; Fernandez-Rodriguez, P. Particulate matter characterization in a hospital's underground car park. *Powders* **2022**, *1*, 194–206. [CrossRef]
28. enviDUST. Available online: https://senzor.envitech.eu/produkty/envidust (accessed on 30 July 2025).
29. Administrator University of Žilina in Žilina. Available online: https://www.uniza.sk/index.php (accessed on 8 March 2026).
30. Zhao, Y.; Song, X.C.; Wang, Y.; Zhao, J.N.; Zhu, K. Seasonal patterns of PM10, PM2.5, and PM1.0 concentrations in a naturally ventilated residential underground garage. *Build. Environ.* **2017**, *124*, 294–314. [CrossRef]
31. Liu, Z.J.; Yin, H.; Ma, S.Y.; Jin, G.Y.; Gao, J.; Ding, W.J. On-site assessments on variations of PM2.5, PM10, CO_2 and TVOC concentrations in naturally ventilated underground parking garages with traffic volume. *Environ. Pollut.* **2019**, *247*, 626–637. [CrossRef] [PubMed]
32. Oh, H.J.; Sohn, J.R.; Roh, J.S.; Kim, J. Exposure to respirable particles and TVOC in underground parking garages under different types of ventilation and their associated health effects. *Air Qual. Atmos. Health* **2020**, *13*, 297–308. [CrossRef]
33. Cheng, Y.H.; Chang, H.P.; Hsieh, C.J. Short-term exposure to PM10, PM2.5, ultrafine particles and CO_2 for passengers at an intercity bus terminal. *Atmos. Environ.* **2011**, *45*, 2034–2042. [CrossRef]
34. Cheng, Y.H.; Chang, H.P.; Yan, J.W. Temporal variations in airborne particulate matter levels at an indoor bus terminal and exposure implications for terminal workers. *Aerosol Air Qual. Res.* **2012**, *12*, 30–38. [CrossRef]
35. Nogueira, T.; Kumar, P.; Nardocci, A.; Andrade, M.D. Public health implications of particulate matter inside bus terminals in São Paulo, Brazil. *Sci. Total Environ.* **2020**, *711*, 135064. [CrossRef] [PubMed]
36. Ngoc, L.T.N.; Kim, M.; Bui, V.K.H.; Park, D.; Lee, Y.C. Particulate matter exposure of passengers at bus stations: A review. *Int. J. Environ. Res. Public Health* **2018**, *15*, 2886. [CrossRef] [PubMed]
37. Wang, J.Q.; Li, Z.X.; Kumar, P.; Ren, C. Mitigating particulate matter exposure at bus stations using green infrastructure. *Sustain. Cities Soc.* **2024**, *113*, 105703. [CrossRef]

38. Hao, X.T.; Hu, X.J.; Zhang, K.; Wang, L.; Wang, C.W. Effects of bus station density on urban air pollution: An empirical analysis based on propensity score matching. *Urban Clim.* **2025**, *59*, 102313. [CrossRef]
39. Thorpe, A.; Harrison, R.M. Sources and properties of non-exhaust particulate matter from road traffic: A review. *Sci. Total Environ.* **2008**, *400*, 270–282. [CrossRef] [PubMed]
40. Zhang, J.S.; Peng, J.F.; Song, C.B.; Ma, C.; Men, Z.Y.; Wu, J.H.; Wu, L.; Wang, T.; Zhang, X.F.; Tao, S.C.; et al. Vehicular non-exhaust particulate emissions in Chinese megacities: Source profiles, real-world emission factors, and inventories. *Environ. Pollut.* **2020**, *266*, 115268. [CrossRef] [PubMed]
41. Jandacka, D.; Durcanska, D.; Cibula, R. Concentration and inorganic elemental analysis of particulate matter in a road tunnel environment (Žilina, Slovakia): Contribution of non-exhaust sources. *Front. Environ. Sci.* **2022**, *10*, 952577. [CrossRef]
42. Jafari, A.J.; Delikhoon, M.; Rastani, M.J.; Baghani, A.N.; Sorooshian, A.; Rohani-Rasaf, M.; Kermani, M.; Kalantary, R.R.; Golbaz, S.; Golkhorshidi, F. Characteristics of gaseous and particulate air pollutants at four different urban hotspots in Tehran, Iran. *Sustain. Cities Soc.* **2021**, *70*, 102907. [CrossRef]
43. Rakowska, A.; Wong, K.C.; Townsend, T.; Chan, K.L.; Westerdahl, D.; Ng, S.; Mocnik, G.; Drinovec, L.; Ning, Z. Impact of traffic volume and composition on the air quality and pedestrian exposure in urban street canyon. *Atmos. Environ.* **2014**, *98*, 260–270. [CrossRef]