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Analysis of the quality of vehicle fleet data as input for modeling emissions and dispersion of pollutants emitted by combustion engine vehicles

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Reliable modeling of emissions and dispersion of pollutants emitted in exhaust gases from motor vehicles is highly challenging due to the presence of multiple variables and inconsistencies in input data quality across different stages of the process. This article focuses on the vehicle fleet. It has been demonstrated that the structure of the vehicle fleet in a given area varies depending on the data collection methods and sources, which ultimately determines the dispersion results. This issue becomes particularly significant in urban environments, where the intensity of road traffic is high, and ventilation conditions are often poor, partly due to the formation of street canyons by dense urban development. The modeling was conducted at a selected intersection in Wrocław for various fleet structure scenarios. The results were compared with the results of pollutant concentrations from a nearby air quality monitoring station. The Copert emission model and emission factors from the European EMEP/Corinair database were used. In contrast, the GRAL model, a CFD model (suitable for urban dispersion modeling), was used to simulate pollution dispersion.

Key words: *road transport, emission modelling, air quality, dispersion modelling, fleet structure analysis*

1. Introduction

Air pollution is one of the most serious threats to public health and the climate worldwide. In particular, urban traffic is considered a key source of emissions of harmful substances such as nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs), particulate matter (PM, including soot), and greenhouse gases (GHG), including carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Numerous reports by Polish environmental protection authorities, such as the National Centre for Environmental Protection (KOBiZE) and the Chief Inspectorate for Environmental Protection (GIOŚ), indicate that road transport contributes significantly to air pollution [9, 13]. They show, among other things, that although transport accounts for about 33% of total nitrogen oxide emissions nationwide, this figure is significantly higher in large cities, reaching about 43% in Warsaw, for example.

Due to the inability to directly measure emissions from all vehicles participating in traffic, as well as the presence of other sources of the same pollutants, such as exhaust fumes from individual building heating systems, it is challenging to determine the impact of motorization on air quality precisely. Therefore, emission estimation methods should be used for this purpose, usually involving emission modelling techniques. Modelling the emission and dispersion of pollutants from combustion engine vehicles is a complex issue that requires high-quality input data on the vehicle fleet [8]. The reliability of modelling results depends to a large extent on the accuracy of information on fleet composition, traffic patterns and vehicle technical characteristics [10, 14]. This literature review presents the current state of knowledge on the quality of vehicle fleet data and its impact on the accuracy of modeling emissions and pollutant dispersion in the urban environment. Traditional approaches to collecting vehicle fleet data rely mainly on official registration statistics and traffic surveys [10]. However, studies show significant discrepancies between different data sources. A study conducted in Toronto found that the emission factors obtained from models were twice as high as those estimated using trace measurements for CO and NO_x [19]. Similarly, an analysis of mobility data during the pandemic revealed a 60% discrepancy between data from mobile applications and actual traffic measurements [8]. This means that a critical approach to the fleet structure must be incorporated into the model. In general, it should be emphasized that the assessment of the impact of motor vehicle traffic using modeling consists of two consecutive steps: emission modeling and pollutant dispersion modeling. At each of these stages, input data from various sources is entered. In emission models, these include traffic intensity, road type and geometry, and vehicle fleet structure (division into categories, age, engine size, etc.). Any error made at this stage is then carried over to the pollutant dispersion modelling stage, where another error is also generated. It is therefore essential to ensure the best possible quality of input data at each stage in order to minimise the final error.

Research confirms the significant impact of fleet data quality on emission modelling results. Sensitivity analysis has shown that greenhouse gas emissions from light vehicles can vary by –2% to 11%, and conventional pollutants by –47% to 228% compared to baseline values. For heavy-duty vehicles, the variability can be –21% to 55% for GHG and –32% to 174% for CAP, respectively [14]. These significant differences highlight the crucial role of accurate fleet characteristics data. A comparison of two popular emission models, MOVES and FIVE, showed significant differences in emission estimates. The MOVES model showed lower systematic errors for ozone and PM2.5 at the national level, while FIVE performed better at the urban scale due to higher NO_x emissions in urban areas [8]. These differences are partly due to different approaches to characterising the vehicle fleet in each model. It should be emphasised that accurate validation of emission model results is extremely difficult, if not impossible.

In Europe, the dominant models are COPERT (Computer Programme to Calculate Emissions from Road Transport) and HBEFA (Handbook Emission Factors for Road Transport) [5, 20]. Shi et al. published a study presenting highly detailed CO_2 emission maps for road transport in 20 major European cities (France, Germany, the Netherlands) for the year 2023. The authors applied Floating Car Data (FCD), utilizing machine-learning algorithms to extrapolate GPS samples into actual traffic volumes, and combined these with the COPERT model to calculate emission factors [15]. While the COPERT model is widely used across EU countries, the HBEFA model is typically applied only in some of them, primarily in Germany, Austria, France, Switzerland, and Sweden [4]. In Slovakia, for instance, HBEFA-based emission factors were used in a study on the introduction of LNG buses in urban transport, demonstrating that this tool is also applied in other European countries [6].

Recent comparative analyses integrating COPERT and HBEFA indicate that both models tend to overestimate NOx emissions relative to field measurements. However, COPERT reproduces traffic conditions in highly urbanized environments more accurately, which confirms its calibration to European measurement campaigns [5]. However, the advantage of COPERT and HBEFA in European applications stems primarily from their close alignment with the characteristics of the vehicle fleet, emission standards, and traffic structures specific to EU member states, which are harmonized under the regulations of the European Environment Agency (EEA). In contrast, MOVES and FIVE were designed primarily to support the U.S. emission inventory system and air-quality policy, using fleet, fuel, and activity data characteristic of the United States [18].

Accurately estimating the impact of road traffic on air quality in cities is a complex and challenging process. Selected issues are briefly described below.

Lack of reliable and detailed data on the fleet – designing effective emission reduction policies is hindered by insufficient and unreliable data on the composition of the vehicle fleet (e.g., age, engine type, emission control technology) and its actual activity [10, 17]. Fluctuations in model estimates of emissions often result from local factors such as variable fleet composition, the presence of external sources of pollution and changing traffic intensity [12]. An overly general classification of vehicles, such as treating all heavy traffic as a single category, may not accurately reflect the actual distribution of emissions.

The evolution of the vehicle fleet – the increasing popularity of vehicles with gasoline direct injection (GDI) engines, which are fuel-efficient but also increase emissions of soot and toxic substances – poses a new challenge [19]. Furthermore, the growing share of electric vehicles (EVs) and hybrids is altering the emissions profile, while simultaneously leading to a significant increase in electricity demand, which necessitates an assessment of the environmental impact of electricity production. This introduces new complexities, such as changing the boundaries of the analysis system (e.g. from 'tank-to-wheel' to 'well-to-wheel') [2, 19].

Limitations of models and measurement data – the accuracy of roadside emission and pollutant concentration inventories is largely dependent on the quality of the emission factors (EFs) used. Models such as MOVES, although based on data from vehicle inspection programmes and dynamometer tests, may not take into account the full range of real-world driving conditions (e.g. variable speeds, acceleration and braking), which can lead to NO_x emissions being overestimated by as much as 50–100% compared to actual measurements [3]. Vehicle emissions vary significantly depending on vehicle type, age, distance traveled, fuel type, combustion processes, and other factors (e.g. tire and brake wear), as well as local weather conditions such as temperature and humidity. Traffic conditions (e.g. traffic density, road conditions, vehicle type) can vary dramatically over short distances (1–10 km) and in short intervals (e.g., hourly). Additionally, factors such as the engine's technical condition and the driver's driving style also impact the amount of emissions [7, 16].

Ageing fleet in developing countries – in many developing countries, the problem of vehicle emissions is exacerbated by an ageing vehicle fleet and less stringent environmental regulations [1, 14].

The aim of this article is to highlight issues with the availability and quality of data on the structure of the vehicle fleet in assessing the impact of road traffic on air quality in urban conditions, using the example of Wrocław. An innovative combination of data sources for modelling emissions from road traffic has been used in the paper. Most models available in the literature rely on the statistical structure of the vehicle fleet. This article demonstrates how different input data sources for the model can significantly influence the final results of modeling the impact of road transport on air quality in urban conditions.

2. Materials and methods

2.1. Analysis of the fleet of vehicles moving around Wrocław

The most critical component in modelling traffic-related emissions is the introduction of the vehicle fleet. An appropriate selection of the fleet structure – especially in terms of vehicle age (compliance with Euro standards), propulsion and fuel type, engine displacement, and other characteristics – is pivotal for the quality of the modelling. Identifying a suitable data source for the composition of the fleet is challenging for several reasons. Ideally, actual measurement data that precisely reflects the fleet structure for the area being modeled and is synchronized in time would be used. However, obtaining such data for every case, especially at a larger scale, is highly challenging, time-consuming, and requires considerable human resources, often with associated error margins (for example, due to variability in driver behaviour and changes in traffic conditions and congestion). In practice, the approach most commonly used is to model traffic emissions using statistical data. However, multiple statistical data sources exist. One example is the national statistics, which consider the entirety of the registered vehicle fleet across Poland. However, national statistics may not always accurately reflect the local context, such as a specific city or a given road segment.

A second approach is to use more regionalised data, for example, the data from the Central Register of Vehicles and Drivers (CEPiK) for the city of Wrocław, as shared by the Municipal Office of Wrocław. However, analyses have shown that this data is also subject to certain limitations. First, local CEPiK databases retain records of vehicles for five years, even if those vehicles have been withdrawn from service. A vehicle is only removed from the database after five years of inactivity (e.g., after no technical inspection), potentially skewing statistics towards an overestimation of older vehicles. Another issue is the fact that many people using the city are not residents – for example, those commuting from nearby smaller towns such as Trzebnica, Oława, or Oleśnica, or students and young professionals who drive vehicles registered in their hometowns. The third challenge is data completeness. Whereas the author had access to the CEPiK database for Wrocław for the years 2015–2017, which included almost all necessary information for accurate emission modeling (year of manufacture, vehicle category, fuel/powertrain, and engine displacement), more recent data lacked certain crucial details. Even within the 2015–2017 dataset, errors were identified – for example, incorrect classification of light commercial vehicles (incorrectly classified as heavy trucks, special-purpose vehicles, or 'other'), and the absence of a 'Light Duty Vehicles' category. Moreover, in the case of articulated trucks, the fact that a vehicle is registered in Wrocław does not necessarily mean that it operates within the city. Figure 1 presents a summary of vehicles registered in Wrocław, based on CEPiK data for the years 2015, 2017, and 2021. Notably, the total number of registered vehicles increased sharply over this period (2015: 394,550 vehicles, 2017: 495,306, 2021: 613,938), and approximately 80% of the total comprised passenger cars (2015: 79%, 2017: 80%, 2021: 81%).

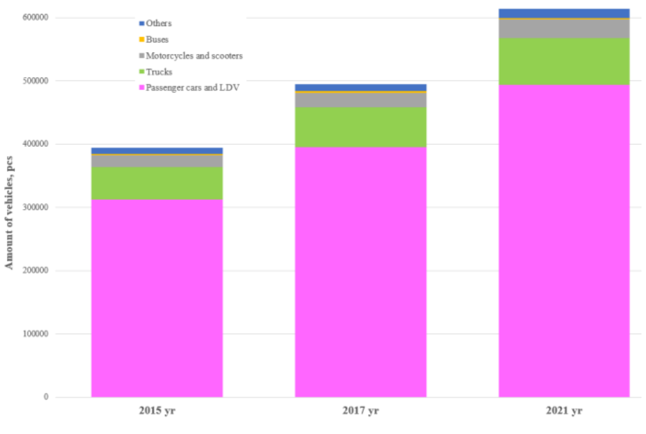

Fig. 1. Vehicles registered in Wrocław according to CEPiK data, broken down by category for 2015, 2017, and 2021 (author's compilation based on CEPiK data for Wrocław

A third important source of fleet data, in the author's view, is through direct observations conducted in actual traffic conditions. To this end, in April 2023, a study was conducted in which license plate numbers were recorded along one of the main streets in the center of Wrocław, near the intersection of Oławska and Podwale Streets. Three half-hour measurement periods were conducted: one in the morning on a Sunday, one at noon on a Sunday, and one in the afternoon of a working day. The focus was not to measure traffic intensity, but to capture the composition of the vehicle fleet, selecting times with relatively smooth traffic flow to maximise the number of registrations. In total, nearly 1000 license plate numbers were recorded and compiled into a spreadsheet. A request was then submitted to the central CEPiK office in Gliwice to obtain data for those vehicles, including: vehicle category, year of manufacture, engine displacement, fuel/powertrain type, alternative fuel, and status (registered/inactive). A statistical analysis was conducted using the received data. At first glance, this approach appears advantageous compared to relying on pre-existing statistics due to its higher data quality. However, such studies are time-consuming, require significant human resources for data recording and processing, and involve a lengthy wait for the data to be released. Moreover, the sample size is a limitation – approximately 1000 observed vehicles account for only a small fraction of those using Wrocław's roads. For example, only one articulated lorry was registered, making statistical analysis challenging. To achieve better statistical significance, more such studies would be required, preferably conducted across multiple locations simultaneously, which further increases resource demands.

Additionally, a fee must be paid to CEPiK for data access. Considering the dynamic changes in the composition of the vehicle fleet, such studies must be conducted frequently. Similar studies were conducted in 2022 by the Wrocław Municipal Office as part of analyses related to the implementation of the Clean Transport Zone. In Section 3.1, the results of that study are compared with those from the author's observations.

2.2. Location of analysis

The analyses were conducted in the area of the intersection of Powstańców Śląskich Street, Hallera Street, and Wiśniowa Avenue. This location was selected for several reasons. First, it is an intersection of some of the city's main thoroughfares. Powstańców Śląskich Street is a primary route leading out of the city towards the A4 motorway. Secondly, this intersection hosts an air quality monitoring station operated by the State Environmental Monitoring network under the auspices of the Chief Inspectorate of Environmental Protection. This is a typical 'traffic' station dedicated to measuring pollutants arising from vehicular activity. This allows for a direct comparison between the dispersion results and actual observed air pollution levels. Notably, in recent years, this station has registered the highest nitrogen oxides (NO_x) concentrations across Wrocław. An additional advantage of the site is the presence of cameras from the Intelligent Transport System (ITS), which significantly facilitates the acquisition of actual traffic data. Figure 2 presents the selected area of analysis, with the air quality monitoring station marked in red.

Fig. 2. Selected area of analysis (basemap: www.geoportal.gov.pl)

2.3. Emission modeling using the Copert model

The first stage of the analysis involved emission modelling for the vehicle fleet in the vicinity of the intersection. The European Copert model was used for this purpose. Copert operates in conjunction with the EMEP/Corinair emission factor database. To build the model, the following data were required:

- road sections and their lengths
- number of traffic lanes in each direction
- vehicle fleet composition (in percentages)
- traffic flow on each lane
- vehicle speed (set to the local speed limit of 50 km/h).

The analyses were conducted for three fleet scenarios:

1) CEPiK data for Wrocław (2021) – ‘Fleet 1’
2) Municipal Office of Wrocław traffic survey data (2022) – ‘Fleet 2’
3) Author’s traffic survey data (2023) – ‘Fleet 3’.

Traffic flow data were based on measurements conducted on the selected date, 17 August 2022. This date was chosen due to its proximity to the data years (2021–2023), and because it was a summer date with no significant additional emissions from heating (there is a nearby area of single-family homes), making it ideal for focusing exclusively on vehicular emissions. This date also coincided with the highest recorded NO_2 concentrations at the monitoring station (Fig. 3).

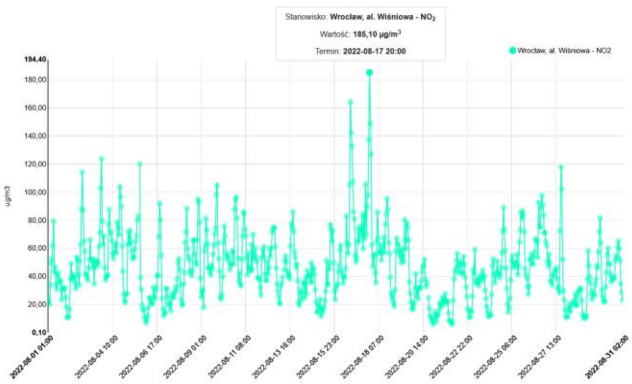

Fig. 3. Variations in NO_2 concentrations measured in 2022 at the air quality monitoring station located on Wiśniowa Avenue (source: https://powietrze.gios.gov.pl/pjp/current/station_details)

Figure 4 presents assumptions about lane counts and traffic directions. Table 1 summarizes the average daily traffic for each direction, as well as the segment lengths.

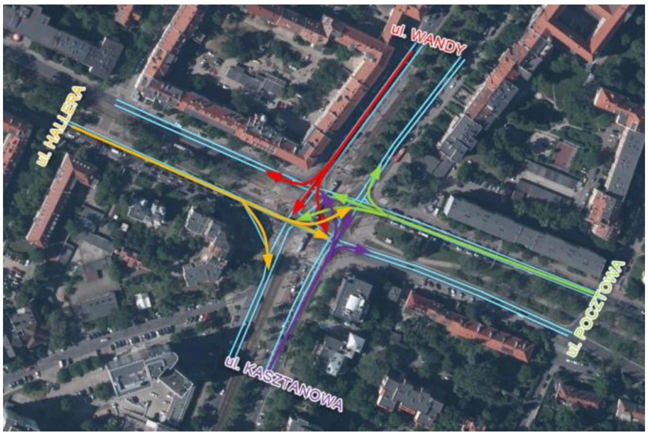

Fig. 4. Analysed road stretches and traffic directions per lane

Table 1. Average daily traffic and stretch lengths

Stretch	Number of vehicles, pcs/day	Number of vehicles, pcs/hour	Length of stretch, m
Wandy_crossroad_left	2724	114	126.1
Wandy_crossroad_straight	8171	341	136.6
Wandy_crossroad_right	2724	114	132.4
Hallera_crossroad_left	2407	101	216.3
Hallera_crossroad_straight	14206	592	198
Hallera_crossroad_right	2328	97	172.2
Kasztanowa_crossroad_left	4808	201	134.7
Kasztanowa_crossroad_straight	9875	412	140.1
Kasztanowa_crossroad_right	3292	138	99.7
Pocztowa_crossroad_left	2406	101	233.2
Pocztowa_crossroad_straight	10055	419	225.5
Pocztowa_crossroad_right	3352	140	175.3
Crossroad_Wandy_line1	2407	101	98.4
Crossroad_Wandy_line2	13226	552	95.3
Crossroad_Hallera_line1	12779	533	131.4
Crossroad_Hallera_line2	4808	201	128.1
Crossroad_Kasztanowa_line2	2406	101	109.8
Crossroad_łącznik	8171	341	45
Crossroad_Kasztanowa_line1	2328	97	46.8
Crossroad_Pocztowa_line1	2724	114	163.8

Measurements of NO_x (including NO_2), CO, and PM2.5 are performed automatically by the nearby air quality station. In the context of combustion-related pollutants from vehicular traffic, NO_2 was selected for this analysis. PM was omitted due to its potential distortion by re-suspended dust caused by traffic (no rain was recorded that day), making PM measurements unsuitable for direct attribution.

2.4. Dispersion modeling using the GRAMM/GRAL model

For dispersion modeling, the GRAMM/GRAL model, developed in Austria, was used. This is a Computational Fluid Dynamics (CFD)-based numerical model, well-suited for low wind speeds and complex terrain, making it ideal for capturing the effects of buildings and other topographical features on airflow and the dispersion of pollutants [11].

In addition to emission data, the model required:
- terrain topography and land-use data
- meteorological data, sourced from the Institute of Meteorology and Water Management (https://dane.imgw.pl/datastore)
- spatial and infrastructural data, sourced from the Wrocław Development Office.

The GRAMM/GRAL model features an integrated GIS (Geographic Information System) module, enabling the precise input of spatial details, including building and terrain characteristics, making it highly suitable for such analyses. The same modelling settings were used across all three fleet scenarios.

3. Results and discussion

3.1. Fleet composition

The three analysed fleets vary significantly in composition. In terms of vehicle category distribution, 'Fleet 1' and 'Fleet 2' are similar (Fig. 5), whereas 'Fleet 3' (derived from the author's observations) diverges, likely due to its relatively small sample size compared with the actual traffic volume. According to numerous statistical analyses, passenger cars comprise roughly 80% of the total urban traffic fleet.

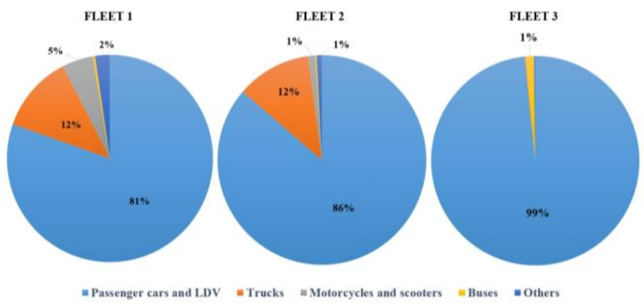

Fig. 5. Distribution of the vehicle fleet by category

Slight variations were also observed in fuel and propulsion types (Fig. 6). Due to data gaps, a comprehensive analysis of the City Office data was not possible. However, the available statistics align closely with those from the CEPiK database. In both instances, nearly 80% of the fleet used conventional fuels (gasoline or diesel), with hybrids and LPG vehicles treated as a separate category.

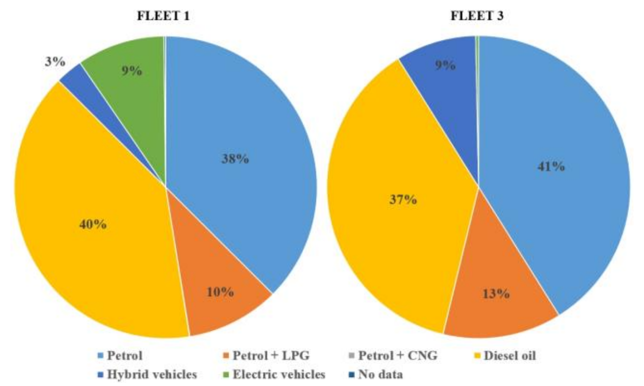

Fig. 6. Fleet composition by fuel or drive system

More significant differences emerged when analyzing the age and emission standard (Euro class) of the vehicles. The CEPiK database (2021) indicated a very high proportion of older vehicles, with over half not meeting the Euro 3 standard. In contrast, the data collected by the Wrocław City Office and the author's survey indicated that roughly three-quarters of the local fleet meets Euro 4 or higher standards (Fig. 7).

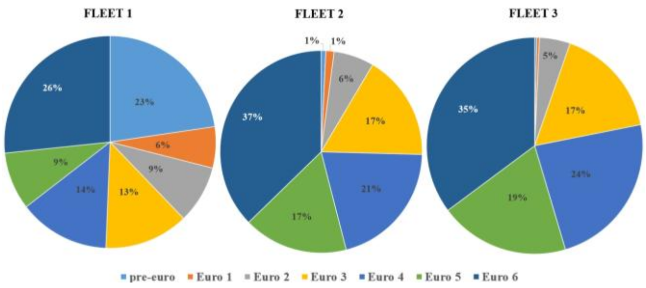

Fig. 7. Fleet composition by Euro standard

3.2. Modeling results

The modeling of the spread of pollutants in the air was carried out to verify the quality of data for the analyzed fleets. For this purpose, in the model, in addition to the standard network of receptors, which calculates the concentrations of substances in the air, an additional point was introduced: the location of the monitoring station, where the calculations were also performed. Figure 8 shows an example of the distribution of nitrogen dioxide concentrations in the modelling area for fleet 2. At the same time, Table 2 presents a summary of the modeling results, along with information on the concentrations recorded at the station. Since the model calculated the average daily maximum concentration value averaged over 1 hour, the concentration values were also averaged over the entire day of 17.08.2022.

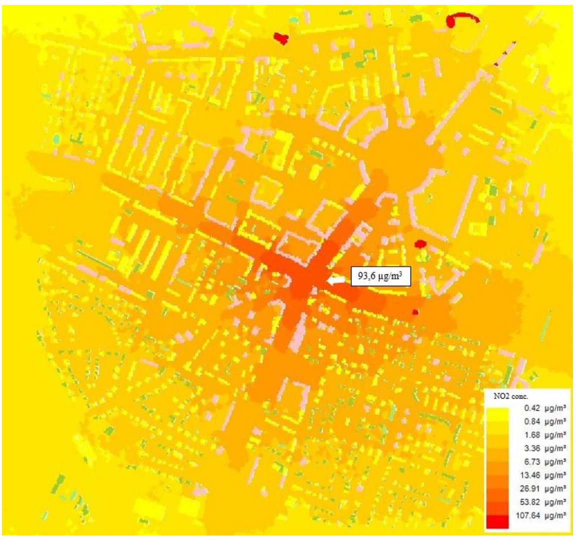

Fig. 8. NO_2 dispersion results for fleet 2

Table 2. Average daily traffic and stretch lengths

	Concentration, µg/m³			
	Monitoring station	Modeling, fleet 1	Modeling fleet 2	Modeling fleet 3
NO_2	86.1	116.2	**93.6**	49.2

As shown in Table 2, the calculations for fleet 1 were significantly overestimated. The nitrogen dioxide concentration calculated at the monitoring station location was overestimated by about 2 times. This is most likely due to the fact that a large part of the fleet was classified as vehicles meeting low Euro standards, and as a result, the calculated emissions were greatly overestimated. In turn, the calculations for fleet 3 indicated underestimated results. The too-small sample of vehicles most likely causes this situation. It should be noted that 99% of this fleet were passenger cars, while trucks and buses with large-capacity engines are also a significant source of exhaust emissions in the city. The closest result was obtained for fleet 2. The calculated concentration is not ideal, but close to the measured one. It is essential to consider that modeling the spread of exhaust gases from vehicle traffic is often marred by numerous errors at various stages. Additionally, it should be emphasised that fleet 2 also had some errors in the data or gaps. Nevertheless, as can be seen from the analyses carried out, it was the best source of data.

4. Summary and conclusions

Assessing the impact of road traffic on air quality is a challenging endeavor, fraught with uncertainties related to statistical data, emission factors, and inconsistencies in other input data. The primary objective of this paper was to assess the quality of fleet data from different sources – statistical data from the CEPiK database, measurement data collected by the Wrocław City Office, and the author's own survey. The results clearly demonstrate that selecting an accurate vehicle fleet structure is crucial for accurately modeling traffic-related air pollution. The analyses revealed numerous data quality issues:

- misclassification of vehicles (e.g., a Fiat Seicento registered as a truck)
- incomplete or missing data
- discrepancies between available data and the classification required by the EMEP/Corinair emissions database
- misassigning Euro emission standards due to relying on the year of production rather than official Euro category. In Poland, the Euro standard is not specified in the vehicle's registration documents, which may lead to errors (e.g., a 2001 car might already be Euro 4 compliant, despite Euro 3 being in force at the time). Similar issues arise with Euro 6 vehicles registered in 2015, when the standard came into force mid-year.

Among the analysed vehicle-fleet data sources, the best-performing dataset was 'Fleet 2', originating from fleet measurements conducted by the Wrocław Municipal Office in real urban traffic. The results obtained for 'Fleet 3' were underestimated, most likely due to an insufficient sample size. In contrast, highly overestimated results were produced using 'Fleet 1'. This was caused by the presence of many old vehicles in the dataset (not meeting any emission standards) which, in reality, no longer operate on public roads. Therefore, to ensure a reliable assessment of the impact of road transport on urban air quality, it is recommended to use vehicle-fleet data that are as representative of real conditions as possible and based on the largest feasible statistical sample.

The study confirms that the most reliable source of data for estimating emissions is direct measurement of the actual traffic fleet in the area of interest. However, obtaining a sufficiently large sample for statistical reliability is challenging, resource-intensive, and time-consuming.

Acknowledgements

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Nomenclature

CEPiK	Central Register of Vehicles and Drivers (Poland)
CFD	computational fluid dynamics
CH_4	metane
CO	carbon monoxide
EEA	European Environment Agency
GHG	greenhouse gases
GIOS	Chief Inspectorate for Environmental Protection (Poland)
GRAL	Graz Lagrangian Model
GRAMM	Graz Mesoscale Model
ITS	intelligent transport system
KOBiZE	National Centre for Emissions Management
NO	nitrogen monoxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides (mixture)
N_2O	nitrous oxide
PM	particulate matter
VOC	volatile organic compounds

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