

MODELLING THE DISPERSION OF POLLUTANTS FROM ROAD TRANSPORT IN STREET CANYONS ON THE EXAMPLE OF SZCZECIN AND OSLO

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Purpose: Emissions of nitrogen dioxide (NO₂) and carbon monoxide (CO) from road transport have a notable impact on everyday life of city dwellers, where traffic congestion is one of the major problems. These emissions have an adverse effect on air quality, human health, and climate change. The aim of this study is to present the possibility of applying the analytical Gaussian Plume Dispersion Model (GPD) to determine the dispersion of air pollutants from freight transport in an urban area with the use of real data obtained from road traffic detectors.

Design/methodology/approach: The pollutant dispersion was modelled for nitrogen dioxide NO₂ and carbon monoxide CO. The study covered the streets of urban agglomerations located near two city centers: in Oslo (Norway) and in Szczecin (Poland). The chemical reactions between NO₂/CO and oxygen were included in the model. Pollutant dispersion was modelled for a height of 2 meters.

Findings: In terms of traffic intensity, the type of vehicles and their speed are the main factors influencing the maximum value of pollutants concentration, occurring along the traffic axis. Both the increase in the share of trucks and the reduction in speed have a negative impact, as they contribute to an increase in local pollution concentrations. It was found that higher wind speeds generally have a positive effect on the faster dispersion of undesirable gas compounds in the air.

Practical implications: The proposed model may be used as a supporting tool when deciding on potential locations for further air quality monitoring stations managed by the city and environmental protection authorities.

Social implications: The proposed modified Gaussian Plume Dispersion Model can be used as a fast-response system for identifying exceedances of permissible pollution standards in urban agglomeration areas which are highly exposed to transport pollution.

Originality/value: In most similar publications, pollutant distribution is modelled at lower heights (reflecting to the emitter heights). Our study results aim to visualize the distribution of

pollutants not in the critical plane parallel to the road, but in the “exposure” plane, particularly in relation to residents of those road segments, as well as pedestrians and workers.

Keywords: Gaussian Plume Dispersion Model, pollution, dispersion, air quality, traffic, urban freight transport, sustainable development.

Category of the paper: Research paper.

1. Introduction

Urban transport system is a complex organizational system, consisting of: pedestrian traffic, bicycle traffic, motorized passenger public transport, individual transport, as well as freight transportation. In recent years, much attention has been paid to the effects of the functioning of freight transport in cities (Taniguchi et al., 2014; Quak, 2008; Macharis, Melo, 2011; Allen et al., 2010; Bjørgen, Ryghaug, 2022; Brusselaers et al., 2023). One of the most important elements affecting air quality in cities, apart from the volume of emissions and the type of pollutants emitted, is the degree of dispersion of emissions. Monitoring the pollutant dispersion in the city influences the management process, especially the planning stage (Chen et al., 2021). Based on the data acquired from the pollution distribution in the city, metropolitan managers can better plan the city’s spatial layout and urban infrastructures.

Air quality in cities

The number of urban residents has been constantly growing — now they account for over 70% of the population — which results in an increased number of motor vehicles, including those used for goods deliveries. The increase in freight transport in urban and metropolitan areas contributes to a rise in congestion, air pollution, noise and logistics costs, which clearly translates into higher product prices (Dablanc et al., 2011; Browne et al., 2016). Additionally, the co-operation of different types of vehicles on the road increases the risk of accidents (Russo, Comi, 2010; Taniguchi, Thomson, 2018). Environmental pollution, and especially the air quality deterioration, poses a particular challenge to today’s society. The extensive impact of transport pollution has an adverse effect on the natural environment, and consequently on the health of inhabitants and city users (Trecuzzi et al., 2022). City managers undertake multifaceted efforts to improve mobility (Taniguchi et al., 2014). However, despite the attempts to reroute motorized transport outside the administrative boundaries of cities, and especially to keep it away from their centers, its complete elimination is not possible. On the one hand, the urban community is not keen on transport, especially freight transport in cities, but at the same time, in pursuit of adequate quality of life, city residents usually require access to various types of goods as close to home as possible (Russo, Comi, 2020). In 2020 in Brussels road transport was the largest source of nitrogen oxides (55%) emitted in the Brussels-Capital Region (BCR) (Brusselaers et al., 2023).

Nowadays, it is possible to observe an increase in ecological awareness as a consequence of the development of technologies for air quality monitoring systems and access to information. City managers implement solutions that are designed to reduce pollution of the urban environment (Holguín-Veras et al., 2016). Monitoring the pollution, especially its spread in real time, is troublesome, costly and not always feasible. In this respect, modeling is helpful, allowing for the forecasting of air pollutant concentrations at the ground level, thus providing a picture of the environmental impact of individual energy sources powering the means of transport.

In the interest of clean air, all European Union countries take measures to reduce the emissions of harmful substances. For this purpose, they implement air quality assessment and control systems through legal regulations at the global, regional, and local level. Additionally, numerous projects in this field are being implemented. They are intended to improve the flow of goods to such an extent and scope that it would simultaneously reduce the negative impact on the urban environment. In Poland, the control system is based on measurements carried out within the national monitoring network. The analysis of measurements does not identify transport as the main pollution generator, but its share in relation to other types of air polluting emissions is significant.

The implementation of distribution processes in urbanized areas faces the greatest challenges within city centers. This is mainly due to the significant concentration of workplaces, commercial and service units, HoReCa sector facilities, schools and universities, as well as public administration units. An additional difficulty is the topological structure of streets, resulting from historical conditions. This applies in particular to European cities, the centers of which were most often developed in periods when the demand for transport services was much lower, and the number of traffic participants did not significantly contribute to the congestion effect. City centers are, on the one hand, hubs of commercial, service, administrative and tourist functions, and on the other hand, they typically concentrate key transport nodes of the urban mobility system. As a result, implementation of deliveries within city centers represents a particular challenge to the efficient functioning of the urban system as a whole, at the same time encountering a significant number of difficulties related to, *inter alia*, traffic restrictions (e.g. restricted zones due to historic buildings), linear infrastructure not adapted to the growing number of vehicles (mainly narrow streets and one-way traffic organization) or the lack of a sufficient number of parking spaces.

Road transport key pollutants – NO₂ and CO

The level of carbon dioxide (CO₂) is most often taken into account as a key factor contributing to the greenhouse effect when analyzing the emissions of anthropogenic pollutants from road transport. In a global context, such an approach is legitimate (Lin, 2010). However, a direct focus on the local impact on the urban environment does not allow for a more complete analysis. Considering the expansion of urban systems into large agglomerations where the number of cars in relation to the number of people per square kilometer is many times higher

than in non-urban areas (Rojas-Rueda et al., 2012), it becomes important to take into account the chemicals directly related to the health condition of the city's population. These pollutants include, first of all, carbon monoxide (CO) which is an odorless and colorless gas with strong toxic properties, nitrogen dioxide (NO₂) — a brown, highly toxic gas with a pungent odor, hydrocarbons (HC) containing carcinogenic compounds, and particulate matter (PM) in the form of carbon-graphite compounds, ashes and soot. Originating from road transport, the compounds: NO_x, HC, CO and CO₂ can form, as a result of photochemical reactions, California smog containing toxic substances such as peroxy-acetyl-nitrile. The detrimental effect of photochemical smog is an increase in morbidity and health disorders of humans, including eye irritation, exacerbation of asthma symptoms, increased sensitivity to infections or pneumonia. Air pollution is a risk factor for cardiovascular and lung diseases including lung cancer. Among others, ischemic heart disease and stroke are the most common causes of deaths attributable to poor air quality (EEA, 2023). Air pollutants known to contribute to cardiovascular diseases include nitrogen dioxide (NO₂), particulate matter (PM), black carbon (BC) and carbon monoxide (CO), even if they are present at concentrations lower than current EU limit values, as the stroke and coronary heart disease risks rise with long-term air pollution exposure. All the above-mentioned compounds are highly exposed in studies on the emission of transport pollutants in urban agglomerations (Kanaroglou, Buliung, 2008; Gallardo et al., 2012). These compounds also form the basis of the European exhaust emission standard (EURO).

According to the European Environment Agency, transport constitutes a primary source of Europe's NO_x emissions (45%) and is also responsible for a significant proportion of the total emissions of other key pollutants (EEA, 2023). In 2022, among 137 air quality measurement stations in Poland, only 32 recorded the annual average NO₂ levels below the threshold recommended by WHO (10 µg/m³), and the majority of the stations (93) showed the annual average concentration in the range of 10-25 µg/m³. Average annual levels exceeding the EU's permissible value (40 µg/m³) were recorded at three urban traffic monitoring stations in large agglomerations (Wrocław, Katowice, Warsaw). In the case of Norway, all of the 46 measurement stations recorded the average annual NO₂ concentrations below 40 µg/m³, among which only 8 stations showed levels below 10 µg/m³. Despite ongoing reductions in key air pollutant emissions, in 2021 most of the EU's urban population was exposed to air pollutant levels detrimental to health. As regards NO₂, the share of the EU urban population exposed to concentrations exceeding the current EU standards was only 1%, but at the same time this share rapidly increased to 90%, while much more severe WHO recommendations for safe concentrations of air pollutants are being considered. In October 2024, the directive on ambient air quality and cleaner air for Europe was adopted, focused on establishment of stricter EU air quality standards, which would apply from 2030. Annual limit values for pollutants with the greatest documented impact on human health will be reduced, for instance in the case of NO₂ from the current level of 40 µg/m³ to 20 µg/m³.

According to Polish national regulations, the permissible level of carbon monoxide in the air established for the protection of human health is 10 mg/m^3 (an 8-hour average), which is compliant with WHO recommendations (WHO, 2021). Typically, such levels are unlikely to be reached in open areas, but long-term exposure to much lower levels of carbon monoxide, which can occur outdoors near roads and parking areas, may also contribute to cardiovascular diseases (Bell et al., 2009). In Norway (Oslo), the average annual CO concentration reached 0.262 mg/m^3 in 2022. In Poland, among 65 measurement stations, the vast majority (55) recorded average annual CO concentrations within the range of $0.25\text{-}0.5 \text{ mg/m}^3$ (EEA, 2023).

In Poland, the analysis of pollutants as part of air quality assessment is carried out by the Voivodship Inspectorates for Environmental Protection and involves testing for compounds directly affecting health, such as CO, NO₂, SO₂, C₆H₆ or PM. Due to the fact that the direct impact of freight transport on the urban environment was assumed to be one of the basic criteria for selecting the research area, its delimitation primarily included data on the level of emissions of toxic compounds, in particular NO₂, which, according to the data of the Voivodship Inspectorate for Environmental Protection, is the highest in the area of Szczecin Śródmieście.

Pollutants dispersion models

The problem with maintaining local concentrations of key air pollutants at a given level is related to the significant impact of factors that go beyond the primary sources of emissions that can be controlled (e.g. by introducing restrictions in city centers, related to the intensity of truck traffic). Air quality in cities is determined by the degree of industrialization, population density, topographic conditions, and meteorological conditions. When analyzing the pollutant dispersion, the following factors may be taken into account: wind speed and direction, precipitation, air temperature, regional topography, amount and type of emission sources, buildings and structures located in the studied area. Numerous models of dispersion can be found in the subject literature (Lushi, Stockie, 2010; Munir et al., 2021; Tominaga, Stathopoulos, 2018; Milando, Batterman, 2018). One of them is the Gaussian Plume Model (GPM) which assumes that pollutant dispersion follows the normal statistical distribution. By assessing various techniques such as CFD simulation (Bady, 2017) or RLiNE (Milando, Batterman, 2018), or Briggs parameterization (Griffiths, 1994), the GPM model is characterized by much higher computational efficiency. The publication (Bady, 2017; Wang et al., 2017) presents a comparison of various models describing the dispersion of inert gas in an idealized urban environment. The authors used experimental data available in the literature as a benchmark to evaluate statistical performance for each model. Their results showed that, using several statistical measures, performance of models such as GPM can be classified differently, based on individual parameters. Consequently, selection of an appropriate parameter can be guided by the intended purpose of the model.

The GPM is based on a single simple formula similar for each receptor point, therefore it has an extremely fast response time, which is important when studying the complex systems. However, the model is constrained by a number of simplifications, one of which is the omission

of chemical reactions in the atmosphere. Only a few studies conducted to date are reported to include chemical reactions — primarily the conversion of NO into NO₂ — in the Gaussian Plume Dispersion Model. Kewley (1978) modelled the atmospheric dispersion of pollutants using the Gaussian plume model, incorporating rapid chemical reactions between NO and NO₂ in the presence of O₃ to achieve instantaneous equilibrium. Kimura (1978) presented a simple reaction model for NO, NO₂, O₃, which could be easily combined with a general atmospheric diffusion model. The constants in the proposed model were estimated directly on the basis of experiments carried out in a smog chamber. Diffusion equations were separated from the chemical reaction equations, and the concentrations of nitrogen oxides and ozone were calculated by means of an approximation method. Arellano et al. (1990) proposed a chemically reactive Gaussian plume model incorporating macro- and micromixing with four chemical reactions of the NO, NO₂ and O₃, which were used to determine the conversion of nitric oxide to nitrogen dioxide. Kitabayashi et al. (2006) developed an Integrated Plume Dispersion Model with Chemical Reactions, where atmospheric diffusion and chemical reactions of NO, NO₂, O₃, O in the plume and ambient atmosphere were described by a set of ordinary differential equations. The model was explored for different emission conditions and background concentrations. Ferrero et al. (2012) developed a fluctuating plume model for pollutant dispersion, taking into account the chemical reactions of NO, O₃ and NO₂ described in the form of partial differential equations. The model was tested against the measured data in a wind tunnel, where NO was emitted from a source in an ozone environment.

The aim of this paper is to present the possibility of applying the analytical Gaussian Plume Dispersion Model (GPDM) to determine the dispersion of air pollutants from freight transport in an urban area with the use of real data obtained from road traffic detectors. In this article, to illustrate the simulation of dispersion of selected pollutants on a plane parallel to the road surface, the height of 2 meters (receptor height) was applied, assuming the constant emitter height of 0.2 m. Similar studies by other authors demonstrate various approaches, including depiction of dispersion of selected pollutants at different heights. However, in most publications pollutant distribution is modelled at lower heights (reflecting to the emitter heights). The concentration of pollutants in the cross-sectional plane relative to the road decreases with increasing height. Therefore, our study results aim to visualize the distribution of pollutants not in the critical plane parallel to the road, but in the “exposure” plane, particularly in relation to residents of those road segments, as well as pedestrians and workers.

In our study, we proposed a model that incorporates chemical reactions for NO₂ and CO pollutants. The reactions were represented by two ordinary differential equations describing the conversion of NO₂ to NO and CO to CO₂. The proposed modified Gaussian Plume Model (GPM) enables identification of street areas that are highly exposed to traffic pollution, and also allows predicting the pollutant dispersion depending not only on the vehicle traffic intensity, but also on the meteorological conditions (wind direction and speed, category of atmospheric stability, etc.). The proposed model may be used as a supporting tool when deciding on potential

locations for further air quality monitoring stations managed by the city and environmental protection authorities.

2. Research area and data

For the purposes of modelling the dispersion of selected pollutants in the urban agglomeration, measurement data concerning traffic intensity and meteorological parameters for two cities: Oslo (Norway) and Szczecin (Poland) were used. When specifying the research area and selecting the certain street sections, the main criteria were the accumulation of commercial and service units in a given area and the intensity of business and private activity, which usually contributes to increased demand for transport. The selected research area was a 300 m long section of Aleja Wojska Polskiego Street in the city of Szczecin, running from the intersection with Jagiellońska Street to Plac Zgody. The entire Aleja Wojska Polskiego Street with the length of 6.9 km is one of the main streets of Szczecin, constituting an important traffic route running from the city center towards the north-west and at the same time being part of regional road No. 115. The street additionally connects national road No. 10 in Szczecin with the Dobieszczyń-Hintersee border crossing between Poland and Germany. The selected research area in Oslo was a 300 m long section of Nylandsveien street, stretching from the roundabout located next to Busterminal and PKS Airport Bus to the intersection with Hausmanns gate. The choice of this section of Nylandsveien Street, located in the very center of Oslo, was determined by the fact that it is part of the access road to the bus and railway stations, and in its close vicinity there are numerous commercial and service facilities, bars and cafes, cultural institutions (opera, museums, etc.), and office buildings.

In the first stage of the research study, traffic intensity and vehicle speed were measured on the selected road sections over a period of 5 weekdays. The data for Aleja Wojska Polskiego in Szczecin were collected from March 7, 2022 to March 11, 2022, while for Nylandsveien in Oslo — from April 4, 2022 to April 8, 2022. The measurements were made using the Sierza SR4 device, over a 15-hour period between 4 a.m. and 7 p.m. for both sections. The measurements were conducted continuously, and the collected data was segmented into one-hour intervals. The device allowed for classification of monitored vehicles into 4 categories: motorcycles, passenger cars, delivery vehicles (6-9.5 m long) and trucks (9.5-25.5 m). Due to the negligible share of motorcycles, this group was eliminated from further research.

Each vehicle category was assigned emission factors, taking into account the speed at which the vehicles were moving. The factors by vehicle class and speed are based on the HBEFA 3.2 emission factor database. Handbook Emission Factors for Road Transport (HBEFA) is a Microsoft Access database application providing emission factors, i.e. the specific emissions

in g/km, for all current road vehicle categories (passenger cars, light duty vehicles, heavy duty vehicles, buses, and motorcycles). Emission factors are provided for all the regulated and the most important non-regulated air pollutants as well as for fuel consumption and CO₂. HBEFA is used to estimate road transport emissions at various spatial aggregation levels, from national to street level.

The second stage of the research data collection included obtaining the meteorological data for Szczecin and Oslo. The parameters related to wind direction and speed for Szczecin were obtained from the available reports issued by the Institute of Meteorology and Water Management (Gdynia Maritime Department), while the corresponding data for central Oslo was sourced from the Norwegian Meteorological Institute (Figure 1). For further research, the wind directions and speeds most frequently occurring in the analyzed area were selected.

3. Research methods

A common application of atmospheric dispersion models can be estimation of emissions of toxic contaminants from cars driving on crowded streets of urban agglomerations, which can be approximated as line sources. One of these models is the Gaussian Plume Dispersion Model (GPDM), which was based on the works of Pasquill (Pasquill, 1961) and Gifford (Gifford, 1961). The GPDM for the continuous point source emitting gaseous pollutants is given by the following equation (Bady, 2017):

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left\{ \exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right) \right\} \quad (1)$$

where:

C is the pollutant concentration (mg/m³) at location of receptor (x, y, z), where x is the downwind distance from source to receptor (m), y is the lateral distance from source to receptor (m), z is the receptor height above the ground (m),

Q is the emission rate from the point source (mg/s), u is the wind velocity (m/s),

σ_y and σ_z are the horizontal and vertical dispersion parameters, respectively (m),

H is the effective emitter height (m). Pollutant dispersion in this study was modelled for height above the ground $z = 2$ m, with effective emitter height of $H = 0,2$ m.

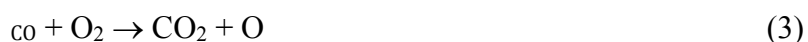
Considering that the model is based on a simple formula describing the three-dimensional concentration field of contaminants generated by a point or line source, and has an extremely fast response time, the dispersion of two key gaseous pollutants from vehicle emissions — carbon monoxide CO and nitrogen dioxide NO₂ — was modeled in this study with the use of the GPDM.

For a line source, the traffic road is treated as a line that contains a large number of continuous point sources (emitters). Thus, in this study, the emitter network was modeled as a line source by dividing the road into equal 1-meter-wide segments, which corresponded to the number of emitters. The mechanism of diffusion from each emitter was assumed to be independent of the presence of other point sources. For each emitter, the origin is shifted to the center of the considered emitter, with the modified x-axis aligned in parallel to the wind direction, and the modified y-axis oriented perpendicular to the wind direction. The concentration of pollutant at any receptor was computed by applying the principle of superposition which states that the concentration at a receptor located at a certain point (x,y,z) is the sum of contributions from all the point sources making up the line source. For the purpose of this study, we assumed a dispersion area (dispersion domain) of 800 x 800 m, with a grid of receptors spaced every 1 meter along the x- and y-axes.

The values of the horizontal (σ_y) and vertical (σ_z) dispersion coefficients for urban areas, used in the model to represent atmospheric diffusion, were determined using the McElroy-Pooler formulas.

The GPDM has some limitations. The model operates under steady-state conditions $\frac{dC(x,y,z)}{dt} = 0$, which implies that the rate of emission from the point source is constant (in this study with an hourly time step). It does not take into account wind variability. The flow is homogeneous, which implies that the wind speed is constant both in time and with height (u does not depend on t and z). It is assumed the pollutant is conservative and there is no gravitational settling. The terrain underlying the plume is flat. Reflection of the plume at the underlying surface is perfect (no ground absorption) and no chemical reactions occur.

Therefore, in the model we included chemical reactions with NO_2 and CO pollutants, which mix with other compounds in the atmosphere and may react with them. Among the numerous reactions occurring in the atmosphere, the following reactions are included:



which can be described by differential equations for second-order reactions:

$$-\frac{d[\text{NO}_2]}{dt} = k_{\text{NO}_2} \cdot [\text{NO}_2] \cdot [\text{O}_2] \quad (4)$$

$$-\frac{d[\text{CO}]}{dt} = k_{\text{CO}} \cdot [\text{CO}] \cdot [\text{O}_2] \quad (5)$$

where $[\text{NO}_2]$, $[\text{CO}]$ and $[\text{O}_2]$ represent the concentration of respective species after time t [mol/cm^3], where t is reaction time [s], k_{NO_2} , k_{CO} is a second-order rate constant [$\text{cm}^3 \text{mol}^{-1} \text{s}^{-1}$]. Assuming that the oxygen concentration in the air is much higher than NO_2 and CO ($[\text{NO}_2]$, $[\text{CO}] \ll [\text{O}_2]$), O_2 can be a constant value $[\text{O}_2] = \text{const}$. Separating the variables $[\text{NO}_2]$, $[\text{CO}]$ and t in equations and integrating both sides, we obtain the concentrations of NO_2 and CO after the reaction:

$$[NO_2] = [NO_2]^o \exp(-k_{NO_2} \cdot [O_2] \cdot t) \quad (6)$$

$$[CO] = [CO]^o \exp(-k_{CO} \cdot [O_2] \cdot t) \quad (7)$$

where:

$[NO_2]^o$, $[CO]^o$ represent the initial concentration of species $[\text{mol}/\text{cm}^3]$ at the location of receptor (x, y, z) ,

t is the diffusion time of NO_2 and CO molecules from the emitter to the receptor [s].

Taking into account equations (1), (6) and (7), we get the final equations as follows:

$$C(x, y, z)_{NO_2} = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left\{ \exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right) \right\} \cdot \exp(-k_{NO_2} \cdot [O_2] \cdot t) \quad (8)$$

$$C(x, y, z)_{CO} = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left\{ \exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right) \right\} \cdot \exp(-k_{CO} \cdot [O_2] \cdot t). \quad (9)$$

Second-order rate constants for reactions (4) and (5) were sourced from (Garvin-Edit., 1973).

4. Results and discussion

To analyze the model outputs shown in Figures (Fig. 2-5) that illustrate the dispersion of selected pollutants, first it is necessary to discuss the data obtained from the measurements of traffic intensity and vehicle speed on the selected road sections. Over the period of 5 weekdays, the total amount of 5960 light- and heavy-duty vehicles were operating on the road section selected for the research study in Szczecin. The delivery vehicle and truck traffic was at its highest on Monday between 10 a.m. and 1 p.m., when 764 vehicles per hour were recorded, while the average for the entire period under study was 80 vehicles from this group per hour. In the case of the road section chosen in central Oslo, a much more even distribution of the traffic intensity of delivery vehicles and trucks was found, both in terms of the time of day and the day of the week, ranging approximately from 60 to 123 vehicles per hour (extreme values for the 4 working days except Thursday, when the number of vehicles of this type per hour did not exceed 29). This relatively even traffic intensity of delivery vehicles and heavy trucks occurred between 10 a.m. and 4 p.m. and was noticeable especially for the first three days of the week (Monday–Wednesday). Over the full workweek, the total amount of 3,453 light- and heavy-duty vehicles were operating on the road section selected for the research study in Oslo, and the average number of vehicles of this type per hour was 46. The total number of passenger cars recorded on the selected road sections in the examined period was similar for both cities and amounted to 48,672 for Nylandsveien in Oslo, and 46,921 for Aleja Wojska Polskiego in Szczecin. The average speed of all the vehicles traveling in the given sections in the entire analyzed period was as follows: 51 km/h for Oslo, and 38 km/h for Szczecin.

Figures 2-5, which show the dispersion of NO₂ and CO on the selected road sections, were prepared based on data from a single hour of measurements on one day (a 1-hour model). The selected period was characterized by relatively high traffic intensity (Wednesday for Szczecin and 12 p.m. for Oslo). The figures show the distribution of concentrations of selected gaseous compounds [mg/m³] in a horizontal projection (x, y), at a constant vertical distance above the ground (z = 2 m), assuming that the source of emissions from road transport is at a height of 0.2 m. The displayed concentrations represent an example of NO₂ and CO dispersion from vehicles operating for one hour on the selected road sections, under specific meteorological conditions. In terms of traffic intensity, the type of vehicles and their speed are the main factors influencing the maximum value of pollutants concentration, occurring along the traffic axis. Both the increase in the share of trucks and the reduction in speed have a negative impact, as they contribute to an increase in local pollution concentrations.

Among the meteorological parameters that influence the change in air pollutants concentration in the horizontal projection (x, y), the wind direction and speed are the most important. In order to show an example of an impact of atmospheric conditions on pollutants dispersion, two variants of wind direction were adopted, assuming moderate conditions in terms of atmospheric stability (type C – slightly unstable). In the first option (a), the wind direction and speed occurring most frequently in a given area were selected: wind direction SW with a speed of 4.2 m/s for Szczecin; and wind direction NE with a speed of 2.9 m/s for Oslo. In the second variant (b), a simulation was developed for wind directions aligned with the vehicle movement axis, i.e. longitudinal to the selected road sections. When analyzing individual streets, usually a higher wind speed has a positive effect on the faster spread of undesirable gas compounds in the air and thus reducing their high local concentration, as long as the wind direction allows free air movement, taking into account the building density in urban agglomerations. In extreme cases, in the case of calm weather, local concentrations accumulate, creating an environment conducive to exceeding the permissible concentration levels.

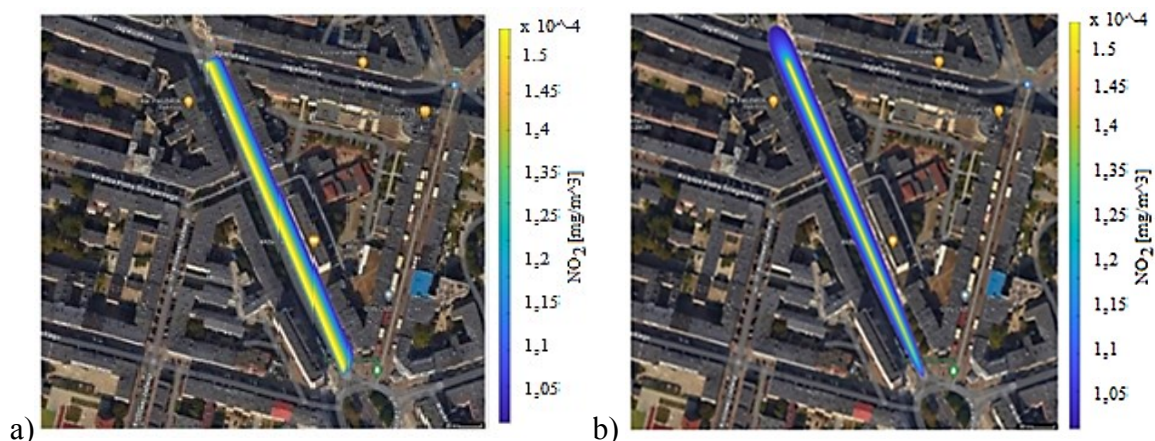


Figure 2. (a) Dispersion of NO₂ in the examined street in Szczecin, under specific traffic intensity and meteorological conditions (SW 225° wind; v = 4.2 m/s); (b) Dispersion of NO₂ in the examined street in Szczecin, under specific traffic intensity and meteorological conditions (156° wind – aligned with road axis; v = 4.2 m/s).

Source: Own study.

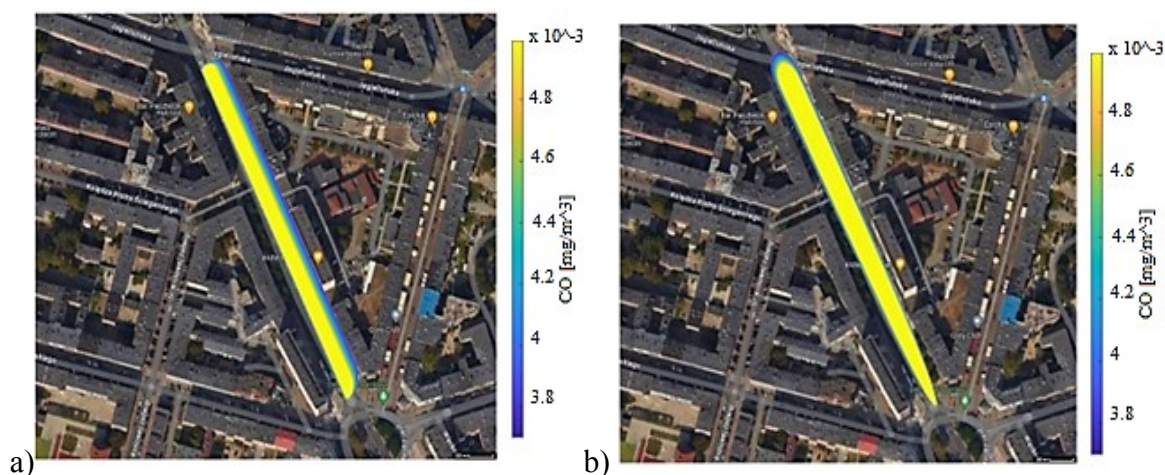


Figure 3. (a) Dispersion of CO in the examined street in Szczecin, under specific traffic intensity and meteorological conditions (SW 225° wind; $v = 4.2$ m/s); (b) Dispersion of CO in the examined street in Szczecin, under specific traffic intensity and meteorological conditions (156° wind – aligned with road axis; $v = 4.2$ m/s).

Source: Own study.

The wind direction changes the pollutant dispersion, but there is no clear pattern of that phenomenon, based on the obtained simulation data. When analyzing Fig. 2a and 2b, in the case of the SW wind, the concentration of NO₂ decreases from the maximum value along the road axis, i.e. 1.5×10^{-4} mg/m³ to 1×10^{-4} mg/m³ approximately 14 meters downwind in the northeast (NE) direction, and drops further to the level of 1×10^{-5} mg/m³ at a distance of ca. 200 meters. At the same traffic intensity level, with the wind parallel to the road axis, the concentration reduction in the range as above (from 1.5 to 1.0×10^{-4} mg/m³) occurs at a much closer distance, i.e. from about 10 m from the road axis. Smaller concentrations (1×10^{-5} mg/m³) are found at a distance of approximately 200 meters (the same as in case of the SW wind), which probably results from the same wind speed. A different pattern is observed in the case of CO dispersion in the examined street in Szczecin: comparison of Fig. 3 a) and b) shows that the area with the highest CO concentration is larger when the wind direction is parallel to the road axis. In the case of SW wind, the width of the street canyon where the CO concentration is the highest reaches about 13 meters, while in the case of a parallel wind — about 21 meters.

Examples of the spread of selected pollutants for the road section in Oslo are shown in Fig. 4 and 5. Compared to the dispersion plots presented for Szczecin, these distributions are generally characterized by higher concentrations at the points (x, y) with the same distances to the road axis, which results from the greater traffic intensity in the examined time period (1276 passenger cars, 83 delivery vehicles and 20 trucks per hour in Oslo versus 947 passenger cars, 48 delivery vehicles and 18 trucks per hour in Szczecin), as well as from the lower wind speed in Oslo (2.9 m/s vs 4.2 m/s in Szczecin).

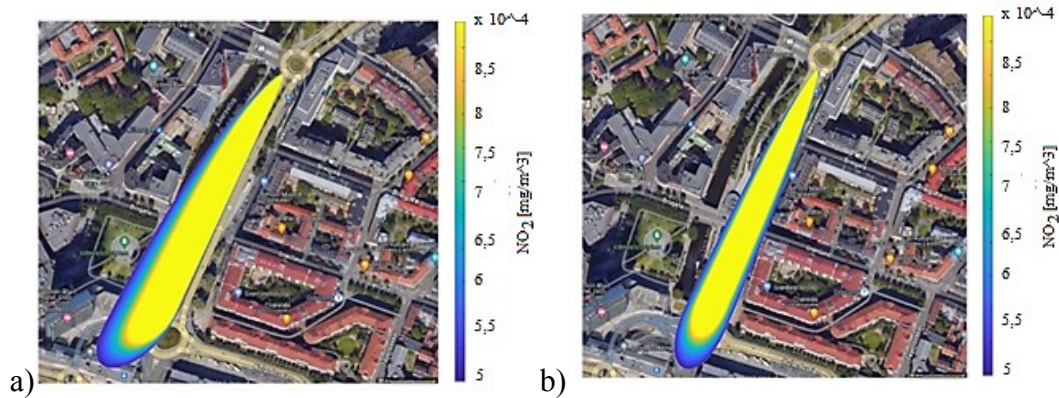


Figure 4. (a) Dispersion of NO₂ in the examined street in Oslo, under specific traffic intensity and meteorological conditions (NE 45° wind; $v = 2.9$ m/s); (b) Dispersion of NO₂ in the examined street in Oslo, under specific traffic intensity and meteorological conditions (25° wind – aligned with road axis; $v = 2.9$ m/s).

Source: Own study.

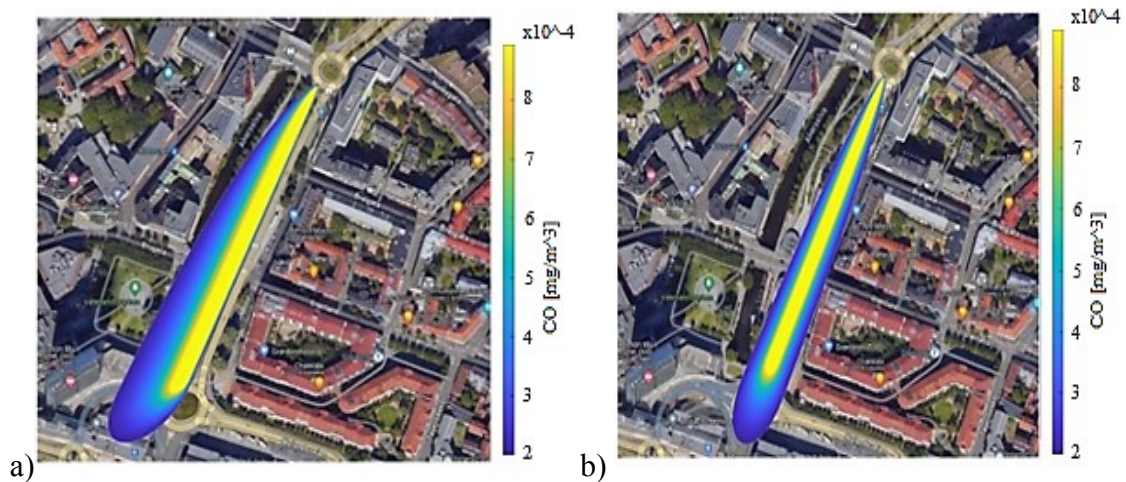


Figure 5. (a) Dispersion of CO in the examined street in Oslo, under specific traffic intensity and meteorological conditions (NE 45° wind; $v = 2.9$ m/s); (b) Dispersion of CO in the examined street in Oslo, under specific traffic intensity and meteorological conditions (25° wind – aligned with road axis; $v = 2.9$ m/s).

Source: Own study.

Despite a slight difference in the wind directions used to illustrate the distribution of pollutants in the selected street section in Oslo (25 and 45 degrees), differences in the dispersion of the tested gaseous compounds are also observed in this case. For example, in the case of NO₂, the maximum concentration of 9×10^{-4} mg/m³ is maintained over a width of approximately 35 m along the traffic axis in the case of the NE wind, and over approximately 20 meters when the wind is aligned with the road axis.

5. Conclusions and future research direction

In this paper, we presented the possibility of applying the modified Gaussian Plume Dispersion Model (GPDM) to study the dispersion of pollutants emitted into the atmosphere from road freight transport. The model was expanded to include chemical reactions of nitrogen dioxide NO_2 and carbon monoxide CO with atmospheric oxygen, allowing for more realistic concentrations and dispersion of contaminants. The study of pollutant dispersion for NO_2 and CO was carried out in the streets of the urban agglomerations of Oslo (Norway) and Szczecin (Poland). The analysis of pollutant distribution was carried out in two variants of wind direction, under moderate conditions in terms of atmospheric stability (type C – slightly unstable). In the first variant, the prevailing wind direction and speed for the area were selected: wind direction SW with a speed of 4.2 m/s for Szczecin; and wind direction NE with a speed of 2.9 m/s for Oslo. In the second variant, a simulation was carried out for wind directions aligned with the vehicle movement axis. It was found that higher wind speeds generally have a positive effect on the faster dispersion of undesirable gas compounds in the air, as long as the wind direction allows free air flow — an effect also influenced by the characteristics of the urban development pattern. The proposed modified Gaussian Plume Dispersion Model can be used as a fast-response system for identifying exceedances of permissible pollution standards in urban agglomeration areas which are highly exposed to transport pollution.

Gaussian Plume Dispersion Model, used in our research is commonly used to map pollution distribution around traffic systems, but has some limitations. One of the limitations is steady-state conditions, which imply that the rate of emission from the source is constant and does not change over 1 h, and the wind speed is constant both in time and with height. This implies that the Gaussian plume equation can be applied only for shorter distances below 10 km, for average wind speeds of more than 1 m/s, and when the meteorological time scale is typically 1 h (Venkatram, Thé, 2003; Khare, Shiva Nagendra, 2007). Despite many limitations Gaussian Plume Model is quite widely used due to appealing conceptually related to a simple mathematical solution, easy of use (require relatively few input data), and high efficient in computer running time. Therefore, our model can be used to forecast, at hourly intervals, dispersion of pollutants from road transport in urban agglomerations. In this case model reflect real-world variability at hourly intervals, taking into account the dynamics of meteorological parameter changes and the flow of vehicle traffic. However, to overcome certain simplifications of the model, further research is necessary in this area, which should include:

- complex terrain in the form of street canyons,
- low wind speeds,
- chemical reactions of pollutants (research proposed in this work),
- absorption of pollutants by the ground or other physical bodies.

Additionally, to monitor the distribution of pollutants over time for a road section/road system, it is necessary to enter additional independent variables in form of meteorological data comprising wind speeds and directions and ambient temperature. Simultaneously, in real-time road traffic measurements must be also performed, in order to obtain data for the number and type of vehicles, and the average speed on the road section.

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