Analysis of the impact of motor vehicles on the air quality on the example of Legionow Square in Wroclaw

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Abstract. Constant increase in number of vehicles and consequently significant contribution of transportation to air pollution level enforce actions leading to better assessment and emission reduction in urban areas. Advanced measurement stations are being located in key city zones to regularly monitor harmful substances concentration. As an alternative, computer modelling can be used for air quality assessment. This paper presents full process of modelling together with data preparation description. Road emission was evaluated by applying Network Emission Model (NEMO) to Legionow Square junction in Wroclaw, Poland. Geometry of study area was defined using GIS software, fleet structure was determined based on data from Intelligent Transport System (ITS) and emission factors were taken from HBEFA database. Simulation provided detailed data about transportation-related emission of various compounds, among which NOx, CO, HC and PM are of the highest importance. Results were analysed both in terms of yearly summary and spatial distribution between traffic lanes. Simulation showed extensive emission of CO, PM and NOx contributing to smog occurrence in Wroclaw. Opportunities for further improvements were discussed as well as the possibilities of applying it in planning systems and integration with dispersion models to develop complete air quality monitoring system for urban areas.

1. Introduction
For over 100 years of automotive history, the possibility of fast relocation and negligible quantity of vehicles on roads allowed to consider negative influence of road transportation as insignificant. However, rapid increase in fleet over recent years has made such approach out of date. According to World Health Organization 30% of world population is subjected to harmful pollutants of amounts exceeding normative values. Road transportation is responsible for 20% of all air pollution in Poland and that percentage is significantly higher in urban areas [1]. Fossil fuel combustion process is responsible for just a portion of transportation-related pollution. The remaining part is driven by automotive industry (i.e. car manufacturers, gas stations, utilization plants), technical condition of vehicles as well as road infrastructure (road conditions, cross roads construction, parking lots, traffic congestion).

As a consequence of growing risk coming from transportation industry, a lot of effort is being placed in building monitoring systems and introducing new regulations leading to limitation of emission levels especially in urban areas. Most of major European cities are investing in sensors measuring contamination level in real time. As an alternative to expensive net of sensors dedicated to each substance, several research teams are developing computer models to simulate emission from vehicles as well as pollution dispersion in the atmosphere [2, 3, 4]. Apart from evaluating contamination level in
a certain point of interest, they offer additional features related with advanced planning as their calculations might be based not only on real data but also on expected values.

1.1. Influence of automotive industry on air quality

1.1.1. Exhaust fumes. Direct impact factor of automotive industry on air quality is exhaust fumes emission from engine vehicles. Those gases are the products of fuel-air mixture combustion process and their composition may vary depending on engine type (spark- or compression-ignition), fuel quality (octane or cetane number, contamination presence) or mixture composition (air to fuel ratio). Ideally, the products of chemical reaction of combustion should not contain any harmful substances but in reality, due to not perfect conditions or some contamination that might occur on different reaction stages, exhaust fumes contain harmful components that pollute the air and as a consequence cause various diseases to human bodies. Key components of exhaust gases that have a huge impact on surrounding environment are the following [5, 6, 7]:

- nitrogen oxides (NOx) are among the most toxic substances emitted from engines; they can react with human hemoglobin disturbing oxygen transportation throughout the body leading to respiratory irritation and pulmonary edema. Together with other compounds they form smog and acid rains. Although they can be emitted from spark-ignition (SI) engines as well, their main source is compression-ignition ones (CI);
- carbon monoxide (CO) – it is lethal substance for human as it blocks hemoglobin binding with oxygen causing immediate hypoxia that results in irreversible changes in brain or even death. What is more, it is odorless and colourless that makes it hard to detect its presence. It is created in the state of oxygen deficiency and is mostly present in exhaust fumes coming from SI engines;
- hydrocarbons (HC) from which the most dangerous are volatile organic compounds (VOC) that have both mutagenic and carcinogenic effect. Their emission from SI engines is higher than CI ones;
- particulate matter (PM) is a general name for everything that is coming from engine exhaust system and is in liquid or solid state. When their diameter is smaller than 10μm they can infiltrate human body opening a path for other toxic substances. CI engines have much higher PM emission than SI ones because of a tendency for soot formation. Apart from combustion process, particulate matter from vehicles is coming also from tire abrasion, brake pads wear and clutch wear;
- ozone (O₃) when present in stratosphere forms a protective layer reducing UV radiation amount that reaches Earth surface. However, when it appears in lower part of the atmosphere, it becomes dangerous causing mutagenic and carcinogenic effect;
- sulphur oxides (SOx) cause rhinitis, conjunctivitis and smell and taste disorders, especially during long-term exposure. SO₂ is one of smog and acid rain components. Gasoline has much lower sulphur content than diesel so emission of sulphur oxides from CI engines is higher than for SI ones.

1.1.2. Smog. It is an artificial phenomenon caused by toxic substances coming from exhaust gases. There are 2 major types of smog that are different both in terms of composition and triggering factor. London smog consists of PM, SOx and CO, it appears both at day and night, mostly during the winter, even during low ozone concentricity. It is toxic for human lungs and can lead directly to death. Photochemical smog is a combination of chemicals that come from automobile and factory emissions and is acted upon by the action of the sun. It occurs only during the day, usually in the summer when the temperatures go above 24°C and the concentricity of ozone is high. It is less harmful for human body than London smog but has a negative effect on eyes and upper respiratory tract. Main components from which that type of smog is made are HC, NOx and CO [7].
1.1.3. Acid rain. Acid rains contain molecules of nitric or sulfuric acid. Those acids are formed from sulphur and nitrogen oxides under the influence of sunlight and water contained in the clouds. Acid rains are toxic for human bodies, they contaminate water and are harmful to buildings [5].

1.2. Emission modelling in urban areas

Point source emissions coming from single vehicles depend on several group of factors. First group is related with the vehicle itself: greater engine power and higher weight lead to higher emission level. There are also differences in exhaust fumes compositions between SI and CI engines. What is more, the age of the vehicle and its technical condition also affect emission (worn engine emits more pollutants, newer cars must comply with more severe regulations and therefore are more environmentally friendly). The next group is associated with road infrastructure – i.e. complexity of road network, number of junctions and traffic lights, parking lots availability – generally, the more starts and stops there are during drive, the more contamination there is in exhaust fumes. Road emissions are also strongly correlated with driving style – main goal of eco-driving is to reduce number of accelerations and rapid brakes because in the state of dynamic conditions fuel consumption increases resulting in extensive emission. The last group of variables that affect emission is connected with surrounding environment – i.e. air temperature, weather, humidity [1, 8, 9, 10].

Air quality assessment in urban areas is based mainly on the network of sensors measuring contamination level of different pollutants in real time. The aim of computer modelling should be primarily complementation of those data, but it might also be applied for contamination peaks location and advanced planning of new or temporary road networks [10]. A good and accurate air quality assessment system should cover several applications and therefore should consist of the following components [1]:

- spatial module that collects data about geometry of selected area, land-use, road network;
- fleet module that contains data about fleet composition and traffic congestion;
- emission module that provides data about road emission;
- dispersion module that simulates spatial distribution of contamination according to weather conditions and data from previous modules.

Not every system has all those modules implemented. Some models calculate only single-source emission but in different conditions, some can assess emission from single traffic junction, others are able to simulate summarized emission from a certain area. The most important for this paper are emission models without dispersion module. Road emission can be modelled either in static or dynamic way depending on application and calculation method. An overview of the most important computer models together with their basic characteristics and key examples is presented in table 1 [3].

| Table 1. Summary of road emission models [3]. |
|---------------------------------------------|
| **Dynamic models**                         |
| Traffic situation models                   |
| Instantaneous models                       |
| Average speed models                       |
| Aggregated emission factor models          |
| Input                                      |
| velocity, traffic situation                |
| engine power                               |
| average velocity                           |
| vehicle travel kilometers, fuel consumption|
| Examples                                   |
| HBEFA                                      |
| ARTEMIS                                    |
| COPERT                                     |
| MOVES                                      |
| PHEM                                       |
| VETESS                                     |
| MODEM                                      |
| ARC’S VEMP                                  |
| NAEI MOBILE                                |
| Scale                                      |
| micro                                      |
| micro                                      |
| macro                                      |
| macro                                      |
2. Materials and methods

Emission modelling was carried out on a real example in Wroclaw, Poland. A large, highly congested junction was chosen, located near the city centre in the area of Legionow Square. For simulations, the Network Emission Model (NEMO) was used. NEMO has been developed at Technical University of Graz in Austria and is dedicated for simulating emission from engine vehicles in urban road networks. It requires proper preparation of data about geometry of each traffic lane within the investigated area, fleet with respect to structure as well as intensity and emission factors for single vehicles [11]. Full structure of modules available in NEMO is presented on Figure 1.

![NEMO structure](image)

Figure 1. NEMO structure.

2.1. Terrain

Legionow Square is one of the major junctions in Wroclaw city centre. It consists of 4 streets going to and from 4 directions labelled I-IV. For each direction, traffic lanes were identified up to the next junction with traffic lights. Lanes entering the Square were marked with a letter A, those going in the opposite direction with B. Letter C was assigned to minor lanes that were influencing the investigated area but were not linked with the Square directly. If there was more than one lane going in the same direction, consecutive numbers were assigned to each of them. Figure 2 shows the outline of the junction with individual lane labelling.

After selection of traffic lanes, geographical coordinates of each lane were defined using ArcGIS software. Coordinates of beginning and ending of each section were measured with reference to PUWG1992 – coordinate system recommended for Polish maps. Due to the fact that ArcGIS allows for 2D maps only (x and y coordinates), the third coordinate (z) associated with height was read from Google Maps. Because of relatively small study area, it was assumed that the whole junction is located at the same height of 121 m above sea level. Length of each segment was calculated based on obtained coordinates.

Next step was to determine the width of each road segment. According to Polish regulations, traffic lanes that were taken under investigation were between 2.75 and 3.5 meters wide [12]. For model
simplification reason, single width of 3 meters was applied to all road segments. NEMO required to classify each lane to one of the following categories:

- **U_MS1/2/3** – main urban road without traffic lights with different traffic intensity (1-light, 2-medium, 3-high),
- **U_TL1/2/3** – main urban road with traffic lights with different traffic intensity,
- **U_Centre** – road inside city centre,
- **U.SideR_compact/casual** – minor road in compact/casual area,
- **U_stop+Go** – urban road with stop+go traffic style.

**U_TL3** was chosen for all selected road segments.

2.2. Fleet

Once geometry was defined according to NEMO requirements, it was critical to define fleet that was going through investigated area, both in terms of its structure and intensity. Model works with the following vehicle categories:

- passenger cars (PC),
- light duty vehicles (LDV),
- heavy duty vehicles (HDV) – divided further for rigid trucks (RT), trucks and trailers or semi-trailers (TTST), coaches (COACH) and urban buses (UB),
- 2-wheelers – divided further for mopeds and motorcycles (MC),
- electric cars,
- vehicles parked along lanes.

It was needed to provide data about annual average daily number of vehicles and then define share of each category in the total amount of vehicles and subcategories within each category. In case of insufficient data, NEMO applies default settings.

Data about Wroclaw was obtained from Intelligent Transport System (ITS) operating in the city since 2013. One of its functionality is to count number of vehicles going through major junctions in the city using vision system – a network of video cameras located above traffic lights. ITS assigns vehicles to one of the following categories: passenger cars, light duty vehicles, bikes and motorbikes, trucks and buses, trucks with trailers and other unclassified. Due to the fact that such classification was not matching NEMO requirements directly, it was necessary to accept some additional assumptions:

- 60% of vehicles assigned to bikes and motorbikes were taken into account as 2-WHEELER in NEMO. Remaining part was considered to be bicycles without combustion engine,
- 100% of trucks and buses category was assigned to HDV in NEMO as trucks of any type are not allowed in Wroclaw city centre,
- 0 was put for TTST and RT, electric vehicles (not popular in Wroclaw) and parked cars (no parking allowed along selected lanes),
- default values were used to divide HDV (between coaches and urban buses) and 2-wheelers (between mopeds and motorcycles).

All calculations were performed on the data coming from year 2015. Location of cameras that were used for simulations is shown on figure 2. As visible on that figure, not every traffic lane had its own camera. Moreover, there were some vehicles that left investigated road before reaching next junction. To compensate all those uncertainties, number of vehicles assigned to each lane was calculated based on formulas listed in table 2.
Figure 2. Traffic lanes within Legionow Square area: I-IV – directions; A – entering lanes, B – escaping lanes, C – additional lanes; dots – cameras for A-lanes, squares – cameras for B/C-lanes.

Table 2. Fleet calculation for individual lanes.

| Lane   | Equation                              | Lane   | Equation                  |
|--------|---------------------------------------|--------|---------------------------|
| I-A1   | CAM*I-A1                              | III-A1| 10/90*CAM-III-A2         |
| I-A2   | CAM-I-A3/2                            | III-A2| CAM-III-A2/2              |
| I-A3   | CAM-I-A3/2                            | III-A3| CAM-III-A2/2              |
| I-B1   | (CAM-I-C+CAM-I-B2)/2                  | III-B1| CAM-III-B2/2              |
| I-B2   | (CAM-I-C+CAM-I-B2)/2                  | III-B2| CAM-III-B2/2              |
| I-B3   | 5/90*(CAM-I-C+CAM-I-B2)               | IV-A1 | CAM-IV-A1                 |
| II-A1  | (CAM-II-A1+CAM-II-A3)/3               | IV-A2 | CAM-IV-A3/2               |
| II-A2  | (CAM-II-A1+CAM-II-A3)/3               | IV-A3 | CAM-IV-A3/2               |
| II-A3  | (CAM-II-A1+CAM-II-A3)/3               | IV-B1 | 10/90*CAM-IV-B2           |
| II-A4  | 5/90*(CAM-II-A1+CAM-II-A3)            | IV-B2 | CAM-IV-B2/2               |
| II-B1  | CAM-II-B2/2                           | IV-B3 | CAM-IV-B2/2               |
| II-B2  | CAM-II-B2/2                           |       |                           |

*a CAM means camera located at indicated traffic lane

2.3. Emission factors
The connection between geometry of road network and traffic situation is emission factor defined for each exhaust fumes component and expressed in grams per 1 kilometer of driven distance. Values of emission factors are selected based on average speed in a certain traffic situation. Despite a possibility to use measured values, NEMO defaults were applied according to road type selected previously: 24.13 km/h for PC and LDV, 18.71 km/h for COACH, 15.63 km/h for UB and 24.5 km/h for MOPED and MC. By default, NEMO assigns emission factors from HBEFA database which is in line with EMEP CORINAIR. This database contains data for all vehicle types divided by categories (PC, LDV, HDV, MOPED, MC), engine size and ignition type (SI/CI). Technological class of vehicles is also taken into account based on regulations applicable (EURO norms) and fuel-saving systems installed. Data collected in HBEFA may vary in terms of obtaining methodology: using existing unambiguous
measurement method (i.e. CO, NOx), emission calculated based on fuel consumption (i.e. CO2, Pb), simplified calculation method (i.e. PAHs) [13]. NEMO user is allowed to use their own emission factors but, in this paper, default values were assigned for simulations.

3. Results

There are 3 main group of parameters than can be retrieved from simulation output file: fleet structure, yearly emission summary and emission distribution according to road sections selected within study area. Primary task of NEMO is to provide data about emission of exhaust gases, such as: NOx, CO, CO2, HC, TSP (Total Suspended Particle), PM down to 0.1μm, BC (Black Carbon), PAH, NMHC (Non-Methane Hydrocarbons), ammonium and methane. However, it is capable of calculating additional parameters like distance driven by analysed vehicles, fuel consumption (FC), AdBlue consumption, TSP emission from non-exhaust sources and hydrocarbons emitted from cars parked along investigated traffic lanes.

Figure 3 shows fleet structure with respect to different grouping parameters. Over 90% of vehicles are passenger cars and the lowest share are the 2-wheelers – 1%. Light- and heavy-duty vehicles together build 8% of fleet. Majority of the vehicles driving within study area have compression-ignition engines installed – over 60% of total fleet. Exhaust fumes emission is strongly correlated with technology class of the vehicle. Half of analysed cars comply with EURO 5 regulation (50% of SI-engine cars and 49% of CI). Around one third of the vehicles meet EURO 3 or EURO 4 norm and the share of older vehicles is negligible (less than 5%).

![Figure 3. Fleet structure: a) by vehicle category, b) by engine type c) by technology class in SI engines, d) by technology class in CI engines.](image-url)
Figure 4 shows the summary of all harmful compounds that form exhaust fumes or are coming from other transport-related sources throughout the year. Nitrogen oxides and carbon oxide account for 75% of total emitted mass of exhaust fumes. Vehicles with SI engines are the main source of CO and emitted 10t of this compound during the year. CI engines are mainly responsible for NOx emission that was also at the level of 10t per year. NEMO enables detailed analysis of Total Suspended Particle. Exhaust system is a source of only 1/6 of TSP – 5 times more is coming from non-engine related sources that can be further divided for tires wear products, brake system wear products and the dust that forms a layer on the road and is stirred up by vehicles. PM from non-engine sources has larger particles than PM related with exhaust fumes.

![Figure 4. Yearly emission of exhaust gases.](image)

Figure 5 contains a map of traffic congestion within Legionow Square. The largest number of vehicles is driving to and from direction number II. The least congested traffic lane is III-A3 which is one of the minor streets entering the junction.

![Figure 5. Vehicles quantity within study area.](image)

Based on simulation results, it was possible to generate maps of pollution distribution between selected traffic lanes. Emission is expressed by kilograms of each substance per one kilometer and one
hour. Maps can be created for every compound calculated during modelling process. Figure 6 shows an example of NOx and CO emission map from passenger cars.

![Figure 6. Distribution of compounds emitted from passenger cars: a) NOx, b) CO.](image)

4. Discussion

Network Emission Model can be used for precise emission calculations of all major transport-related contaminants. Due to a wide range of default settings and built in algorithms, it can be easily applied even in case of incomplete data. Its accuracy can be further improved by replacing standard files with data collected from real measurements, i.e. average speed, fleet age structure or emission factors.

Vehicles meeting EURO 5 emission regulation have the largest share in fleet structure. This norm accounts for the cars produced between 2008 and 2014. It must be noted that those data are default values implemented in NEMO and were determined for Austria where the share of older vehicles is smaller than in Poland. One way of fleet age structure definition would be to analyze statistical data of new vehicles registration year by year. Even such data would not be sufficient though for Wroclaw that is a large cultural, industrial and science center and majority of its inhabitants register their cars somewhere else, in their home towns. What is more, a significant group of people in the city are the students that due to their financial status, usually own older cars. Large variety of variables impacting fleet structure makes it impossible to define it precisely. According to some assessments, fleet structure in Poland should be taken as Austria or Germany 5 years earlier [10]. The same argument applies to SI/CI engines division.

Harmful exhaust gases are mainly NOx and PM in CI engines and CO and HC in SI engines. There is an additional emission of PM from non-exhaust sources. All those compounds are strongly correlated with smog creation – NOx and CO in the presence of sunlight become a source of ozone that in combination with dust form smog. In fact, this phenomenon poses a great danger to inhabitants in Wroclaw, especially in the summer.

The next aspect of proposed methodology is a possibility to use such process for advanced planning of new transport solutions. Graphic tools allow for direct visualization of simulation results in the form of eye catching maps with spatial distribution of traffic or air pollution. Such maps can be useful in comparative analysis of multiple options. Moreover, NEMO can be used during rebuilding of existing road structure as it can provide data about traffic congestion in each direction that helps to quickly react in accordance with current situation. NEMO output files can be directly applied in dispersion models (i.e. GRAL or VISUM) and act together as a complete air quality assessment system.
5. Summary

In this paper, an approach for analysis of motor vehicles impact on air quality was shown on the basis of Legionow Square in Wroclaw and Network Emission Model application. The effects of performed simulations consist of detailed fleet definition, yearly emission levels of all compounds from transport-related sources, detailed division of emission between different vehicle types and spatial distribution of data according to selected road sections. Results of the analysis confirm that high traffic congestion within study area leads directly to smog creation due to extensive NOx, CO and PM emission. Output files allow for direct visualization of all data connected with motor vehicles traffic and can be an input for dispersion models. Computer modelling is a cost-effective alternative for sensors network development and has an additional feature of multiple options analysis useful for advanced planning.

Data that is available for Wroclaw is incomplete and the assumptions and simplifications that were made might have affected simulation accuracy. This paper can be a starting point for further development so that a model can become a part of incomplete air quality monitoring system.

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