Comparison of exhaust emission on the basis of Real Driving Emissions measurements and simulations

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Abstract. Designing of modern transport systems involves the need to meet a large number of requirements. The influence of designed road infrastructure on the environment is very wide and important. The most valid aspect in this case is the reduction of emissions of harmful compounds by increasing the fluency of vehicles flow and building collision free road intersections. But it should be started from establishing the initial emission level of harmful compounds. This paper presents a methodology for determining exhaust emissions from vehicles moving on the national road no. 50 in area of Zyrardow. Modern measuring tools such as the PEMS and the microscopic road simulation software, using the application to determine exhaust emissions, were used for this purpose.

1 Introduction

Important issues in case of the impact of automotive on the environment are traffic congestion, its fluency and the share of heavy vehicles. In 2013, motor vehicles in Poland had a significant share in pollutant emissions [1]:

- 32% of nitrogen oxides,
- 22% of hydrocarbons,
- 20% of carbon monooxide,
- 19% particulate matter.

Air pollution caused by fuel combustion occurs mainly in large urban agglomerations where there is heavy traffic and there are a lot of buildings which prevents good ventilation. This problem may rise, as it is expected, that between 2015 and 2020 the traffic volume of vehicles will increase about 15%. This problem can be solved, for example, by introducing vehicles that meet stringent emission standards. However, sudden change of the entire fleet of vehicles is impossible. For this reason, many solutions need to be introduced at the same time, which will enlarge the possibility to achieve the stated goal. The directions of development of road infrastructure and transport systems have been included in the relevant documents: European Transport Policy [2, 3] and Transport Policy of the Country 2006-2025 [4].

Despite the fact that in Poland in 2007-2015 more than 200% of the increase in motorway and expressway networks was registered, national road infrastructure still requires development and modernization expenditures. New ventures significantly increase the capacity of national roads and meet citizen' expectations for comfortable, fast and secure communication. The main objective of the National Road Construction Program for 2014-2023 (with a view to 2025) adopted in 2015 is to build a coherent and modern national road system to ensure the efficient functioning of road and passenger transport. The program is diagnosing the state of the current road sector, defining both the objectives to be achieved and the key areas constituting the so called "Bottlenecks" in passenger and freight transport. The document assumes the completion of the construction of expressways and motorways and the construction of dozens of bypasses in national roadways. In addition, the Program includes a list of investment tasks related to the improvement of traffic safety so called: Dangerous Places Elimination Program.

The implementation of the projects planned in the above mentioned documents allows many places to shift transit traffic from city centers to newly built ring roads and improve the smoothness of car communication. Investments in the construction of bypasses allow about 90% of all transit traffic of cars and trucks outside the city to be delivered in large cities. Traffic in cities without ring roads represents a very serious burden on road infrastructure, while at the same time being a source of significant noise and air pollution. However, the construction of the ring road is not limited to the construction of a new single-lane or two-lane road, for example. It consists also the construction of viaducts over the ring road, intersections and access roads, as well as solutions that improve traffic safety and provide better environmental protection. In Poland in 2014-2018, 12 new bypasses are planned to be built in the most sensitive transit points (Fig. 1).

To accurately assess the exhaust emission of a single vehicle and the entire traffic stream, existing and new designed road infrastructure, there should be the appropriate method selected. The accuracy of the chosen method affects many aspects. Most important from the perspective of reliability of the assessment are two issues: the degree of simplicity adopted in emission modeling and sources of emission data. In the second

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case, they may be: homologation data, emission factors as a function of the mass of consumed fuel, road measurements and simulation evaluations of road infrastructure [5, 6]. Increasingly popular are the Real Driving Emissions measurements of vehicles in which actual emissions of harmful emissions are known. The performance of the vehicle's driving units in bench tests is often understated and does not correspond to those used in road conditions, which contributes to the false image of vehicle exhaust emission. Computer simulations are also gaining popularity, which has several advantages, including the ability to change arbitrary the traffic density and parameters of the road infrastructure, limited only by the functionality of the software, and time savings compared to traditional methods.

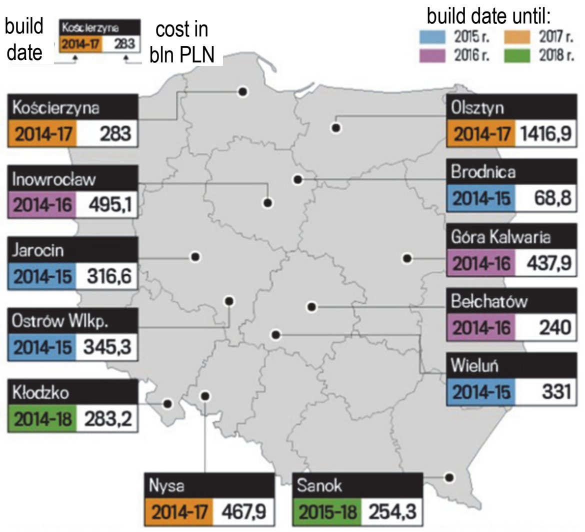

Fig. 1. Location of new bypasses in Poland in 2014-2018 [7].

This article compares the exhaust emission factors for the selected road infrastructure section obtained during RDE (Real Driving Emissions) and computer simulation using specialized software. Until now the authors obtained results of gaseous compounds. It is well known that the particulate matter also is very harmful. In future the authors will determine the influence of road infrastructure on particulate matter emission. This aspect needs to be considered very precisely, because there are some important cases that must be taken into consideration, as: mass and number evaluation or particulate filter regeneration [8-10].

2 Research methodology

The issue described later in the article concerns National Road No. 50 within Zyrardow (Fig. 2). At present, DK 50 is run by the Zyrardow bypass, but all of the performed evaluations have been applied to the situation when all transit traffic was carried out by the town. Due to the high daily traffic (about 17,000 vehicles per day) and the urban nature of the road, the traffic was intermittent often by stops. This situation is confirmed by pictures from the camera recording the image in front of the research vehicle (Fig. 3).

In order to reduce the impact of the driver's driving style on the obtained results, the study was conducted in the form of driving behind the preceding vehicle, trying to maintain its speed, acceleration, thus adopting its driving style. Such a methodology is commonly used and is called driving "behind the leader". The beginning and the end of registration of the measured values fell to the point of connection of the bypass and the national road no. 50. A lot of attention was paid to repetition of the measurements, so 10 road trips were performed during the road tests (5 passes in both directions). Time of measurements: 10:58-14:55. The ambient temperature was 23-29 °C.

Fig. 2. Research route (using [11]).

Fig. 3. Situation on the road during RDE measurements.

Passes during road tests were carried out by a passenger car, driven by a 1.8 liter supercharged SI engine (Table 1). This vehicle complied the Euro 4 emission standard. The exhaust aftertreatment system is typical for SI engines with multi-point injection, a three-way catalytic converter.

Table 1. Research vehicle.

Vehicle type	Passenger car
Engine type	SI, 4-cyl.
Emission standard	Euro 4
Max. power/max. torque	130 kW/250 Nm
Aftertreatment system	three-way catalytic converter
Mileage	80,000 km
Curb weight	1430 kg
Load	300 kg

Exhaust emission measurements were conducted using the Semtech DS mobile exhaust gas analyzer system (Fig. 4). This instrument has been designed to measure exhaust emissions in real traffic conditions and meets the requirements of the relevant standards [12-15]. For the concentration of harmful compounds in the exhaust can be refer to the driving characteristics and conditions of the drive system, the Semtech DS device enables communication with the vehicle diagnostic system. It is possible to read data from systems supported by different data protocols, making it compatible with PC, LDV and HDV vehicles. Also a GPS module and a meteorological system for measuring pressure and ambient temperature is included. All of these are recorded at a frequency of 1 Hz, which allows the observation of dynamic changes in the concentration of substances contained in the exhaust gases.

For the Semtech DS, but also for other types of systems used to measure exhaust emissions of gaseous pollutants [16, 17], collected exhaust gases are supplied with a heated line (Fig. 4). This element is maintained at 191 °C to prevent the hydrocarbons condensation in the measuring line. The next step is to filter out the mechanical pollutants, then the exhaust gas is conducted directly into the FID analyzer where the hydrocarbon concentration is measured. Subsequently, the analyzed gases are cooled to 4 °C, followed by nitrogen, carbon monoxide, carbon dioxide and oxygen measurement. After passing the whole circuit, exhaust gases are discharged into the environment. Signals from all analyzers and GPS modules, weather stations, and on-board diagnostic systems go to the control unit.

The computer simulations of the passage through the analyzed road infrastructure were made using PTV Vissim software [18], which is a tool for traffic simulation in the microscopic scale [19-21]. The advantage of this system is the ability to accurately design the geometry and parameters of the modeled road section and traffic [22]. The programmed software has extensive databases, including traffic models for different vehicle groups such as passenger cars, trucks, buses, motorcycles. In addition, the expanded version contains data to simulate the exhaust emission of pollutants from SI and CI vehicles that meet current and previous emission standards. The software has implemented a VERTIS+ emission models [23-25] developed jointly with TNO (Netherlands Organization for Applied Science Research) from the Netherlands. This kit is used to forecast emission indicators and energy usage rates that are representative for vehicle fleets in different countries. Emission factors vary by vehicle type and traffic situation. The VERSIT+ emission database is based on information from 12,000 different driving cycles including road test results. They are generalized for vehicles and may vary from specific vehicle groups.

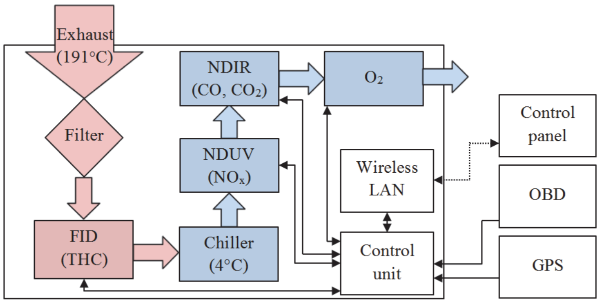

Fig. 4. Functional diagram of the Semtech DS exhaust emission device.

During the analysis in PTV Vissim software, it is possible to view vehicles in the network, for example, from the perspective "from bird's eye view" or from the perspective of the selected vehicle on the network (Fig. 5). At any time of simulation, it is also possible to preview selected parameters of any vehicle, such as speed, position in the network or temporary exhaust emissions. In addition, current data on vehicle traffic on the analyzed road infrastructure was used in the simulations [26].

Fig. 5. View of selected part of modeled infrastructure in PTV Vissim.

3 Research results

3.1 Road tests

The characteristics of rides by analyzed section of road infrastructure (in the north-south direction – referred to as 1-x and in the south-north direction – designated as 2-x): time, distance and average speed of each passage are shown in Fig. 6–8. Values of these parameters were recorded at 1 Hz using GPS data, then summed and calculated to determine the average speed. From the presented data it follows that the travel time from north to south was from 1086 s to 1209 s (at an average of 1137 s, so the scatter was from 51 s less to 72 s more), whereas in the opposite direction time was definitely longer (for ex. due to the higher traffic volume) and was from 1461 s to 1594 s. The distance between the research trail in successive passes was about 13.7 km. In this respect, high repetition was also achieved, because for urban journeys distance differences are only 0.39 km, which is about 2% of the smallest recorded value. The average speed of passing through the city was 38.5 km/h.

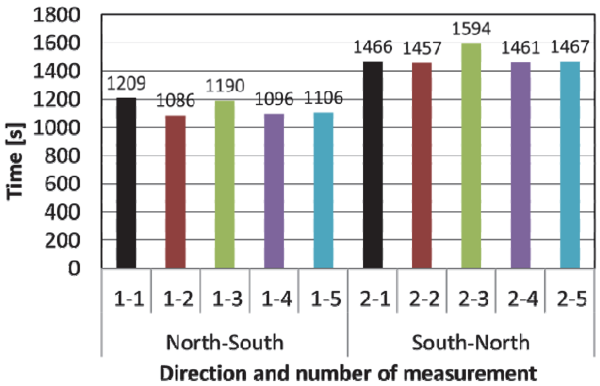

Fig. 6. Drive time during RDE measurements.

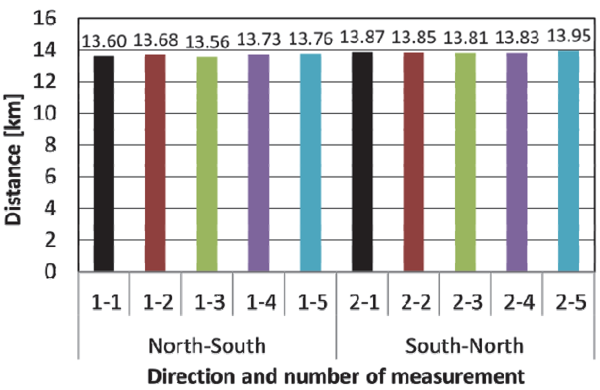

Fig. 7. Travelled distance during RDE measurements.

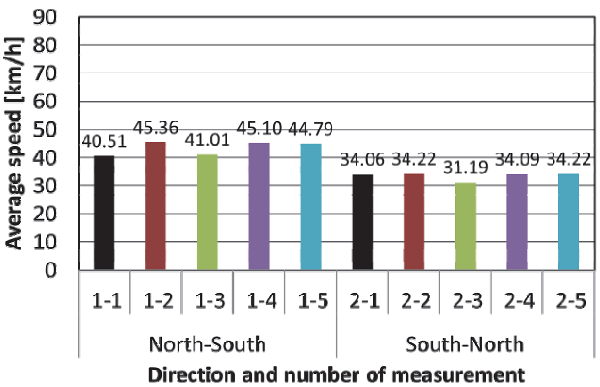

Fig. 8. Average speed during RDE measurements.

At the next stage of the analysis, the course of the masses of harmful compounds was presented in growing way. This was intended to demonstrate not only the final value, but also the changes in individual journeys. The intensity of emissions of particular harmful compounds, summed up every 1 s, allowed for the mass of the harmful compound emitted on the measuring section. The following diagrams show cumulative emission values – the maximum values represent the total mass of the harmful compound determined in each run. Because of space constraints, only values recorded during north-south passes are shown.

The carbon monoxide masses (cumulatively) generated during the passage through the city are characterized by a specific increase in this value in the middle of the route (Fig. 9). This has to do with intersections that occurred on this part of road - and this would require multiple stops and acceleration to a steady speed. All recorded mileage during the measurements was characterized by considerable repetition. The resulting end values largely relied on dynamic traffic conditions.

The mass of the hydrocarbon emitted for all journeys through the center of Zyrardow marked with the symbols 1-x is within 150-200 mg (Fig. 10). The mass distribution of hydrocarbons was small and the graphs were similar to those of carbon monoxide masses.

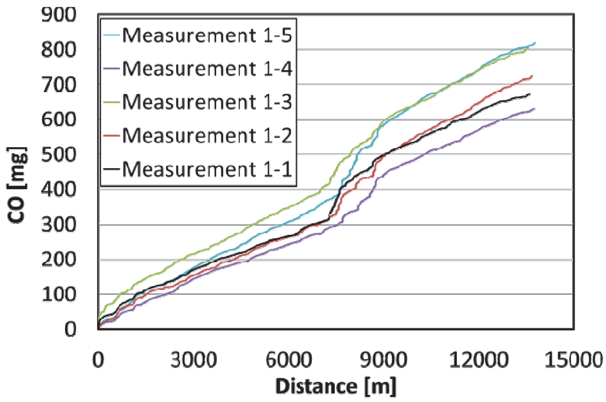

Fig. 9. Cumulative mass of carbon monoxide during RDE measurements for the north-south direction.

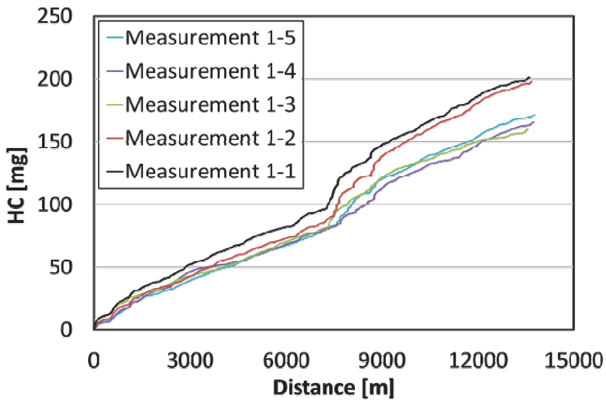

Fig. 10. Cumulative mass of hydrocarbons during RDE measurements for the north-south direction.

The course – of cumulative defined mass of nitrogen oxides during passing through the city was very repetitive (Fig. 11). The final values obtained are in range from 170 mg to 220 mg. For the same direction of study scatter results were not greater than 50 mg. Such a small dispersion of nitrogen oxides can be seen in similar operating conditions of the combustion engine due to the high volume of traffic. The lack of dynamic acceleration of the vehicle contributed to the low emissions of this compound.

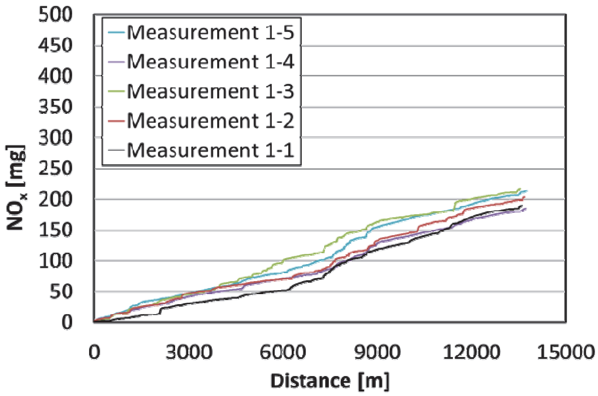

Fig. 11. Cumulative mass of nitrogen oxides during RDE measurements for the north-south direction.

Cumulative carbon dioxide mass is characterized by the smallest scatter (regardless of the direction of the study). The spread of these values during urban journeys does not exceed 200 g (which is less than 10% of the obtained results – Fig. 12). Carbon dioxide emissions can be directly attributed to fuel consumption, Also, for each test, similar fuel consumption values were achieved.

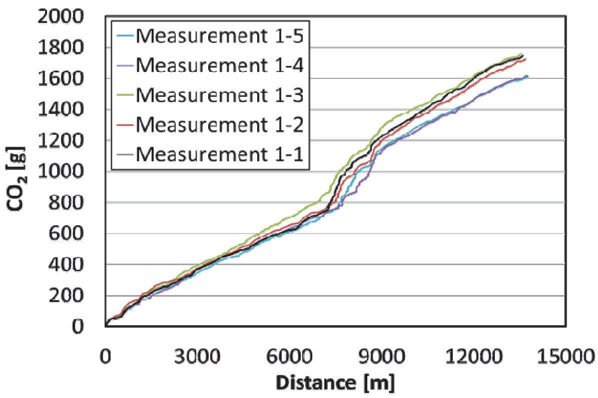

Fig. 12. Cumulative mass of carbon dioxide during RDE measurements for the north-south direction.

3.2 Simulations

A route model (Fig. 13) was created for the purpose of simulation of the vehicle passing through the city, consisting of the characteristic sections of the road (road mark 50 – before the bypass opening). These were, for example, straight ahead driving and crossing through crossections with traffic lights, located in the middle of the town (in different configurations.) The initial phase of the modeling was the selection of part of the road, followed by the geometry of the model based on the Google satellite image. The end stage was the parameterization of the modeled sections of the road infrastructure, which consisted mostly of setting the routes of individual vehicle groups and description of the type and emission structure of vehicles moving along the road.

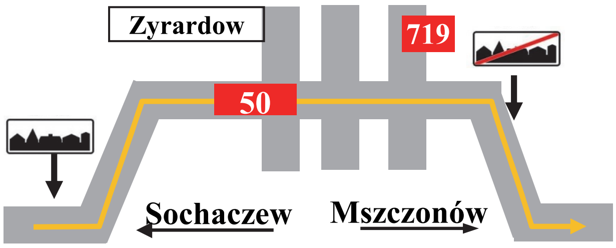

Fig. 13. Scheme of the road infrastructure model created in PTV Vissim.

For the assumed parameters, simulations of the modeled section of the road were carried out. The parameters of the journey (time of travel, distance and average speed) are shown in Fig. 14. The analysis of this drawing and its comparison with parameters obtained during road tests are the basis for the claim that the modeling of the analyzed road infrastructure was performed correctly. Travelling time during the simulation was 1193 s, which, compared to the average of 1313 s, is less than 120 seconds, or 2 minutes. At such a long distance, it should be considered this result as rewarding. In the case of a section length of 13.4 km, we managed to obtain almost the same result as the average from road tests (13.8 km). The distance and time parameter, the average speed is 40.3 km/h and its value is about 5% higher than the average value obtained during the real tests.

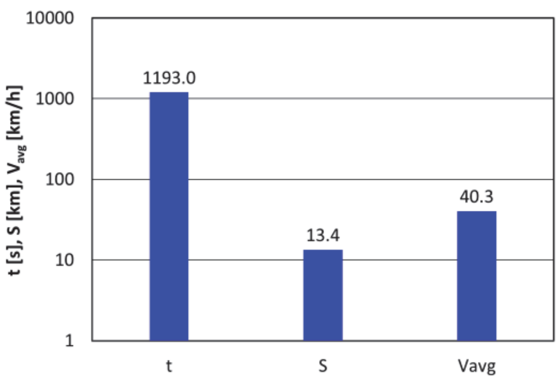

Fig. 14. Trip parameters of Euro 4 passenger car during simulation in PTV Vissim software.

Emission values obtained during the simulation are shown in Fig. 15. The Euro 4 vehicle emits 1701 mg of carbon monoxide, 210 mg of hydrocarbons, 407 mg of nitrogen oxides and 1987 g of carbon dioxide under the simulator. Not all of these values are consistent with road measurements, as will be discussed later in this chapter. The comparison of the mass of carbon

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monoxide emitted during the passage of the National Road 50 within Zyrardow (Fig. 16) shows that the results obtained during the simulation are much higher than the results obtained from the measurements. Also pay attention to the characteristic values of mass at arrival at intersections, passing through three intersections and reaching the end point of measurements. The sum of the masses from all the sections and the comparison with the results of the measurements shows a significant difference, which is 133% higher than the average from RDE tests. This proves that the results of the simulation are significantly overestimated in relation to the road value.

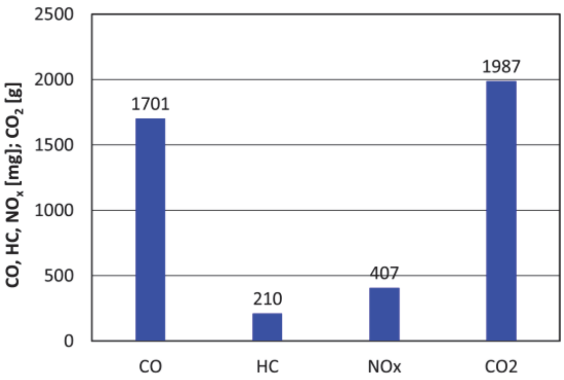

Fig. 15. Emission parameters of Euro 4 passenger car during simulation in PTV Vissim software

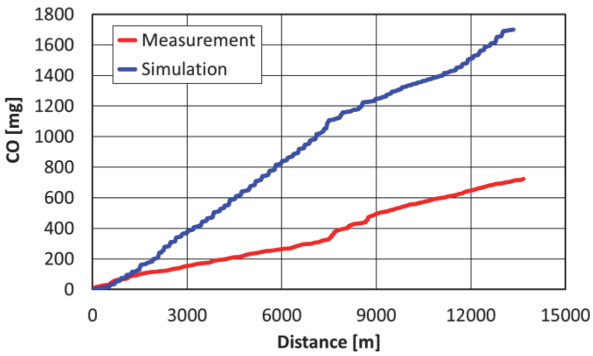

Fig. 16. The mass of carbon monoxide during RDE measurements and simulation.

Different character of the results (real and simulated) was obtained with respect to the comparison of the mass of hydrocarbons emitted during the passage through the city. In the first part of the route (up to about 3 km), the higher values were obtained from the measurements in real traffic conditions, while in the rest of the route the simulation results were higher (Fig. 17). For the whole run, the simulation results are only 17% higher than the measured values.

The comparison of the mass values of nitrogen oxides determined from the tests and during the simulation shows, as in the case of carbon monoxide, the incompatibility of the obtained values (Fig. 18). They note the increased mass values of this compound in all the parts of the urban route examined, which are twice as the value obtained from the measurements.

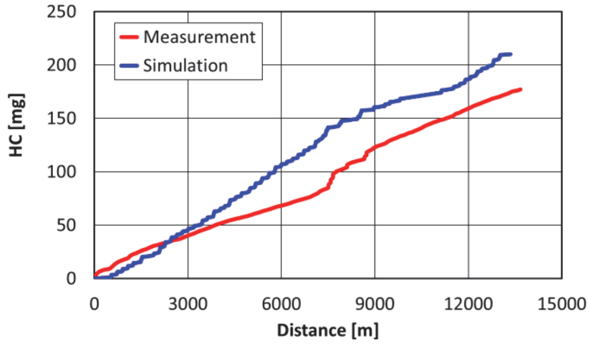

Fig. 17. The mass of hydrocarbons during RDE measurements and simulation.

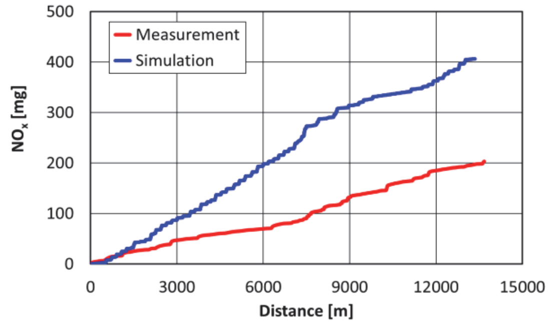

Fig. 18. The mass of nitrogen oxides during RDE measurements and simulation.

The highest compliance of mass results from measurements and simulation was recorded for carbon dioxide (Fig. 19). In the case of characteristic sections, where the compatibility of the results was significant (except the approach to the intersection), the similarity of the results achieved was the same across the entire urban route. The results obtained from traffic measurements differed by approximately 17% in relation to the determined value obtained using the Vissim software.

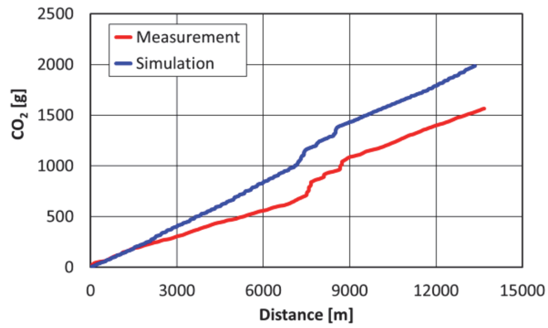

Fig. 19. The mass of carbon dioxide during RDE measurements and simulation.

It was assumed that the incompatibility in the mass of emitted harmful compounds during the simulation results from improper emission values of in the simulation software. For this reason, the emission values have been changed based on the data obtained during the RDE emission test. In the further part of the article the modified emission data is used.

3.3 Entire vehicles stream simulation

Using modified emission data and urban traffic patterns and vehicle structure information, simulations of the average speed and emissions of the entire vehicle stream were made (taking into account the differentiation of vehicles in terms of emission type and class) under such conditions after the analyzed road. In addition, the analysis of these parameters was performed for 50% less and 50% greater traffic density than the standard value. The analysis of Fig. 20 shows that, with the increase in vehicle traffic, the average speed of vehicles in the modeled road network decreases. For traffic density 50% smaller than standard, the average vehicle speed was 42.7 km/h. Increasing the traffic density to 100% and 150% resulted with reduction in average speeds to 40.3 km/h and 27.2 km/h, respectively.

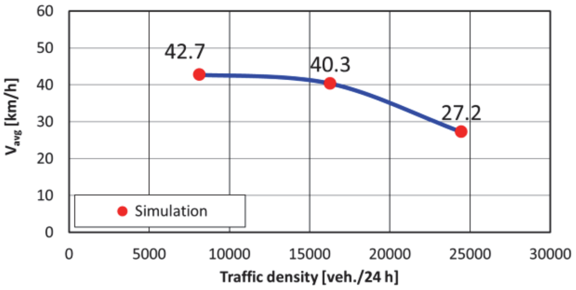

Fig. 20. Average speed of vehicles in the road network during the simulation of different traffic density on selected road.

Inversely look the graphs of the mass of harmful emissions from vehicle streams emitted over a 24-hour period. In this case, the increase in traffic intensity increases the emission of all analyzed components of the exhaust gases. For standard traffic density, the daily carbon monoxide emission is 390 kg/day (Fig. 21).

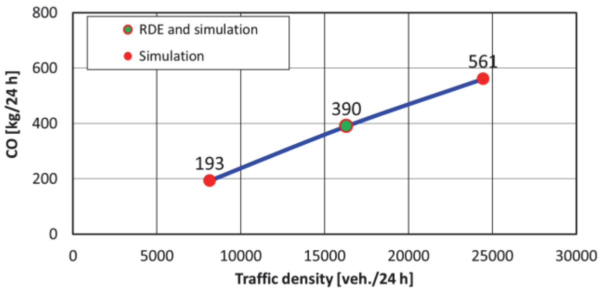

Fig. 21. Daily carbon monoxide emission from vehicles in the road network during the simulation of different traffic density on selected road.

A 50% reduction in the number of vehicles in the network resulted in a 50% reduction in carbon monoxide emissions, while a 50% increase in vehicle traffic led to a 44% increase in carbon monoxide emissions. Also, the mass of hydrocarbons increases with the increase in vehicle traffic in the modeled road network (Fig. 22). It shows that the mass of hydrocarbons emitted during the passage of the 50% smaller vehicle stream is 47% less than the passage of the whole vehicle stream through the city, and for much greater traffic – 46% greater. The mass of emitted nitrogen oxides during the passage of 50% less vehicle stream than that resulting from the General Measurement of Movement was 132.5 kg/day. For standard vehicle traffic, this result was approximately 52% higher. On the other hand, 50% more traffic from standard vehicles contributes to a 50% increase in nitrogen oxide emissions (Fig. 23).

Also similar in character to previous ones is the mass of carbon dioxide: for low traffic, the passing of the entire vehicle stream across the city generates 52% less mass than the standard traffic, and for higher traffic density, respectively 45% more carbon dioxide (Fig. 24).

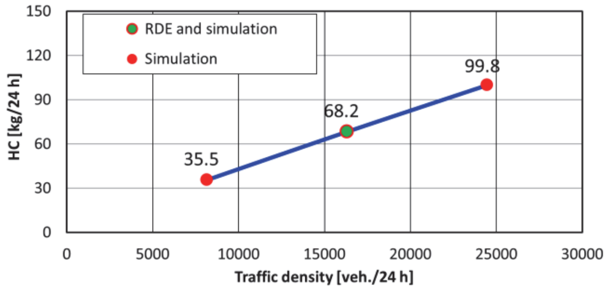

Fig. 22. Daily hydrocarbons emission from vehicles in the road network during the simulation of different traffic density on selected road.

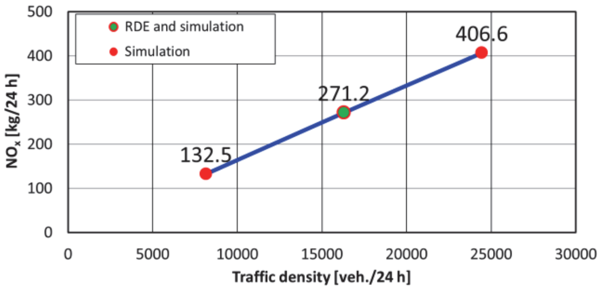

Fig. 23. Daily nitrogen oxides emission from vehicles in the road network during the simulation of different traffic density on selected road.

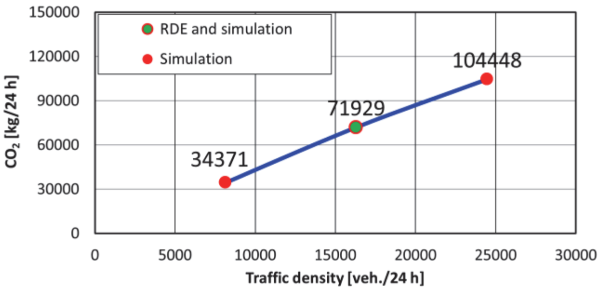

Fig. 24. Daily carbon dioxide emission from vehicles in the road network during the simulation of different traffic density on selected road.

4 Conclusions

Reducing the negative impact of transport on the environment can take place in many ways. Most often these actions are directed towards changing vehicles moving on the road to more environmentally friendly. But another aspect that can also contribute to reducing environmental pollution is a well-designed road infrastructure that ensures the smoothest possible flow.

During design of new roads, it is necessary to assess the existing infrastructure in terms of ecology and to carry out an analysis of the environmental impact of the new road infrastructure. For this purpose, specialized computer software is useful for analyzing not only emissions from a single vehicle but also the emission of the entire traffic stream. Another advantage of this approach is the ability to evaluate multiple variants of the course and configuration of the new road and almost any change in the number of vehicles moving in the modeled road infrastructure. However, in order to present the results in a reliable manner, attention should be paid to the appropriate validation of the model, which should include, among other things, determining the direction of travel, selecting the appropriate structure of vehicles in terms of categories and emission standards, and applying appropriate emission values. Particularly advantageous in the last aspect is the use of data obtained during emission measurements in real driving conditions.

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