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Analysis of harmful compounds concentrations in the exhaust behind a vehicle with compression ignition engine

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The article presents issues related to the assessment of concentrations of harmful substances in the exhaust gas cloud behind a compression-ignition passenger vehicle. The introduction describes issues related to the impact of air pollution on the environment and on human health and life expectancy. The article presents exhaust gas dispersion tests behind the vehicle were carried out both in stationary conditions (a specially prepared laboratory stand) and in real operating conditions. PEMS testing equipment was used for this type of measurements. During the measurements, concentrations of harmful exhaust gas compounds were analyzed in relation to the distance of the measuring probe from the exhaust system. In stationary conditions, the influence of the engine speed on the dispersion of pollutants was also studied. The tests carried out show that the concentrations obtained behind a moving vehicle significantly decrease with the distance of the measuring probe, and their dispersion is much smaller in most cases than in the case of stationary tests. This is the basis for recognizing that thanks to this, it is possible to analyze the concentrations obtained and conduct tests using the emission gate.

Key words: *remote sensing system, car emission, teledetection, combustion engines, optical measurement method*

1. Introduction

The latest State of Global Air report published in 2019 states that air pollution was the fourth leading risk factor for premature death worldwide. It is estimated that it contributed to 6.67 million deaths per year, which is almost 12% of the global number (Fig. 1). The report also reports on the effects of pollution, which is the focus of the Global Burden of Disease Study (GBD). The GBD analysis estimates the burden on society in terms of the impact on years lived with the disease and the number of deaths resulting, in most cases, from long-term exposure to air pollution. The research focuses on mortality from the five chronic non-communicable diseases for which there is currently the strongest evidence – diabetes, stroke, chronic obstructive pulmonary disease, lung cancer, and coronary heart disease, and one infectious disease, lower respiratory tract infection. Nitrogen oxides and particulate matter have a particularly negative impact on human health and life. Therefore, scientists are constantly trying to find new ways to reduce them, including by using biofuels [9, 13, 15].

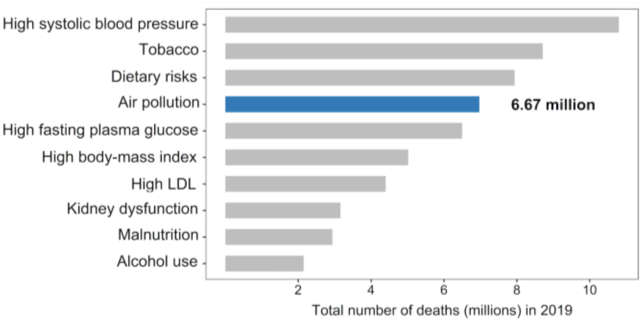

Fig. 1. Global ranking of risk factors by total deaths from all causes in 2019 [9]

One of the main threats to the environment is CO_2 emissions. About 50 billion tonnes of greenhouse gases, measured in carbon dioxide equivalents, are emitted around the world each year. The EEA (European Environment Agency) reports from 2019 state that transport is responsible for approximately one quarter of total CO_2 emissions in the European Union, of which almost 72% came from road transport, including passenger vehicles (60.6%), light commercial vehicles (11%), trucks (11%) and motorcycles (1.3%) (Fig. 2). Due to the significant impact of transport on air pollution, newer regulations are being introduced to reduce emissions of harmful exhaust gases. The main goal of the European Union is to introduce zero CO_2 emission regulations for these vehicles by 2035. However, transport is the only sector where greenhouse gas emissions have increased by 33.5% between 1990 and 2019 over the past three decades. Significant reductions in CO_2 emissions will therefore not be easy as the rate of reduction has slowed. To achieve the assumed goals and solve the health crisis related to air pollution, it is necessary to quickly take all possible actions. In highly developed countries, a number of solutions are being introduced to improve air quality, such as the creation of low-emission zones in city centers [6, 12, 14, 16, 25]. The feasibility of introducing zones of this type can be achieved by using devices for remote measurement of harmful exhaust gas compounds based on the study of the actual flow of vehicles moving within the low-emission zone. The main advantage of this type of measurements is obtaining the actual condition of vehicles driving in a given area in terms of legislative regulations and the level of wear and tear of research facilities. Remote sensing measurement makes it possible to determine the concentrations of harmful compounds from vehicles driving in low-emission zones and outside these zones. Thanks to this, it is possible to obtain information regarding the actual impact of their introduction on reducing the impact of automotive pollution on the environment [23–25].

A literature study showed that for several years in various global research centers [1, 3–5, 7, 8, 10, 11, 17, 19] work has been carried out on devices for assessing pollutant emissions both in stationary and real conditions. However, the solutions being developed are still insufficient. Due to the problem of emissions of harmful exhaust gases from motor vehicles, there is a need for further research using more developed measurement equipment.

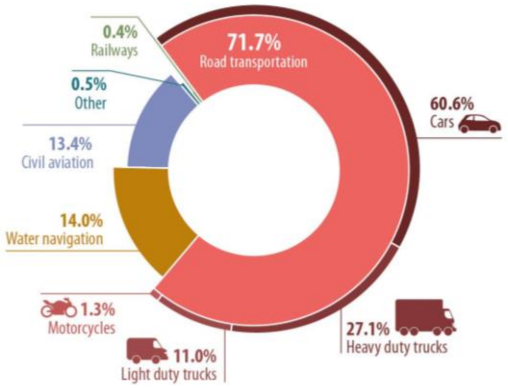

Fig. 2. Transport emission in the EU – greenhouse gas emissions breakdown by transport mode [23]

2. Research methodology

2.1. Research object

The tests were carried out using a passenger car equipped with a compression-ignition drive unit with a capacity of 1.9 dm^3 (Fig. 3, Table 1). The engine had a rated power of 110 kW at 4000 rpm and a maximum torque of 320 Nm at 2000 rpm. The vehicle was equipped with a diesel particulate filter (DPF) and was approved in accordance with the Euro 4 standard.

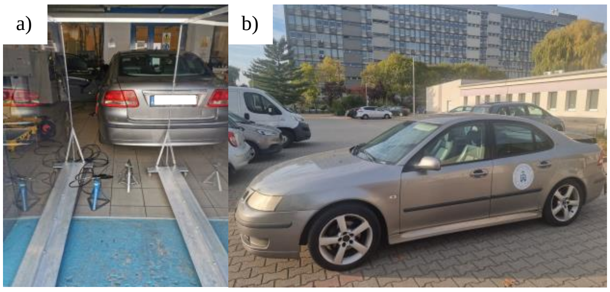

Fig. 3. Test object a) on a measuring stand, b) in real operating conditions

Table 1. Basic parameters of the research object

Parameter	Data
Year of production	2006
Fuel type	Diesel oil
Stroke capacity [dm^3]	1.9
Engine layout	R4
Power [kW]/at engine speed [rpm]	110/4000
Maximum torque [Nm]/at engine speed [rpm]	320/2000
Injection type	Common Rail
Compression ratio	18.4:1
Euro standard	Euro 4

2.2. Measuring station and research route

Tests of concentrations of harmful compounds in exhaust gases were carried out both in stationary and real conditions. Laboratory tests were carried out at a measuring station located on the campus of the Poznań University of Technology. They included measurements of concentrations of harmful compounds in the cloud of exhaust gases behind a stationary vehicle. The measurement points (Table 2) were placed at different distances and at different heights from the flue gas exhaust system. In addition, the influence of engine speed (idling, 1500 rpm, and 3000 rpm) on the obtained measurements was investigated. In the next stage, measurements were carried out in real operating conditions. The measurement route was the first communication frame of the city of Poznań, covering the very center of the city (Fig. 4). The journey covered a section of road with a length of 8.9 km.

Table 2. Basic parameters of the research object

Measurement point	Distance from the Exhaust Pipe l [cm]	Height from the Exhaust Gas System h [cm]
1	0	0
2	5	10
3	10	10
4	20	10

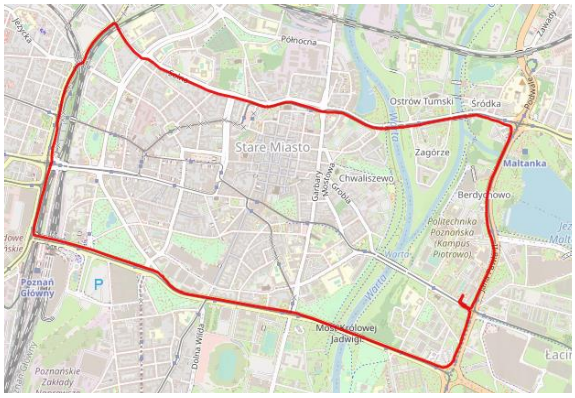

Fig. 4. Test route used [22]

2.3. Measurement equipment

The mobile Micro PEMS Axion R/S+ analyzer manufactured by Global MRV was used for the measurements (Table 3). It enables the measurement of the concentration of gaseous toxic compounds using: a non-dispersive infrared analyzer – NDIR (CO_2, CO, HC) and an electrochemical analyzer (NO). The equipment also allows testing the concentration of PM using the method based on Laser Scatter, in which the speed of particle movement is measured (taking into account the values assigned to PM_{10}) [18, 20].

Table 3. Axion R/S+ Analyzer Specifications [2]

Gas	Measurement Range	Accuracy	Resolution	Type of Measurement
HC	0–4000 ppm	±3%	1 ppm	NDIR
CO	0–10%	±3%	0.01 vol. %	NDIR
CO_2	0–16%	±4%	0.01 vol. %	NDIR
NO	0–4000 ppm	±3%	1 ppm	E-chem
O_2	0–25%	±3%	0.01 vol. %	E-chem
PM	0–300 mg/m^3	±2%	0.01 mg/m^3	Laser Scatter

3. Measurement results

Passenger vehicles with SI and CI were tested at four measurement points, differing in the distance of the measurement probe from the exhaust gas outlet system. The points were selected on the basis of previously conducted tests, which showed that the test objects should be tested directly in the exhaust system and 10 cm, 15 cm, and 20 cm behind the exhaust system. The dispersion of harmful exhaust gas compounds was determined on the basis of the last analyzed measurement point. Laboratory tests of vehicles were carried out for various rotational speeds – idle (800 rpm – SI vehicle, 850 rpm – CI vehicle), 1500 rpm, and 3000 rpm. The tests were carried out without checking the influence of load on the obtained results. The authors intend to pursue further steps in this direction. Analogous measurements were also carried out in real operating conditions on a route covering the very center of the city. These measurements were performed to confirm the possibility of conducting dispersed exhaust gas tests. These studies constitute the basis for determining the appropriateness of using the emission gate for remote sensing measurements, as well as for establishing the conditions under which such a measurement would take place.

Carbon dioxide concentrations measured stationary directly in the exhaust system were characterized by similar values – 3.58% for idling, 4.36% for 1500 rpm, and 3.67% at 3000 rpm (Fig. 5). At point 4, 20 cm away from the exhaust system, these values were between 0.39% and 0.6%. This means that the CO_2 values were similarly dispersed for all vehicle speeds. The obtained dispersion exceeded 83% for idling and 89% for rotational speeds of 1500 rpm and 3000 rpm. Measurements in real conditions for the first measurement point (3.43%) were identical to those obtained in stationary conditions. In point 4, the value of carbon dioxide was obtained at the level of 1.08%. This means that the obtained dispersion (68%) was about 20% lower than in the case of measurements on a stationary vehicle.

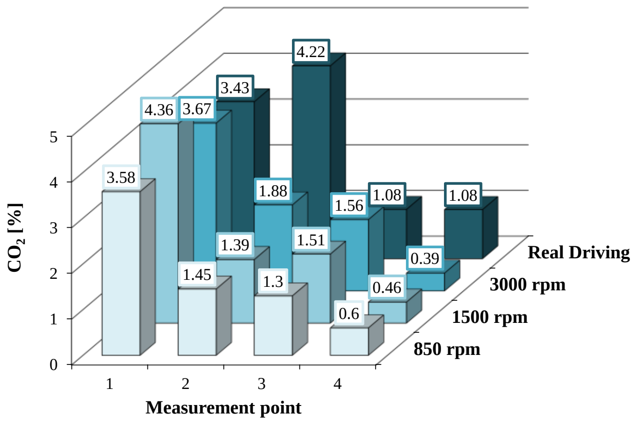

Fig. 5. Carbon dioxide concentration in relation to the measuring point and engine speed

In the case of stationary tests, the obtained CO results for the first measurement point closely depended on the engine speed. The concentration of carbon monoxide at idling was 342 ppm, for 1500 rpm 561 ppm, and for 3000 rpm – 735 ppm (Fig. 6). At the 4th measurement point, the concentration obtained for the rotational speed of 850 rpm was characterized by the lowest value, at the level of 8 ppm. For the remaining engine speeds, the following values were recorded – 122 ppm (1500 rpm) and 212 ppm (3000 rpm). The obtained dispersion for idling was therefore 97.5%, while for higher rotational speeds it was 78% and 71%, respectively. In the case of driving in real conditions, the values obtained directly from the exhaust system (550 ppm) were similar to those obtained in stationary conditions for 1500 rpm. At the farthest point from the exhaust system, 95 ppm was obtained. Thus, an exhaust gas dispersion of 83% was obtained. The achieved results were therefore only lower than those obtained at idling.

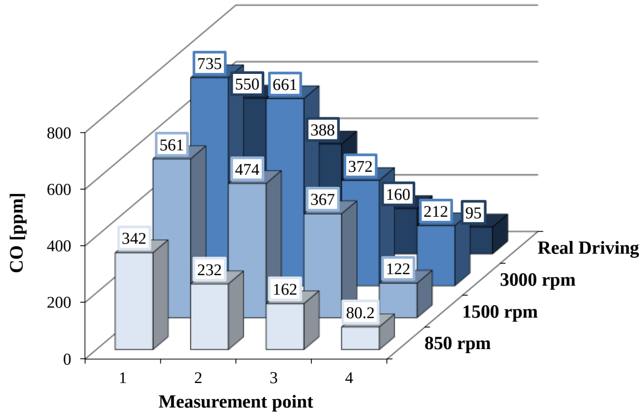

Fig. 6. Carbon monoxide concentration in relation to the measuring point and engine speed

Stationary tests of hydrocarbons for all engine speeds were similar (Fig. 7). Directly in the exhaust system, hydrocarbon concentrations ranged from 33.2 ppm to 35 ppm, while at the farthest point from 8.3 ppm to 8.6 ppm. Therefore, the HC dissipation was maintained for idling and engine speeds equal to 1500 rpm and 3000 rpm at the level of about 75%. It follows that the dispersion of this compound did not depend on the rotational speed of the vehicle. In the case of measurements in real conditions, the dispersion was at the same level (75.2%), although the concentrations obtained at the first measurement point were characterized by much higher values – 129 ppm.

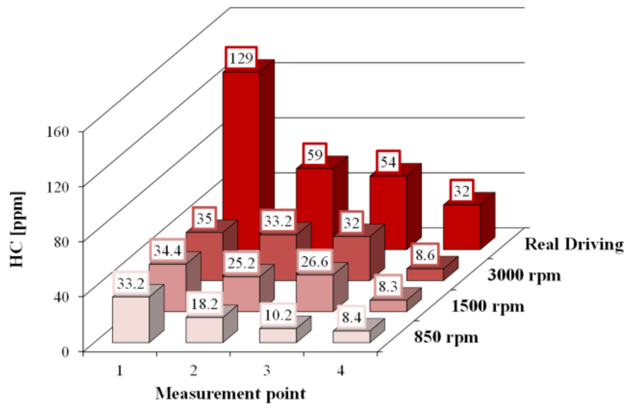

Fig. 7. Hydrocarbon concentration related to measurement point and engine speed

The concentration of nitrogen oxide also depended on the engine speed (Fig. 8). They increased in direct proportion to the rotational speed. In tests performed in laboratory conditions with the probe placed directly in the exhaust system, the following results were recorded – 96.4 ppm at idle, 144 ppm at 1500 rpm, and 229 ppm at 3000 rpm. At the furthest point, relatively similar values from 8.9 ppm to 19 ppm were recorded. The obtained dispersion for all rotational speeds was about 90%. This indicates that the dispersion of exhaust gases from the vehicle was not affected by the rotational speed of the drive unit. Measurements in real operation conditions indicate that NO dispersion obtained during the tests was much lower than in stationary conditions and amounted to 61%. At the first measurement point, a value of 154 ppm was obtained, while at the last 60 ppm.

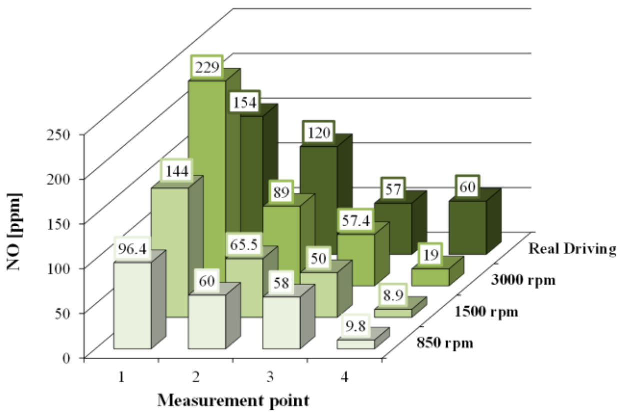

Fig. 8. Nitrogen oxide concentration related to measuring point and engine speed

The concentration of particulate matter strictly depended on the engine speed. Its increase was directly proportional to the increase in PM (Fig. 9).

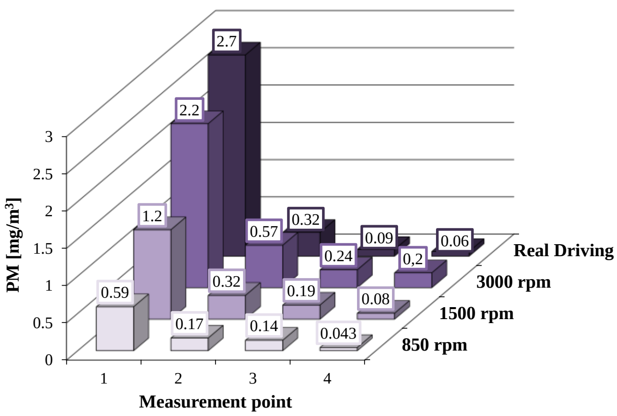

Fig. 9. Particulate matter concentration related to measurement point and engine speed

In the first point, the following results were obtained – 0.59 mg/m^3 for idling, 1.2 mg/m^3 for the rotational speed of 1500 rpm, and 2.2 mg/m^3 for 3000 rpm. These values successively decreased to 0.043 mg/m^3, 0.08 mg/m^{3,} and 0.2 mg/m^3, respectively. Thus, exhaust gas dispersion exceeding 90% was obtained at all points (92.7% – 850 rpm, 93.3% – 1500 rpm, 90.9% – 3000 rpm). Measurements in real conditions were characterized by the highest values of particulate matter concentration measured directly in the vehicle exhaust system (2.7 mg/m^3). However, at the most distant point, the result obtained was only higher than that obtained at idling and amounted to 0.06 mg/m^3. Road measurements indicate that dispersion remained at around 98%.

4. Conclusions

The conducted empirical research on the analysis of concentrations of harmful compounds in the cloud of exhaust fumes behind an object equipped with a diesel engine is part of the problem of evaluating emissions from moving vehicles. The summary of the relative dispersion of the exhaust gases behind the vehicle for both stationary and dynamic tests is presented in Table 4. As the table shows, the dispersion obtained for all stationary measurement points exceeded 90% only in a few cases. The obtained results ranged from about 70% to over 97%. The highest values were characterized by solid particles and the lowest by hydrocarbons. During real operation, the results ranged from 61% for nitrogen oxides to almost 98% for particulate matter. The dispersion values of other harmful compounds of exhaust gases ranged from about 68% to over 82%.

Table 4. Dispersion of harmful exhaust compounds

Harmful compound	Measuring point	Engine speed n [rpm]			
		850	1500	3000	Real driving
CO_2 [%]	1	3.58	4.36	3.67	3.34
	2	1.45	1.39	1.88	4.22
	3	1.3	1.51	1.56	1.08
	4	0.6	0.46	0.39	1.08
Dispersion of CO_2 [%]	1–4	83.2	89.5	89.4	67.7
CO [ppm]	1	342	561	735	550
	2	232	474	661	388
	3	162	367	372	160
	4	8	122	212	95
Dispersion of CO [%]	1–4	97.7	78.2	71.2	82.7
HC [ppm]	1	33.2	34.4	35	129
	2	18.2	25.2	33.2	59
	3	10.2	26.6	32	54
	4	8.4	8.3	8.6	32
Dispersion of HC [%]	1–4	74.7	75.9	75.4	75.2
NO [ppm]	1	96.4	144	229	154
	2	60	65.5	89	120
	3	58	50	57.4	57
	4	9.8	8.9	19	60
Dispersion of NO [%]	1–4	89.8	93.8	91.7	61
PM [mg/m^3]	1	0.59	1.25	2.2	2.7
	2	0.17	0.32	0.57	0.32
	3	0.14	0.19	0.24	0.09
	4	0.043	0.08	0.2	0.06
Dispersion of PM [%]	1–4	92.7	93.3	90.9	97.8

The results of the measurement obtained indicate that the greatest diffusion of exhaust gas is obtained at low rotational speeds in laboratory conditions. In addition, the presented summary shows that the movement of the vehicle is conducive to the assessment of concentrations behind the moving vehicle, because the obtained exhaust gas dispersion is not as large as in the case of laboratory tests (especially for low engine speeds). It is possible to analyze the obtained concentrations and conduct tests using the emission gate. The most constant conditions should be used for this, so that the dispersion remains at a similar level for each research object.

The emission gate is a modular device for quick assessment of the concentration of harmful exhaust gas compounds. It enables the identification of concentrations of harmful exhaust gases from various means of transport. The device enables individual analysis of the obtained values for each vehicle or set of vehicles moving in a given area (road in the case of road vehicles or track for rail vehicles) and time. The emission gate has extensive measurement capabilities and allows you to carry out measurements on at least several vehicles within one hour. This is undoubtedly the greatest advantage over PEMS equipment, in which the measurement of one vehicle on a precisely defined route takes at least several hours. A quick assessment of the value of harmful exhaust gases from the tested objects allows the identification of the largest emitters (worn-out, damaged and technically neglected vehicles), which may constitute the basis for eliminating them from traffic if certain standards are exceeded.

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Nomenclature

CO	carbon monoxide	l	distance
CO_2	carbon dioxide	n	engine speed
DPF	diesel particulate filter	NDIR	non dispersive infra red
h	height	NO	nitrogen oxide
HC	hydrocarbons	PM	particulate matter

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