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Measurement of Exhaust Emissions from a Two-Wheeler – an Experimental Validation of the Remote-Sensing Method

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ABSTRACT

The paper presents the problem of testing vehicles, which are some of the main sources of air pollution. The authors suggested the remote-sensing method as a tool for the measurement of the vehicle exhaust emissions and an on-going control thereof. This is an economical solution that allows measuring a large number of vehicles in a short time. The presented work aims at an experimental validation of the measurement method of exhaust emissions on the example of a two-wheeler. To that end, two parallel laboratory tests were carried out: measurement of the exhaust emissions obtained directly from the tailpipe using the PEMS (Portable Emission Measurement System) equipment and from the exhaust cloud, utilizing a module emission gate. A significant mutual correlation of the results confirms the efficiency of the method. The highest value of the coefficient of determination was obtained for the CO_2, PM and NO analyzers. Different orders of values were primarily caused by the dissipation of the exhaust gas and the influence of the ambient conditions on the measurement process. Further works are therefore necessary to allow an assessment of the actual measurement uncertainty of the equipment irrespective of the fueling system and type of vehicles.

Keywords: remote sensing system; motorcycle; PEMS; teledection; exhaust concentration.

INTRODUCTION

Urbanization processes, relaxation of the migration laws within the EU member states as well as economic development have significantly contributed to the growing population in large European cities. The increase in the population directly impacts the number of vehicles on the roads [Caban and Droździel, 2020]. Due to its geographic location and the lack of low and zero-emission zones (Figure 1), Poland has become a good market for older vehicles that come from Western Europe. Imported vehicle models of several years of age are not subject to any restrictions in terms of their exhaust emissions. This results in a lack of the possibility of controlling the situation in this context [Basińska et al., 2021].

The implementation of low-mission zones in Europe has a clear impact on the advancement of open path exhaust emissions measurement technologies. Thus far, the system has been exclusively based on data analysis obtained from cameras operating within the zones. The fundamental function of the software is to read the license plate and identify the vehicle based on available databases. This is how the basic data (model, year of manufacture or type of powertrain) are verified. The system, however, is not capable of identifying malfunctions or modifications that could influence the vehicle exhaust emissions. Implementing remote-sensing systems in city traffic enables an ongoing control of the exhaust emissions. This provides the possibility of measuring the exhaust emissions from vehicles at a low cost

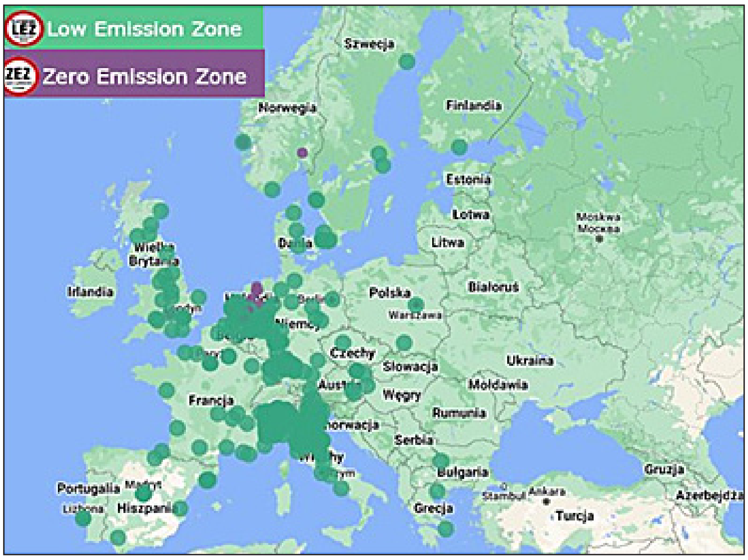

Figure 1. Geographic location of low and zero-emission zones [urbanaccessregulations, 2022]

of the measurement itself and the maintenance of the equipment. An undoubted advantage of this system is remote measurement with the results available in a very short time. Organizational units that choose this technology support their decisions by performing research aiming at determining of the impact of different parameters (means of transport, make, model, year of manufacture, type of powertrain, weight, engine displacement, emission standard) on the exhaust gas composition. Irrespective of the motifs, remote sensing has become an important, but very demanding (requires maintaining very specific measurement conditions) tool in the research on the concentration of exhaust emissions [Bernard et al., 2019; Borken-Kleefeld and Dallmann, 2018; Dallmann et al., 2018; Davison et. al., 2020].

Because of the influence of the ambient conditions on the reliability of the measurements, technology based on the exhaust gas dissipation measurement, is most frequently used as a portable installation for shortterm supervised testing. One should note the sensitivity of the equipment to air movements – excess wind or the speed of the vehicle will result in a faster dissipation of the exhaust gas (Figure 2), thus imposing a high level of uncertainty on the results or the risk of failure to record the gas sample.

The influence of the vehicle speed on the recording of the results has not yet been clearly identified due to the fact that at higher engine loads, the exhaust flow rate also increases, which may cause slower dissipation. This, however, would have to result in a lower frequency of the recording (a longer time of recording of a single sample and a repeated measurement). Besides, at a very high rate of the gas flow, the measurement may fail to register. Therefore, the authors have

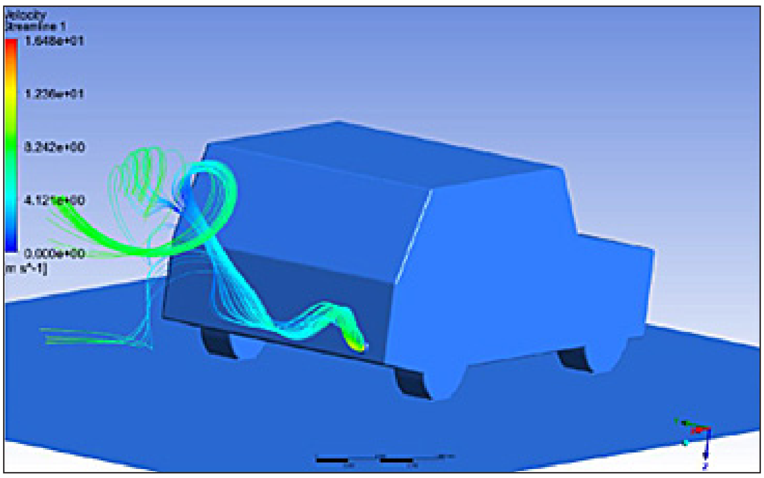

Figure 2. Exhaust gas tumble at a cross wind

concluded that the best results at a fairly stable dissipation level can be obtained for the speed of up to 30 km/h [Huang et al., 2020].

When investigating the exhaust gas dissipation based on monolinear absorption spectroscopy, the atmospheric phenomenon that has the greatest impact on the measurements is the cross wind. As has been proven in [Huang et al., 2020], the nature of dissipation of the exhaust gas is entirely changed. It is particularly the case for instances where the resultant is directed downwards. This results from the flow distortion and air tumbles caused by blocking of the free flow by the vehicle body. Very similar conclusions were made following the authors' own research realized within the project. Given the above, the authors confirm that the parameter responsible for the exhaust gas dissipation is not only the speed of wind but also its direction. For this reason, the measurements should be performed at possibly stable ambient conditions during windless weather.

In order for the obtained results of exhaust gas dissipation to be reliable, it is of key importance to select the right location for the equipment. In order to fully utilize the research potential, the location should be characterized by a high throughput with no traffic disturbance. Despite the fact that the equipment should be resistant to elevated ambient temperatures (approx. 30°C) and humidity, one should note that a high level of dust may affect the reliability of the measurements [Huang et al., 2018].

Given the above and minding the necessity of a reduced speed of the vehicle (approx. 30 km/h), the authors suggest the potential locations for the equipment:

- Entrance to a parking lot – setting up the equipment past the turnpike will result in a reduction of the influence of other vehicles' emissions on the measurement results, low speeds will result in a high probability of the measurement success and the above will not impact the throughput on public roads. Setting up the equipment at the exit of the parking lot may result in a high measurement error due to the influence of the engine thermal state on the aftertreatment system;
- Expressway toll plazas – low speeds and appropriate distance between vehicles at this location ensures a good varied sample additionally providing the possibility of applying the technology to trucks and coaches;
- One-way streets with a wide shoulder – these are locations frequently subject to additional speed limits, usually characterized by a compact building pattern, which additionally reduces the impact of wind on the measurement error;
- All other locations that require the engine to operate under increased load (exits from tunnels), which better reproduces the engine operation under real world conditions [Huang et al., 2018].

The values obtained in the exhaust emission measurements must be referred to the additional information such as road inclination or the vehicle speed and acceleration during the test. The above have significantly influence the engine load, thus generating increased emissions and exhaust gas dissipation [Dallman et al. 2019].

When analyzing example simulations of exhaust gas dissipation (Figure 3) generated by EDAR (Emissions Detection and Reporting) developed by Hager Environment and Atmospheric Technologies, one may observe that each of the indicated exhaust components is characterized by variable dissipation. Besides, the motorcycle exhaust gas dissipates in a quicker but more stable way compared to a passenger car. Due to such a wide variation in the exhaust gas dissipation, depending on the exhaust component, vehicle type and ambient conditions, the device records the concentrations of individual exhaust components referred to CO_2 [Agarwal and Mustafi, 2021]. This aims at increasing the accuracy of the measurements.

Based on the research carried out at Leeds University, it is confirmed that the results obtained with EDAR and PEMS were characterized by a high correlation with the following coefficients of determination [Ropkins et al., 2017]:

- $R^2 > 0.95$ for NO/CO_2;
- $R^2 > 0.90$ for CO/CO_2 and PM/CO_2;
- $R^2 > 0.80$ for NO_2/CO_2.

EMISSION GATE

The device is composed of several functional systems such as measurement analyzers, a power supply system, a data recording system and a vehicle identification system. The multiple components necessary for the system to operate correctly required connecting and integrating

a) b)

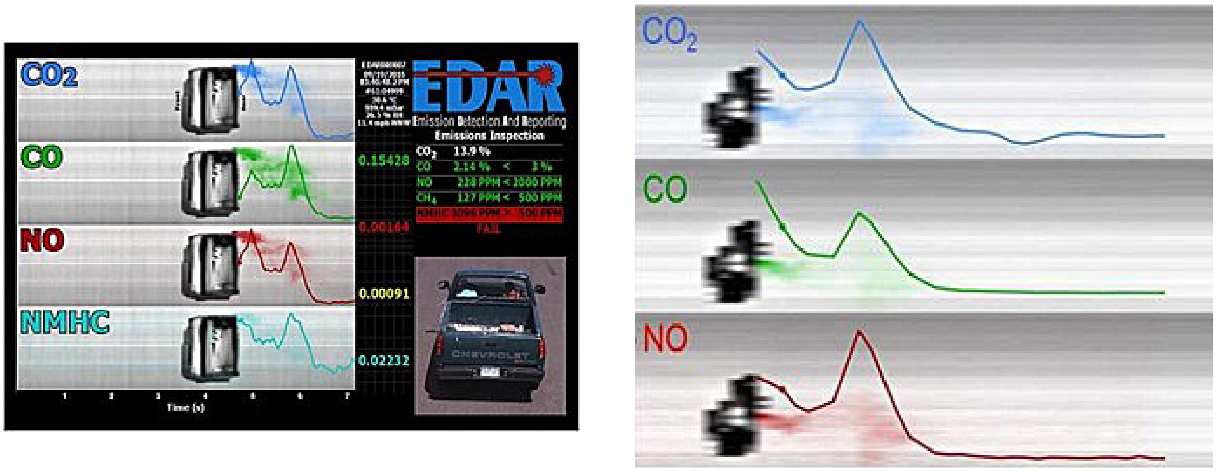

Figure 3. EDAR – exhaust gas dissipation a) a passenger vehicle b) motorcycle [Ropkins et al., 2017]

with the control system implemented with appropriate control algorithms and an automatic adjustment system.

The measurement system is composed of several subsystems and functional blocks, the most important of them being the following (Figure 4):
- A system of analyzers for the measurement of the concentrations of the exhaust gas components;
- Vehicle identification system;
- Vehicle thermal state and motion parameters assessment system;
- Measurement initiation system;
- Data recording system;
- Power supply system.

Each exhaust component analyzer is an optical device based on the transmission of a laser infrared light from the transmitter to the receiver on the opposite side. The measurement technique is based on light absorption by the gas molecules present in the measurement track. The applied measurement principle is the spectroscopy of absorption of a single light line and is based on the fact that majority of gases absorbs light at certain wavelengths. The extent of the absorption is a direct function of gas concentration in the measurement track.

In the case of particulate matter and smoke opacity measurements, an optical device is used based on sending a laser beam from the transmitter

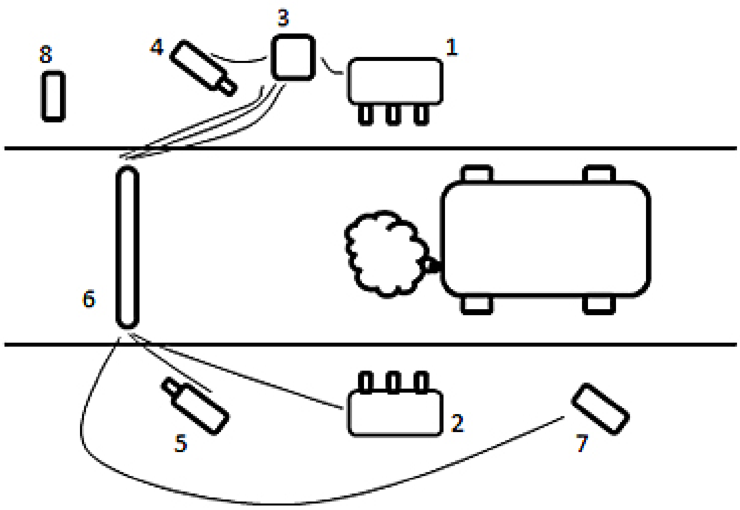

Figure 4. Schematic diagram of the operation of a modular device for evaluating pollutant emissions from passing vehicles: 1) transmitter, 2) receiver, 3) power supply system, recording system and weather station, 4) vehicle thermal assessment, 5) identification of the vehicle, 6) speed bump, 7) vehicle motion parameters, 8) warning sign

on one side of the exhaust channel to the receiver on its opposite side. It operates in two measurement modes because the receiver is composed of two sensors. The measurement technique is based on determining the absorption and light dispersion generated by particulate matter present in the measurement track. At the same time, transmission is determined – the sensor measures the intensity of the beam sent directly from the transmitter to the receiver. The first sensor measures the laser beam absorption (reduced intensity caused by the presence of particulate matter) while the second sensor measures the dispersed light.

The analyzers that were used are optical devices. The measurement principle is based on the transmission of laser beam from the transmitter to the receiver. The transmitter is located on the opposite side of the receiver, perpendicular to the path of the tested vehicle. As a result, an indirect measurement of a given toxic compound concentration is obtained on the optical path (between the transmitter and the receiver). A voltage generated from a beam spread is measured directly. When the transmitter is covered by a passing vehicle, a measurement is taken. As a result, a smoke value of 100% in obtained. That is due to the total reflection of the measurement beam by the object structure elements. In addition, there are no findings on the receiver located behind the tested object (measuring line interruption). The decrease in air transparency due to the absorption of radiation (the measurement principle), is proportional to the decrease in light visibility. Therefore, in the situation when the laser beam from the transmitter does not reach the receiver, the measuring system detects the conditions as in the case of the maximum opacity at the optical path. The control unit interprets it as the appearance of an object, because even in heavily polluted exhaust gases, the change in transparency does not occur as rapidly as when the object appears on the measurement line. In the case of uncovering the receiver and restoring the measurement path between the devices, there is possibility to measure real values. Thus, the recorded result shows the correct value, generated by exhaust gas emissions from the vehicle's exhaust system. Due to this fact, it is possible to determine the operation moment of the other analyzers and the vehicle motion evaluation system based on physical dependencies. As a result, it is possible to carry out the exhaust gases measurements without needing any additional sensors.

As a measurement starts, the data is collected for 5 seconds. The obtained results are processed with appropriate algorithms. First of all, the extreme voltage values are filtered out, resulting from the greatest opacity. The measuring system is equipped with a laser emitter. That allows to get an immediate measurement, which is impossible to achieve with NDUV and NDIR lamps, because a shortterm (minimum 10 seconds) tuning of the device after beam interruption and comparing them to the reference values is required. Speed and acceleration values are determined when the vehicle passes through the measurement line. The obtained results allow to determine the number of axles. As a result, the object speed can be determined. These indicators can be used to correct the results of the concentration of toxic compounds in the cloud formed behind the research object. The thermal imaging camera is coupled with a license plate recognition software – a vehicle identification system that collects parameters just before passing through the measurement line. That allows to save the results and identify high polluted vehicles.

RESEARCH METHODOLOGY

Research object

The exhaust gas dissipation measurements were performed on a motorcycle fitted with a 0.249 dm^3 four stroke engine [Szymlet et al., 2020]. The two-wheel vehicle was homologated as Euro 3 and, as at the date of the tests, had a mileage of 60 000 km. The technical specifications of the vehicle have been presented in Table 1. The motorcycle was fitted with a single overhead camshaft (SOHC) [Yamaha, 2023]. Prior to the tests, the motorcycle was inspected. Despite a high level of wear and tear (the motorcycle is used in a driving school on a daily basis), its technical condition was assessed as good (no malfunctions were detected).

Measurement equipment

PEMS

For the investigations of the exhaust dissipation, the authors applied laboratory PEMS equipment mainly used for investigations of exhaust emissions [Kęska, 2022, 2023; Kęska et al., 2022] under actual traffic conditions [Bajerlein et al., 2017; Bajerlein and Rymaniak, 2014; Cieślik and

Table 1. Research object and technical specifications [Yamaha, 2023]

Parameter	
Engine type:	four-stroke
Displacement:	0.249 dm^3
Bore/stroke:	74/58 mm
Max. Power output:	15.4 kW/7500 rpm
Max. torque:	20.5 Nm/6500 rpm
Cooling:	air-cooled
Timing:	SOHC
Weight:	138 kg
Year of manufacture:	2009
Emission standard:	Euro 3

Antczak, 2023; Fuć et al., 2018; Kamińska et al., 2019; 2021; Merkisz et al., 2016; Sarkan et al., 2022]. This was a Micro PEMS Axion R/S+ portable analyzer that allows a direct measurement of the concentrations of the emission components in the exhaust gas (Figure 5).

Owing to its small size and low weight, the device is appropriate for the measurement of the exhaust emissions from light-duty vehicles and two-wheelers. Its main parameters have been presented in Table 2. The device utilizes three methods of measurement, individually adapted to a given exhaust component.

Test stand and measurement conditions

The investigations covering the measurements of the exhaust cloud dissipation behind a stationary vehicle were carried out on a test stand [Fuć et al.,2017] located within the campus area of Poznan University of Technology (Figure 6). The measurements were performed when the vehicle was stationary under laboratory conditions for the following engine speeds: 1500 rpm, 3000 rpm, 4000 rpm, 5000 rpm and 6000 rpm [Rymaniak et al., 2022]. The first measurement point for each of the five engine speeds was performed for the probe located directly in the vehicle exhaust pipe.

The main research was performed with the use of both the PEMS equipment [Banasiewicz et al., 2022; Merkisz et al., 2015] and the emission gate [Kamińska et al., 2022]. In order to enable a simultaneous measurement, a tube was installed in the exhaust pipe of the motorcycle as an extension of the exhaust system. Three holes were made in the tube to fit the measurement probes. The holes were sealed with a tape. When performing the measurements on the emission gate, the authors installed the analyzers and the receivers in a parallel fashion with a distance of 1.4 m from one another (Figure 7). For each of the analyzers, the obtained transmission values (23–90%) were sufficient to correctly carry out the measurements, which is confirmed by the axiality.

Figure 5. Axion R/S+

Table 2. Axion R/S+ – technical specifications [globalmrv, 2023]

Exhaust component	Measurement range	Measurement accuracy	Distribution	Type of measurement	Measurement time [s]
CO_2	0–16%	± 0.3% absolute ±4% relative	0.01 vol.%	NDIR	< 3.5
CO	0–10%	± 0.02% absolute ±3% relative	0.001 vol.%	NDIR	< 3.5
HC	0–4000 ppm	± 8 ppm absolute ±3% relative	1 ppm	NDIR	< 3.5
NO	0–4000 ppm	± 25 ppm absolute ±3% relative	1 ppm	E-chem	< 5
PM	0-300 mg/m^3	± 2%	0.01 mg/m^3	Laser Scatter	2

EXPERIMENTAL VALIDATION OF THE REMOTE-SENSING METHOD

The aim of the research was primarily the validation of the remote measurement of the concentrations of the exhaust components behind the vehicle. The values obtained with the two methods are significantly divergent, therefore the analysis was based on the determination of their mutual correlation. The said correlations of the measurements were analyzed during variable engine speeds without engine load.

Based on the presented results, the authors concluded that the highest coefficient of determination was obtained for nitrogen oxides. The relations of the values between the two measurement methods can be described with a linear function with the coefficient of determination R^2 of 0.9701 (Figure 8a). Despite significant differences in the concentrations, it is clear that the best correlation obtained for nitrogen oxides can be caused by the smallest difference between the values from the two methods compared to other exhaust components.

The increase in the engine speed at idle was directly related to the increase in the concentration of nitrogen oxides as it has been presented in Table 3. At lower engine speeds, a gradual increase in the values was observed for both measurement methods. A significant increase was observed in the case of the Axion R/S+ analyzer for 1500 rpm (increase by 65% compared to the previous measurement point) and the highest value was recorded for the maximum engine speed – 153.50 ppm (6000 rpm). When comparing the obtained values with readings from the emission gate, the authors observed that for lower engine speeds the concentrations oscillate around 1 ppm. The highest value was recorded for 6000 rpm – 3.8 ppm. Based on the above, the authors may confirm that despite significant differences in the readings, the analyzer exhibits a high sensitivity to abrupt changes in the concentrations.

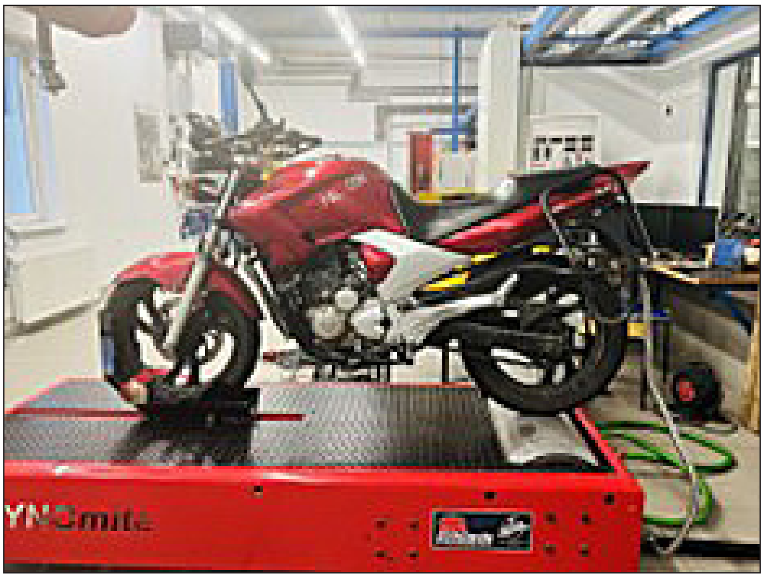

Figure 6. Research object on a two-wheeler dynamometer

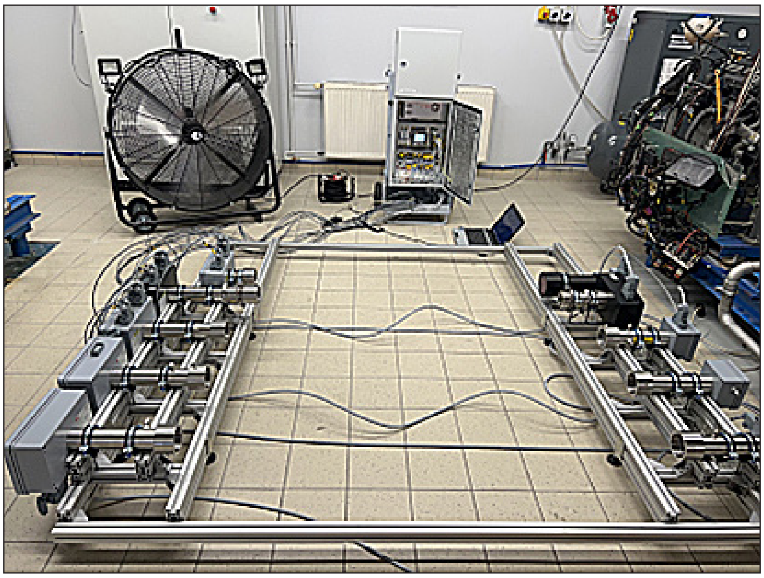

Figure 7. Emission gate – the setup of the measurement equipment

A high R^2 coefficient was also recorded for CO_2 (0.915). The distribution of values can be approximated with an exponential function (Figure 8b). The values of the concentrations obtained from the recorder connected to the remote-sensing analyzers also exhibited mutual relations with the Axion R/S+ equipment.

For the performed measurements, the authors observed a gradual increase in the concentration of carbon dioxide (Table 3). For the results obtained with the Axion R/S+ analyzer, the greatest difference was recorded at the engine speed of 5000 rpm, resulting in an almost 39% increase in the value compared to the previous measurement point. At the same point, the authors also recorded the greatest increase of values for the emission gate (40%). Axion R/S+ showed the lowest value for the idle speed (5.03%) and the highest at 6000 rpm (12.59%).

When analyzing the correlation of values recorded for CO, the exponential nature of the relations was again observed, similar to CO_2, yet, with a lower coefficient of determination (0.7831) (Figure 8c). One may observe two characteristic points that stray from the trend line. The values recorded by Axion R/S+ for carbon monoxide were characterized by an initial increase in the value at lower engine speeds reaching the maximum at 3000 rpm (2.17%) and then an abrupt decrease to the level of 0.12% at 6000 rpm (Table 3). The trend was not accurately reproduced by the remote-sensing analyzer. The maximum reading of 252.30 ppm was obtained at the previous measurement point (1500 rpm). From this moment onward, the authors observed a gradual drop of the value to 29.80 ppm at 6000 rpm. The greatest difference in the values occurred at 4000 rpm and was 75% compared to the previous measurement point. A high dynamic of changes of the carbon monoxide values may result from the fact that, at the initial engine speeds, sudden changes of those speeds led to an incorrect mixing of air and fuel, the results of which was the increased emission of CO. Besides, as has been ascertained in the preliminary research, the engine may have a trend to adopt local values of $\lambda < 1$. At 5000 and 6000 rpm, the greatest drops in the values were recorded of 57% and 87% respectively compared to the previous value. It is noteworthy that the fifth reading (5000 rpm) was the measurement point of the greatest increase in the value of CO_2, compared to the previous measurement point. Therefore, the authors confirmed that along the increase in the engine speed the temperature in the combustion chamber grew, which could accelerate the reaction of oxidation of CO to CO_2.

A high R^2 coefficient was also obtained for PM (0.99) and the correlation of the measurement results assumes a character of a logarithmic function (Figure 8d). The values obtained for PM were pulled directly from the analyzer due to the difference in the measurement units (the recorder utilizes ppm) and the fact that they could exceed the scale. Their nature significantly differs from the results recorded for the gaseous exhaust components. Despite the direct reading and maintained correlation, the values were much higher compared to the results obtained with the

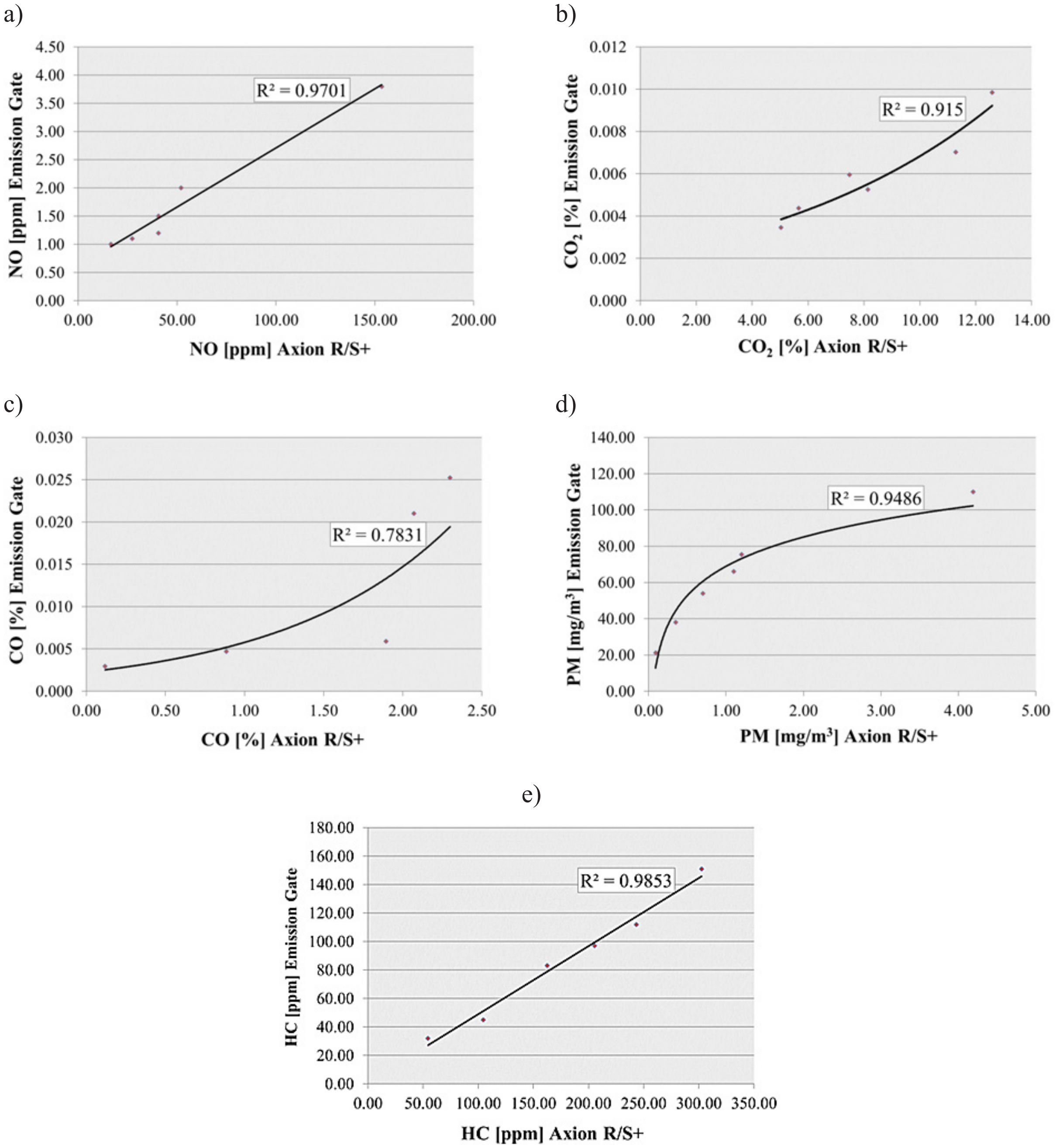

Figure 8. Coefficient of determination for the concentration of a) NO, b) CO_2, c) CO, d) PM, e) HC as obtained from the PEMS equipment and the emission gate

conventional method and they significantly exceeded the values expected for a spark ignition engine. This results from the fact that the measurement equipment operates on the wavelength of 670 nm, which is also the absorption area of other components such as water. Given the above, it can be confirmed that the values do not only record PM10 (as is in the case of the Axion R/S+ analyzer), but also other non-toxic components.

For the recorded measurements, the authors observed a systematic increase in the values of PM, irrespective of the measurement method. The increase in the engine temperature is the main reason for the fuel carbonization, which leads to an increased emission of PM. Lower values were recorded for lower engine speeds and the lowest value was pulled from the Axion R/S+ analyzer for the idle speed (0.09 mg/m^3). The greatest difference compared to the previous measurement point (the value increased almost three times), hence, the highest value for the Axion R/S+ analyzer (4.19 mg/m^3) was observed at the highest engine speed of 6000 rpm. In the case of readings from the remote-sensing analyzers, the greatest

Table 3. Concentrations of the exhaust components pulled from Axion R/S+ and the emission gate

Exhaust component	Measurement method	Idle speed	1500 rpm	3000 rpm	4000 rpm	5000 rpm	6000 rpm
CO_2 [%]	Axion R/S+	5.03	5.66	7.49	8.14	11.29	12.59
	Emission gate	0.0035	0.0044	0.006	0.0053	0.007	0.0099
CO [%]	Axion R/S+	1.89	1.90	2.17	2.06	0.89	0.12
	Emission gate	0.0059	0.0252	0.021	0.019	0.0047	0.003
HC [ppm]	Axion R/S+	302.5	243.5	205.5	162.5	104.5	54.5
	Emission gate	151	112	97	83	45	32
NO [ppm]	Axion R/S+	16.5	27.25	40.5	40.5	52	153.5
	Emission gate	1	1.1	1.2	1.5	2	3.8
PM [mg/m^3]	Axion R/S+	0.09	0.35	0.7	1.1	1.2	4.19
	Emission gate	21.2	38.1	53.9	66	75.4	110

increase in the values was 46% and it was recorded between the last two measurement points. The highest recorded value was 110 mg/m^3, which may have been caused by the increased ambient dust level and the emission of water vapor from the exhaust system at a higher engine temperature.

The change in the concentration of HC for individual engine work points and measurement systems exhibited a linear nature and the coefficient of determination R^2 amounted to 0.9657 (Figure 8e). The values obtained at variable engine speeds were, thus, heavily correlated. This indicates a high level of stability of the readings from the emission gate with rather miniscule oscillations. The greatest difference in the values when pulling data from the remote-sensing device occurred between two subsequent measurement points, i.e., 4000 rpm and 5000 rpm (relative drop by 54%). A similar change was recorded by the PEMS equipment. Therefore, the authors can confirm that the HC analyzer has shown a higher sensitivity to abrupt changes in the readings. Besides, one should note that the varied concentration of hydrocarbons may be influenced by fueling systems of older generation. Older fueling systems encourage unstable conditions inside the combustion chamber (uneven mixture composition).

CONCLUSIONS

Performing measurements of exhaust emissions generated by motor vehicles is extremely important in the context of air pollution. Ongoing control is particularly important in large agglomerations, where the number of vehicles grows continuously. Using remote-sensing technologies allows carrying out multiple measurements in a short time. Additionally, the population of vehicles is varied, and the unit cost of measurement is much lower compared to other measurement methods.

The aim of this paper was an experimental validation of the discussed method based on the measurement of the concentrations of gaseous exhaust components from a two-wheeler vehicle. The investigations were performed on a motorcycle fitted with a 0.249 dm^3 engine. The assessment of the method was possible thanks to the application of two measurement techniques: PEMS and emission gate. Based on the analysis of the performed measurements, the authors have concluded that the concentrations of the exhaust components generated by the motorcycle changed dynamically depending on the operating conditions. The investigations have shown that the emission level and the composition of the air-fuel mixture were influenced by the fueling system. The remote-sensing method in most cases correctly reflected the variable nature of the engine operating parameters, including the abrupt changes in the concentrations of the exhaust components resulting from the unstable mixture composition. A higher efficiency of the method was observed for greater differences in the values. The lowest correlation was observed for the HC and CO analyzers at idle, compared to the PEMS method.

It is noteworthy that the values obtained from the remote-sensing analyzers were much lower compared to Axion R/S+. The equipment measures each component separately, which limits the absorption of radiation by other components.

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