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*Marek BRZEŻAŃSKI*
*Michał MARECZEK*
*Marcin NOGA*

**Combustion Engines**
**Polish Scientific Society of Combustion Engines**

# The concept of a maintenance-free drive-thru inspection station for commercial vehicles

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*The article presents the concept of a maintenance-free inspection station intended for conducting drive-thru tests of commercial vehicles. The main purpose of building this type of diagnostic line is to carry out non-invasive, preliminary tests of heavy-duty vehicles entering the vehicle service area in terms of parameters affecting the safety of their operation in relation to the applicable standards. The main parameter to be assessed will be the concentration of toxic exhaust components, measured using remote sensing methods. In addition, the proposed diagnostic line can be supplemented with additional remote measurement systems, such as, for example, systems for assessing the condition of vehicle lighting, loads on individual axles and individual wheels of the vehicle, tire pressure, thermal load of the brake system, as well as a system for detecting leaks of fluids from the vehicle. Based on the carried out work, it has been shown that using the current specialist knowledge and the components of measurement systems available on the market, it is possible to develop an innovative diagnostic line using remote measurement methods.*

Key words: *exhaust emissions, screening tests, vehicle inspection, remote sensing*



## 1. Introduction

At the present stage of the development of the road transport means, all kinds of activities relating to their impact on the environment play an extremely important role [3]. In this area, a number of legal regulations have been established regarding the conditions of admitting vehicles to roads and a number of control regulations that determine the day-to-day operation of vehicles [4, 10]. However, due to the very diversified car fleet and very different conditions of vehicle operation, the existing control regulations do not always effectively and quickly identify vehicles that are operated with faults that endanger their safe operation or exceed the established emission limits.

In June 2019, in Cracow, as the first city in Poland, emissions from the streams of passing vehicles were tested using optical methods. Initial estimates showed that approx. 3% of vehicles are responsible for approx. 40% of traffic pollution [11]. These vehicles often did not meet the requirements in force during periodic technical inspections. For this reason, it is important to further develop and disseminate methods enabling effective detection of sources of air pollution as well as systems enabling the construction of databases and statistics in still not fully recognized area.

Therefore, it is advisable to develop a concept of a maintenance-free inspection station intended for non-invasive, initial screening of vehicles involved in the road. The main idea of creating this type of diagnostic tool is to perform screening tests addressed to domestic and foreign shippers operating in the European Union. The results of this type of research will be particularly important in terms of meeting the EU requirements, both for domestic forwarding companies and for vehicles from outside the EU, which are subject to other types of regulations in this area.

The effect of the project may be the protection of the EU area in terms of adverse effects of road transport, which is inconsistent with the applicable standards.

Ultimately, the operational experience of the diagnostic line can be used in the development of standard control procedures used in real road traffic, e.g. for the so-called motorway gates, entrances to urban agglomerations, etc.

The legal and logistic concept of developing this type of diagnostic station will require a separate analysis.

## 2. Assumptions for the proposed concept

The concept proposed by the research team from the Department of Automotive Vehicles at the Cracow University of Technology is based on the use of spectrophotometric and thermovision techniques as well as computer image analysis to identify exhaust gas composition and the opacity. It is based on the optical detection of the exhaust cloud near the vehicle and the spectral analysis of the light in the infrared and UV range to register individual compounds in the cloud. According to the assumptions, the measurements are to be non-contact, remote and immediate.

The diagnostic line based on the concept proposed by the team from the Cracow University of Technology, may become one of the first installations operating for in the long term conditions on Polish roads, having a beneficial effect on the protection of the natural environment against automotive pollution. An innovative approach in the proposed concept is the use of computer image analysis, which will allow to determine with high accuracy the location of the source of the emitted exhaust gases, i.e. around the end of the tail pipe outlet. A targeting of the measuring beam at the exhaust gas cloud with the lowest possible dilution by air, will allow to obtain the most reliable results.

A further goal of building this type of diagnostic line is to conduct preliminary, non-invasive screening tests of commercial vehicles in terms of all parameters affecting the safety of their operation in relation to the applicable standards. The assumed diagnostic procedure will take place during one run along the designated measuring track with appropriately selected characteristics.

The main parameter to be assessed will be the concentration of toxic exhaust gas components measured by remote sensing. This parameter is of key importance for the assessment of the technical condition of the vehicle's powertrain, mainly the fuel system, as well as the technical condition of the exhaust gas aftertreatment system. In addition, the proposed diagnostic line can be supplemented with additional remote measurement systems, such as:

- vehicle lighting condition assessment system,
- system for detecting leaks of operating fluids from the vehicle,
- system for assessing the load of axles and individual wheels of the vehicle,
- tire pressure estimation system,
- system for estimation the thermal load of the brake system components.

Those types of tests are aimed at making an initial, comprehensive assessment of the technical condition of selected vehicle components and identifying the most important faults that affect operational safety. According to the assumptions, the entire diagnostic procedure should take place during one run along a designated measuring track with appropriately selected characteristics. The result of the tests will be forwarded to the vehicle driver by a message displayed at the end of the diagnostic line.

The proposed approach differs from that used in road emission tests, e.g. in the USA, in that it applies to selected vehicles whose drivers volunteer for screening, not all vehicles passing the road section under test. This reduces the number of vehicles tested, but on the other hand allows a much more complete assessment of the technical condition of commercial vehicles, which has a significant impact on road safety and overall automotive emissions.

## 3. The concept of remote measurement of the concentration of exhaust gas components

The role of screening control for automotive exhaust gases is to detect irregularities in the level of harmful components emitted by the vehicle. Exceeding the permissible values may indicate a failure of the engine, fuel system or exhaust gas aftertreatment system. It is not intended to precisely determine the composition of exhaust gases, nor to diagnose the cause of a failure. The result of such inspection is to be a suggestion that the vehicle should be directed to a service or for further tests to a vehicle inspection station.

The main features of the screening control of exhaust are its non-invasive nature and the least possible involvement of third parties, including the driver. Measurements must be automated. The only requirement is that the vehicle must run in such a way that it is possible to take a sample of the exhaust gases. The most beneficial place to sample exhaust gases is at the outlet of the vehicle's tailpipe. However, the need to locate it and place the measuring probe in it, additionally while the vehicle is in motion, excludes the possibility of direct measurement. The outlet of the tailpipe is often placed under the vehicle at some distance from the vehicle's contour. Therefore, it was assumed that the measurement would be made in the vicinity of the exhaust gas outlet, taking into account the dilution of the exhaust gas with ambient air. However, it still does not completely eliminate the problem of locating the exhaust gas outlet. For this purpose, it is necessary to use the technique of computer image analysis.

When analyzing the available measurement methods, it was necessary to choose the most appropriate one for remote tests, in which reliability and maintenance-free are also an important factor. Table 1 summarizes the basic measurement methods with their main features.

Table 1. Methods of measuring the concentration of the components of exhaust gases [5]

| Method | Advantages | Disadvantages |
|---|---|---|
| Optical spectroscopy | – direct and fast,<br>– selective with good sensitivity,<br>– minimal measurement drift,<br>– no effect on other gases | – the need to define carefully selected areas of the radiation spectrum |
| Gas chromatography | – very accurate and selective | – continuous measurement difficult to implement,<br>– gas sample delivering needed,<br>– very expensive |
| Semiconductor sensors | – low cost,<br>– possible exposure measurements,<br>– very sensitive (ppm) | – poisoning effect possible,<br>– is subject to irreversible wear,<br>– measurement susceptible to the influence of other gases,<br>– sensitive to moisture |
| Catalytic (pellistor) | – low cost,<br>– detects the presence of flammable gases | – possible poisoning effect,<br>– sensitive to gas groups,<br>– errors under the influence of other flammable gases,<br>– zero error (ppm) |

Among the methods used in industry, there are also thermally conductive sensors (TDC), electrochemical sensors and sensors based on the phenomenon of surface acoustic wave (SAW). Optical measurement methods themselves, usually based on emission or absorption spectroscopy, constitute a numerous group of solutions [7]. The above-mentioned methods of remote measurement of the concentration of carbon monoxide, hydrocarbons, nitrogen oxides and smoke in exhaust gases were initially analyzed in laboratory conditions in the Department of Automotive Vehicles at the Cracow University of Technology.

Measurement methods are marked with international symbols:

- NDIR (Non-Dispersive Infrared Spectroscopy),
- FTIR (Fourier Transform Infrared Spectroscopy),
- TDLS (Tunable Diode Laser Spectroscopy),
- CRDS (Cavity Ring-Down absorption Spectroscopy),
- DOAS (Differential Optical Absorption Spectroscopy),
- DIAL (Differential Absorption Lidar),
- PAS (Photoacoustic Spectroscopy),
- MUPASS (Multipass Spectroscopy), etc.

Optical gas concentration measurement (NDIR) is widely used in the automotive industry, but not only [9]. The popular solutions used so far, however, did not allow for the study of the exhaust cloud from vehicles traveling on the road. In recent years, due to the interest in the problems of urban traffic pollution, solutions are developed and implemented that enable monitoring of the air condition [1]. There are portable systems recording passing vehicles together with an estimated assessment of the composition of the exhaust gases emitted by them.

## 4. Verification of the proposed concept of remote measurement of the concentration of exhaust gas components in real conditions

In order to pre-verify the proposed concept of a remote-sensing diagnostic line appropriate measurements were made to quantify the assumptions for selected exhaust components. Measurements of $CO_2$ and $O_2$ concentrations were made for two exemplary vehicles – a Mercedes Actros 1842 truck and a Mercedes Tourismo coach (Fig. 1). The tested Mercedes Actros truck had a mileage of approximately 500,000 km, while the Mercedes Tourismo coach was a brand new vehicle. Both were technically sound. The aim of the measurements was to determine the area around the outlet of the exhaust system within which it is possible to measure the concentration of toxic exhaust components with a diagnostic analyzer.

Fig. 1. Test vehicles – Mercedes Actros 1842 truck (top) and Mercedes Tourismo coach (bottom)

The Capelec Cap 3201 analyzer used for the measurements consisted of two modules: a five-gas exhaust gas analyzer and an opacimeter (Fig. 2).

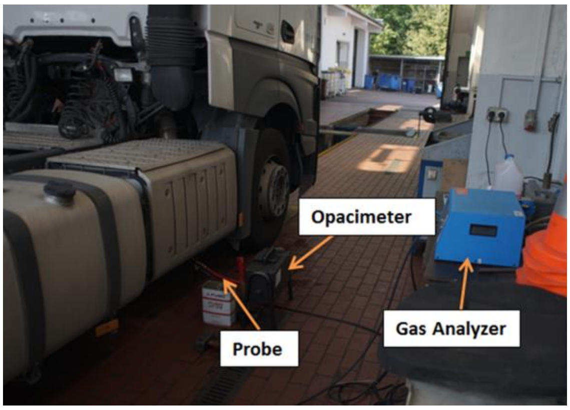


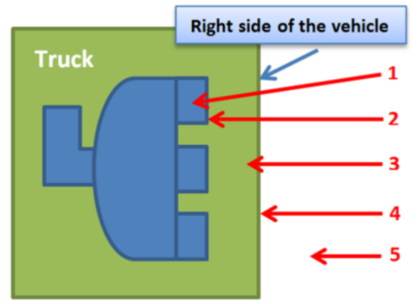

Fig. 2. A general view of the stand for measuring the composition and opacity of exhaust gases

The measurements were carried out for both vehicles while the engine was idling. The limit line was considered to be the achievement of 0.2% of $CO_2$ concentration, which is the lower measurement threshold of the popular analyzers, however lower values are achievable [2]. In the case of a truck, the outlet of the exhaust pipe is located on the right side of the vehicle (Fig. 3). In the case of the coach, the exhaust gases come out from the bottom of the vehicle, in the left rear part of the body (Fig. 4). The Mercedes Actros truck is equipped with a diffuser-shaped exhaust pipe with a flattened shape and several nozzles. This results in the dispersion of the exhaust gas stream and a significant dilution of the sample with the ambient air.

Fig. 3. View of the outlet of the exhaust system – Mercedes Actros truck

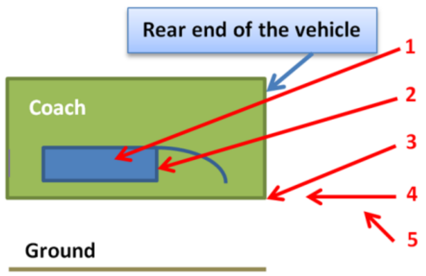
Fig. 4. View of the outlet of the exhaust system – Mercedes Tourismo coach

Figures 5 and 6 show the schemes for measuring the volumetric concentration of carbon dioxide $CO_2$ and oxygen $O_2$ in the exhaust gas for both tested vehicles at different distances from the outlet of the exhaust system. For screening tests, the area beyond the outline of the vehicle to which exhaust gases are emitted is important.




| Concentration (vol.) at the point: | % $CO_2$ | % $O_2$ |
|---|---|---|
| 1. Inside the exhaust system | 1.8 | 17.3 |
| 2. Edge of the outlet of muffler | 0.7 | 19.3 |
| 3. 10 cm from the outlet edge | 0.5 | 19.7 |
| 4. At the vehicle's lateral contour | 0.4 | 19.9 |
| 5. 35 cm from the outlet edge | 0.2 | 20.2 |

Fig. 5. Distribution of $CO_2$ and $O_2$ concentration as a function of distance from the exhaust outlet of the Mercedes Actros truck




| Concentration (vol.) at the point: | % $CO_2$ | % $O_2$ |
|---|---|---|
| 1. Inside the exhaust system | 2.3 | 16.4 |
| 2. Edge of the outlet of muffler | 2.3 | 16.3 |
| 3. At the vehicle's rear contour | 0.4 | 19.9 |
| 4. 10 cm from the vehicle's contour | 0.3 | 20.0 |
| 5. 50 cm from the vehicle's contour | 0.2 | 20.3 |

Fig. 6. Distribution of $CO_2$ and $O_2$ concentration as a function of distance from the exhaust outlet of the Mercedes Tourismo coach

The concentration of carbon dioxide $CO_2$ is in this case taken as a reference value allowing the identification of the exhaust gas cloud. It is important to locate the area where the concentration of carbon dioxide $CO_2$ is higher than 0.2%. In the case of a vehicle with an efficient exhaust aftertreatment system, the remaining exhaust components, such as carbon monoxide CO, nitrogen oxides $NO_x$, HC hydrocarbons and $NH_3$ ammonia, may remain at the analyzer measurement threshold, which is acceptable in the case of screening tests. The measurements show that in the area up to approx. 30–50 cm from the contour of the vehicle, at the height of the exhaust pipe, it is possible to measure the exhaust gas with sufficient accuracy, using an analyzer for diagnostic tests.

In order to evaluate the performed measurement, it is necessary to find the correlation between the concentration of $CO_2$ and $O_2$ and the toxic components of the engine exhaust as a function of the engine load and the place of sampling. Measurement of the opacity of the exhaust gases, taken with a standard opacimeter, did not show any measurable values, however it is planned to implement exhaust opacity testing in the final version of the system. That will require additional exploratory research. The value of the exhaust gas temperature at the end of the exhaust pipe as indicated by the analyzer was 50–60°C. In the case of the NDIR measurement method used in the diagnostic exhaust gas analyzer, the time needed to stabilize the measurement is about 30 seconds.

## 5. Measurement techniques in the proposed concept of remote measurements

During the preliminary tests the NDIR detector was used to determine the $CO_2$ concentration in the exhaust gas cloud. It is important as it is a method based on spectrophotometric measurement. However, the NDIR analyzer, the general scheme of which is shown in Fig. 7, imposes certain limitations in a typical design, preventing remote measurement.

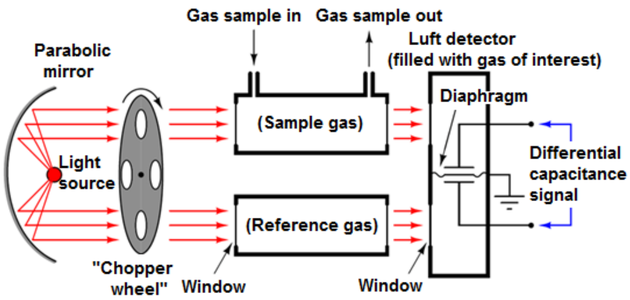



Fig. 7. NDIR gas analyzer working principle – prepared basing on [12]

The principle of operation uses the effect of the absorption of a narrow band of electromagnetic radiation by the tested chemical compound. The proportion of the amount of light passing through the measuring tube with the tested gas and the reference tube in which the light passes through the reference gas is proportional to the concentration of the tested gas in the reference gas. In the case of bench tests, the reference gas is air taken from the environment. In order to carry out such a measurement, a sample of the tested gas mixture should be delivered to the measuring tube. The radiation energy passing through the measuring tube and the reference tube heats the measuring chamber unevenly. The pressure difference in the measuring chamber is read as the concentration of a given compound. The need to deliver the tested gas to the measuring tube is related to the location of the probe in the flue gas stream. It would be a complex problem in the field of automation and mechanics when the test vehicle is driven through the test stand. The second limitation is the mere fact of the time it takes the sample to get to the measuring tube and properly heat the measuring chamber. Assuming that the vehicle is in motion during the measurements, which is necessary to cause the engine load, this seems to be an additional argument in the search for other solutions.

The proposed concept assumes the identification of the exhaust gas cloud and the determination of its composition based on the analysis of the image recorded in the infrared and ultraviolet UV spectrum. This method will consist in comparing the selective spectra of the band in the range of 2–11 μm and the UV radiation generated by the radiator and passing through the exhaust gas cloud in the immediate vicinity of the tested vehicle [6]. Figure 8 shows a general diagram of the measuring system.

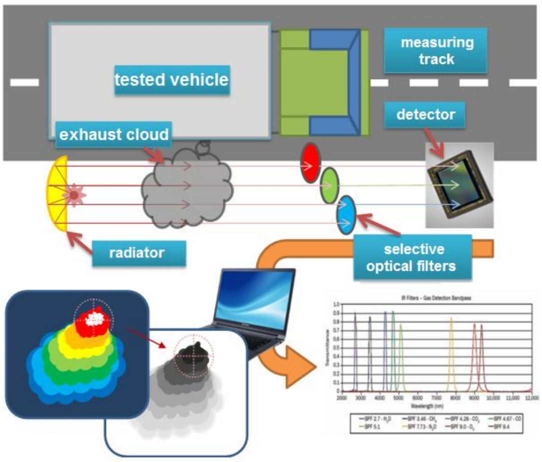



Fig. 8. General diagram of the stand for spectral measurements of exhaust gas composition

It is assumed that the vehicle traverses the measurement path with a forced engine load. A specially profiled track is set for the vehicle to travel. The image of the vehicle surroundings is to be recorded in real time during the test and analyzed at the same time. This approach differs from usually used in inspection station conditions, but the forced engine load gives a much better opportunity to reveal possible malfunctions. The result of the measurements from a given sample will be displayed on the monitor screen after the completion of the test track.

The principle of the measurement is based on comparing the spectrum of radiation incident directly on the detector and the spectrum after passing through the exhaust gas cloud. The gas contained in the exhaust cloud absorbs a certain part of the spectrum, strictly defined for a given chemical compound. The amount of radiation that reaches the detector after passing through the narrowband optical filter is proportional to the energy absorbed by the gas, and therefore to its concentration. Figure 9 shows a spectral diagram of the absorption of individual exhaust gas compounds from internal combustion engines.

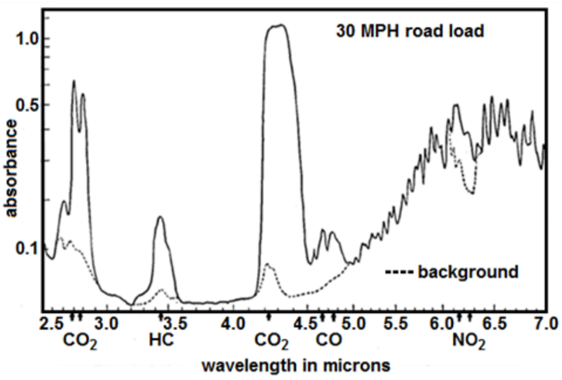



Fig. 9. Absorption spectrum for exhaust gases of motor vehicles – prepared basing on [8]

The areas of the spectrum where individual components of the exhaust gas have a high absorption capacity are clearly marked. Figure 10 shows the image recorded by a thermal imaging camera, additionally equipped with an optical filter with a band corresponding to carbon dioxide $CO_2$.

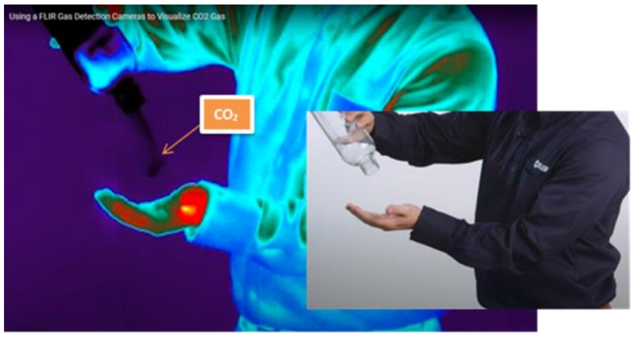



Fig. 10. Image from a thermal imaging camera and a standard camera showing the outflow of carbon dioxide $CO_2$ from a bottle [13]

Contemporary thermal imaging techniques operate in a wide range of infrared radiation. Combining high sensitivity and resolution, they enable the creation of accurate images in real time, which allows for even better analysis, especially in the case of dynamic changes in the engine load.

## 6. The concept of an integrated data analysis system from subsequent stages of vehicle diagnostics

The project of an innovative diagnostic line using remote measurement methods for diagnostic screening tests of commercial vehicles entering the area of vehicle service stations assumes the creation of a uniform system for the acquisition and processing of measurement data. It is planned to develop this type of system in the LabView programming environment, consisting of acquisition and computing modules.

The first stage of processing data from all measurement modules will be their synchronization as a function of the measurement time and their collection with division into individual measurement blocks. Then, they will be used to select the data that is important from the point of view of interaction with data from other measuring blocks and requires processing according to the developed algorithms.

Calculated data from all measurement modules will be subject to verification on the basis of established ranges of values assumed as correct or exceeding the adopted range. The final data, resulting from the examination along the entire diagnostic track, will be archived in memory modules and stored at the time determined by the owner of the facility. The remaining intermediate data collected during the research procedure will be deleted from the computer system.

It is planned to develop a general calculation algorithm using measurement and calculation data, the final effect of which will be to provide information on the technical condition of the analyzed vehicle components. Limit values of the tested vehicle parameters will be established, the exceeding of which requires further analysis in a specialist vehicle service station. The values of the measured and calculated operational parameters of the vehicle being tested on the designed diagnostic track will be subject to basic verification based on the criteria related to the regulations authorizing the vehicle to travel on the roads of the European Union. Additional criteria for the evaluation of the test results will be criteria related to the vehicle manufacturer's standards.

The diagnostic system under development has as a priority the identification of vehicle faults or ailments in screening tests, which are important from the point of view of the vehicle operation and the applicable regulations in the field of admitting the vehicle to traffic on public roads. It is assumed that test result information will be displayed on the monitor at the end of the diagnostic track. It is also possible to make a printout of the course of the study. As the proposed system will have a diagnostic potential that goes beyond the above-mentioned criteria, an additional effect of this type of research will also be the identification of other deficiencies that affect the durability and reliability of the vehicle's operation. This additional information will encourage vehicle users to use this type of diagnostic line.

## 7. Conclusions

The article presents the concept of assessing the concentration of selected exhaust gas components measured remotely using remote sensing methods. This parameter is of key importance for assessing the technical condition of the vehicle's powertrain, mainly the fuel system, as well as the technical condition of the exhaust gas aftertreatment system. In addition, the proposed diagnostic system has further development potential and can be supplemented with additional remote measurement systems for many other vehicle parameters responsible for its proper operation and road safety.

The analysis of the existing solutions shows that so far no similar system of automated vehicle screening tests has been implemented. The target assumption of the developed concept is the creation of an automatic diagnostic line that would enable screening of possible irregularities in commercial vehicles to the extent similar to periodic mandatory technical inspections carried out at vehicle inspection stations. For this reason, vehicle test stations may, to some extent, be a reference for the developed concept of vehicle diagnostic screening lines. The main differences between the developed concept of the diagnostic line and the test procedure carried out in vehicle inspection stations are that this innovative concept assumes a completely automatic vehicle testing procedure, which enables a quick diagnosis of the technical condition to be carried out at any time. The report generated for the user of the vehicle after the test will contain information whether any irregularities that require repair or adjustment have been discovered within individual areas of control. On this basis, the vehicle user will decide on the further treatment of the vehicle and may have it inspected and repaired at a vehicle service station. For this reason, the proposed concept of a diagnostic line for vehicle screening is characterized by a very high level of innovation. The implementation of such solutions will certainly have a significant impact on increasing the level of road safety and reducing the environmental nuisance of commercial vehicles.

The presented concept showed that, based on the current specialist knowledge and the components of measurement systems available on the market, it is possible to develop an innovative diagnostic line using remote measurement methods intended for diagnostic screening tests of vehicles participating in road traffic. It is estimated that at the time of preparing the article, the proposed system had reached the technology readiness level 3. It means that the adopted solutions have proved successful, but a lot of efforts still need to be made to develop a ready-made system.

The measurable effect of launching this type of diagnostic line may have a significant impact on increasing the safety of vehicle operation, reducing the environmental burden and controlling the applicable standards.

## Nomenclature

| | | | |
|---|---|---|---|
| CRDS | cavity ring-down absorption spectroscopy | NDIR | non-dispersive infrared spectroscopy |
| DIAL | differential absorption lidar | PAS | photoacoustic spectroscopy |
| DOAS | differential optical absorption spectroscopy | SAW | surface acoustic wave |
| FTIR | Fourier Transform Infrared Spectroscopy | TDC | thermally conductive sensors |
| MUPASS | multipass spectroscopy | TDLS | tunable diode laser spectroscopy |

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Prof. Marek Brzeżański, DSc., DEng. – Faculty of Mechanical Engineering, Cracow University of Technology.

e-mail: *marek.brzezanski@pk.edu.pl*



Michał Mareczek, DEng. – Faculty of Mechanical Engineering, Cracow University of Technology.

e-mail: *michal.mareczek@mech.pk.edu.pl*



Marcin Noga, DSc., DEng. – Faculty of Mechanical Engineering, Cracow University of Technology.

e-mail: *marcin.noga@pk.edu.pl*