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Methods of evaluating the exhaust emissions from driving vehicles

The type approval tests of vehicles with internal combustion engines increasingly include issues regarding the assessment of ecological indicators in real traffic conditions. This is done with the help of specialized equipment from the PEMS (Portable Emissions Measurement Systems) group. This requires not only a series of test procedures, but also assembly of technically advanced equipment along with the proper preparation of the vehicle's exhaust system. Currently, activities are being carried out to develop solutions for non-invasive assessment of ecological indicators from moving vehicles. The article discusses these types of solutions, at the same time indicating their strengths and weaknesses. Also presented are pollutant emission tests in real operating conditions that will be used to develop a modular exhaust emission gateway. The result of the analysis was to indicate the development directions of methods for exhaust emission assessment from vehicles in motion.

Key words: *emission gate, net emission factor, real driving emissions*

1. Introduction

In 2018, Poland broke air pollution records despite a general downward trend in non-commercial sectors, in recent years emissions in the transport sector have risen again. In the winter months of 2018, air pollution in Polish cities was higher than in the Chinese metropolises famous for smog [11]. An important component of urban pollution is motorization. This is due to the large number of vehicles moving between buildings (often tall buildings) that limit air flow. Therefore, actions are being continuously taken in the European Union and around the world to limit this process. This is served, among others, by the adopted and implemented Sustainable Development Policy [3].

The global trend of motor vehicle tests is focused on the assessment of ecological indicators in real operating conditions [1, 4, 5]. Currently, this is carried out for passenger cars and heavy vehicles in the approval process. This is due to the significant costs of this type of research. On the national roads, the vast majority of vehicles are several or even several dozen years old, which are often characterized by a significant degree of exploitation wear. This results in them generating excessive exhaust emissions, especially of heavy hydrocarbons and particles. In the aspect of annual inspections of technical condition of vehicles, measures are taken to increase the scope of control measurement of pollutant emissions, but there is no definitive methodology that could be introduced for general use. This is mainly due to the difficulty of applying load of the engine at vehicle inspection stations.

For a dozen or so years, devices aiming at non-invasive assessment of pollutant emissions from moving motor vehicles have been developed in various scientific centers around the world. These solutions are often technically limited, and the operating parameters of drive systems are not recorded. As a result, current solutions are insufficient. Such devices are commonly referred to as "emission gates". Their measurement principle is based on optical analyzers or the analysis of the spectra of images taken behind the vehicle. Due to the problem of pollutant emissions from vehicles, it is necessary to further develop such devices. Therefore, taking into account the significant research and implementation experience of the Institute of Diesel and Transport Engines at the Poznan University of Technology and ODIUT Automex Sp. z o.o. a project is under way: "Emission gate – a modular device for quick assessment of road and rail vehicles emission" (described in chapter 3).

In the studies of ecological indicators of vehicles, the conditions under which they are implemented are very important. This is about road conditions, as well as the nature of roads, weather conditions and ambient (local) air pollution. Determining the exhaust emission characteristics for cities is also very interesting in terms of application possibilities for emission gates. This was the reason for carrying out road tests in the Poznan agglomeration, where the city's emission map was prepared and the ecological indicators of the vehicle with regard to local air pollutants were determined. The research routes adopted included three main communication rings of the Poznan agglomeration, related to the so-called urban communication frames.

2. Solutions for the assessment of emissions from moving vehicles

Solutions for assessing ecological indicators from vehicles in motion have been in the works for decades. However, these constructions are often limited to specific applications (selected ecological indicators, specific type of vehicles or restrictions related to environmental conditions). In some systems, the emission of pollutants is estimated, and for the most part, data on the variability area of the drive system's operation parameters and its thermal state are unknown. For this reason, these devices are characterized by low precision. It should also be noted that they are the subject of patent applications, however in the long term their commercialization is carried out only to a small extent.

Examples of solutions for the assessment of emissions from moving vehicles:

- Patent marked US5498872(A) titled "Apparatus for remote analysis of vehicle emissions" (Fig. 1) [9]. The subject of the patent is a vehicle exhaust gas analysis device: measuring concentrations and recording levels of NO, CO, CO_2, HC and H_2O. The analyzers used are based on infrared and ultraviolet radiation with a coupled detection unit. The elements are placed on opposite sides of the road. The detector unit divides combined infrared and ultraviolet radiation into separate bands. The ultraviolet ray is directed to a photodiode array in a spectrometer that generates an NO measurement signal. The rotating reflector multiplies the infrared beam over time into many infrared sensors that generate electrical signals that measure: CO, CO_2, HC and H_2O in the vehicle's exhaust. Computer calculates the relative concentrations of CO, CO_2, HC, NO and H_2O on the infrared and ultraviolet beam paths. This device measures only gaseous components without taking into account particulate matter and smoke, NO_2 measurement has also not been taken into account [9].

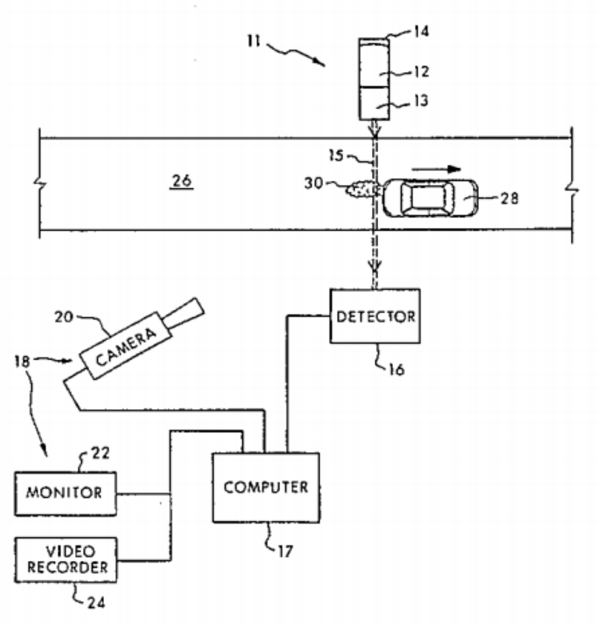

Fig. 1. Operating principle of the device described in Patent US5498872(A) titled „Apparatus for remote analysis of vehicle emissions" [9]

- Patent designated DE4235235(A1) titled "Continuous determination of traffic-generated pollution – employing vehicle-mounted digital signal transmitters which, on passing reference station, identify vehicle to enable pollution assessment" (Fig. 2) [6]. The invention includes a method for determining the intensity of pollutants produced by a vehicle while moving through a reference station. A digital signal transmitter must be used in each vehicle. The signals identify the vehicle type, mass, displacement, fuel type, etc. The reference lines provide the determination of instantaneous speeds. The receivers send signals to the central computer in which the statistical data are classified, where the exhaust emission characteristics related to the above variables are determined. This allows the assessment of ecological indicators of the research object. The video camera provides coarse classification for vehicles not equipped with a transmitter [6].

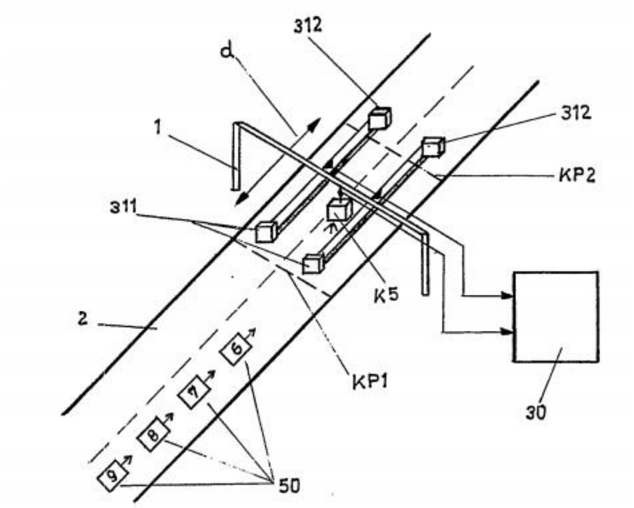

Fig. 2. Operating principle of the device described in Patent DE4235235(A1) titled „Continuous determination of traffic-generated pollution – employing vehicle-mounted digital signal transmitters which, on passing reference station, identify vehicle to enable pollution assessment" [6]

3. Emission gate – a modular device for a quick assessment of road and rail vehicles emission

Emission gates can have a positive impact on the transport sector and the environment. The possibility of testing the actual emission from vehicles with them will significantly affect air purity and reduce the rate of environmental degradation, which is important in the aspect of sustainable development policy. The introduction of gates may affect local emissivity regulations and force them to comply with vehicles of different categories. In an increasing number of European cities, there are laws restricting the entry of older vehicles that do not meet the current emission standards. This applies to the date of manufacture and the fulfillment of certain type of approval standards, and does not refer to actual emissions. Meanwhile, vehicles are often in poor technical condition and thus end up exceeding the pollution limits, especially in the case of $PM_{2.5}$ and PM_{10} particulate matter. Their level is significantly influenced by solid particles emitted from the exhaust systems. The applicants' research and professional literature confirm that the real emission level differs significantly from the emission determined in the type approval tests and at the vehicle control station (if the latter is performed at all). The impact of motor vehicles on air quality is widely known and described in the literature worldwide, and more and more often these observations concern rail vehicles. This is related to a reduction in the life expectancy of people and an increase in disease rates, which mainly concerns upper respiratory diseases and cancers.

The Institute of Combustion Engines of the Poznan University of Technology together with the company ODIUT AUTOMEX Sp. z o.o. from Gdansk, through the National Center for Research and Development, carry out a research project funded by the European Union Development Fund; (POIR.04.01.02-00-0002/18).

The aim of the project is to develop a tool (including manufacturing technology) for measuring emissions of toxic compounds and smokiness of exhaust gases from passing road and rail vehicles. Excessive emission of toxic exhaust fumes from motor vehicles is a frequent phenomenon and has a significant impact on environmental degradation. The emission gate will enable quick assessment of emissions from vehicles travelling in a given area. It is an important action to protect the environment for current and future generations, which is the basic principle of sustainable development. As part of the project, a modular device based on optical analyzers (NDIR, UV) is developed that can be adapted to the needs of customers. The gate will enable the measurement of: CO, HC, NO_x, PM and smoke opacity in relation to vehicle operation parameters. The properties of the exhaust gases behind the vehicle depend on many factors, which is why the necessity to perform specialized multi-range research works is foreseen. The project includes road and rail vehicles, which will increase the possibilities of commercialization of the project's effects.

4. Measurements of pollutant emissions from a passenger car, taking into account ambient air quality

4.1. Method

The tests were carried out using a passenger car equipped with a plug-in hybrid drive system (Table 1, Fig. 3). It uses an SI combustion unit with a displacement of 1.4 dm^3, characterized by a nominal power of 110 kW at 5000 rpm (maximum torque is 250 Nm). The drive uses an

Table 1. Technical data on the propulsion system of the test vehicle

Parameter	Value
Date of manufacture	2018
Displacement	1.4 dm^3
Engine type	SI, plug-in hybrid
Combustion engine power	110 kW at 5000–6000 rpm
Electric engine power	75 kW at 2500 rpm
Maximum combustion engine torque	250 Nm at 3500 rpm
Maximum electric engine torque	330 Nm at 1600–3500 rpm
Engine boost	A turbocharger
Cylinder number	4
Exhaust emission norm	Euro 6

Fig. 3. The test vehicle equipped with the PEMS device during tests in real operating conditions

electric motor, whose maximum power is 75 kW at 1600 rpm (maximum torque of 330 Nm). The electric motor in this unit is powered by a 8.7 kWh battery installed in the floor in front of the back seat. The drive system uses a 6-speed DSG gearbox (direct shift gearbox). The drive system used complies with the Euro 6 emissions standard.

The test drive cycle was carried out in real operating conditions divided into three routes. The first route included a 8.9 km route in the city center of Poznan. The second route covered the city route with a length of 19.3 km, while the third route had the distance of 46.8 km on non-urban roads (Fig. 4). All test sections were carried out on a weekday during the rush hours (afternoon traffic peak). The presented routes ran through the ring communication frame of the Poznan agglomeration.

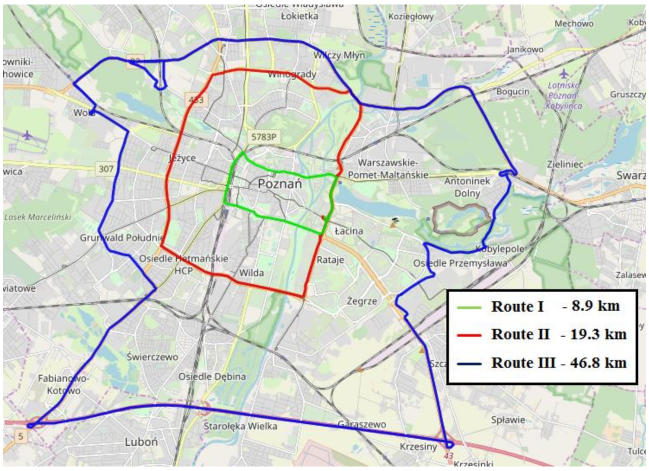

Fig. 4. Test routes in the Poznan agglomeration

Mobile analyzers from the PEMS group were used for measurements. A SEMTECH DS instrument manufactured by Sensors Inc. was used to measure the concentration of gaseous components, exhaust gas flow (CO_2, CO, HC, NO_x) and the oxygen content in the exhaust gas. The measurement was started with calibration. The specific measurement was carried out by taking off the exhaust gases to the analyzer using a measuring probe (gas temperature – 191°C). The sample was taken in through a heated line to prevent the condensation of hydrocarbons. Then the solid particles were filtered from the exhaust gases since they could disrupt the proper functioning of the device. The FID (flame ionization detector) analyzer was used to measure HC concentration. The exhaust gases were then cooled to 4°C. Using the NDUV (non-dispersive ultraviolet) analyzer, NO_x was measured and the content of nitrogen oxides (NO + NO_2) was determined. The concentration of CO and CO_2 was determined using NDIR (Non Dispersive Infrared). Oxygen concentration measurement was measured using an electrochemical analyzer [7].

AVL Micro Soot Sensor was used to determine the concentration of particles. The exhaust sample was collected by a second independent conduit. The apparatus was equipped with a flue gas conditioning system, and the principle of its operation is based on the photoacoustic method. In the resonant measuring chamber in which the volume of the exhaust gas is located, it alternates heating and cooling.

This causes vibrations of the elastic medium in the chamber. Vibrations are recorded by sensitive microphones as a sound wave. Recorded signals are filtered and amplified, and then converted to PM concentration values [1].

The Axion R/S+ analyzer manufactured by Global MRV was used to assess the emission of pollutants in ambient air. The device measured the concentration of gaseous toxic compounds using an infrared non-dispersive analyzer – NDIR (CO_2, CO, HC) and an electrochemical (NO) and PM analyzer using the Laser Scatter method, in which the particle velocity is measured. The sample of ambient gases was collected near the vehicle's inlet system [2].

Direct data from CAN (controller area network)/OBD (on-board diagnostic) was sent to all the measuring devices, which enabled continuous recording of engine operation parameters. In addition, a GPS location signal (Global Positioning System) was used to determine the speed and position of the vehicle. The control of the apparatus was carried out using a wired LAN (Local Area Network).

4.2. Results and analysis

Due to the hybrid drive present in the test vehicle, different shares of the engine operating time were obtained in subsequent tests (Table 2). During the measurements, the drive system was not interfered with. For strictly urban conditions (route I), the vehicle has obtained over 99% of operating time being exclusively on electric power. It resulted from a large share of downtime. In urban conditions (route II) for the internal combustion engine, the share of operating time accounted for 60%, while in the third section it amounted to 44%. There was a significant load on the vehicle drive system that could not be managed solely by the electrical system and had to be supported by the internal combustion engine. In subsequent tests, maximum speeds of: 60 km/h, 75 km/h and 125 km/h were obtained.

For all three cases of considered measurement routes, a similar share of accelerations was obtained (a > 0), which ranged from 30.6%–32.13%. The largest share of vehicle stop equal to 41.52% was obtained for the first section, the smallest for the second 36.53%. While driving on route III, there was a stop at the rail crossing, which significantly increased the share of working time in this area. For the negative acceleration shares, similar values were also obtained in the range of 27.88%–30.54%.

Table 2. The test vehicle operating time share on the test routes in the Poznan agglomeration

Route	Operation time share of the combustion engine	Operation time share of the electric engine	a < 0	a = 0	a > 0
	%				
I	0.33	99.67	30.6	41.52	27.88
II	60.2	39.8	32.93	36.53	30.54
III	44	56	32.13	39.06	28.81

When carrying out the measurements on the test routes, both the ecological indicators of the vehicle and local air pollution were measured. The air sampling probe was located next to the intake manifold inlet. The comparison of the values obtained, including flows in the intake manifold, allows to determine the net emission of pollutants from the vehicle (Net Emission Factor – NEF). Measurement of pollutants in the air is also extremely valuable in the environmental assessment of a given agglomeration. Performing a series of measurements, in various weather conditions and at different times, allows creating a kind of environmental map. The combination of such data may be useful in the selection of measuring points for the emission gate. In addition, it can be used in the long-term planning and control of traffic (especially freight traffic). An example of a map with the concentration of solid particles is shown in Fig. 5.

The average concentration of PM in the air over the entire test cycle was 0.035 mg/m^3. On the other hand, the maximum values reached up to 0.33 mg/m^3 locally. Areas with increased air pollution are: the entire route I, the south-eastern part of the route II and the northern part of the route III. The increased concentration of toxic compounds was mainly caused by other vehicles driving in front of the test vehicle.

Fig. 5. Local ambient PM concentration during road tests [10]]

The results of vehicle road emissions including local pollutants are shown in Fig. 6. The local concentration was referred to the air flow in the vehicle's intake manifold, thanks to which the net emission of toxic compounds was determined. To determine the emission of pollutants of particular emission factors, the following relationships were used:

$$E_{NEF,j} = E_{RDE,j} - E_{ENV,j} \quad (1)$$

where: E_j – emission of the given compound j; NEF – Net Emission Factor; RDE – real driving emission value; ENV – ambient pollution.

For the first route, negligible emission values were obtained, which resulted from the prevailing share of driving on electric drive. However, it should be noted that PM emission has negative values of $-0.31 \cdot 10^{-2}$ mg/km. It follows that the vehicle has acted as an air cleaning filter, i.e. when the internal combustion engine was in operation, the ambient air sucked into the engine was characterized by a higher concentration of PM than the exhaust gases released after the aftertreatment systems in the exhaust manifold. The highest values of pollutant emissions were obtained for route II. This was due to the fact that the largest share of combustion engine operation time occurred. On route III, the emission rates were halved on average.

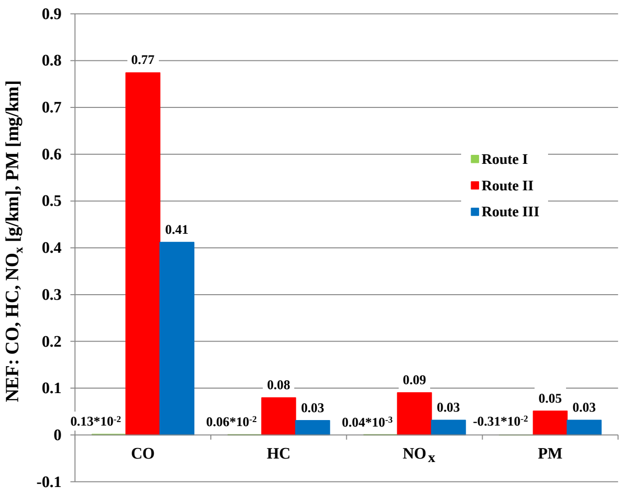

Fig. 6. Net road emission of CO, HC, NO_x and PM from road tests on individual routes

Due to the adopted research methodology, the authors proposed the introduction of a new emission indicator referring to the emission standards of the tested object:

$$CF_{NEF,j} = (E_{RDE,j} - E_{ENV,j}) / E_{limit,j} \quad (2)$$

where: CF – Conformity Factor; limit – pollution limit value j, in which the vehicle was tested for type approval.

CF net indicators have been determined for the presented test vehicle. On the first route, no results exceeded 0.01. As it has already been proved, this resulted from a significant share of driving on an electric motor. For the second route, the highest CF_{NEF} were obtained, with the limit exceeding (i.e. $CF_{NEF} > 1$) being obtained for NO_x emissions. In the third test route, the type approval limits were not exceeded. For gas compounds in the II and III route, the indicator considered assumed values in the range of 0.31–0.8, and for the PM it was in the range of 0.007–0.011.

Taking into account the obtained pollutant emission results, fuel consumption was determined (Table 3). The analysis was based on the carbon balance method for fuel density and toxic carbon-containing compounds. Analogously to the pollutant emission results, the lowest value of fuel consumption was obtained for route I, where the vehicle primarily moved on electric power. For route II, fuel consumption was 6.65 dm^3/100 km, while in the third route it amounted to 5.32 dm^3/100 km.

Table 3. CO, HC, NO_x and PM net road emissions during road measurements throughout the whole test

Route	Fuel consumption dm^3/100 km
I	0.008
II	6.65
III	5.32

Taking into account the weights (durations) of individual trips on routes, emission factors for the entire test were determined (Fig. 7). The share for each route was 19%, 26% and 55% respectively. In the whole test, the net road emission of individual toxic components was for: CO – 0.43 g/km, HC and NO_x – 0.04 g/km and PM – 0.03 g/km. Fuel consumption in the whole test overall reached the level of 4.66 dm^3/100 km. The registered emission of pollutants from the vehicle taking into account the locally occurring air pollutants would be higher for: CO by 1.3%, HC by 1.5%, NO_x by 1.6%, and for PM by as much as 46%. It should be noted that it is not possible to add net air pollution locally to the net emissions, because the engine aftertreatment systems are characterized by different conversion rates. Therefore, as in the case of PM, it is possible to have the effect of cleaning the ambient air quality.

Referring to the legislative guidelines for the Euro 6 norm, the test vehicle met all the requirements. However, the research did not meet the assumptions of some of the RDE test requirements, and therefore these values cannot be unambiguously compared.

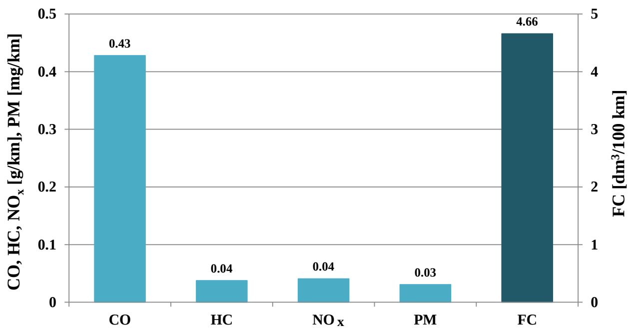

Fig. 7. Net road emission of CO, HC, NO_x and PM in road tests as well as fuel consumption from the whole test drive

5. Conclusions

Exhaust emissions from vehicles in the urban agglomeration pose a serious threat to human health. This is both due to the number of moving cars and the high population density. Therefore, it is necessary to introduce ecological solutions. It is accomplished by implementing a policy of sustainable development, tightening emission standards, intelligent traffic control, etc. Unfortunately, there are vehicles that significantly damage the natural environment – aged, overloaded or converted/repaired not in accordance with the art of engineering, which creates the need for ongoing control of the moving vehicles.

Exhaust toxicity tests in real operating conditions are time consuming and cost-intensive. Implementation of one vehicle tests requires at least one day of work and funds of several thousand Euro. For this reason, measures have been taken to assess the emission of pollutants from moving vehicles in a non-invasive way. This is to be implemented by the use of emission gates, which will carry out the assessment of ecological indicators and vehicle operation parameters. The works are carried out as part of the project: "Emission gate – a modular device for a quick assessment of road and rail vehicles emission" within the Smart Growth Program (contract No. POIR.04.01.02-00-0002/18).

To build the gate, it is necessary to perform a series of preliminary tests, mainly vehicle tests in real operating conditions. The article presents hybrid vehicle tests in the Poznan agglomeration, including local ambient air pollution. It allowed to create the city's emission map, define the net ecological indicators of the vehicle and indicate the directions of further activity.

In the route located mostly in the city center the tested vehicle moved almost exclusively using the electric engine, which was very beneficial in terms of reducing the local environmental impact. In some cases, the vehicle acted like a filter because the intake manifold air had a higher concentration of pollutants than the exhaust gases. This type of phenomenon was observed mainly for particulate matter. Thus it can be concluded, that there is a need to continue to measure not only their concentrations, but their dimensional distribution and number.

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Nomenclature

a	acceleration
CAN	controller area network
CF	Conformity Factor
DSG	direct shift gearbox
FC	fuel consumption
FID	flame ionization detector
GPS	global positioning system
LAN	local area network
NDIR	non-dispersive infrared
NDUV	non-dispersive ultraviolet
OBD	on-board diagnostic
PEMS	portable emission measurement system
RDE	real driving emissions
SI	spark ignition

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