Assessment of pollutant concentrations from a rail vehicle during remote sensing research

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Abstract. Remote sensing research was carried out for a standard-gauge railbus used for passenger transport in the Wielkopolska voivodeship (Poland). Pollution concentrations were measured using a modular device for ecological assessment of moving vehicles - an emission gate. The basic tests were carried out using equipment from the PEMS group. The results from the remote sensing device were compared to them. Taking into account the results, it was concluded that the newly developed device allows for the assessment of pollutant concentrations in a non-invasive way, both for gaseous compounds and solid particles. The presented analyzes indicate that most of the concentrations reached values close to the minimum indications from the PEMS equipment.

1 Introduction

The environmental impact of motor vehicle emissions is a prominent issue in works concerning the protection of the natural environment. In individual countries / communities / areas of the world, various types of regulations are being introduced, aimed at limiting emissions from internal combustion engines. In the European Union, restrictions on selected toxic compounds have been increased by more than 90% over the past 30 years. Such measures represent a major challenge for powertrain and vehicle manufacturers in the development of power units and non-engine exhaust gas treatment systems.

In the certification of rail vehicles, a single approval test of the combustion engine is performed. During the entire life cycle of the vehicle, current or major repairs are performed without any additional emissions control. Taking into account the fact that, based on data from the largest national carrier, currently over 1,400 diesel locomotives in Poland are over 30 years old, and only a few dozen are up to 10 years old.

In recent years, advanced work has been performed in the scope of the use of alternative propulsion systems [1-4]. Here, hybrid and all-electric designs should be mentioned in particular. Hybrid solutions make it possible to exploit the advantages of both electric and internal combustion engines. Scientists and manufacturers agree that these drives represent a transition phase to full electrification. In the area of rail vehicles, this is also being pursued. Due to the large areas of non-electrified railway lines, diesel-powered units are being used, however manufacturers are developing hybrid or dual-propulsion designs. This work is being conducted in particular for railbuses and passenger transport vehicles [5].

All these activities are conducive to reducing environmental degradation. However, for this work to be complete, it is becoming necessary to modernise and improve motor vehicles currently in operation. One vehicle that does not meet any emission standards with a worn-out powertrain can generate as much pollution as a hundred modern designs. Retrofitting - a process aimed at reducing vehicle emissions by applying modern solutions to the in-service powertrain, e.g., modernisation of exhaust gases treatment systems, the use of modern energy storage devices or upgrading the power supply system – is therefore becoming increasingly popular. Currently, the greatest hopes are pinned on the implementation of innovative solutions in batteries [9-13].

Analysing the current rolling stock in Europe, it is becoming necessary to control emissions from operated rail vehicles. The application of PEMS group apparatus requires significant financial investment and effort to develop test methodologies. In 2022, at the Institute of Combustion Engines and Powertrains of the Poznan University of Technology, a non-invasive system for assessing emissions from moving vehicles, adapted to track operation, was developed [14-16].
2 Non-invasive assessment of the motor vehicles environmental performance

Global work on protection of the natural environment requires implementation of new technologies to control emissions from moving vehicles. The feasibility of such work has a significant impact on air cleanliness and will reduce the rate of environmental degradation, which is significant in terms of sustainable development policy. The main objective of such work is to identify and eliminate defective vehicles.

Large-scale testing of vehicles using PEMS group equipment in accordance with the RDE methodology would involve excessive costs and would not be possible due to limited access to such measurement equipment. Therefore, non-invasive solutions are being developed for the ecological assessment of vehicles - solutions that do not require installation on the object. Remote sensing solutions belong to this group [17-19]. Currently, the most common remote sensing solution in the world is open path, cross-road type analysers, placed parallel to each other on two sides of the road. The introduction of such solutions can influence local emissions regulations and force them to be met by vehicles of different categories. An increasing number of European cities are seeing restrictions on the entry of older vehicles, meeting emission standards with higher limits than those currently in force. This refers to the date of manufacture and compliance with certain type-approval standards and does not refer to actual emissions. Meanwhile, vehicles are often in a poor state of repair and contribute to exceeding pollution limits, especially for PM2.5 and PM10. Their levels are significantly influenced by particulate matter emitted from exhaust systems. The studies by authors, confirm that actual emissions differ significantly from those determined in type-approval tests and at the vehicle inspection station (if the latter occurs at all).

Due to the significant influence of the environment on the reliability of measurements, remote-sensing technology is most often used as a mobile installation, for short-term, supervised testing. There are several measurement techniques, based on absorption spectroscopy, used depending on the apparatus. Each set used for this type of survey consists of an analyser, which emits electromagnetic radiation, and a receiver, which processes the signal received (Fig. 1). In order for the results obtained to be reliable, the choice of the location of the apparatus is of a crucial significance. It is important that the place where the measurements are conducted does not pose a hazard both to road users and those operating the measuring equipment. In order to fully exploit the potential of the surveys, the location should be characterised by high throughput and free passage (no traffic obstructions).

Fig. 1. Schematic diagram of the emission gate developed at the Institute of Combustion Engines and Powertrains of the Poznań University of Technology: 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

3 Research methodology

3.1 Emissions gate

The modular device for assessing emissions from moving vehicles – the emissions gate – can operate continuously or when triggered by the movement of the test vehicle. According to the developed assumptions, the tested object must stop at a distance of 50-70 m in front of the device. At this point, the vehicle is registered by reading the markings on the front of the vehicle or identification by the operator. After a 10-second stop, the vehicle accelerates with maximum traction capability and enters the optical measuring line.

The analysers used are laser-based solutions. During the drive from 1 m in front of the measuring line to 1 m behind it, the temperature of the vehicle is measured using a thermal imaging camera located in the measuring module (thermal evaluation of wheels and brakes). All the information is transferred via LAN cables to the calculation module, where algorithms determine the concentration of emitted harmful compounds in terms of CO2, CO, NO, NO2, HC, particulate matter – concentration, number, size distribution, as well as smoke opacity – on the basis of the measurements taken. The wavelengths of the diode laser are scanned within the limits of the selected absorption line, the intensity of the measured light changes as a function of the laser wavelength as a result of absorption by a specific gas molecule in the optical path between the diode laser and the detector. To increase the sensitivity of the measurement, a wavelength modulation technique is used: the laser wavelength is slightly modulated when scanning the absorption line. The detector signal is spectrally decomposed into frequency components, as harmonics of the laser modulation frequency.

To precisely determine the wavelengths that are absorbed by harmful compounds, software was used, available on the website spectralcalc.com, made available, administered and developed by GATS Inc. It was used to determine the integral power of the spectral
line, which determines the ability of a given compound to absorb a specific wavelength, and to create high-resolution models of absorption, transmittance and radiation. Following computational rounding and determining wavelengths based on them may result in the absorption of electromagnetic radiation by more than one compound. Using data from the HITRAN database, a preview of absorption bands was generated for compounds whose presence can be registered in car exhaust gases and the surroundings (Fig. 2). Precise calculations for the light modulation of the beam were made with an accuracy of seven significant digits, on the basis of which the maximum intensity of the compound in a given band was adjusted – the lines interfere with its band [20, 21].

![Absorption spectra of selected molecules with their relative intensities](image)

**Fig. 2.** Absorption spectra of selected molecules with their relative intensities [20, 21]

The wavelengths of the diode laser are scanned within the limits of the selected absorption line, the intensity of the measured light changes as a function of the laser wavelength as a result of absorption by a specific gas molecule in the optical path between the diode laser and the detector. To increase the sensitivity of the measurement, a wavelength modulation technique is used: the laser wavelength is slightly modulated when scanning the absorption line. The detector signal is spectrally decomposed into frequency components, as harmonics of the laser modulation frequency.

The current speed and acceleration of the vehicle will be measured by radar. In front of the station, a warning sign about the performance of measurements and a yellow light signal will be placed. For road vehicles other boundary parameters are defined for the area of variation of traffic parameters. For the prototype of the emission gate being tested, activities were carried out to prepare it for use, including (Fig. 3):

- The relationship between exhaust gas dilution downstream of the exhaust system was developed, taking into account the detection characteristics of the analyzers. The area in which research was carried out to assess the detected concentrations was defined.
- Tests and characterization, on the basis of which the correlation between the concentration of individual toxic compounds and the opacity of raw exhaust gases and diluted exhaust gases was determined.
- Measurements and calibrations aimed at verifying measurement accuracy depending on ambient conditions, especially in terms of the occurrence of rainwater drops in the measurement line.

![View of the emission gate during testing of rail vehicles](image)

**Fig. 3.** View of the emission gate during testing of rail vehicles: a) view of the station; b) power supply cabinet with main computer; c) and d) view of the laser transmitters; e) thermal assessment of the facility

### 3.2 Baseline studies

Baseline studies, to which the results from the emission gate were related, were performed, using equipment from the PEMS group. The first of these was a mobile Micro PEMS Axion R/S+ analyser manufactured by Global MRV, which allows the concentration of gaseous toxic compounds to be measured using: a non-dispersive infrared – NDIR analyser (CO₂, CO, HC) and an electrochemical analyser (NO). The apparatus also allows PM concentrations to be studied, using a method based on Laser Scatter, in which the speed of movement of particles is measured (considering the quantities attributed to PM10). The TSI Engine Exhaust Particulate Sizer 3090 was used for particle size distribution and number testing and can measure particle concentration and size distribution from 5.6 to 560 nm with a time resolution of 10 Hz. This is advantageous in terms of evaluating transients in the operation of an internal combustion engine – measurements can be performed in dynamic tests and transients. The recorded data is continuously converted on a linear and logarithmic scale, among others. Concentration units are standardised (dN/dlogDp) to facilitate the comparison with data obtained by measurement with other instruments.
3.3 Test object

A normal-gauge railbus used for passenger transport in the Wielkopolskie Voivodeship (Poland, Fig. 4) was subjected to the evaluation of ecological parameters. Its design enables it to carry 302 passengers. The length of the vehicle is 59.3 m. The test facility uses two compression-ignition engines (Table 1). The units are turbocharged, have a cubic capacity of 12.8 dm³ and achieve a power output of 390 kW at 1800 rpm and a maximum torque of 2300 Nm at 1100 rpm. The engines were type-approved to Stage IIIB standard and therefore controlled in NRSC (Non-Road Stationary Cycle) and NRTC (Non Road Transient Cycle) tests. The vehicle is equipped with the European Train Control System.

![Fig. 4. Research object during tests at the emission gate](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition type</td>
<td>CI</td>
</tr>
<tr>
<td>Number of cylinders / arrangement</td>
<td>6/in-line</td>
</tr>
<tr>
<td>Powertrain</td>
<td>2 × CI engines</td>
</tr>
<tr>
<td>Displacement [dm³]</td>
<td>12.8</td>
</tr>
<tr>
<td>Combustion engine power [kW]</td>
<td>390</td>
</tr>
<tr>
<td>at rotational speed [rpm]</td>
<td>1800</td>
</tr>
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<td>Maximum torque [Nm]</td>
<td>2300</td>
</tr>
<tr>
<td>at rotational speed [rpm]</td>
<td>1100–1400</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>119 000</td>
</tr>
<tr>
<td>Exhaust emission standard</td>
<td>Stage IIIB</td>
</tr>
</tbody>
</table>

Table 1. Summary of test object parameters

4 Test results

The developed measuring device - an emission gate with all its assemblies - was installed on a track in Poznań. Its placement allowed for non-invasive measurement of pollutant concentrations, considering the influence of ambient conditions. The installation was built on tracks without overhead catenary line. All analysers were adjusted and calibrated to obtain the best possible optical path parameters and to determine the distance between the transmitter and receiver. In addition to the actual measurement, the operating parameters of the vehicle at the time of measurement were determined, as well as the ambient conditions. The developed battery system was used for power supply.

Figure 5 presents the obtained results of the tests. Certain values were determined for each tested compound: those obtained with the PEMS apparatus and with the aid of the remote sensing device. The values represent the results of an analysis of tests under actual operating conditions. Based on the time-density characterisation method, concerning vehicle motion. The values were calculated for the same object movement parameters that occurred during the emissions gate measurement. An example of the characteristics developed using PEMS devices for CO is shown in Figure 6 – the values presented are the weighted average of the share in a given concentration point. As can be seen from the data presented, most of the concentrations reached values close to the minimum indications from the PEMS apparatus. This was due to the terrain and the current loading of the facility. According to the assumed implementation of the measurements, the facility was technically operational, therefore the results are within the limits set by the PEMS method.

![Fig. 5. Results of measuring the concentrations of compounds during measurements and comparison with the concentrations obtained from the PEMS equipment](image)

![Fig. 6. CO concentration in speed and acceleration ranges for a diesel engine](image)

During the measurement, the highest concentration values in the exhaust gases were obtained by CO₂ –
5.3%. The maximum values recorded with the PEMS equipment (12%) occurred for the same vehicle acceleration parameters, but with the vehicle fully loaded and the relative height on the track changing (driving up a small hill). Similar relationships were obtained for all other toxic compounds, both gaseous and particulate, in terms of concentrations and numbers. The value of $1 \times 10^6$ l/cm$^3$ for the number of particulate matters was determined for the limits marked with the PEMS apparatus of $0.9 \times 10^6$–$1.9 \times 10^6$ l/cm$^3$. The use of a double laser in the dust analyzer also made it possible to determine the opacity, which amounted to 4%.

Based on the implemented database, the emission gate makes it possible to determine the approximate dimensional distribution of particulate matter (Fig. 7). Based on the emission standard of the tested object and the implemented mathematical matrix, data from dual particulate and smoke detectors, as well as the hydrocarbon measuring line, are converted. In this way, characteristics of the number of particulate matters are created as a function of their equivalent diameter – the shape of a ball. The test also takes into account dust (pollution) of the ambient air before measurement and analysis.

![Fig. 7. Determined dimensional distribution of PM](image)

In vehicle tests based on real measurements, the toxicity index $M_j$ is increasingly used. It is the quotient of the $j$-th toxic compound and CO$_2$ emissions, multiplied by the constant $b$ (CO, HC, NO$_x$ = $10^3$, PM = $10^6$), as presented in formula (1). Comparative analyzes of pollutant emissions for different groups of vehicles may be difficult to implement. This results from the nature of the facility’s purpose and operating conditions. This applies especially to the NRMM (Non-Road Mobile Machinery) vehicle group.

$$M_j = b \cdot \frac{e_{val,j}}{e_{CO2}}$$  (1)

The basic products of combustion in engines are CO$_2$, water and heat converted into mechanical work. CO$_2$ emissions are directly related to fuel consumption. At the same time, it can be a measure of the correctness of the combustion process and the quality of operation of non-engine exhaust gas treatment systems. Toxic compounds such as CO, HC, NO, and PM are products of incomplete combustion and combustion at high temperature and pressure. Taking these facts into account, it is possible to compare CO$_2$ emissions with other emitted toxic substances and, on this basis, determine toxicity indices $M_j$.

For the tested object, the obtained results (Fig. 8) of the toxicity index ranged from 0.4 (NO$_2$/CO$_2$) to 24.9 (PM/CO$_2$). It is important to take into account emissions or concentrations determined in the same units. Therefore, for the particulate calculations, the CO$_2$ concentration was expressed in mg/m$^3$, taking into account a molar mass of 44.01 g/mol.

![Fig. 8. Summary of dimensionless toxicity indicators](image)

The obtained results indicate the correctness of the measurements. Referring to other publications where rail vehicles were also tested [16, 22, 23], the obtained values are similar, especially in terms of gas components. The cited publications and our own research prove that the toxicity index is highly sensitive. In the event of damage to power supply systems, failure of exhaust gas treatment systems or other failures, toxicity indicators for individual compounds reach values several dozen times higher. Therefore, in the developed emission gate, not only the concentrations are controlled, but also the ratio of toxic compounds to CO$_2$.

5 Summary

Testing the actual emissions of pollutants from vehicles is very important in terms of environmental protection. The emission gate allows ongoing and non-invasive vehicle control. Its use allows you to find objects with above-standard emissions. Thanks to this, damaged vehicles can be immediately excluded from traffic. More and more new solutions of drive systems and non-engine exhaust gas treatment systems are used in rail vehicles. However, it happens that transport companies do not use 32.5% urea solution for the SCR (Selective Catalytic Reduction) system in order to reduce costs. This causes significant nitrogen oxide emissions. The use of a broadcast gate allows you to find such activities.

The tested object was technically inspected before the measurements and had a P2 inspection. Based on the tests carried out, it was found that the developed emission gate correctly assesses the signals from passing vehicles. The measured values are within the ranges determined by actual tests based on the PEMS apparatus. The determined values of the $M_j$ toxicity index also indicate the correctness of the measurement.
References

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