PREDICTIVE EMISSIONS MONITORING WITH REAL-TIME OXYGEN SENSORS

Research hypothesis

It is possible to improve the detection of the causes of excessive emissions by using advanced analysis of on-board lambda sensors installed in standard spark-ignition engines, combining data from different sensors and using advanced predictive methods.

Thesis of the thesis

The development of a comprehensive telemetry system for real-time predictive monitoring of exhaust emissions, using on-board oxygen sensors and advanced data analysis techniques, is an innovative solution that enables more precise diagnostics of the technical condition of vehicles, early detection of anomalies in pollutant emissions, optimization of engine operation in terms of reducing harmful emissions, and providing tools to support the implementation of increasingly stringent emission standards.

INTRODUCTION

In the face of the observed climate change, it has become important to change the attitude and approach to environmental protection. The change that will allow us to take better care of the natural environment is hidden, among other things, in the automation of measurement and active analysis of exhaust gases. Today, the problem of air pollution in Europe is a challenge for public health and the environment. The European Union has introduced a number of regulations, such as Euro emission standards, to reduce harmful emissions from internal combustion vehicles. However, despite progress, there are challenges related to the effective implementation and enforcement of these regulations, as well as the manipulation of emissions test results. The increase in emission standards has forced car manufacturers to implement advanced exhaust gas treatment technologies, which is leading to an evolution in the automotive industry. Designing emissions tests that faithfully reflect the real-world conditions of vehicle use remains a challenge, highlighting the need for continuous improvement of measurement methodologies. Test procedures such as WLTP and RDE are crucial for assessing the environmental impact of vehicles, but they require regular updates and the development of new measuring devices. In the field of technical sciences, a creative holistic approach and a fresh perspective on familiar problems play a key role in innovation and technological progress. It is not only about "thinking outside the box", but also about the ability to look at problems from different perspectives, combining different fields to find comprehensive solutions. One of the benefits of such an approach is the possibility of discovering new ways of using already existing systems, among others, these were the premises of the author of this dissertation.

The paper verifies the hypothesis that it is possible to increase the effectiveness of detecting the causes of excessive emissions of harmful substances using the analysis of on-board lambda sensors installed in standard spark-ignition engines. The dissertation was divided into a theoretical and empirical part, within which the aim of the thesis was to develop a project and implement a system for monitoring and predicting exhaust emissions, which will base its activities on the use of on-board oxygen sensors in real time.

In order to achieve the main objective of the work, the following specific objectives were assumed:

1. analysis of the current state of knowledge about telemetry systems and measurement and determination of exhaust emissions;
2. review of legal acts regulating exhaust emission standards;
3. review of test procedures for measuring exhaust emissions;
4. review of technical inspection procedures;
5. development of a design and system for mobile analysis of carbon monoxide exhaust;
6. development of the concept of a mobile exhaust gas analysis system using lambda sensors;
7. conducting comparative tests at a diagnostic station and in real traction conditions, vehicles in various technical condition;
8. determination of the dependence of the influence of the lambda sensor voltage on the emission of harmful factors (CO, HC, NO_X);
9. development of an algorithm for archiving, visualization, analysis and prediction of data.

In order to achieve the aim of the work and verify the research hypothesis, this dissertation has been divided into an introduction, seven chapters, a summary, a list of tables, figures and a bibliography.

In the first chapter of the paper, a literature review was carried out on issues related to the analysis of the current state of knowledge about telemetry systems and measurement of exhaust emissions. In the light of a review of the literature on exhaust gas analysis, the technical condition of the vehicle emerges as a key factor affecting the effectiveness of these systems. The importance of this aspect stems from the fact that all other factors, such as driving style, road infrastructure, route travelled or even weather conditions, ultimately affect the vehicle, and thus its technical condition. According to a literature review, each of these factors has a direct impact on the load on the vehicle and its systems, and thus on the efficiency of the exhaust system, engine and other key components responsible for emission control. Focusing research on only one aspect, such as driving style or road infrastructure, without considering the technical condition of the vehicle, may lead to erroneous conclusions and distortions in the reasoning of the actual impact of these factors on exhaust emissions. The actual efficiency of the vehicle in road conditions may be significantly different from theoretical assumptions if the current technical condition of the vehicle is not considered. Therefore, in order to obtain a completer and more realistic picture of the impact of different factors on emissions, an integrative approach is needed that combines research on individual aspects with a thorough analysis of the technical condition of vehicles. This is the only way to develop effective emission management strategies that consider all key variables. Such a holistic perspective not only enables a better understanding of the mechanisms affecting emissions, but also contributes to the creation of more effective technologies and operating practices that make a real contribution to improving air quality and protecting the environment.

The second chapter reviews the legal acts regulating exhaust emission standards that have been introduced by the European Union. These standards, evolving from Euro 1 to the planned Euro 7, tightened the limits for nitrogen oxides, hydrocarbons, carbon monoxide and particulate matter. Despite the introduction of these regulations, however, there are still challenges related to their effective implementation and enforcement, as illustrated by various cases of manipulation of emission test results by car manufacturers. At the same time, these standards have a significant impact on technological development in the automotive industry, forcing manufacturers to implement advanced exhaust gas cleaning technologies. Advances in this area include the development of more efficient filtration systems and innovations that reduce the overall environmental impact of vehicles. However, the challenge is to design tests that faithfully reflect the real-world conditions of vehicle use, highlighting the need for continuous improvement of measurement methodologies, such as the transition from NEDC tests to more representative WLTP and RDE procedures. Emission control therefore remains a complex problem, requiring not only strict regulations, but also ongoing monitoring of compliance with them and continuous research into new emission reduction technologies. The effectiveness of these actions is crucial to protect human health and ecosystems from degradation, which obliges both industry and regulators to continuously validate and adapt in response to dynamically changing technologies and environmental conditions.

The third chapter reviews the exhaust emission test methods using test procedures such as WLTP and RDE. The methods described were developed in response to the need for a more realistic reflection of vehicle operating conditions and an adequate assessment of their impact on air quality. The WLTP and RDE procedures are complex due to the need to consider variability in real-world driving conditions, such as road variety, changing weather conditions and dynamic driver behaviour, which makes these tests much more complex compared to traditional laboratory methods. The exhaust emission analysis covers a number of factors, from the characteristics of the vehicle, through the route travelled, road infrastructure, to driving style and weather conditions. As the review shows, each of these elements has an impact on fuel consumption and the level of pollutants emitted. Measurement systems must be adapted to changing technologies and emission standards, which involves regular updates and development of new devices.

Chapter four presents the design of a mobile carbon monoxide probe, which is an innovative approach to monitoring exhaust emissions during real vehicle operation. The designed companion app allows users to easily track and analyze CO concentrations under different driving conditions. It presents data in a graphical and numerical form, which makes it easier for the user to understand the measurement results. The app also allows you to record vehicle data, such as model, fuel type or Euro emission standard, which can be used for further analysis and comparison of results. Analysis of the test results using a mobile probe reveals that the concentration of CO varies significantly depending on the driving conditions. The results show that CO concentrations increase at higher engine loads and in more difficult road conditions, such as uphill driving. These studies highlight that even vehicles that meet Euro standards can emit significant amounts of CO during certain types of use, suggesting that cars may not be as environmentally friendly as initially assumed. This sheds light on the importance of the actual operating conditions of vehicles in terms of their environmental impact, and not just on the basis of the results obtained in controlled laboratory tests. In addition, the results of preliminary studies are important for public policies and air quality management strategies, as they point to the need for more diverse emission management strategies that consider real-world driving conditions. The results also point to the need for further research to better understand how different operating factors affect pollutant emissions.

The fifth chapter describes the design of the telemetry system, i.e. a mobile exhaust gas analysis system with an advanced diagnostic device using the OBD-II interface via the popular ELM 327 module. The application was written in Python with the use of libraries for data analysis and visualization, it offers the possibility of interactive loading, selection and visualization of data from files in xlsx, xlsm, xls, xltx, xltm, csv, xml, txt formats. Importantly, in addition to the standard visualization, the user can interactively manage the displayed data by turning on and off individual series on the chart. A proprietary data visualization application offers several significant advantages over using only a regular database or commercial software, especially in the context of data analysis and presentation. Visualizations allow you to quickly spot patterns, trends, deviations, and anomalies that you might miss when viewing raw data tables.

The sixth chapter contains a description of the research procedure used in the work. The aim of the methodology is to present the research steps that have made it possible to verify the effectiveness and correctness of operation of both proposed systems. In preparation for the main tests, preliminary tests of both systems were carried out on devices from renowned manufacturers such as Autel and Bosch. These tests were aimed at verifying the correctness of the data collected by the proprietary OBM system and their compliance with measurements obtained with the use of standard, recognized diagnostic devices on the market. Importantly, the final stage of the research was the verification of the obtained data using a flue gas analyzer. Determination of the relationship between the indications of lambda sensors and the level of exhaust emissions. This critical stage of the research process was designed to ensure the objectivity, accuracy and reliability of the results by comparing them with the results obtained using a standard measurement method. The analysis of the data obtained during the verification included a statistical assessment of the agreement between the readings from the proprietary systems and the data from the exhaust gas analyzer. Statistical techniques ensured the accuracy, precision and reliability of the proposed monitoring systems in the context of real-life vehicle operating conditions. In addition, a detailed analysis of outliers or inconsistencies in the results allowed for the identification of potential areas for further optimization and improvement of the proposed systems.

The seventh chapter contains information on the prediction of exhaust emissions, which is a key element of this work, as it enables a dynamic assessment of the technical condition of the vehicle and the potential impact on the environment in real time. The main assumptions of the prediction are based on the use of data from on-board lambda sensors and additional engine operating parameters.

The following input variables were used in the predictive models:

- voltage generated by lambda sensors (V);
- short-term (STFT) and long-term (LTFT) fuel corrections;
- Sensor-measured airflow values (MAF)
- intake manifold pressure (MAP);
- engine and intake air temperature;
- and other data collected during testing, which can significantly contribute to improving the performance of
  prediction model.

The R programming environment was used for prediction, which enables effective data processing and statistical modeling. The prediction results can be used in early warning systems that inform the driver or service when a technical inspection is required. In addition, they can be used as a basis for automatic adjustment of engine operating parameters, which will allow for real-time optimization of emissions.

The work is concluded with conclusions and directions for further research. The research shows that the use of modern oxygen sensors and telemetry systems can significantly improve the accuracy of exhaust emission measurements and the effectiveness of emission reduction systems in internal combustion vehicles. Mobile measurement systems allow for monitoring of emissions in real driving conditions, providing valuable data, and can be used to further improve predictive models, internal combustion engines and exhaust aftertreatment systems. The implementation of such systems allows for a more dynamic and flexible response to changing engine operating conditions and changing emission standards, which is crucial in the context of growing ecological and environmental standards. Future research will focus on further development and optimization of mobile exhaust gas monitoring systems. It will be important to integrate oxygen sensor technology with artificial intelligence systems that They will allow for automatic data analysis and quick adaptation to changing traction conditions of vehicles. In addition, the development of new methods for calibrating and validating data obtained from mobile measurement systems should be considered to ensure maximum precision and reliability. Considering the impact of different weather and operating conditions on the accuracy of exhaust emission measurements will be another step towards improving the efficiency and reliability of future monitoring systems.