Article citation info:
Dzieniszewski G., Kuboń M., Zieliński D. 2024. Assessment of the Possibility of Using Exhaust Gas Composition in Predicting the Technical Condition of the Engine. *Journal of Research and Applications in Agricultural Engineering* 69 (2): 39-46.
https://doi.org/ 10.53502/jraae-199729

Journal of Research and Applications in Agricultural Engineering

Journal website: https://tech-rol.eu/

Assessment of the Possibility of Using Exhaust Gas Composition in Predicting the Technical Condition of the Engine

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Article info
Received: 2 September 2024
Accepted: 10 December 2024
Published: 8 January 2025

Keywords
internal combustion engines
diagnostics
composition
exhaust gases

The study describes possibilities of using exhaust gas composition to predict the technical condition of piston engines. Examples of failures and their correlation with diagnostic symptoms of exhaust gas composition are analyzed. The usefulness of exhaust gas analysis in non-invasive diagnostics of piston engines is highlighted. Practical examples of the studied relationships applied in diagnostic and maintenance practices are discussed. It is concluded that exhaust gas composition can be considered a valid diagnostic signal for assessing the technical condition of an engine.

DOI: 10.53502/jraae-199729

1. Introduction

Internal combustion engines are integral to numerous industries, ranging from the automotive to energy sectors. Contemporary demands for energy efficiency, sustainability, and emissions reduction present engineers with new challenges in engine diagnostics and technical condition monitoring [1].

There are numerous methods for diagnosing engine defects without disassembly. Traditional methods, such as organoleptic and vibroacoustic diagnostics, especially engine auscultation, form the basis of many diagnostic procedures for piston engines. However, these methods are limited by a wide range of interferences that complicate the accurate interpretation of diagnostic signal variations. Classical methods like compression pressure measurements and combustion chamber tightness assessments also face significant limitations due to various interfering factors affecting the measurements and their interpretation.

Self-diagnosis of internal combustion engines is currently a fundamental method for engine diagnostics. However, this method has drawbacks, mainly due to the monitoring of electrical or electronic signals from sensors and actuators. These signals may introduce errors during the conversion of physical parameters into digital data.

Indirect methods, such as evaluation of the engine's technical condition based on the intensity of the starting current, despite the ease of measurement, exhibit low accuracy and repeatability. Thus, they can only serve as preliminary diagnostic procedures.

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Given the aforementioned limitations, exhaust gas composition emerges as a valuable diagnostic parameter for assessing the condition of piston engines. Continuous monitoring of exhaust gas composition has evident applications in diagnostic processes and constitutes a significant and valuable parameter in diagnosis and causation analysis. Therefore, the exhaust gas composition, characterized by a broad range of variations, can also be utilized for predicting the technical condition of piston engines.

Predicting the technical condition of an engine often relies on analyzing long-term trends in operational parameters [4]. The use of statistical tools, time series, and data analysis techniques enables the identification of potential changes in engine performance characteristics [5]. Advanced diagnostic systems employ artificial intelligence (AI) algorithms for real-time data analysis. Machine learning algorithms can identify patterns that indicate potential problems, even before traditional diagnostic methods can detect them.

In this context, the analysis of exhaust gas composition, which reflects the combustion processes inside the engine, becomes a crucial tool for assessing engine performance parameters and technical condition.

For predicting the technical condition of an engine, various data analysis and predictive techniques are used for monitoring, diagnosing, and forecasting potential failures [2]. Diagnostic systems collect data from multiple sensors monitoring engine parameters such as temperature, pressure, RPM, and fuel consumption [3]. These data are analyzed in real-time, enabling early detection of deviations from normal operation.

As previously mentioned, analyzing exhaust gas composition can be useful in forecasting the technical condition of an engine. Changes in exhaust gas composition may indicate issues related to the combustion process, engine component wear, or pollutant emissions [6].

The use of predictive models, such as mathematical models, neural networks, or machine learning algorithms, facilitates the development of systems capable of predicting potential engine failures based on historical data [7, 8]. Valuable data for training these models can be sourced from prior failures, vehicle operation, and laboratory measurements.

An optimal approach to predicting the technical condition of an engine involves integrated diagnostic systems that utilize various methods and technologies. The integration of data from multiple sources and the application of advanced analytical algorithms lead to a more comprehensive assessment of the engine's technical condition [9]. With technological advancements and the growing availability of advanced diagnostic tools, engine condition prediction is becoming increasingly precise and effective. The integration of modern technologies, such as artificial intelligence and data analytics, enables the development of systems that not only identify current issues but also predict potential failures, resulting in improved reliability and durability of engines.

The development of diagnostic technologies, such as exhaust gas analysis, allows for more accurate monitoring of engine technical condition. Exhaust gas composition contains valuable information about combustion processes, the wear of components, and potential problems related to pollutant emissions [9, 10]. Therefore, it is crucial to delve deeper into this topic in the context of its application to engine condition forecasting and diagnostics.

The aim of this study is to verify the presumed correlations between the engine's technical condition and the appearance and composition of exhaust gases, and to develop methods for predicting an engine's technical condition based on the exhaust gas composition and appearance, which are the most readily accessible diagnostic parameters.

2. Methodology

The objective of using a diagnostic method based on exhaust gas composition is to simplify diagnostic procedures as much as possible, eliminate the need for engine disassembly, and support other diagnostic procedures by utilizing exhaust emissions and composition as diagnostic parameters.

The experimental methodology involves correlating the technical condition of the engine with pollutant emissions in the exhaust gases or the overall appearance of the exhaust, evaluated using organoleptic methods.

For the study, a Certus exhaust gas analyzer was used (Fig. 1); its specifications are provided in Table 1.

The exhaust gas analysis during the study was conducted under standardized conditions, which included ensuring that the engine reached its normal operating temperature (oil temperature between 80 and 120 °C) and performing measurements at idle speed and at ¾ of the engine's maximum power RPM.

The methodology combines exhaust gas analysis with other diagnostic procedures to identify failures, followed by verification of the diagnosis using component inspection methods.

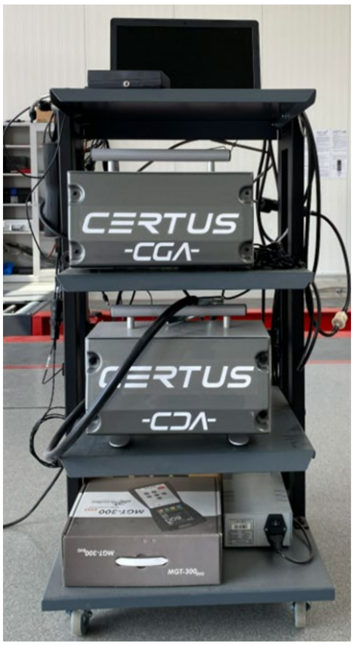

Fig. 1. Certus exhaust gas analyzer (Source: Author's own work)

Table 1. Technical specifications of the Certus analyzer

Measured exhaust components	Unit
CO – carbon monoxide from 0 to 9.99% vol	[%vol]
CO_2 – carbon dioxide from 0 to 19.9% vol	[%vol]
HC – hydrocarbons from 0 to 19,999 ppm vol	[ppm vol]
O_2 – oxygen from 0 to 25% vol	[%vol]
NOx – nitrogen oxides from 0 to 5000 ppm vol	[ppm vol]

According to the adopted methodology, specific cases of engine component failures were analyzed, where exhaust gas composition was utilized in the preliminary diagnostics. It was initially assumed that the vast majority of piston engine failures significantly affect the appearance and composition of exhaust gases. Some diagnostic symptoms are straightforward, such as the sudden loss of piston chamber sealing, which disrupts the combustion process, leading to the emission of toxic exhaust components like hydrocarbons (HC).

On the other hand, failures in the engine timing system also cause significant disturbances in exhaust gas composition. However, in this case, the changes are multidirectional and require complex analysis.

3. Utilization of signals in diagnostic assessment of engine technical condition engine technical condition

Diagnostic systems in vehicles are utilized to monitor engine performance and the functioning of other vehicle components. These systems enable early detection of failures, allowing for timely corrective actions. Modern vehicles are equipped with systems like On-Board Diagnostics (OBD), which collect data from various sensors and analyze it to identify potential issues [11].

Automatic design of diagnostic systems involves creating algorithms and tools capable of independently analyzing input data and generating optimal diagnostic solutions without requiring manual intervention by an engineer. The automotive engine is one of the most complex mechanical and electronic systems in a vehicle. Engine diagnostics involve analyzing various parameters such as fuel combustion, exhaust gas emissions, exhaust gas composition, cylinder pressure, and cooling system pressure [12].

In his work, Isermann highlights various applications of model-based diagnostics in practice. These systems are mentioned as being effective for detecting faults in machinery such as car engines, power plant turbines, and various industrial equipment [12]. This method is particularly well-suited for identifying issues related to improper combustion, ignition system failures, or sensor malfunctions.

The growing use of automatic control systems in vehicles and the expansion of on-board diagnostics necessitate the search for minimally invasive diagnostic methods. Electronic control technologies in internal combustion and electric engines allow better management of power, fuel efficiency, and exhaust emissions [13].

Combining signal-based methods with those based on a process model significantly enhances fault detection compared with traditional approaches [14]. Applying these techniques can improve engine performance and reduce the emission of harmful substances.

4. Results

The wear of the TPC system (piston-ring-cylinder assembly) is strongly correlated with processes occurring in the internal combustion engine. Exhaust gas composition is highly dependent on the sealing of the piston chamber, although this relationship is often complex [15, 16]. This complexity arises because a loss of sealing in the piston chamber, typically due to TPC system wear, triggers a variety of processes within the engine. On the one hand, it leads to consumption of oil as it enters the piston chamber, while on the other, it exacerbates combustion disturbances, resulting in incomplete or inefficient combustion. This often increases the operating temperature, which can subsequently raise exhaust gas temperatures and cause "afterburning" of hydrocarbons produced from the combustion of oil leaking through the worn TPC system into the piston chamber [14].

The composition of exhaust gases generated by a car engine is closely related to its overall condition and wear. Exhaust gas composition refers to the proportion of various gases and particulates in the combustion byproducts [14].

Under ideal combustion conditions, fuel (e.g., gasoline or diesel) is mixed with an appropriate amount of air and burned in the combustion chamber, producing the energy that powers the vehicle. Deviations of exhaust gas composition from expected values can indicate issues with combustion efficiency.

Incomplete or inefficient fuel combustion can lead to the formation of harmful substances in exhaust gases. For example:

- An air-fuel mixture with too little air relative to fuel can result in the emission of toxic substances, such as nitrogen oxides (NOx) and particulates.
- Excessive fuel in the mixture can increase emissions of carbon monoxide (CO) and soot particles.
- Failures or malfunctions in emission control systems, such as catalytic converters, also affect exhaust gas composition. Analyzing exhaust gas composition can thus serve as a diagnostic indicator of engine condition. Sensors such as the lambda probe monitor exhaust gas parameters and allow adjustments to engine operating conditions to maintain optimal exhaust gas composition.
- Improper combustion, particularly if chronic, contributes to wear on engine components, such as pistons, piston rings, and valves [17]. Excessive particulate emissions can clog the exhaust system and accelerate the wear of catalytic converters.

Monitoring and controlling exhaust gas composition are essential not only for environmental protection but also for maintaining engine health. Modern vehicles are equipped with diagnostic systems that monitor and regulate exhaust gas composition, helping to keep the engine in optimal condition and comply with emissions standards. Regular maintenance and inspections are crucial for ensuring the combustion system functions efficiently [18].

4.1. Correlation between engine wear and exhaust gas composition

Engine wear and exhaust gas composition are interconnected in diagnostics and engine performance efficiency. As engine components wear over time, changes in exhaust gas composition may occur, impacting both pollutant emissions and overall engine efficiency. Key examples include:

- Piston and piston ring wear: increases oil leakage into the combustion chamber, leading to higher particulate emissions and contamination.
- Valve wear: affects combustion chamber sealing, reducing combustion efficiency and increasing emissions of CO and NOx.
- Catalytic converter wear: reduces the ability of the converter to lower harmful emissions such as CO, NOx, and particulates.
- Worn spark plugs: cause incomplete combustion of the air-fuel mixture, increasing harmful emissions.

Table 2. Major mechanisms of hydrocarbon (HC) formation. Source: Author's own work based on [5]

Causes of hydrocarbon (HC) formation	Crevice effect (crevice volume)	Oil layer (adsorption/desorption)	Wall effect (quenching on the wall)	Incomplete combustion
Bore-to-stroke ratio (D/S)	x	X		
Combustion chamber design	X		X	
Swirling surfaces (squish zones)	X		X	X
Wall temperature	X	X	X	
Residual oil layer		X		
Valve timing (phases)	X	X		X
Exhaust backpressure	X	X		X
Mixture quality				X
Heating of intake air			X	X
Charge motion				X
Charge mixing			X	X
Ignition timing advance			X	X

– Worn lambda sensors: provide inaccurate oxygen readings, potentially misleading the engine control system and altering exhaust gas composition.
– Fuel injection system irregularities: lead to uneven fuel distribution, resulting in suboptimal combustion and altered exhaust gas composition.

Regular engine diagnostics, parameter monitoring, and exhaust gas analysis are critical for maintaining optimal engine performance. Timely detection of issues can prevent further wear and potential damage. Proper maintenance, replacement of worn parts, and regular technical inspections are essential for preserving engine health and minimizing environmental impact [20].

As shown in Table 2, the primary mechanisms of hydrocarbon (HC) formation are induced by the structural parameters of the engine. This implies that increased HC emissions can be considered a diagnostic factor. If an engine complies with emissions standards during the homologation phase but loses its nominal environmental parameters after a period of operation, HC emissions can serve as an indicator of the engine's technical condition.

A striking example of the use of exhaust gas composition for preliminary engine diagnostics is demonstrated in the valve timing system of the Opel Astra 1.4 Turbo engine, type NEL, shown in Figure 2.

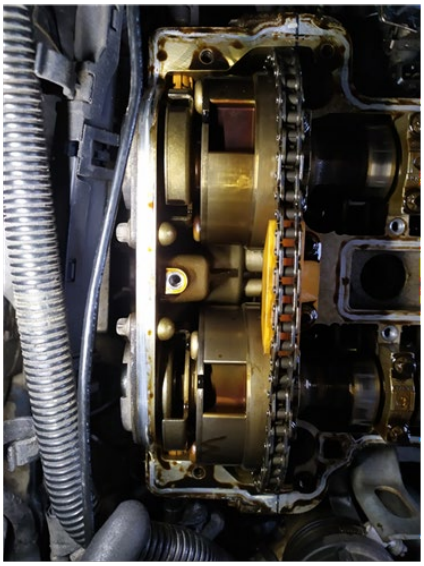

Fig. 2. Valve timing system of the Opel Astra 1.4 Turbo engine. Source: (Author's own work)

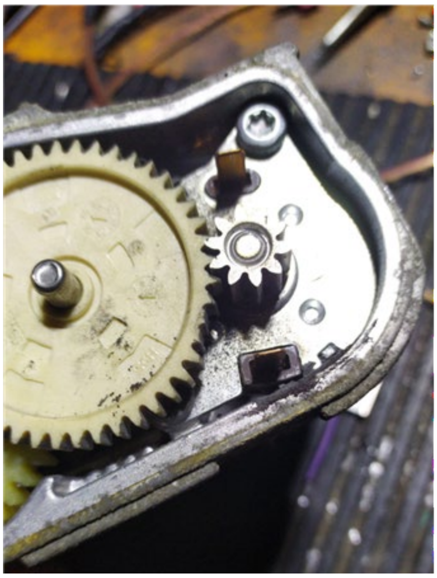

Fig. 3. Hyundai Tucson 1.7 CRDI – sheared teeth preventing engine operation. Source: (Author's own work)

Fig. 4. Contaminated engine throttle Source: (Author's own work)

In the case of the failure shown in Figure 3, the appearance of the exhaust gases alone indicated a malfunction. The engine was extremely difficult to start and emitted heavily polluted exhaust gases. The exhaust appearance clearly suggested an insufficient amount of air being delivered to the cylinders. A continuously open exhaust gas recirculation (EGR) valve allowed exhaust gases to enter the cylinders, displacing fresh air. As a result, combustion did not proceed correctly, leading not only to excessive smoke but also to high carbon monoxide emissions. In this case, the composition and appearance of the exhaust gases contributed to quick and effective diagnostics.

Figure 4 shows the throttle of a spark-ignition engine, which regulates the air intake to the engine. Deposits on the throttle plate cause it to stick, resulting in uneven engine operation, which significantly impacted the quality of the exhaust gases emitted. In the analyzed case, the engine underwent exhaust gas analysis before any service actions were taken.

The hydrocarbon (HC) content in the exhaust gases was measured at approximately 800 ppm (limit: 100 ppm). Significantly, the exhaust composition showed frequent fluctuations. The carbon monoxide (CO) content, measured at around 1.5% (limit: 0.5%), was also elevated. This indicated not only that the issue was related to improper combustion, but that the combustion process was incomplete and inefficient.

The preliminary diagnosis included further analysis focused on the intake system, leading to the identification of the root cause of the malfunction. Contaminated throttles, as illustrated, are a common issue in internal combustion engines. This type of fault often results in highly variable symptoms, but improper exhaust composition is consistently a key indicator of the problem.

In practical diagnostics and vehicle repair, it is often necessary to combine various available methods to assess the engine's technical condition. The first diagnostic step involves non-invasive techniques using exhaust gas appearance and analysis, along with a diagnostic tester. Errors read using the Launch X 431 Euro Pro 5 tester indicated that the vehicle had insufficient boost pressure, preventing the engine from reaching full power. This issue may be caused by a malfunctioning turbocharger, an air intake system leak, or a malfunctioning EGR valve, as suggested by additional error codes.

Figure 5 shows the description of a diagnostic trouble code (DTC) related to excessive emissions of toxic exhaust components.

In this specific case, the final determination of the malfunction's cause was achieved through integrated diagnostics, combining a diagnostic tester and exhaust gas analysis. It was observed that the appearance and composition of the exhaust gases showed irregularities under certain engine operating conditions. These irregularities occurred when the control unit activated the EGR valve. At other times, the engine operated without issue. The diagnosed cause was a faulty EGR valve. Replacing the valve effectively resolved the engine's operational issues.

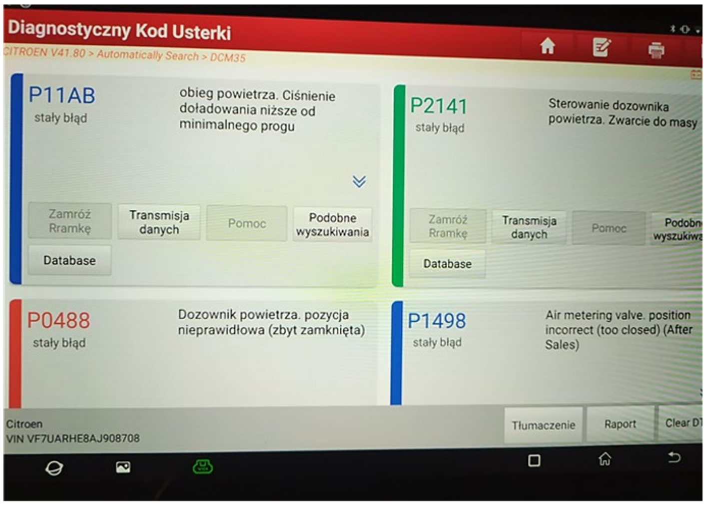

Fig. 5. Diagnostic code characteristics. Source: Author's own work

The condition of the timing system significantly influences vehicle exhaust parameters. The previously discussed case of damaged variators in an Opel engine is just one example. A common cause of timing system failure is to the timing chain tensioner or chain elongation. While this can eventually lead to chain breakage, phase misalignment in the timing system usually occurs beforehand. Any disturbances in the synchronization of the timing system manifest as changes in the appearance and composition of the exhaust gases.

Figure 6 illustrates a damaged timing system in a Kia Sportage 1.6 TGDI engine.

A damaged timing drive significantly affects engine operation. A timing system as worn as the one shown in Figure 6 can lead to engine damage. It also has a substantial impact on exhaust gas composition.

When the analyzed engine was brought in for diagnostics, exhaust gas analysis revealed hydrocarbon (HC) concentrations of 1000 ppm. An additional indicator of timing system damage was the acoustic diagnostic symptoms accompanying engine operation.

The next diagnostic case involves the engine of a Hyundai Tucson 2.0 DOHC, as illustrated in Figure 7.

The engine shown in Figure 7 exhibited significant oil consumption. This was accompanied by very high hydrocarbon (HC) emissions—exceeding 2000 ppm—and elevated carbon monoxide (CO) emissions of over 2%. Despite the diagnosis, the vehicle owner opted not to repair the engine and continued to operate the damaged vehicle.

Fig. 6. Damaged timing system in Kia Sportage 1.6 TGDI engine Source: (Author's own work)

Fig. 7. Connecting rod breakage – Hyundai Tucson 2.0 DOHC engine
Source: (Author's own work)

During intensive highway driving, the oil consumption led to a drastic reduction in oil levels and insufficient engine lubrication. Consequently, the engine seized, resulting in a catastrophic failure involving the breaking of a connecting rod. The oil pan was damaged due to the rod's fracture, causing further destruction to the block and oil pan. The engine was completely destroyed, as depicted in Figure 7.

5. Summary and Conclusions

The present research has focused on an innovative approach to monitoring the technical condition of engines by using exhaust gas composition as a key diagnostic indicator. The studies confirm the effectiveness and applicability of this method. Based on the analyses of individual diagnostic cases performed in this work, the following conclusions can be drawn:

1. Exhaust gas composition is a reliable diagnostic parameter that can be used to assess the technical condition of an engine.
2. Hydrocarbons are the exhaust component best correlated with changes in the technical condition of spark-ignition engines, and serve as the best indicator of condition changes.
3. In compression-ignition engines, the degree of exhaust smoke is an indicator describing the engine's technical condition.
4. Predicting the technical condition of engines based on exhaust gas quality is feasible, but is subject to certain interferences caused by various factors affecting exhaust composition.
5. The analyses of numerous diagnostic cases presented in this study, verified during engine disassembly, confirm the validity of the assumptions adopted.

These findings support the recognition of exhaust gas composition as a valid diagnostic signal for assessing an engine's technical condition. However, a significant limitation of the method discussed is the requirement that the engine be started, making it unsuitable for engines that cannot be started. Despite this limitation, the method is characterized by exceptional ease and accessibility of measurement, and can serve as an independent diagnostic method or support the diagnostic process in conjunction with other methods.

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