Article citation info:
Laskowski P, Zimakowska-Laskowska M. Simulation study of the effect of ethanol content in fuel on petrol engine performance and exhaust emissions. Combustion Engines. 0000;XXX(X):xx-xx. https://doi.org/10.19206/CE-204049

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Simulation study of the effect of ethanol content in fuel on petrol engine performance and exhaust emissions

ARTICLE INFO

Received: 30 November 2024
Revised: 16 March 2025
Accepted: 14 April 2025
Available online: 20 May 2025

In response to the growing problems associated with road transport emissions, increasing emphasis is being placed on biofuels and bio-additives as a more ecological alternative to traditional fossil fuels. Biofuels, produced from renewable raw materials such as oil plants, cereals, or organic waste, aim to reduce greenhouse gas emissions and limit the consumption of non-renewable raw materials. The introduction of additives to fuels can have a positive effect on reducing harmful substances in exhaust gases. Still, the effectiveness of this solution depends on many factors, such as the type of bio components and the design of the engines. The article discusses research on bio-additives impact on exhaust emissions, with particular emphasis on combustion processes and the formation of harmful substance emissions. It presents two complementary modelling methods: COPERT, which allows for estimating emissions in real conditions, and Diesel-RK, which simulates engine combustion processes for a detailed analysis of emission mechanisms. The combination of these tools allowed for a precise assessment of the impact of biofuels on pollutant emissions and may be an essential step towards optimising engine designs for more ecological solutions. Despite certain technological and economic limitations, using bio-additives to fuels can significantly reduce emissions from road transport, accelerating the implementation of global environmental protection and sustainable development goals.

Key words: *fuel, alcohol, modelling, emission, combustion engine*

1. Introduction

One of the key elements of reducing the threats associated with climate change is a significant reduction in the emission of harmful substances from exhaust gases from combustion engines of motor vehicles. In connection with this, numerous actions have been taken in recent years to reduce greenhouse gas emissions and increase the share of renewable energy sources in transport. An example of such actions is the introduction of the RED III (Renewable Energy Directive), which sets new targets for using renewable energy in transport. The directive imposes an obligation to increase the share of biofuels, such as bioethanol, which is crucial for reducing carbon dioxide emissions and supporting the pursuit of climate neutrality in Europe by 2050 [6]. In parallel, fermentation processes – a key element in the production of biogas and bioethanol – are being optimized to improve energy efficiency and reduce consumption in biofuel production systems [19]. The RED III requirements emphasise the use of advanced biofuels produced from non-food raw materials, limiting their impact on land use changes. At the same time, they impose restrictions on first-generation biofuels to minimise their negative environmental effects. These biofuels can potentially reduce carbon dioxide emissions in the transport sector, which is responsible for a significant part of greenhouse gas emissions.

The increase in the share of biofuels, such as ethanol, also aligns with the strategy to reduce carbon dioxide emissions from transport, agreed as part of the European Green Deal [6]. Thanks to its physicochemical properties, such as high-octane number, latent heat of vaporisation and oxygen content, ethanol is one of the most commonly used biofuels in spark-ignition engines. It reduces toxic exhaust emissions and improves fuel combustion efficiency, which helps achieve environmental protection goals [6, 25].

Consequently, in recent years, there has been a growing focus in academic, scientific, public, and automotive industry sectors on developing alternative technological solutions for vehicles and fuels (e.g. hybrid vehicles, electric cars, or hydrogen fuel cell cars) [5]. However, in the short and medium term, referring to the passenger car sector, spark-ignition combustion engines, used alone or in hybrid systems, still dominate. All this broadly justifies the latest research and development directions in vehicle design, such as the achievable reduction in fuel consumption or the overall reduction of toxic exhaust emissions. The goal is to reduce the impact of the automotive industry on the natural environment [5].

Although the impact of ethanol as a bio-additive has been widely addressed in previous literature, this study brings an added value by integrating two distinct modelling approaches – Diesel-RK and COPERT – to analyse both engine performance and emission characteristics comprehensively. Unlike earlier studies on in-cylinder combustion or general emission inventories, this paper bridges the gap between detailed engine-level simulations and real-world emissions estimation for a modern Euro 6-compliant direct-injection turbocharged gasoline engine. The novelty lies in systematically comparing multiple ethanol blends (E5 to E100) under unified conditions using realistic fuel properties and driving scenarios. The approach provides practical insights into the feasibility of ethanol-rich fuels in everyday and performance-oriented vehicle applications, which remains underexplored in current literature. The analysis focuses on a modern gasoline engine with direct injection, as ethanol's effect differs significantly between direct and port fuel injection systems.

2. Research problem and literature review

Bioethanol as an additive to engine fuels has become one of the key directions of research in automotive and combustion technology. Its high-octane number (RON = = 108 for pure ethanol) improves resistance to combustion knock, which allows the use of a higher compression ratio in gasoline engines, leading to improved efficiency [3]. Bioethanol as an additive to engine fuels has become one of the key directions of research in automotive and combustion technology. Its high-octane number (RON = 108 for pure ethanol) improves resistance to combustion knock, which allows the use of a higher compression ratio in gasoline engines, leading to improved efficiency [3].

The relationship between fuel composition and engine operating parameters has been confirmed in numerous studies on the effect of different bioethanol concentrations on the performance of spark-ignition (SI) engines and exhaust emissions. Rimkus et al. [18] showed that increasing the bioethanol content in gasoline to 70% leads to a slight improvement in engine torque and thermal efficiency (up to 1.7%), as well as a significant reduction in carbon monoxide (CO) and hydrocarbon (HC) emissions – by 15% and 43%, respectively. Similar results were obtained by Al-Rousan et al. [1] in their literature review, which confirmed that most engine studies indicate an improvement in combustion properties and a decrease in CO and HC emissions when using bioethanol as an additive to gasoline. At the same time, however, no significant changes in carbon dioxide (CO_2) and nitrogen oxides (NO_x) emissions were recorded, which suggests that their levels are strongly dependent on specific combustion conditions and exhaust gas after-treatment systems in a given engine [1, 4].

A detailed analysis of the combustion process for different bioethanol blends was carried out by Paluri et al. [17]. Studies on a single-cylinder spark-ignition engine showed that higher ethanol concentrations in the fuel improve combustion efficiency and reduce harmful emissions. Barua [2] indicated that bioethanol has the potential to be a sustainable engine fuel, contributing to the reduction of greenhouse gas emissions and limiting the dependence on fossil fuels. However, their studies emphasize the need for further work on optimizing fuel blends and adapting engines to higher ethanol contents [8].

Despite the numerous benefits associated with bioethanol, its effect on combustion parameters and exhaust emissions requires more detailed analysis. Dhande et al. [4] studied the effect of different bioethanol proportions and ignition timing on engine performance and emissions. They found that increasing the ethanol content to 70% improved torque and thermal efficiency and increased fuel consumption. This is consistent with the results of Huang et al. [7], who showed that the lower calorific value of ethanol requires burning more fuel to obtain the same amount of energy. To compensate for this effect, it is necessary to adjust the fuel injection control systems and, in the case of E85 and E100, also increase the fuel tank capacity.

In addition to the effect of bioethanol on engine performance, changes in exhaust emissions are an important aspect. Bioethanol as a fuel additive can significantly reduce CO and HC emissions, resulting from better mixing of fuel with air and more efficient combustion processes. Wu et al. [22] showed that for E85 and E100 blends, CO emission levels can be even 30% lower compared to gasoline. However, the increased oxygen content in bioethanol causes a higher combustion temperature, which can lead to an increase NO_x emissions.

Although bioethanol is considered an environmentally friendly fuel, it is associated with certain technological challenges. One of them is the increased corrosiveness of the fuel system, resulting from the hygroscopicity of ethanol and its ability to absorb water, which can lead to the degradation of metal engine components [5]. Additionally, problems with the cold start of engines on ethanol fuels are well documented in the literature. Yamin et al. [23] suggest that increasing the injection pressure and using fuel heating systems can alleviate this problem, but additional modifications to the engine control system are required.

Using biofuels such as ethanol is still challenging, especially in older vehicles. These problems include corrosion of metal components, swelling and cracking of rubber and polymer parts of the fuel system, and difficulties related to cold starting. These limitations must be considered when designing modern vehicles, which must be factory-adapted to operate on fuels containing more than 10% alcohol [7].

Ethanol, although promising as an alternative fuel, poses a number of challenges. Its hygroscopic properties increase the risk of water contamination, leading to metal parts corrosion. The action of organic acids and chlorides in the fuel system exacerbates this problem [7]. Additionally, ethanol, acting as a solvent, contributes to the degradation of rubber and polymer components, causing them to soften, swell, and even crack. The effects of these processes can result in fuel leaks, incorrect dosing by injectors, and engine failures. To counteract these problems, fuel systems use materials more resistant to ethanol, such as aluminium, nylon, or fluorinated elastomers [7, 8].

Problems related to cold engine starting are another challenge [10, 16]. At low temperatures, fuel-air mixtures containing ethanol may be too lean to initiate the combustion process, which leads to increased emissions of toxic substances in the initial phase of engine operation. The solution is techniques such as increasing the injection pressure, modifying the shape of injector nozzles, or using dual fuel systems. In modern vehicles, fuel heating technologies are also used, which improves their evaporation and mixing in cold conditions [1, 14, 16, 19, 25].

The lower calorific value of ethanol compared to gasoline means increased fuel consumption and, in some cases, the need to modify injectors and fuel pumps. Advanced management strategies are introduced to improve efficiency and adjust engine operating parameters, such as precise fuel dose divisions into the pilot, main, and tail parts [5].

Modern engine control unit (ECU) combined with advanced sensors minimize the need for interference in the vehicle design, allowing for adjustment of operating parameters to the requirements of ethanol fuels. Solutions such as high-pressure fuel injection, injection split strategy, or instant fuel boiling significantly improve engine efficiency and reliability in difficult operating conditions [5, 23].

The article aims to analyse bio-additives' impact on the properties of liquid fuels, including their ability to improve fuel parameters and reduce emissions of harmful substances. The work focuses on environmental and technological benefits and challenges related to their implementation.

Another critical yet often underrepresented aspect in discussions about ethanol-blended fuels is their impact on particulate matter (PM) and particle number (PN) emissions, especially in gasoline direct injection (GDI) or spark-ignition direct injection (SIDI) engines. Several studies have demonstrated that increasing ethanol content in gasoline leads to a noticeable reduction in both PM and PN emissions. Jin et al. [9] reported that ethanol blends significantly reduce particulate emissions in SIDI engines, particularly under transient conditions. Similarly, Kozak et al. [11] observed a considerable drop in PM when using high-ethanol fuels such as E85 and E100. Lai et al. [13] further confirmed the positive impact of ethanol on combustion cleanliness, noting improvements in regulated and unregulated emissions, including particles. Timonen et al. [20] also highlighted the role of ethanol in limiting both primary PM and the potential for secondary aerosol formation in flex-fuel vehicles. Although PM/PN emissions were not directly assessed in the current simulation due to model limitations, these findings underscore the additional environmental benefit of ethanol fuels beyond gaseous emissions.

3. Methodology

Using the Diesel-RK program [12, 24], the operation of a 1.4 dm^3 internal combustion engine, which meets the Euro 6 standard, was simulated. Diesel-RK allows the creation of fuel mixtures directly in the program by determining the volumetric shares of individual components. Still, this function only works when creating gaseous fuels, not liquid. Hence, information was needed on specific gasoline-ethanol mixtures' physical and chemical properties. All parameters and data for the calculation model were selected when gasoline (E5) was used to power the engine, i.e., one containing up to 5% ethanol. The Diesel-RK model is an advanced calculation tool that simulates creating a fuel-air mixture and combustion in internal combustion engines. Similar approaches combining experimental and numerical analysis were presented by Tucki et al. [21], who investigated the influence of various fuels on engine parameters and exhaust emissions. Developed by Razleytsev and improved by Kuleshov [12] the model allows for precise representation of processes such as the division of fuel injection into doses, the shape of spraying in the combustion chamber, the dynamics of air vortices, or the interaction of fuel with the cylinder surface. Thanks to these capabilities, Diesel-RK supports the development of modern engine technologies.

The software enables the analysis of engine operating parameters in two- and four-stroke systems, regardless of the type of supercharging. Combustion chambers are treated as open thermodynamic systems, allowing for modelling actual operating conditions. Thanks to the ability to simulate the full range of engine operation – from idle to maximum load – Diesel-RK is a versatile tool supporting the development of algorithms controlling fuel injection systems and optimising engine designs in terms of efficiency and compliance with emission standards. Its wide application makes it a valuable tool for engineers, designers and researchers dealing with modern engine technologies.

The COPERT (Computer Programme to Calculate Emissions from Road Transport) model was used to estimate pollutant emissions [15, 25]. This model is a tool developed by the European Environment Agency (EEA), which is used to inventory pollutant emissions from the road transport sector. It provides significant support in developing environmental policies and monitoring their effectiveness. COPERT allows for estimating emissions of substances such as nitrogen oxides, particulate matter (PM), hydrocarbons, carbon monoxide, carbon dioxide, methane and nitrous oxide. The model considers emissions generated during driving and a standstill and non-exhaust emissions related to road dust or tyre and brake wear.

One of the model's key elements is its ability to simulate various emission scenarios depending on operating conditions and vehicle parameters. COPERT considers vehicle type, fuel type, fleet age, speed profiles and environmental conditions. It also considers alternative fuels such as biofuels, natural gas, hydrogen or synthetic fuels, making it a versatile tool for analysing emissions in the transport sector.

Using the above-mentioned models, simulations were performed, and the impact of fuels with ethanol addition on selected engine performance indicators was compared. The data for the specific gasoline + alcohol mixture were selected based on information from available literature and scientific articles [5], and the physicochemical properties of the mixtures used for simulation are presented in Table 1.

Table 1. Physical and chemical properties of fuels with different ethanol additions [5, 22]

Properties	Unit	E5	E10	E85	E100	Petrol
Density	kg/m^3	740	752	783	790	720–775
Heat of vaporization	kJ/kg	265	322.3	752.1	838	180–350
Research octane number	–	95	95.7	108	109	95
Motor octane number	–	85	85.7	95	98	85
Cetane number	–	8	9	9	9	8-14
Kinematic viscosity	mm^2/s	0.494	0.572	1.352	1.519	0.494
Dynamic viscosity	Pa·s	0.0004	0.0004	0.0011	0.0012	0.0004
Oxygen content	% (m/m)	2.70	3.473	29.52	34.73	0
Hydrogen content	% (m/m)	14.10	13.913	13.26	13.13	14.5
Carbon content	% (m/m)	83.20	82.614	57.22	52.14	85.5
Autoignition temperature	K	520	533	635	698	465–743
Calorific value	MJ/kg	42.90	40.90	29.34	26.95	44

As mentioned above, the Diesel-RK model allows for analysing many engine parameters. Still, for this study, the following were selected: maximum useful power and maximum torque for a given fuel. The following mixtures were tested: pure gasoline, gasoline with 5% ethanol (E5), 10% ethanol (E10), 85% ethanol (E85) and pure ethanol (E100).

Then, using the COPERT model, the pollutant emissions were estimated for the same mixtures. The effect of ethanol content in the fuel mixture on the following pollutants was examined: methane, carbon monoxide, carbon dioxide, non-methane hydrocarbons, hydrocarbons and fuel consumption.

Table 2 presents the useful power and maximum torque for various fuel mixtures with ethanol and for comparison with commercial gasoline (E5) and gasoline alone. As can be seen for E10 mixtures, where the ethanol content is quite low, there was a decrease in the value of the maximum useful power obtained. The primary influence on this may be the decrease in the calorific value of the entire mixture. A noticeable change is seen when we use a mixture of E85 and 100% ethanol for power. Then, there is a more than 10% increase in maximum power compared to gasoline alone. The observed improvement in performance for E85 and E100 may be due to the properties of ethanol, such as a higher octane number, fuel density, and significantly higher oxygen content.

Table 2. Maximum net power and maximum torque for a given fuel

Maximum net power [kW]				
Petrol	E5	E10	E85	E100
104.05	103.24	101.47	113.89	115.38
Maximum torque [Nm]				
Petrol	E5	E10	E85	E100
221.64	220.16	217.03	222.90	225.25

In the case of torque, the situation is similar to that of useful power. For E10 blends, the values of the obtained torques are lower than those of petrol and E5. The increase in performance is also visible for E85 and E100. The differences are not as large as in the case of power and do not exceed 2.5% between ethanol fuels and petrol for the maximum values.

The research began with detailed simulations of the engine operation in the Diesel-RK program. The model covered a wide range of operating conditions, from idle to full load, taking into account different engine speeds (800–6000 rpm), boost pressure (maximum 1.2 bar) and fuel mixtures (E5, E10, E85, E100). The engine under study, was a 1.4-litre gasoline engine with direct fuel injection (DI), turbocharging, and variable valve timing, compliant with the Euro 6 standard. Direct injection systems differ significantly from port fuel injection (PFI) regarding mixture formation and combustion dynamics, which strongly influence the engine's response to ethanol-blended fuels.

The simulation results obtained in Diesel-RK, such as maximum power (104.05 kW at 5200 rpm), maximum torque (221.64 Nm at 4000 rpm), and mean effective pressure (IMEP),

Emission simulations were carried out in the COPERT program. The COPERT model, unlike the detailed Diesel-RK model, does not include detailed engine operating parameters. Instead, it is based on general vehicle characteristics, such as engine type, emission standard, and driving cycle. In the case of this study, simulations were carried out for a passenger car with a 1.4 dm^3 petrol engine meeting the Euro 6 standard, running on the WLTP cycle. The figures below refer to the average distance travelled per km. The results of the simulations in COPERT provided information on pollutant emissions and fuel consumption in real operating conditions. In particular, the average energy consumption per kilometer was analysed and presented in Fig. 4.

Emission values presented in the results (Fig. 1–7) are expressed in grams per kilometre (g/km), and fuel energy consumption is given in mega joules per kilometre (MJ/km), as calculated by the COPERT model for a Euro 6 gasoline vehicle operating under the WLTP driving cycle.

Knowing the engine parameters used for simulation in the Diesel-RK model, the COPERT model was used to calculate pollutant emissions and fuel consumption for the same blends.

Figures 1–7 show the interpretation of emission results for different fuel-ethanol blends.

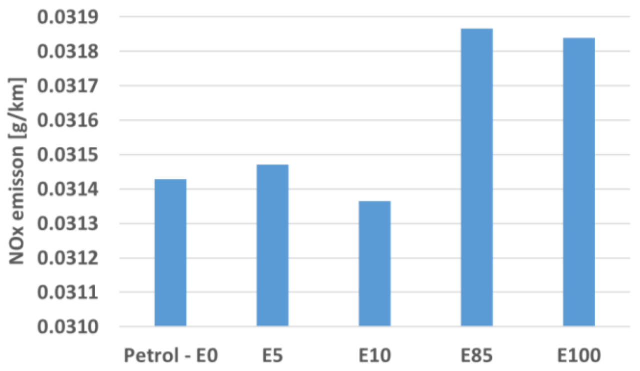

Fig. 1. Emission of nitrogen oxides (NO_x) depending on the type of fuel

The analysis of the results shows that the nitrogen oxides emission level increases with the increase of ethanol content in the fuel mixture. This is related to the higher oxygen content in ethanol than standard gasoline, leading to more intensive combustion and higher temperatures in the combustion chamber. Higher temperatures favour the formation of nitrogen oxides, because this process is strongly dependent on temperature (Zeldovich mechanism).

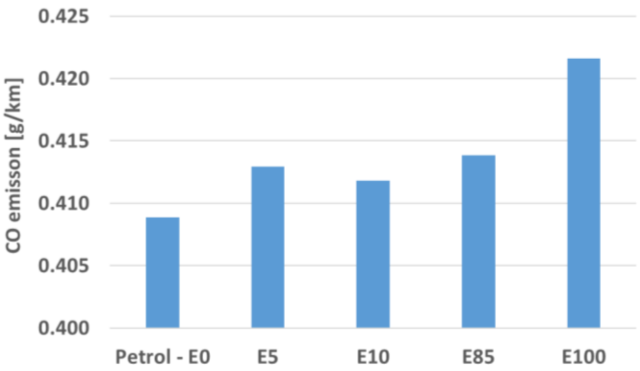

Fig. 2. Carbon monoxide (CO) emissions depending on the fuel type

Carbon monoxide (CO) emissions increase with increasing ethanol content in the fuel, reaching the highest values for the E100 blend. This is due to several factors. First, the high enthalpy of ethanol vaporization leads to a lower temperature in the combustion chamber, making it challenging to fully oxidize CO to CO_2 in certain engine operating conditions. Second, the lack of gasoline in the E100 can result in less efficient combustion, especially at low engine loads. Additionally, although effective for gasoline, the three-way catalyst (TWC) may not be fully optimized for burning pure ethanol, which limits its ability to convert CO.

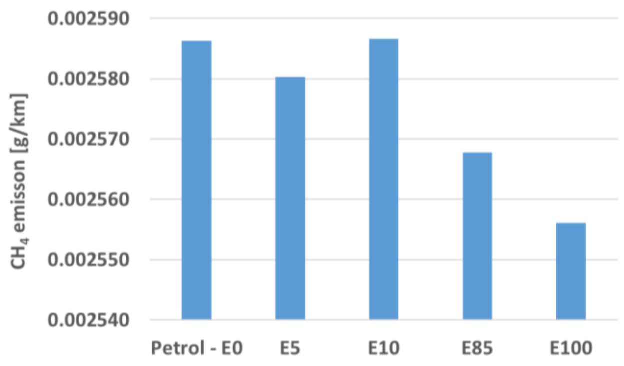

Fig. 3. Methane (CH_4) emissions depending on the fuel type

The highest methane (CH_4) emissions were recorded for the E10 blend, while the values for E85 and E100 were lower. The specificity of ethanol combustion can explain this result. Adding ethanol to gasoline changes combustion properties, forming local zones of insufficient oxidation, where methane is formed. In the case of E10, where the ethanol content is lower, the fuel-to-air ratio is similar to gasoline. However, ethanol introduces some disturbances in the combustion process, promoting higher CH_4 emissions. In turn, in E85 and E100 blends, the higher combustion temperature promotes more efficient conversion of hydrocarbons and lower methane emissions.

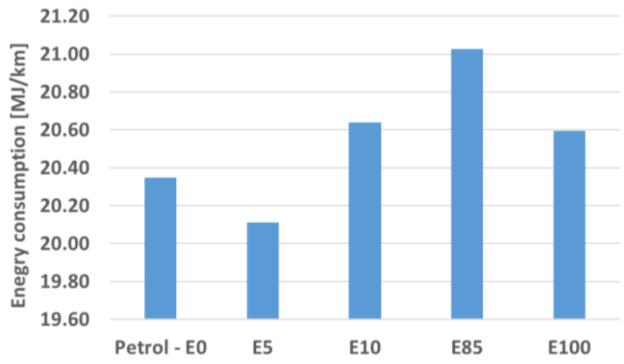

Fig. 4. Fuel consumption depending on the fuel type

The energy consumption shown in the graph shows the amount of energy the vehicle uses to travel 1 km in average driving conditions. The increased ethanol content in fuel affects fuel consumption in a nonlinear manner. For E10 and E85 blends, an increase in fuel consumption is observed compared to unleaded petrol. This is due to the lower calorific value of ethanol, which requires a larger dose of fuel to obtain the same power. In addition, engine management systems compensate for the difference in calorific value by extending the injection time and increasing consumption. In turn, with full ethanol (E100), a decrease in fuel consumption is observed. This is the effect of more stable combustion resulting from the homogeneity of the fuel, which allows for the optimization of engine operation and more efficient use of energy. Additionally, a smaller amount of deposits in the combustion chamber when using pure ethanol can reduce heat losses, improving the overall thermal efficiency of the engine.

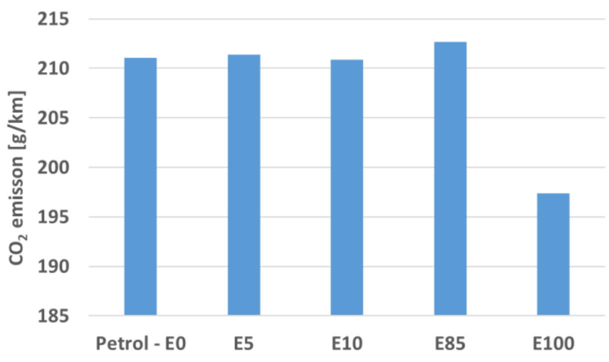

Fig. 5. Carbon dioxide (CO_2) emissions depending on fuel type

Carbon dioxide (CO_2) emissions do not increase proportionally with increasing ethanol content in fuel. Although fuel consumption for E85 and E100 blends is typically higher than for petrol, total CO_2 emissions are lower. This is due to the ethanol molecule's lower carbon content than petrol. Less carbon in the fuel means less CO_2 is produced during combustion. In addition, modern engine management systems, especially in Euro 6 vehicles, are designed to optimise combustion and minimise pollutant emissions, which contributes to further reducing CO_2 emissions when using ethanol fuels.

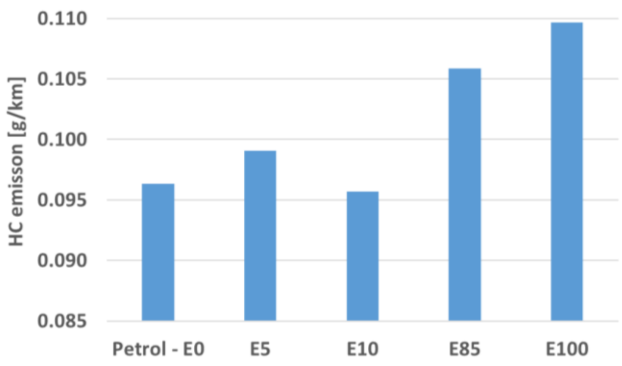

Fig. 6. Hydrocarbon (HC) emissions depending on the fuel type

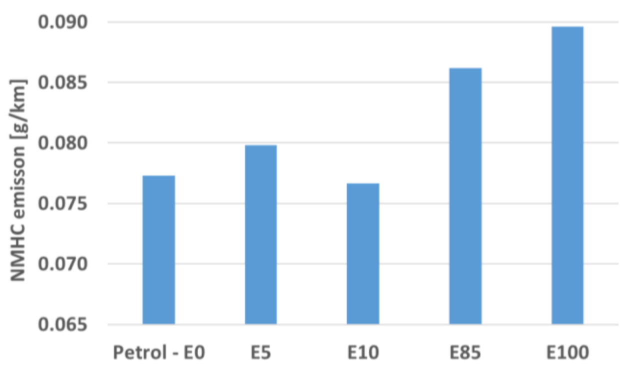

Fig. 7. Non-methane hydrocarbon (NMHC) emissions depending on the fuel type

Emissions of hydrocarbons (HC) and non-methane hydrocarbons (NMHC) were highest for the E85 blend. This is due to several factors. The high volatility of ethanol in E85 leads to increased fuel evaporation and, consequently, higher HC emissions. Additionally, the evaporative emissions control (EVAP) system in Euro 6 vehicles may not be fully optimized for high ethanol fuels, exacerbating the problem. NMHC emissions are lower for E100 due to the lack of gasoline, which is the main source of these compounds. However, despite lower NMHC emissions compared to E85, overall hydrocarbon emissions for E100 may still be higher than for gasoline due to other factors related to the combustion of pure ethanol.

4. Summary and conclusions

Reducing emissions from transport is critical in the fight against climate change. Increasing the share of biofuels such as ethanol is essential in achieving climate neutrality goals. Biofuels, especially ethanol, can help reduce carbon dioxide emissions from transport, but their use is associated with specific challenges. These include problems related to corrosion of fuel systems, cold starting, and higher nitrogen oxides emissions due to more intensive combustion. Fuel blends with a higher ethanol content (E85, E100) can improve power and torque at higher engine speeds, thanks to the properties of ethanol, such as higher octane number, density, and oxygen content. However, a higher ethanol content increases fuel consumption, especially in E85 and E100 blends. This is due to the lower calorific value of ethanol, which means that more fuel is needed to obtain the same energy.

The impact of ethanol content on engine efficiency is relatively small. Blends with a lower ethanol content (E10) have a minimal effect, while for E85 and E100, the efficiency reduction is more noticeable but still offset by power gains. For everyday vehicle use, especially for long distances and cost efficiency, lower ethanol blends are preferable. However, for high-performance and competition vehicles, where maximum power and performance are key, high ethanol content fuels (E85, E100) are more suitable despite increased fuel consumption.

Given these general observations, the following section provides a detailed analysis of specific effects observed in the simulations.

Analysis of the results shows a slight decrease in power and torque for the E5 and E10 blends compared to the base fuel (petrol). This is the effect of the lower calorific value of ethanol, which results in less energy available in the combustion process. In the case of E85 and E100 fuels, an increase in maximum power by over 10% was noted, which may be a consequence of the higher octane number of ethanol, its higher oxygen content, and improved fuel-air mixing.

These results are consistent with the research of Rimkus et al. [18] who showed that for the E85 blend, an increase in engine efficiency they also noted, along with an increase in torque by 1.7% for engines fuelled with fuel with a high bioethanol content.

One of the main challenges related to using fuels containing bioethanol is the increase in nitrogen oxide emissions. The results show that increasing the ethanol content in the fuel leads to increased NO_x emissions, with the highest values recorded for the E100 fuel. This is a consequence of the higher oxygen content in the fuel, which leads to more intensive combustion and an increase in the temperature in the combustion chamber, which promotes the formation of nitrogen oxides according to the Zeldovich mechanism.

The phenomena described by Wu et al. [22] indicated that higher combustion temperature increases the formation of NO_x, showing that increasing the ethanol content in the fuel by 10% can increase NO_x emissions by 5-10%. This problem can be mitigated using emission reduction strategies such as exhaust gas recirculation (EGR) or optimizing exhaust gas after-treatment systems.

Carbon monoxide (CO) emissions increase with increasing ethanol content in the fuel, reaching the highest values for the E100 blend. This may be due to the difficulty in fully oxidizing CO to CO_2 at lower combustion temperatures under some engine operating conditions. Wu et al. [22] indicated that ethanol fuels may lead to less efficient combustion at low engine loads, resulting in increased CO emissions. Furthermore, three-way catalysts are not fully optimized for pure ethanol combustion, which may additionally affect higher CO emissions. This problem can be mitigated by improving the fuel-air mixture management and optimizing the ignition timing.

High-ethanol fuels (E85, E100) improve engine power and torque but are associated with higher NO_x and CO emissions and increased fuel consumption. The optimal choice for everyday use may be E10 fuel, which minimizes the disadvantages of biofuels while providing moderate emission reductions. However, in sports and competitive applications, where power parameters are key, E85 and E100 may be a better solution despite the increased fuel consumption.

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