energies

Article

Exhaust Emissions from a Direct Injection Spark-Ignition Engine Fueled with High-Ethanol Gasoline

Miłosław Kozak [1,*], Marek Waligórski [1], Grzegorz Wcisło [2], Sławomir Wierzbicki [3,*] and Kamil Duda [3]

[1] Institute of Powertrains and Aviation, Faculty of Civil and Transport Engineering, Poznań University of Technology, 60-965 Poznań, Poland; marek.waligorski@put.poznan.pl
[2] Department of Bioprocess Engineering, Energy and Automation, Faculty of Production Engineering and Power Technologies, University of Agriculture in Kraków, 31-120 Kraków, Poland; grzegorz.wcislo@ur.krakow.pl
[3] Department of Mechatronics, Faculty of Technical Sciences, University of Warmia and Mazury in Olsztyn, 10-719 Olsztyn, Poland; kamil.duda@uwm.edu.pl
* Correspondence: miloslaw.kozak@put.poznan.pl (M.K.); slawekw@uwm.edu.pl (S.W.)

Abstract: Ethyl alcohol is a known additive to automotive gasoline. In commercially available gasolines, its concentration is between 5 and 10%. Since ethyl alcohol can be considered as a renewable fuel, efforts are being made to further increase its content in gasoline. This article describes the results of comparison experiments on a Euro 5 direct injection spark-ignition car engine fueled with conventional gasoline and gasoline with 30% v/v ethyl alcohol content (E30). The test results showed that a significant share of ethanol in the fuel did not affect most of the regulated emissions of gaseous components (namely: CO, HC, NO), i.e., a three-way catalyst effectively removed these components, regardless of the fuel composition. Slightly lower CO_2 emissions with the E30 fuel were noticeable. A significant difference, however, in lower particulate number emissions for the fuel with high-ethanol content was seen. At high engine load, the use of the E30 fuel resulted in a tenfold reduction in particulate number emissions. This might be considered as a very valuable effect of ethanol since direct injection spark-ignition engines are typically characterized by higher particulate emissions compared to engines equipped with other types of injection systems.

Keywords: ethyl alcohol; spark-ignition engine; direct injection; exhaust emissions; particulate number

Academic Editors: Constantine D. Rakopoulos and Jianbing Gao

Received: 8 November 2024
Revised: 31 December 2024
Accepted: 17 January 2025
Published: 21 January 2025

Citation: Kozak, M.; Waligórski, M.; Wcisło, G.; Wierzbicki, S.; Duda, K. Exhaust Emissions from a Direct Injection Spark-Ignition Engine Fueled with High-Ethanol Gasoline. *Energies* **2025**, *18*, 454. https://doi.org/10.3390/en18030454

1. Introduction

Ethyl alcohol has enjoyed great interest for over 100 years as a component of motor fuel, especially those intended for spark-ignition engines. This is understandable because ethanol has a high octane number, and its chemical composition favors the combustion process. Another important issue is the possibility of producing ethanol as a renewable fuel in the biomass fermentation process. The state of the art of the process is well mastered, and high production capabilities are ensured since there is no problem in providing substrates. Bioethanol is most often produced from the following [1]:

1. Raw materials containing sucrose;
2. Raw materials containing starch;
3. Lignocellulosic biomass.

The first group of raw materials includes plants such as sugar cane, beetroots and sugar sorghum as well as certain fruits. The second group includes wheat, rye, barley, potatoes, maize, rice and cassava. The third group includes raw materials that have no food significance, i.e., energy crops, by-products from the agriculture industry and the wood industry, paper and cardboard, despite being a fraction of municipal waste. Bioethanol from the raw materials of the third group (lignocellulose) is regarded as a second generation biofuel. The technological details of the production of ethanol for fuel purposes can be found in many bibliographic items, for example, in [2,3]. Similarly, many articles present the properties of ethyl alcohol as a motor fuel [4–6]. Although ethyl alcohol is currently used mainly as a fuel for combustion engines, work is also underway to use it in fuel cells [7,8]. Ethanol can be used to produce dimethyl ether (DME)—a promising alternative fuel component for compression-ignition as well as spark-ignition engines [9,10]. Ethanol is also considered as a fuel for new generations of high-performance combustion engines [11,12].

Bioethanol is still considered a fuel worthy of interest, both for private cars and for public transport. Bioethanol was selected as an environmentally friendly fuel for urban transport in the CIVITAS (the CIVITAS initiative works to make sustainable and smart urban mobility a reality for all of Europe and beyond. https://civitas.eu/, accessed on 30 December 2024) [13], see Table 1. The main benefit associated with the use of bioethanol is the long-awaited reduction in greenhouse emissions in transport. According to Lewandrowski et al. [14] current trends in the ethanol industry and actions refineries could take to reduce emissions offer opportunities to lower the greenhouse gases (GHG) profile of corn ethanol even up to 70% with respect to pure gasoline.

Table 1. Possible and most promising bus technologies for different energy carriers according to CIVITAS.

	The Most Promising Options	**Less Favorable Options**
Fossil fuels	Diesel EURO VI CNG	LPG LNG
Biofuels	FAME HVO Bioethanol Biomethane	Landfill-liquefied methane
Electricity	Electric busses Trolley busses	
Hydrogen	Hybrid hydrogen/electricity	Fuel cell without battery Hydrogen internal combustion
Hybrid	Parallel ICE/electricity hybrid Serial hybrid configuration with dominating electricity	

The addition of ethanol to gasoline to reduce the toxicity of exhaust gases was widely used in the 20th century, particularly in Poland. The ethanol present in the fuel improves the availability of oxygen in the combustion zone, thus reducing the tendency to create incomplete combustion products. With currently highly efficient exhaust gas aftertreatment systems, the impact of ethanol in gasoline on the final emission of most of the regulated exhaust components from the vehicle exhaust system is diminished (Figure 1) [15]. According to Bielaczyc et al. [16], it mainly concerns lower CO emissions, while Yuan et al. [17] indicate that the greater impact of ethanol only concerns particulate matter emissions. However, some research results show that by increasing the ethanol content in gasoline, the share of hydrocarbons, including highly toxic ones such as aromatic hydrocarbons, is reduced. According to Schifter et al. [18], the presence of ethanol in fuel effectively reduces the emission of benzene, toluene and xylenes, as well as all aromatic hydrocarbons in total. Benzene emissions are four times lower for E45 fuel and more than ten times lower for E85 than for conventional gasoline. The total emissions of aromatic hydrocarbons are reduced to a similar extent. Therefore, ethanol's positive impact can also be seen in terms of unregulated exhaust gas components.

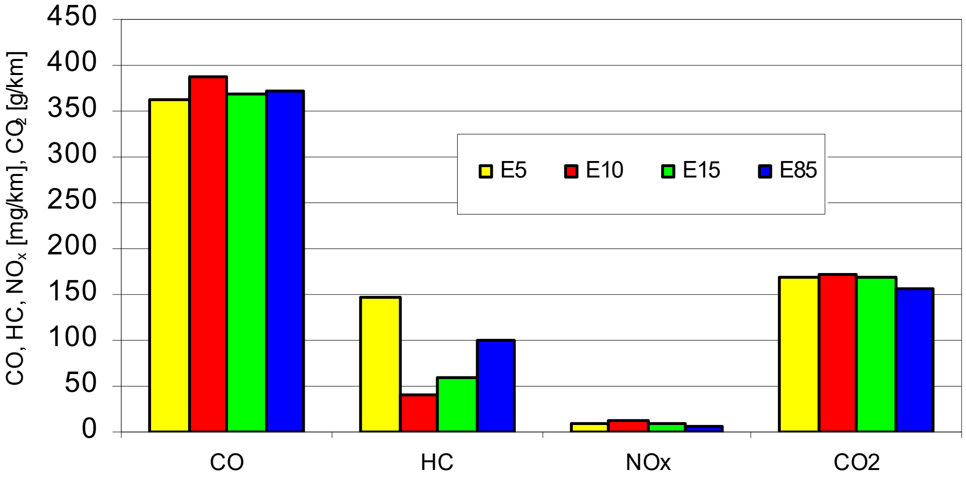

Figure 1. Exhaust emission from an FFV Euro 5a passenger car (direct injection engine) fueled by various blends of gasoline and ethanol over the WLTC [15].

As part of the research described in this article, exhaust emissions from a direct injection, spark-ignition car engine fueled with gasoline without ethanol and with a high-ethanol content, 30% v/v, were tested. The main goal of this research was to determine how much the addition of ethanol to gasoline affects particle number (PN) emissions, as this specific aspect of the use of this biofuel is less commonly described in the literature. This issue is very important as particulate matter is one of the most harmful components emitted from engine exhaust gases. The scope of the harmful impact of suspended dust on human health is multidirectional. Acute or short-term exposure to particles may cause sudden irritation (mainly of the eyes, throat and bronchi), neurophysiological symptoms (including dizziness, nausea) and respiratory symptoms, as well as the intensification of allergic reactions. Long-term exposure to particulate matter increases morbidity and mortality, as well as increases the number of cases of chronic bronchitis, chronic obstructive pulmonary disease and the risk of lung cancer. According to estimates by the European Environment Agency, approximately 275,000 premature deaths per year are caused by excessive exposure of the population to PM2.5. Studies show that large numbers of ultrafine particles can penetrate the blood–brain barrier. These particles then have a direct harmful effect on the human central nervous system [19]. Oxygenated fuel contains oxygen atoms in its molecule, which reduces the formation of soot precursors and promotes the subsequent oxidation of soot, consequently reducing soot emissions compared to pure gasoline operation.

It should be noted that the information available in the literature on the impact of ethanol on particulate number emissions from spark-ignition engines with direct injection is not entirely unequivocal [20,21]. In work by [22], a decrease in PN emissions was recorded when E10 and E20 fuels were used. In a paper by [23], it was found that the E20 fuel causes a significant reduction in PN emissions but only at high engine load. The research of Lv et al. [24] shows that E10 fuel reduces PN emissions but only to a small extent. In turn, in tests by Wang et al. [25] carried out using pure ethanol (E100), higher PN emissions were obtained than when fueled with conventional gasoline. The conclusions of work by [26] stated that ethanol–gasoline-blended fuels increase the PN concentration at low-load operating conditions, but PN concentration reduces at higher load conditions. In the tests described in [27], PN emissions were reduced by 73% in the NEDC cycle using E20 fuel. According to the last-cited study, the level of PN emissions is very different in both phases of the NEDC cycle; in the UDC phase it is about five times higher than in the EUDC phase, which can be, among others, explained by fuel settling on the walls of the cold combustion chamber. Interestingly, the efficiency of the E20 fuel in reducing PN emissions was very similar in both phases, 71% for UDC and 77% for EUDC, respectively.

The next important study that should be mentioned in the context of the impact of ethanol is the work by Jin et al. [28]. It showed a decrease in PN emissions during tests of a passenger car over the FTP-75 cycle fueled with E10, E30, E50 and E85 fuels. At levels above 30% ethanol, the drop in nanoparticle emissions was dramatic. The reason for such changes in PN emissions was because neat ethanol does not contain aromatic compounds, and etlanol's carbon content is lower than that of gasoline. Interesting conclusions are also presented in the study by [29]. It was found that the effect of ethanol content varies depending on engine operating conditions. As for the emissions of PN, they most often decrease with the increase in ethanol content in gasoline, but this trend is not confirmed for high engine load. Opposite observations can be found in an already mentioned study [26]. It was namely stated that the addition of ethyl alcohol reduces particulate emissions at high engine loads and increases these emissions at low engine loads. Ethanol's effectiveness in reducing PN emissions was attributed in [30] to reducing the amount of soot precursors in the fuel, such as aromatic hydrocarbons and large n-alkanes. A comparison of particulate number emissions for an FEV vehicle is presented in [30]. The tests were carried out over the NEDC, and the vehicle was fueled with E10, E85 and E100 fuels. Apart from the cold-start period (the first elementary cycle of the UDC phase), the number of particulate matter was much lower for high-ethanol fuels. It was also noticed that there was no significant increase in the number of particles during vehicle acceleration with the E85 fuel and especially with the E100 fuel. It should be noted, however, that such fuels cannot be used in conventional vehicles.

The process of formation of particulate matter (mainly soot) in the engine combustion chamber has been described in many publications, for example, in [21,31–33]. Therefore, only the most important information about this process will be mentioned here, and the main attention will be focused on the influence of ethyl alcohol on the formation of particulate matter. The soot formation process takes a very short time. Fuel molecules generally contain from a few to a dozen carbon atoms and approximately twice as many hydrogen atoms. In a very short time, within a few milliseconds, soot particles are created, which are a completely different substance, as they already contain thousands of carbon atoms and about ten times fewer hydrogen atoms. A detailed analysis of this process shows that it occurs in a few steps, namely pyrolysis, nucleation, surface growth, agglomeration and oxidation. As a consequence of these transformations, soot precursors are produced; they then evolve into soot nuclei and then into single spherules, agglomerated spherules, young particulates and finally mature particulates. In a laminar diffusion flame, the sequential course of the particulate formation elementary processes can be clearly observed, while in pre-mixed combustion, these processes most often occur simultaneously.

One of the first studies explaining the mechanism of the influence of ethyl alcohol on the formation of particulate matter was presented by Rubino and Thomson [34]. Their research included analyzing the impact of ethanol on the process of creating soot precursors in a diffusion flame. They found that the concentration of fuel (propane) drops rapidly within the flame, while intermediate products such as ethylene, methane, ethane, acetylene, propylene, butane, hexane and benzene appear. The addition of ethyl alcohol to the fuel stream resulted in a reduction in the content of intermediate products in the flame, including benzene and acetylene, which are soot precursors. According to the mentioned study, the reduction in acetylene concentration takes place due to the presence of additional oxygen atoms from the pyrolysis of ethanol in the areas of the rich mixture within the flame.

Another work analyzing the influence of ethyl alcohol on the soot formation process is the study of Westbrook, Pitz and Curran [35]. Their work describes chemical kinetic modeling of the effects of oxygenated compounds on soot emissions. Calculations performed for mixtures containing n-heptane and oxygenated compounds showed a reduction in the amount of soot precursors in the combustion products of a rich mixture proportional to the concentration of oxygen in the fuel. Simultaneously, an increase in the amount of CO and CO_2 was noted, with oxygen occurring in this phase mainly in the form of CO and H_2O. Ethanol was indicated as one of the most effective oxygenated compounds in reducing the amount of soot precursors. With the content of 30% ethyl alcohol in a mixture with n-heptane, the conversion of carbon in the fuel into soot precursors was reduced by more than 20%.

Similar research was performed by the team of Cheng, Dibble and Buchholz [36], i.e., soot formation during the combustion of a mixture of n-heptane and ethanol was also modeled. It was noticed that the presence of ethanol causes significant decreases in the peak concentrations of soot precursors in the rich mixture combustion zone. The concentration of acetylene and benzene decreased approximately linearly with increasing oxygen content in the fuel. With 30% ethyl alcohol content in the fuel, an approximately 60% reduction in the mass of soot released was achieved.

A detailed analysis of the ignition kinetics of oxygenated compounds indicates that most of the oxygen atoms contained in oxygenates' molecules react directly to produce CO. The strong CO bond is not broken during ignition; therefore, the C atom bound to it does not participate in the formation of soot. Data on the energy of breaking intermolecular bonds are helpful in this assessment. For the C–C bond (methylbenzene), this energy is 272 kJ/mol, while for the C–O bond in carbon monoxide, this energy is about four times higher and amounts to 1071 kJ/mol [37]. However, an additional and probably more important factor is the increase in the concentration of radicals such as O, OH and HCO in the combustion chamber, which result from the presence of oxygenated compounds. The increased supply of these radicals affects the formation of soot in two ways. First, high concentrations of O and OH support the oxidation of carbon atoms in the flame which diminishes the amount of carbon that is available for the formation of soot precursors. Creating large amounts of HCO works similarly, i.e., carbon is converted to CO or CO_2; this does not produce soot. Secondly, the increased concentration of radicals, especially OH radicals, in the soot formation region downstream of the rich mixture combustion zone reduces soot nucleation by oxidizing aromatic compounds and suppressing the development of polycyclic aromatic hydrocarbons [33]. The release of the OH radical in ethyl alcohol in rich mixture conditions occurs at temperatures above 1400 °C [38].

The analysis of the impact of ethyl alcohol on soot formation was also carried out by experiment using acceleration mass spectroscopy. This method allows for the marking of individual carbon atoms in a molecule followed by experimental tracking of their fate during the combustion process. In the study by Buchholz, Cheng and Dibble [39], this method was used to test a mixture of conventional fuel with ethanol, containing from 9 to 37% of the latter. The analysis of the obtained particulate matter indicated that carbon which comes from ethyl alcohol also takes part in the formation of particulates, but the probability of forming soot is 50% lower for carbon atoms originating from ethanol than for carbon atoms from hydrocarbons.

The above-mentioned facts indicate that there are theoretical foundations for reducing particulate emissions by introducing ethyl alcohol into the fuel composition. As part of this work, in order to fully illustrate the impact of ethyl alcohol, in addition to the particulate number emissions, the emissions of gaseous components (CO, CO_2, HC, NO) and fuel consumption were measured.

2. Materials and Methods

The tests were performed on a direct injection-stratified charge spark-ignition engine. In this engine, the air–fuel mixture was richer in the area near the spark plug and leaner throughout the rest of the combustion chamber. The overall air–fuel mixture composition (i.e., average for the entire combustion chamber) was lean. Technical data of this engine are presented in Table 2. A view of the test bed is shown in Figure 2. The measurements of engine parameters were carried out at a constant rotational speed of 2400 rpm and with a variable load from 0 to 100 Nm, which comprised 6 operating points represented by loads 0, 20, 40, 60 80 and 100 Nm. Increasing the load between measurement points was not included in the measurement. After achieving the set load, the results of exhaust gas composition and fuel consumption were expected to stabilize. After stabilizing these results, we waited 2 min, three subsequent measurements were made at 20 s intervals. Particulate matter was measured every second for one minute.

Table 2. Specifications of the test engine.

Engine Type. **Manufacturer** **Engine Model**	**Spark-Ignition** **Volkswagen** **1.2 TSI EA111 CBZB**
Displacement	1.2 dm^3
Maximum power	77 kW @ 5000 rpm
Maximum torque	175 Nm @ 1550–4100 rpm
Injection/combustion type	Direct injection, turbocharged
Compression ratio	10:1
Emissions control	Three-way catalyst
Number of cylinders/valves	4/8
Calibrated to	EURO 5 [40]

Figure 2. The view of engine test bed.

All measurements were carried out when the engine was fully warmed up, the engine coolant and lubricating oil were maintained at 85 °C. During the tests, the composition of exhaust gases was measured, specifically the concentrations of gas components such as

CO, HC, NO and CO_2, as well as the particle number emissions. The emission of gaseous components was measured using the AVL Digas 4000 analyzer, while the PN measurement was carried out using the EEPS 3090 (Engine Exhaust Particle Sizer Spectrometer) analyzer from TSI (Shoreview, MN, USA) with a measurement range of 5.6 to 560 nm. Fuel consumption was measured gravimetrically (g/s).

Two types of fuel were used in the experiments: commercial gasoline without ethyl alcohol which was marked as E0 and gasoline with a high-ethanol content (30% v/v) which was marked as E30. The E30 fuel was composed on the basis of E0 by mixing 70% by volume of the E0 fuel with 30% of ethyl alcohol. Thus, the ethanol content in the final E30 fuel was 30% by volume. Table 3 presents the parameters of the E0 gasoline used in the tests, and Table 4 presents the requirements for ethyl alcohol used as a component of the motor gasoline. The ethyl alcohol used in the tests was an analytic-grade dehydrated alcohol and had an assay score above 99%. It is worth noting that the E0 fuel was a fairly light type of gasoline, over 40% of the gasoline composition had a boiling point lower than ethanol. Moreover, the E0 fuel had the maximum oxygen content permitted for conventional gasoline, i.e., 2.7% (m/m). The oxygen content in the E30 fuel was almost five times higher than in E0, which was exactly 12.3% (m/m).

Table 3. Parameters of the base gasoline (E0) used in the tests.

Parmeter	Unit	Value
Research octan number (RON)	–	98.1
Motor octan number (MON)	–	89.1
Density at 15 °C	kg/m^3	747.8
Oxygen content	% (m/m)	2.7
Oxygenates content—ethers with ≥5 C atoms	% (v/v)	14.9
MTBE content	% (v/v)	14.9
Ethanol content	% (v/v)	0.17
Benzene content	% (v/v)	0.78
Total aromatics content	% (v/v)	34.9
Olefin content	% (v/v)	0.6
Percentage of evaporation to 70 °C (E70)	% (v/v)	41.2
Percentage of evaporation to 100 °C (E100)	% (v/v)	61.8
Percentage of evaporation to 150 °C (E150)	% (v/v)	88.6
Final boiling point (FBP)	°C	180.9

Table 4. Quality requirements for bioethanol used as a fuel biocomponent [41,42].

Parmeter	Unit	Value
The content of ethanol and higher saturated alcohols	% (m/m)	min. 98.7
The content of mono-saturated alcohols (C3–C5)	% (m/m)	max. 2.0
Methanol content	% (m/m)	max. 1.0
Water content	% (m/m)	max. 0.300
The content of inorganic chlorides	mg/kg	max. 6.0
Copper content	mg/kg	max. 0.100
Total acidity (expressed as acetic acid content)	% (m/m)	max. 0.007
Appearance		clear and transparent
Phosphorus content	mg/L	max. 0.15
The content of dry residue after evaporation	mg/100 mL	max. 10
Sulfur content	mg/kg	max. 10.0
Electric conductivity	µS/cm	max. 2.5
Sulfate content	mg/kg	max. 4

Pure gasoline fuel was examined first, followed by the E30 blend. Each fuel was tested using the same procedure. Before the application of the E30 fuel, the whole injection apparatus was thoroughly drained and then flushed with a proper amount of E30 fuel to ensure its purity and homogeneity throughout the injection system.

3. Test Results and Discussion

A comparison of the concentrations of gas components in the exhaust gases of the test engine fueled by E0 and E30 fuel is presented in Figures 3–6. It is worth recalling that the engine exhaust system was equipped with a three-way catalyst which reduced the concentrations of toxic components in the exhaust gases. However, for carbon monoxide (Figure 3), lower concentrations of this compound can be observed when the engine is powered with fuel containing ethanol. A simple ethanol molecule, additionally containing oxygen, promotes the complete combustion of the fuel. This effect of ethanol on CO emissions is also confirmed by other studies, such as by [16]. The concentration of hydrocarbons (HC) in the exhaust gases (Figure 4) was considered low regardless of the fuel used, fluctuating around 15–25 ppm. However, the concentration of HC turned out to be slightly lower in most of the analyzed cases, in favor of E30 fuel. As for nitrogen oxide (Figure 5), no noticeable differences were noted between both examined fuel compositions.

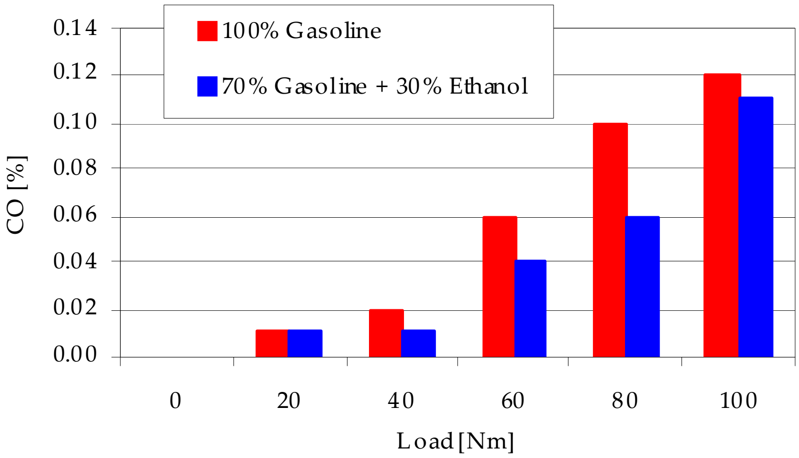

Figure 3. Carbon monoxide (CO) concentration in the exhaust gases of the test engine fueled with E0 and E30 fuels.

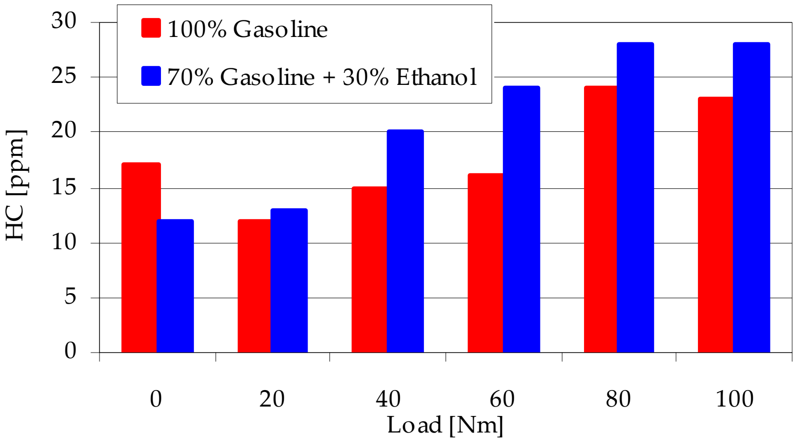

Figure 4. Hydrocarbon (HC) concentration in the exhaust gases of the test engine fueled with E0 and E30 fuels.

For the entire range of engine loads, slightly lower carbon dioxide concentration was observed (Figure 6), in favor of E30 fuel. This difference is easily explained by a more favorable H/C ratio; for ethanol it is 3, and for gasoline it is about 2.2. Similarly clear differences were found in terms of fuel consumption (Figure 7). As expected, a higher fuel consumption (by several percent) was recorded for the fuel with ethanol, and the reason is the lower calorific value of ethanol (26.8 MJ/kg), with respect to 44 MJ/kg for gasoline.

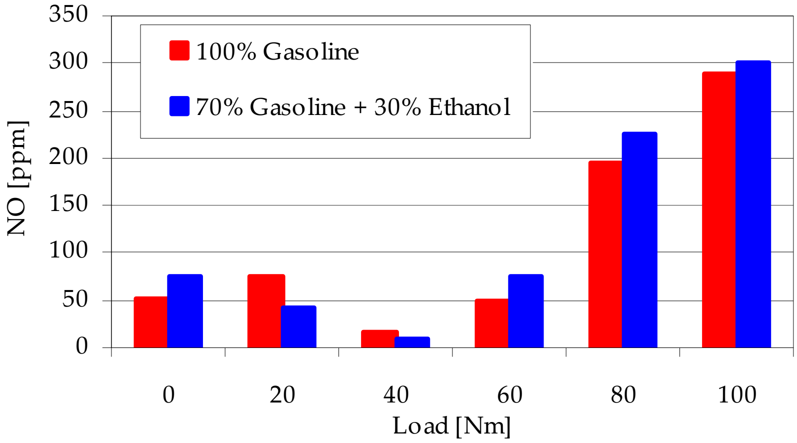

Figure 5. Nitrogen oxide (NO) concentration in the exhaust gases of the test engine fueled with E0 and E30 fuels.

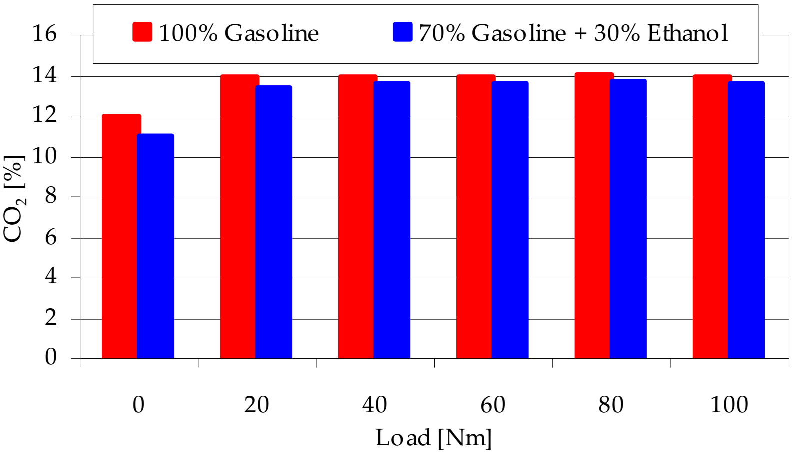

Figure 6. Carbon dioxide (CO_2) concentration in the exhaust gases of the test engine fueled with E0 and E30 fuels.

As an essential part of this research, particle number emissions were measured at points corresponding to a previous exhaust analysis, specifically for engine loads from 0 to 100 Nm (Figure 8). For conventional gasoline, an increase in the number of particles is visible with increasing load. For the fuel with ethanol, particle number emission is radically lower. A 40% reduction was observed at 0 Nm load operation, which was an almost 90% reduction under the highest examined load applied. The following figures, Figures 9–11, show the dimensional distribution of the emitted particulates for the engine operation with loads of 20, 60 and 100 Nm, respectively.

First of all, it should be stated that the influence of engine load on the particle emission profile is clearly noticeable. With a higher load, the number of particles emitted is higher, and moreover, particles of a larger diameter are emitted. When fueled with conventional fuel with a load of 100 Nm, the peak emission falls in the dimensional range of 34.0–69.8 nm, while for a load of 20 Nm, it is in the range of 16.5–29.4 nm. At high loads, the dimensional distribution of particles has the clear shape of a Gaussian curve. The most important issue, however, is the radical reduction in PN emissions when fueled with ethanol. At high loads, the emission reduction is on average tenfold (or an order of magnitude). At low loads, the reduction is slightly smaller.

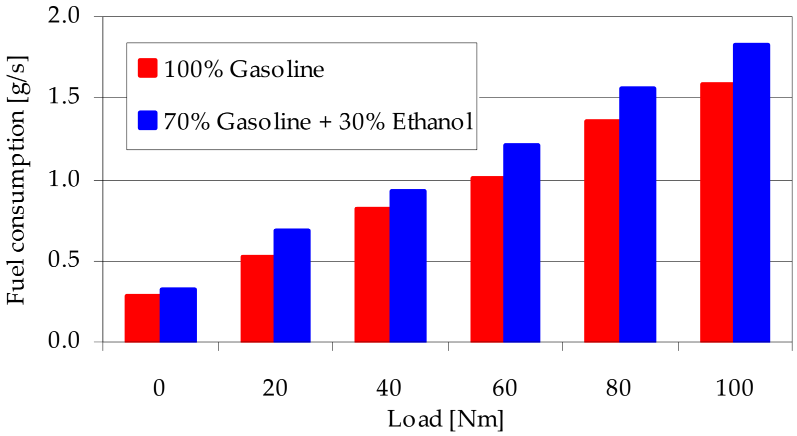

Figure 7. Fuel consumption of test engine fueled with E0 and E30 fuels.

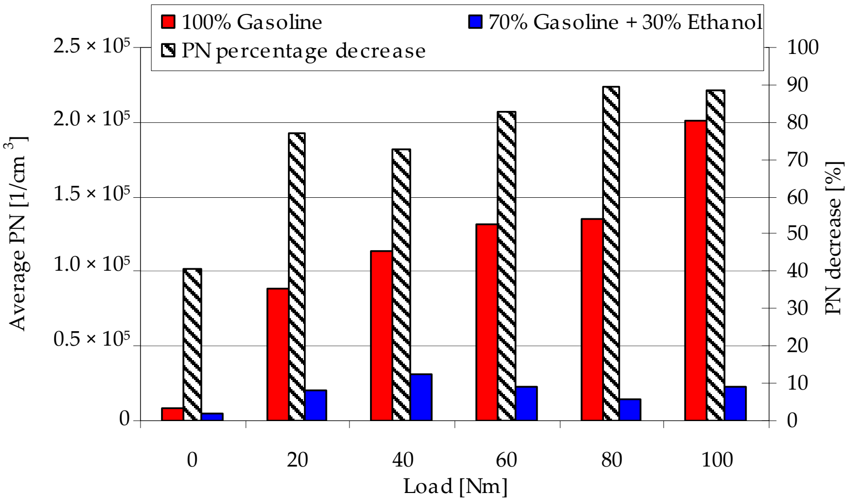

Figure 8. Average transient total number of particulates in the exhaust gases of the test engine fueled with E0 and E30 fuels as well as the percentage difference in the number of particulates for both fuels.

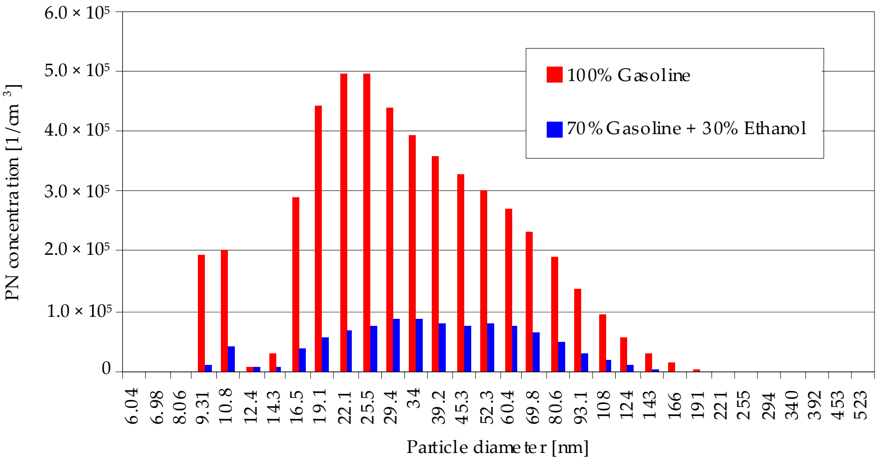

Figure 9. Dimensional distribution of particulates emitted by the test engine fueled with E0 and E30 fuels at a load of 20 Nm.

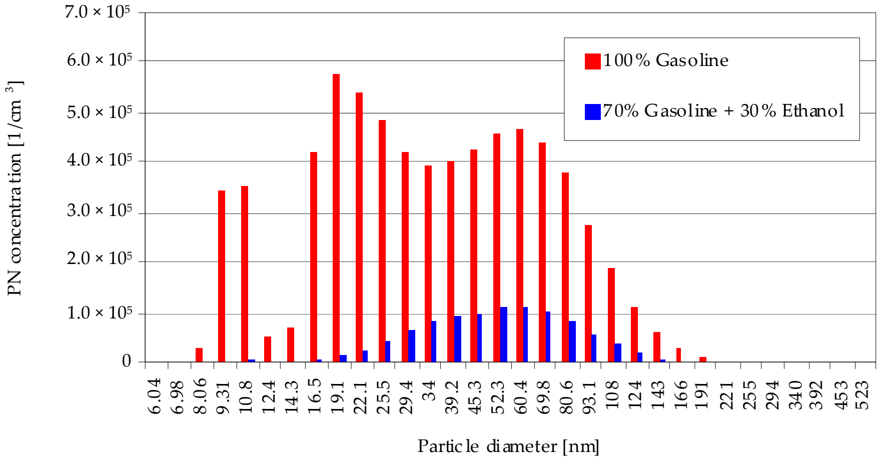

Figure 10. Dimensional distribution of particulates emitted by the test engine fueled with E0 and E30 fuels at a load of 60 Nm.

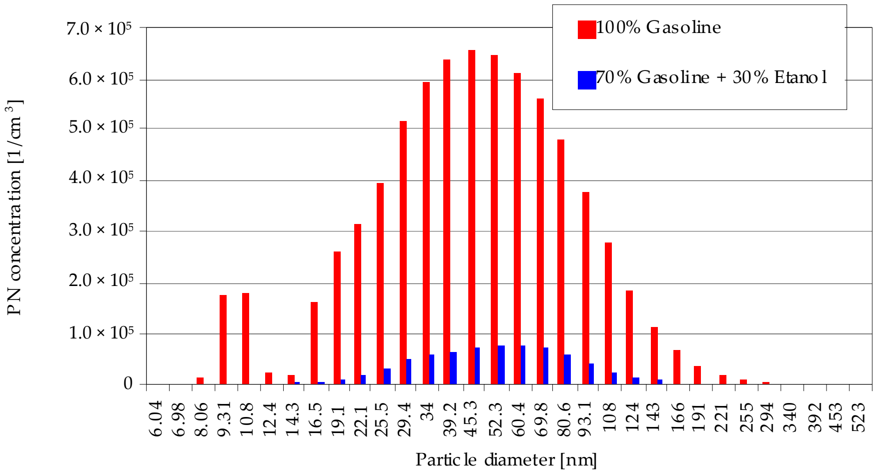

Figure 11. Dimensional distribution of particulates emitted by the test engine fueled with E0 and E30 fuels at a load of 100 Nm.

The recently published work by [43] showed an approximately fivefold reduction in PN emissions when using E25 fuel in the WLTC cycle. Importantly, the emission of larger particles ($N > 23$ nm) was reduced the most, approximately 10 times. The emission of smaller particles (10 nm $< N <$ 23 nm) decreased by approximately two times for E25. The authors of the above-mentioned work also found that particles originating from ethanol, being smaller and less complex, are easier to burn in catalytic exhaust gas aftertreatment systems. As for the effectiveness of PN emission reduction, the result described in [40] is very similar to that presented in this article for low engine loads. It is easy to combine this with the load profile in the WLTC cycle, where the share of a light load is significant. As can be seen from Figures 9–11, a significant difference in the amount of particles emitted was noted specially for larger and smaller particle diameters. When the E30 fuel was used, particles of the discussed dimensions appeared in practically trace amounts. This phenomenon is particularly visible in the case of the 100 Nm load conditions, as shown in Figure 11. However, as can be seen from Figures 9–11, no radical differences in PN reduction were noted for different particle diameters.

By analyzing the average particle diameters for both fuels (Figure 12), it can be seen that slightly larger diameters are obtained for gasoline with alcohol. As is known, it is more difficult for larger particles to penetrate the human respiratory system, so they are less harmful. On the other hand, larger particles are more difficult to burn in the particulate filter. However, it seems that this would not be a problem when using gasoline with alcohol, as the number of particles is then dramatically lower.

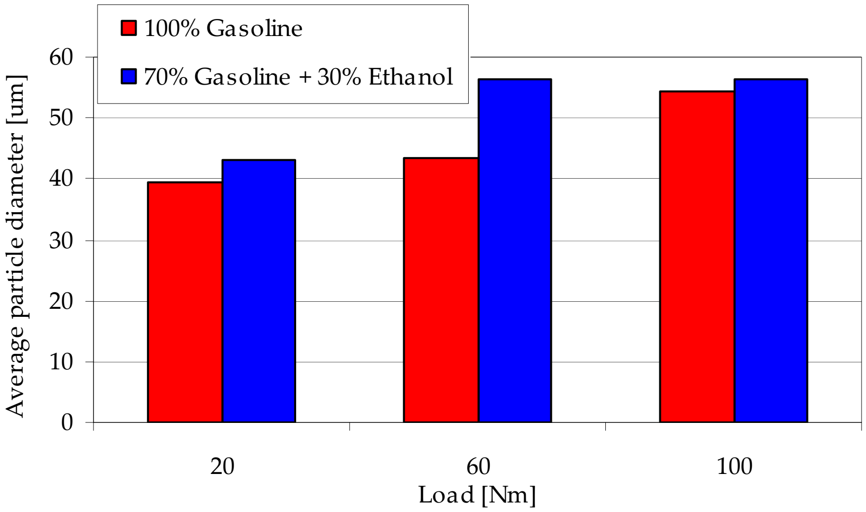

Figure 12. Average particle diameter depending on engine load and fuel type (E0 or E30).

4. Conclusions

Ethyl alcohol has been a valuable component of motor fuels for many years, especially gasoline. The known advantages include a high octane number, a positive impact on the emission of incomplete combustion products, a low price, high availability and well-established production technologies as a renewable fuel (biofuel), thereby ensuring a low carbon footprint. With the spread of direct injection spark-ignition engines, another advantage of ethanol as a fuel component became apparent. Namely, a potentially significant reduction in particulate number emissions with the addition of 20–30% ethanol (by volume). The analysis of the phenomenon of soot formation in the engine combustion chamber indicates that the presence of ethyl alcohol in the fuel inhibits the formation of soot precursors and supports the subsequent oxidation of soot, consequently reducing soot emissions, compared to operation with a neat gasoline. A very favorable effect of ethyl alcohol on PN emissions was also demonstrated in the experiments described in this article. Specifically, by using a mixture of 70% (v/v) gasoline and 30% ethanol, a 40% reduction in PN emissions was achieved at the idle speed, and when the engine was under load, the PN emission reduction was 80 to 90%. Because there was a catalytic converter in the exhaust system, the emissions of exhaust gas components were similar regardless of the presence or absence of ethanol in the fuel.

Importantly, this large emission reduction in PN emissions is achieved in a simple and cheap way that can be widely used. With the mentioned ethanol content in gasoline, no engine modifications are necessary. A widely used modern spark-ignition engine with direct injection was used in the experiments described in this article. It was tested at medium speed and low to medium load, i.e., in typical conditions of a real car's engine operation. We can therefore expect similarly favorable changes in PN emissions from vehicles participating in real road traffic.

It should be emphasized that the use of gasoline with ethanol is also rational for engines equipped with particulate filters. Firstly, the filter load and the frequency of its regeneration are significantly reduced. Secondly, the emitted particles are smaller and structurally simpler, which favors their effective further oxidation. Also, realizing how much importance is currently attached to the climate neutrality of products, bioethanol remains a very promising component of fuels for spark-ignition engines.

Author Contributions: Conceptualization, M.K. and S.W.; methodology, M.K., G.W. and K.D.; validation, M.W., S.W. and K.D.; formal analysis, M.K.; investigation, M.K., M.W., G.W. and S.W.; resources, M.K. and G.W.; data curation, M.W., S.W. and K.D.; writing—original draft preparation, M.K. and M.W.; writing—review and editing, S.W. and K.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available from the corresponding authors upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

CNG	compressed natural gas
CO	carbon oxide
CO_2	carbon dioxide
DME	dimethyl ether
E0	gasoline containing no ethyl alcohol
Ex	gasoline with an ethanol content of x% v/v
EUDC	Extra Urban Driving Cycle (second part of the New European Driving Cycle)
FAME	fatty acid methyl esters
FFV	flexible fuel vehicle
FBP	final boiling point
GHG	greenhouse gas
HC	hydrocarbon
HVO	hydrotreated vegetable oil
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MON	motor octane number
MTBE	methyl tert-butyl ether
NEDC	New European Driving Cycle
NO	nitrogen oxide
NO_x	nitrogen oxides
PN	particulate number
RON	research octane number
UDC	Urban Driving Cycle (first part of the New European Driving Cycle)
WLTC	Worldwide Harmonized Light Vehicles Test Cycle

References

1. Balat, M.; Balat, H. Recent trends in global production and utilization of bio-ethanol fuel. *Appl. Energy* **2009**, *86*, 2273–2282. [CrossRef]
2. Cardona, C.; Sanchez, O. Fuel ethanol production: Process design trends and integration opportunities. *Bioresour. Technol.* **2007**, *98*, 2415–2457. [CrossRef] [PubMed]
3. Klimiuk, E.; Pawłowska, M.; Pokój, T. *Biofuels—Technologies for Sustainable Development*; PWN Warszawa: Warsaw, Poland, 2012. (In Polish)
4. Kozak, M. Ethyl alcohol as a fuel for contemporary internal combustion engines. *Diagnostyka* **2019**, *20*, 27–32. [CrossRef]
5. Pałuchowska, M.; Stępień, Z.; Żak, G. The prospects for the use of ethanol as a fuel component and its potential in the reduction of exhaust emissions. *Combust. Engines* **2014**, *158*, 80–92. [CrossRef]
6. Yusuf, A.A.; Inambao, F.L. Progress in alcohol-gasoline blends and their effects on the performance and emissions in SI engines under different operating conditions. *Int. J. Ambient Energy* **2021**, *42*, 465–481. [CrossRef]
7. Park, J.; Hao, N. Direct ethanol-fueled protonic ceramic fuel cell with reforming layer operating at low temperature. *Int. J. Hydrogen Energy* **2023**, *48*, 19207–19216. [CrossRef]

8. Zhang, P.; Hu, L.; Zhao, B.; Lei, Z.; Ge, B.; Yang, Z.; Jin, X.; Peng, S. Direct power generation from ethanol by solid oxide fuel cells with an integrated catalyst layer. *Fuel* **2023**, *333*, 126340. [CrossRef]
9. Smolec, R.; Idzior, M.; Karpiuk, W.; Kozak, M. Assessment of the potential of dimethyl ether as an alternative fuel for compression ignition engines. *Combust. Engines* **2017**, *169*, 181–186. [CrossRef]
10. Flekiewicz, M.; Kubica, G.; Marzec, P. The possibilities of using DME (BioDME) as an additive to conventional gaseous fuels in SI engine. *Combust. Engines* **2017**, *171*, 150–155. [CrossRef]
11. Kałużny, J.; Merkisz, J.; Gallas, D.; Runka, T.; Kozak, M.; Pielecha, I. An innovative system for piston engine combustion with laser-induced ignition of the hydrocarbon fuel consisting carbon nanotubes. *Combust. Engines* **2017**, *168*, 3–14. [CrossRef] [PubMed]
12. Schwaderlapp, M.; Adomeit, P.; Kolbeck, A.; Thewes, M. Ethanol and its potential for downsizing engine concepts. *MTZ Mot. Z.* **2012**, *73*, 120–125. (In German) [CrossRef]
13. CIVITAS, Policy Note—Clean Buses for Your City. Available online: http://civitas.eu/sites/default/files/civitas_policy_note_clean_buses_for_your_city.pdf (accessed on 30 March 2024).
14. Lewandrowski, J.; Rosenfeld, J.; Pape, D.; Hendrickson, T.; Jaglo, K.; Moffroid, K. The greenhouse gas benefits of corn ethanol—Assessing recent evidence. *Biofuels* **2020**, *11*, 361–375. [CrossRef]
15. Suarez-Bertoa, R.; Zardini, A.; Keuken, H.; Astorga, C. Impact of ethanol containing gasoline blends on emissions from a flex-fuel vehicle tested over the Worldwide Harmonized Light Duty Test Cycle (WLTC). *Fuel* **2015**, *143*, 173–182. [CrossRef]
16. Bielaczyc, P.; Woodburn, J.; Gandyk, M.; Szczotka, A. Ethanol as an automotive fuel—A review. *Combust. Engines* **2016**, *166*, 39–45. [CrossRef]
17. Yuan, W.; Frey, C.H.; Wei, T.; Rastogi, N.; VanderGriend, S.; Miller, D.; Mattison, L. Comparison of real-world vehicle fuel use and tailpipe emissions for gasoline-ethanol fuel blends. *Fuel* **2019**, *249*, 352–364. [CrossRef]
18. Schifter, I.; González, U.; Díaz, L.; Rodríguez, R.; Mejía-Centeno, I.; González-Macías, C. From actual ethanol contents in gasoline to mid-blends and E-85 in conventional technology vehicles. Emission control issues and consequences. *Fuel* **2018**, *219*, 239–247. [CrossRef]
19. Wang, Y.; Sun, J.; Lu, J.; Tang, M. Toxicity of diesel exhaust particles on central nervous system. *Nanomed. Nanotechnol. Biol. Med.* **2018**, *14*, 1751–1752. [CrossRef]
20. Leach, F.; Stone, R.; Richardson, D.; Turner, J.; Lewis, A.; Akehurst, S.; Remmert, S.; Campbell, S.; Cracknell, R. The effect of oxygenate fuels on PN emissions from a highly boosted GDI engine. *Fuel* **2018**, *225*, 277–286. [CrossRef]
21. Raza, M.; Chen, L.; Leach, F.; Ding, S. A Review of Particulate Number (PN) Emissions from Gasoline Direct Injection (GDI) Engines and Their Control Techniques. *Energies* **2018**, *11*, 1417. [CrossRef]
22. Zhang, Z.; Wang, T.; Jia, M.; Wei, Q.; Meng, X.; Shu, G. Combustion and particle number emissions of a direct injection spark ignition engine operating on ethanol/gasoline and n-butanol/gasoline blends with exhaust gas recirculation. *Fuel* **2014**, *130*, 177–188. [CrossRef]
23. He, X.; Ratcliff, M.A.; Zigler, B.T. Effects of Gasoline Direct Injection Engine Operating Parameters on Particle Number Emissions. *Energy Fuel* **2012**, *26*, 2014–2027. [CrossRef]
24. Lv, Z.; Yang, L.; Wu, L.; Peng, J.; Zhang, Q.; Sun, M.; Mao, H.; Min, J. Comprehensive Analysis of the Pollutant Characteristics of Gasoline Vehicle Emissions under Different Engine, Fuel, and Test Cycles. *Energies* **2022**, *15*, 622. [CrossRef]
25. Wang, C.; Xu, H.; Herreros, J.M.; Wang, J.; Cracknell, R. Impact of fuel and injection system on particle emissions from a GDI engine. *Appl. Energy* **2014**, *132*, 178–191. [CrossRef]
26. Luo, Y.Q.; Zhu, L.; Fang, J.H.; Zhuang, Z.Y.; Guan, C.; Xia, C.; Xie, X.M.; Huang, Z. Size distribution, chemical composition and oxidation reactivity of particulate matter from gasoline direct injection (GDI) engine fueled with ethanol-gasoline fuel. *Appl. Therm. Eng.* **2015**, *89*, 647–655. [CrossRef]
27. Liu, H.; Wang, X.; Zhang, D.; Dong, F.; Liu, X.; Yang, Y.; Huang, H.; Wang, Y.; Wang, Q.; Zheng, Z. Investigation on Blending Effects of Gasoline Fuel with N-Butanol, DMF, and Ethanol on the Fuel Consumption and Harmful Emissions in a GDI Vehicle. *Energies* **2019**, *12*, 1845. [CrossRef]
28. Jin, D.; Choi, K.; Myung, C.; Lim, Y.; Lee, J.; Park, S. The impact of various ethanol-gasoline blends on particulates and unregulated gaseous emissions characteristics from a spark ignition direct injection (SIDI) passenger vehicle. *Fuel* **2017**, *209*, 702–712. [CrossRef]
29. Lai, J.; Lee, K.; Yap, J.; Yadollahi, B.; Bhave, A.; Zhang, Z.; Ma, X.; Xu, H. *Effects of Ethanol-Blended Fuel on Combustion Characteristics, Gaseous and Particulate Emissions in Gasoline Direct Injection (GDI) Engines*; Technical Paper 2021-26-0356; SAE: Warrendale, PA, USA, 2021. [CrossRef]
30. Timonen, H.; Karjalainen, P.; Saukko, E.; Saarikoski, S.; Aako-Saksa, P.; Simonen, P.; Murtonen, T.; Dal Maso, M.; Kuuluvainen, H.; Bloss, M.; et al. Influence of fuel ethanol content on primary emissions and secondary aerosol formation potential for a modern flex-fuel gasoline vehicle. *Atmos. Chem. Phys.* **2017**, *17*, 5311–5329. [CrossRef]
31. Dastanpour, R.; Rogak, S.N. Observations of a Correlation Between Primary Particle and Aggregate Size for Soot Particles. *Aerosol Sci. Technol.* **2014**, *48*, 1043–1049. [CrossRef]

32. Eastwood, P. *Particulate Emissions from Vehicles*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2008.
33. Kozak, M. *Study on the Influence of Diesel Fuel's Oxygenated Compounds on Exhaust Emissions from Diesel Engines*; Publishing House of Poznań University of Technology: Poznań, Poland, 2013. (In Polish)
34. Rubino, L.; Thomson, M.J. The Effect of Oxygenated Additives on Soot Precursor Formation in a Counterflow Diffusion Flame. In Proceedings of the SAE International Fuels & Lubricants Meeting & Exposition, Dearborn, MI, USA, 3–6 May 1999; Technical Paper 1999-01-3589; SAE: Warrendale, PA, USA, 1999.
35. Westbrook, C.K.; Pitz, W.J.; Curran, H.J. Chemical Kinetic Modeling Study of the Effects of Oxygenated Hydrocarbons on Soot Emissions from Diesel Engines. *J. Phys. Chem. A* **2006**, *110*, 6912–6922. [CrossRef]
36. Cheng, A.S.; Dibble, R.W.; Buchholz, B.A. The Effect of Oxygenates on Diesel Engine Particulate Matter. In Proceedings of the Spring Fuels & Lubricants Meeting & Exhibition, Reno, NV, USA, 6–9 May 2002; Technical Paper 2002-01-1705. SAE: Warrendale, PA, USA, 2002.
37. Zabłocki, M. *Fuel Injection and Combustion in Diesel Engines*; Communications Publishing House: Warsaw, Poland, 1976. (In Polish)
38. Marinov, N.M. A Detailed Chemical Kinetic Model for High Temperature Ethanol Oxidation. *Int. J. Chem. Kinet.* **1999**, *31*, 183–220. [CrossRef]
39. Buchholz, B.A.; Cheng, A.S.; Dibble, R.W. Isotopic Tracing of Bio-Derived Carbon from Ethanol-in-Diesel Blends in the Emissions of a Diesel Engine. In Proceedings of the Spring Fuels & Lubricants Meeting & Exhibition, Reno, NV, USA, 6–9 May 2002; Technical Paper 2002-01-1704. SAE: Warrendale, PA, USA, 2002.
40. EU Cars and Light Trucks Emissions Standards. Available online: https://dieselnet.com/standards/eu/ld.php (accessed on 30 August 2024).
41. Regulation of the Polish Minister of Economy of 14 May 2015 Amending the Regulation on Quality Requirements for Biocomponents, Methods for Testing the Quality of Biocomponents and the Method of Sampling Biocomponents. Polish. Dz.U. 2015 poz. 780. Available online: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20150000780/O/D20150780.pdf (accessed on 30 August 2024).
42. Regulation of the Polish Minister of Economy of 17 December 2010 on Quality Requirements for Biocomponents, Methods for Testing the Quality of Biocomponents and the Method of Sampling Biocomponents. Polish. Dz.U. 2010 nr 249 poz. 1668. Available online: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20102491668/O/D20101668.pdf (accessed on 30 August 2024).
43. Di Iorio, S.; Catapano, F.; Magno, A.; Sementa, P.; Vaglieco, B.M. The Potential of Ethanol/Methanol Blends as Renewable Fuels for DI SI Engines. *Energies* **2023**, *16*, 2791. [CrossRef]