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Article

Influence of the Use of EtG Synthetic Fuel in Spark-Ignition Engines on Vehicle Fuel Consumption and Pollutant Emissions

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Abstract: This article presents the properties of EtG synthetic fuel (Ethanol to Gasoline) as a substitute for fuels in an installation using ethanol from food waste as a raw material. The results of this research on the process of supplying the engine with EtG fuel are presented, in which the operational suitability of this fuel was verified, including environmental requirements. The results of pollutant emission tests from vehicles with spark-ignition engines in dynamic driving conditions in the New European Driving Cycle (NEDC) type approval tests and the World Harmonized Test Cycle (WLTC) test, both on a "cold" and "hot engine", are presented. It was found that EtG fuel is characterized by lower emissions of carbon monoxide, nitrogen oxides, and methane, and higher emissions of non-methane hydrocarbons compared to E10 commercial gasoline, while the specific distance emission of carbon dioxide for both fuels was very similar.

Keywords: advanced biofuels; EtG fuel; engine test; exhaust emission; drop-in biofuels

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1. Introduction

The transition of the conventional economy to the bioeconomy requires a search for new energy carriers, intended, among others, for transport purposes. These innovative energy carriers can be fuels of biological origin, called advanced biofuels. The prospects for the development of advanced biofuels, including the use of ethanol as a raw material, were discussed in the IEA Task 42 report from 2022 [1].

Motor fuels of biological origin are subject to the same operational requirements as conventional fuels. A particularly advantageous solution is achieved in fuels of biological origin of the standard of substitute fuels, as this makes it possible to disseminate biological fuels.

Other ways of using fuels of biological origin to power internal combustion engines than as substitute fuels are:

- use of special engines, e.g., self-ignition engines, adapted to be powered by E95 bioethanol fuel (other designation: ED95) and flexi-fuel spark-ignition engines powered by E85 fuel;
- the use of fuels of biological origin as biocomponents for the conventional fuels in concentrations compliant with applicable regulations and engine specifications.

The subject of ecological evaluation of the operation of engine fuels produced in biorefinery installations is a relatively new issue. Until the development of fuels produced from biological raw materials, only analyses of pollutant emissions from vehicles were dealt with, without taking into account the emissions of pollutants generated at the stage of fuel production. For biofuels produced from biomass and other organic raw materials, there is a need to assess the energy demand and the emission of pollutants harmful to the health of living organisms and greenhouse gases, not only in the TtW (Tank to Wheel) cycle, i.e., from the delivery of fuel to the vehicle tank to its consumption in engine and emission of pollutants, but in the WtW (Well to Wheel) cycle, i.e., from the source of obtaining the energy carrier to the consumption of the produced fuel in the vehicle engine and emission of pollutants to the environment.

The issue of the use of engine fuels, including fuels of biological origin, in the internal combustion engines, and also in terms of ecological evaluation, has been described in many monographs, scientific articles, and legal acts, in not only national but also international regulations, including United Nations Organization UN [1–10]. Many scientific publications also deal with the subject of ecological evaluation of biorefinery installations in the cycle from raw materials to products obtained as a result of biorefinery processes [2–4,11–20]. The description of SHELL [11] indicates the potential of ethanol for both SAF (Synthetic Aviation Fuel) and EtG (Ethanol to Gasoline) aviation fuel. However, a comprehensive approach to both topics, i.e., the stage of fuel production and then operation within the meaning of the ecological evaluation of the use of engine fuels produced in biorefineries, has been presented in a much smaller number of studies due to the novelty of the topic. The IRENA [12] report found that over the past two decades, climate concerns have become an increasingly strong motivation for policies to promote biofuels. This has resulted in growing support for biofuels and their production, including ethanol. According to the authors, however, the direct use of ethanol in spark-ignition engines poses some operational problems [2,21,22]. Due to the design of the power supply and combustion systems, which is adapted to the use of hydrocarbons as fuel, it would be more advantageous to process ethanol into these biohydrocarbons, which can be gaseous and liquid biofuels [23]. The use of renewable energy sources in the EtG fuel production process may lead to the development of electrofuel production technologies that can also be used after 2035 in Europe, which could be a solution to the continued supply of internal combustion engines in Europe [24].

In the article [2], the author compared the useful parameters of the engines powered by conventional and bioethanol fuel, such as torque, useful power, and overall efficiency. The unit emission of pollutants from the bioethanol engine was compared with the EEV (Enhanced Environmentally Friendly Vehicle) limits. The article presents the results of the fuel consumption tests for classic and bioethanol buses in the SORT UITP (Standardised On-Road Test cycles by Union Internationale des Transports Publics) driving tests, as well as a comparison of the operating costs of bioethanol and classic buses in Stockholm and Słupsk.

In the article [25], the authors conducted a comparative analysis of WtW cycles for various passenger vehicles based on three key indicators: energy consumption as a result of burning fossil fuels, carbon dioxide emissions, and economic costs. Various so-called fuel pathways were compared, specific to the five representative countries where they are predominant, namely Brazil, China, France, Italy, and the United States of America. The results show no fundamental differences in the fossil fuel pathways among the five scenarios considered, so the different environmental costs of electricity generation have minimal impact on the total cost. These results can be used to inform policy makers on the multidimensional impact of vehicles, including environmental impact, economic costs and depletion of primary energy resources, with a particular focus on crude oil.

The article [26] presents the results of pollutant emission tests from internal combustion engines of the city buses meeting the Euro V standard with the use of selected fuel additives that positively affect the combustion process, and at the same time additionally improve the quality of operation of the exhausts purification systems used in such vehicles.

The factors shaping ecological evaluation of the operation of vehicle engines were discussed by the authors of the publication [27] based on their own experience, e.g., in the field of testing motor fuels with respect to general efficiency and ecological aspects of engine operation in terms of pollutant emissions. The authors paid particular attention to the fact that the chemical formula of the final products, which are motor fuels, is evolving due to the requirements for environmental protection and the development of internal combustion engines. Hence, the refining industry in the country has been intensively developing its production base for several years, allowing it to meet the quality and environmental protection requirements applicable in the European Union countries.

The authors of the article [28] conducted an environmental assessment of the effects of the production and use of engine fuels that can be produced in biorefineries, mainly from the emission of pollutants point of view. By biofuels produced in biorefineries, the authors meant second-generation biofuels. The possibility of producing fuels in biorefineries, which can be used in powering internal combustion engines as biocomponents as well as self-contained fuels, including the so-called substitute fuels for the classic petroleum fuels, was also analysed.

In articles [21,22], the authors presented their views on the comprehensive evaluation of the environmental risk caused by the operation of motor vehicles. Methods of analysing emission of the pollutants harmful to the environment and energy inputs at the stages of production and distribution of energy carriers (from the source of obtaining the energy carrier to the fuel tank—WtT (Well to Tank) and vehicle use (from the fuel tank to the wheel of the vehicle—TtW), were considered. The results of the research were analysed in accordance with the procedures of Eco-indicator 99 and the Swiss Ecological Scarcity Method, otherwise known as the Ecoscarcity method or UBP'06. In conclusion, the authors criticized the existing methods of comprehensive assessment of the harmfulness of the automotive industry for the environment and proposed an original system indicator characterizing the energy and ecological effects due to the emission of pollutants related to the automotive industry at the stages of production and distribution of energy carriers and the use of motor vehicles.

The article [29] presents the influence of the physical parameters of biofuels on the operation of a self-ignition engine. The article presents an impact analysis of the biofuel's physical parameters on the self-ignition engine operation. Physical parameters such as fractional composition, viscosity and density of rapeseed oil and methyl ester of higher fatty acids of rapeseed oil (RME) were characterized and compared, with the parameters of diesel oil as a reference point.

The subject of 2,5-dimethylfuran (DMF), i.e., an advanced biofuel that can be produced in the biorefinery installations and used as a biocomponent in the existing spark-ignition engines, was taken up in the article [30]. The author evaluated DMF as a prospective second-generation biofuel in comparison to the currently available biofuel for spark-ignition engines, which is bioethanol, along with an analysis of raw material possibilities. The possibilities of using DMF in modern internal combustion engines have been analysed with reference to the existing research on pollutant emissions.

2. Tests Methodology

The tests of the operational properties of a motor vehicle were carried out in the driving test conditions because they depend on the operating states of the internal combustion engine, which are determined primarily by the process of vehicle speed.

The operating states of an internal combustion engine that determine its operational properties are:

- engine rotational speed;
- engine load, which is usually measured by torque or mean useful pressure (the measurement of load can also be useful power, which is a linear function of torque, and engine control; engine control is understood as a physical quantity describing the operator's activities with the internal combustion engine, e.g., in the case of a vehicle engine the angle of depressing the accelerator pedal);
- thermal state of the internal combustion engine.

The thermal state of an internal combustion engine is understood as a set of temperatures of the engine and its operating factors, primarily engine oil and cooling agent in the case of indirectly cooled engines it is the temperature of the cooling liquid, in the case of direct cooling it is the temperature of the cooling air at the outlet of the cooling system.

Typically, the thermal state of an internal combustion engine is described by the thermal state parameter; it is usually the temperature of the selected operating medium.

The operational properties of an internal combustion engine depend on the properties of its operating states, both static and dynamic.

The operational properties of internal combustion engines can be classified as:

- dynamic properties—due to the useful power or the ability to accelerate the vehicle;
- economic properties—due to the overall efficiency of the engine or fuel consumption;
- ecological properties—mainly due to emission of pollutants or noise emission;
- durability, reliability, and serviceability.

In this work, the subjects of research were:

- average specific distance emission of substances harmful to the health of living organisms: carbon monoxide, total hydrocarbons, non-methane hydrocarbons, and nitrogen oxides in the WLTC (Worldwide Harmonized Light Vehicles Test Cycle) test,
- average specific distance emission of methane and carbon dioxide in the WLTC test as substances conducive to the intensification of the greenhouse effect in the atmosphere,
- operational fuel consumption in the WLTC test.

Measurements of pollutants emissions from the vehicle's exhaust system were carried out in accordance with the WLTP (Worldwide Harmonized Light Vehicles Test Procedure) in the WLTC type 3 test in accordance with an Annex XXI to Commission Regulation (EU) 2017/1151 [31] as last amended by Commission Regulation (EU) 2018/1832 [32].

The tests of pollutant emissions from the exhaust system were carried out using commercial gasoline (BS designation) and liquid biohydrocarbons—synthetic fuel, named for the purposes of this work is BIO gasoline, enriched with 12% (v/v) ethyl tert-buthyl ether (ETBE).

The tests were carried out for the engine start-up not warmed up to the temperature of stabilized operation and for the engine warmed up to a stabilized thermal state.

The following test and measurement devices were used in the research:

- a system for measuring pollutant emissions produced by AVL; during the tests, the configuration "13 Diluted Bag Particles Gasoline" containing the following measuring devices was used:
  - exhaust gas collection system CFV-CVS type CVS i60 LD S2 by AVL;
  - PSS i60 particulate emission measurement system by AVL;
  - AVL489 APC ADVANCED particulate matter counter by AVL;
  - a set of AMA i60 D1-CD LE analysers by AVL equipped with two-band analysers enabling the measurement of concentrations of the following gases: carbon dioxide—CO_2, nitrogen oxides—NO_x, carbon monoxide—CO, total hydrocarbons—THC, and methane—CH_4;
  - VAISALA PTU303 weather station for measuring air temperature, pressure and humidity in the chassis dynamometer room;
- one-roller chassis dynamometer with adjustable resistance curve by AVL-Zoellner;
- MT5 microbalance by Mettler Toledo;
- OBD system AVL DIOBD 880 error code reader;
- LAB-EL thermo-hygrometer type LB-701, version M with a reading panel LB-702B

The chassis dynamometer was adjusted so as to reproduce the total road load measured for the tested vehicle. The measuring equipment met the requirements set out in UN Regulation 83 [9]. The accuracies of the main measuring equipment are given in Table 1.

Table 1. Accuracy of the measuring equipment.

Measured Parameter	Measuring Equipment	Accuracy
Flow	Exhaust dilution system	±0.5%
Speed	Chassis dynamometer	±0.025%
Distance	Chassis dynamometer	±0.1%
Concentration	Analyzers	±2%

The tests were carried out on a Hyundai i30 passenger vehicle, the basic data of which are presented in Table 2.

Table 2. Basic data of the Hyundai i30 vehicle.

Make and Model	Hyundai i30
VIN Number	TMAH281CAMJ085654
Engine type	G4LG
Engine displacement	1498 cm^3
Rated power	80.9 kW
Number of cylinders	4
Vehicle category	M1
Emission level when running on Euro 6AP petrol	Euro 6AP
Odometer reading	8624 km

3. Results of Empirical Tests

In 2016, a new installation related to the production of unconventional fuels was built in Poland: the "EkoBenz" Synthetic Fuels Production Plant from Bioethanol, located in Bogumiłów in the Łódź Voivodeship. The plant uses ethyl alcohol produced entirely from biomass as a raw material for the production of synthetic fuels in the EtG (Ethanol to Gasoline) installation. As a result of chemical transformations, the technological process involves complete, irreversible, chemical transformation of ethyl alcohol into synthetic hydrocarbons and water. In the technological process, a mixture of liquid hydrocarbons (biohydrocarbons) with a boiling point range of approx. (27 ÷ 260) °C with a composition of C3 to C13 is obtained (hydrocarbons above C14 are present in trace amounts), a mixture of gaseous hydrocarbons and water [24].

The production process is characterized by low demand for external energy sources, which significantly reduces greenhouse gas emissions and improves the indicators of the technological process itself in the economic terms. The installation in Bogumiłów is innovative; it is first installation of this type not only in Poland but also in the world with a production capacity of 22,500 Mg/year [24].

The main products are liquid biohydrocarbons, mentioned above, which can be added to fuels in any proportions, thus exceeding the technical limitations of the bioethanol used so far as a biocomponent. They meet the quality requirements set out in the Regulation of the Minister of Economy of 17 December 2010 and can be added to gasoline as a biocomponent, intended for the production of liquid fuels used in spark-ignition engines, in a proportion of even up to 85% v/v. The chemical composition of biohydrocarbons is identical to the chemical composition of gasoline, so its addition ensures maintaining high quality of the final fuel. Liquid biohydrocarbons meet the criteria of sustainable development and can be produced from waste and residues. They make it possible to meet the National Index Target (NIT) and the National Reduction Target (NCR) in gasoline fuels at the level provided for in the European Union directives for the years 2020–2030, and even higher.

Table 3 presents the parameters of the liquid fuel obtained in the EtG installation.

Table 3. Parameters of EtG fuel produced in the Ekobenz installation [24].

Parameter	Unit	Result
Research Octane Number (RON)	-	91
Kinematic viscosity	mm^2/s (at 40 °C)	<1
Autoignition temperature	°C	480
Density at the temperature 15 °C	kg/m^3	761.1
Appearance	-	bright and transparent
Vapour pressure (dry vapour pressure equivalent)	kPa	57.0
Fraction composition, distillation start temperature	°C	30.3
distills up to 70%	% (v/v)	23.8
distills up to 100%	% (v/v)	40.8
distills up to 150%	% (v/v)	69.1
Fraction composition, distillation end temperature	°C	206.7
Residue after distillation	% (v/v)	1.1
N-paraffins	% (v/v)	11.44
I-paraffins	% (v/v)	32.59
Olefins	% (v/v)	1.95
Naphthenes	% (v/v)	7.60
Aromatic hydrocarbons	% (v/v)	41.84
Polycyclic hydrocarbons	% (v/v)	0.31
Not specified	% (v/v)	4.27
Oxygen derivatives	% (v/v)	0.00
Oxygen	% (m/m)	0.00
Benzene	% (v/v)	0.30

Liquid biohydrocarbons produced in the installation in Bogumiłów were used in comparative tests (in relation to commercial gasoline) on a chassis dynamometer at the Motor Transport Institute in Warsaw.

Carbon dioxide emissions and fuel consumption were tested in accordance with UN Regulation 101 [33], and their values were determined in accordance with the paragraph 6.1.2.4.3. UN Regulation 115 [34].

Figures 1–4 show the results of pollutant emissions and operational fuel consumption tests for cold and hot engine start-up with the use of commercial gasoline (BS) and EtG (BIO) fuel. The obtained test results meet the homologation requirements of road emission of pollutants.

The average specific distance emission of carbon monoxide in the WLTC test was clearly lower for the start-up of both, hot and cold engine. The increase in carbon monoxide emissions at the start-up of a cold engine is related to supplying the cold engine with a rich mixture and disturbances in the combustion process. The lower emission value of carbon monoxide from the engine supplied with BIO fuel may be due to the addition of 12% (v/v) ethyl-tert-butyl ether to this fuel.

In the case of total hydrocarbons, the situation was different for hot and cold engine start-up. For the start-up of a cold engine, the average specific distance emission of total hydrocarbons in the WLTC test was slightly lower for classic petrol, while for the start-up of a warm engine, the average specific distance emission of total hydrocarbons in the WLTC test was much lower for BIO fuel. These outcomes are probably related, as in the case of carbon monoxide, to the addition of ethyl tert-butyl ether to BIO fuel.

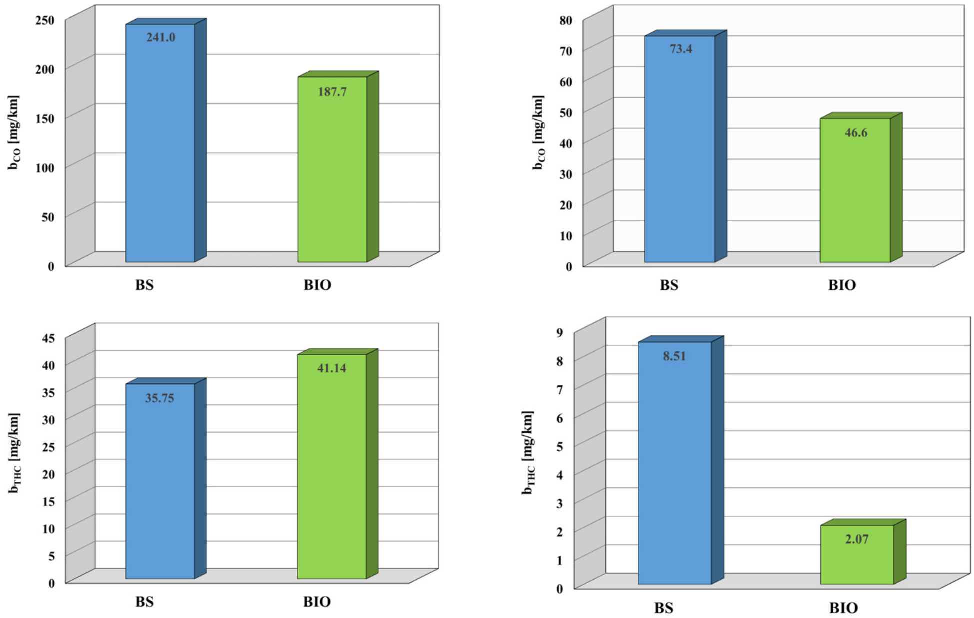

Figure 1. Average specific distance emissions of carbon monoxide and total hydrocarbons—b_{CO} and b_{THC} in the WLTC test when the vehicle was running on petrol (BS) and EtG (BIO) fuel at the start-up of a cold engine (diagrams on the left) and a hot engine (diagrams on the right). Measurement error ±5%.

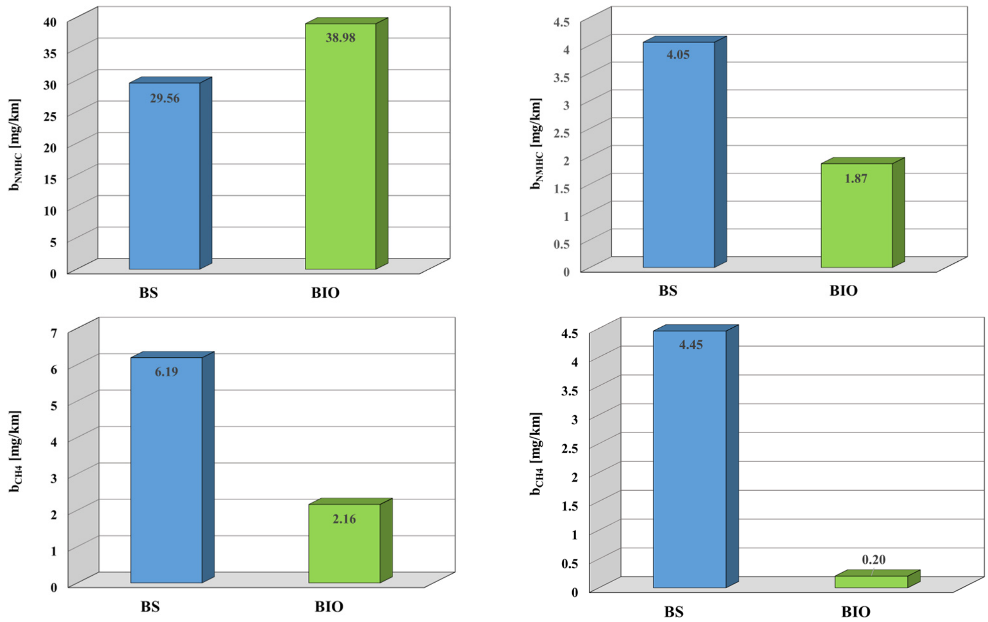

Figure 2. Average specific distance emissions of non-methane hydrocarbons and methane—b_{NMHC} and b_{CH4} in the WLTC test when the car was supplied with motor gasoline (BS) and EtG fuel (BIO) at the start-up of a cold engine (diagrams on the left) and a hot engine (diagrams on the right). Measurement error ±5%.

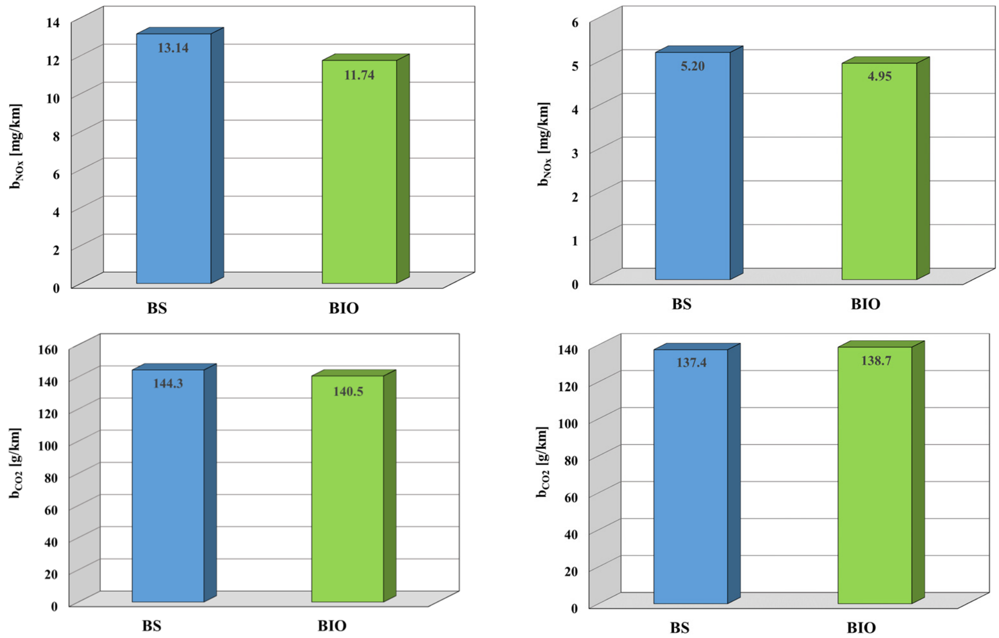

Figure 3. Average specific distance emissions of nitrogen oxides and carbon dioxide—b_{NOx} and b_{CO2} in the WLTC test when the car is running on petrol (BS) and EtG (BIO) fuel at the start-up of a cold engine (diagrams on the left) and a hot engine (diagrams on the right). Measurement error for NO_x is ±5%, and for CO_2—±3%.

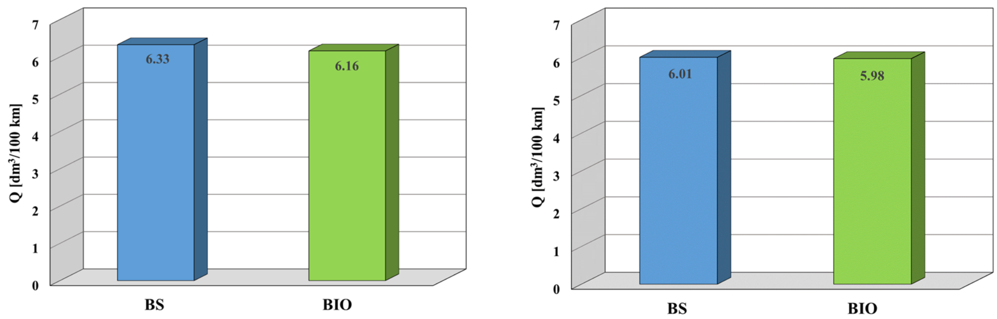

Figure 4. Operational fuel consumption—Q in the WLTC test with the car is supplied with petrol—BS and BIO fuel when starting a cold engine (left-hand diagram) and a hot engine (right-hand diagram). Measurement error is ±3%.

The relationships between the average specific distance emission of non-methane hydrocarbons and methane in the WLTC test for both types of fuels and cold and hot engine start-up are similar as in the case of total hydrocarbons.

The average specific distance emissions of nitrogen oxides and carbon dioxide in the WLTC test are lower for EtG (BIO) fuel, and for the warm engine start-up the difference is small. However, it should be noted that in the case of EtG fuel, in the production of which the main raw material is ethanol produced from biological sources, it is not fossil carbon dioxide (a substance that contributes to the intensification of the greenhouse effect in the atmosphere) unlike classic motor gasoline, produced from flammable crude oil.

The relationship between the operational fuel consumption due to the type of fuels and the thermal state at engine start-up is understandably similar to the case of specific distance carbon dioxide emissions. Due to fuel consumption, however, it is important to significantly reduce the depletion of natural resources in the case of EtG fuel if it is possible.

4. Conclusions

Based on the research conducted, the following conclusions can be drawn:

1. Specific distance emission of carbon monoxide is much lower for EtG fuel, especially when starting a hot engine.
2. Specific distance emission of nitrogen oxides is slightly lower for EtG fuel, the difference is particularly small when starting a warm engine.
3. Specific distance emission of organic compounds, i.e., both total hydrocarbons and non-methane hydrocarbons, at the start of a cold engine is higher for EtG fuel, while at the start of a hot engine it is much lower for EtG fuel.
4. Specific distance emission of methane is much lower for EtG fuel, and when starting a hot engine it is almost negligible.
5. Specific distance emission of carbon dioxide for both fuels is very similar.

The most important ecological benefit of using synthetic fuels produced from bioethanol (EtG) to power spark-ignition engines is the practical elimination of fossil carbon dioxide emissions which are the basic substance in the internal combustion engines contributing to the intensification of the greenhouse effect in the atmosphere. Also, methane emissions when using EtG fuel are much lower than when using petrol produced from fossil fuels, and methane is a greenhouse gas many times stronger than carbon dioxide.

Another important benefit of using synthetic fuels from biological raw materials is the protection of natural resources.

The authors are aware that the operational properties of internal combustion engines may vary significantly depending on the conditions of vehicle use, because the speed process determines the operating states of the internal combustion engine, both static and dynamic, thus affecting the operational properties of the engine, mainly fuel consumption and pollutant emissions.

For these reasons, the authors of the article intend to continue research on the use of synthetic fuels of biological origin in other conditions of vehicle use than only in the homologation test on a chassis dynamometer. The authors plan, after completing the equipment, to carry out tests in the conditions of real vehicle use in accordance with the RDE (Real Driving Emissions) procedure.

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Nomenclature

(m/m)	mass share
(v/v)	volume fraction
b	specific distance pollutant emission
BIO	synthetic gasoline EtG
BS	gasoline
CFV	Carbon Footprint Verification Constant Volume Sampler
CVS	Constant Volume Sampler
CH_4	methane

CO	carbon oxide
CO_2	carbon dioxide
E85	bioethanol fuel for flexi-fuel spark ignition engines
E95 (ED95)	bioethanol fuel for diesel engines
EEV	Enhanced Environmentally Friendly Vehicle
EtG	ethanol to gasoline
NCR	National Reduction Target
NCW	National Indicator Target
NMHC	non-methane hydrocarbons
NO_x	nitrogen oxides
OBD	On-Board Diagnostics
Q	operational fuel consumption
RDE	Real Emissions Driving
SORT	Standardised On-Road Test Cycles
THC	total hydrocarbons
TtW	Tank to Wheel
UE	European Union
UITP	Union Internationale des Transports Publics
UN	United Nations
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
WtW	Well to Wheel

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