The Improvement of Fuel Efficiency and Environmental Characteristics of Diesel Engine by Using Biodiesel Fuels

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1 Introduction

In order to generate energy with minimal fuel consumption, diesel engines are among the most efficient internal combustion engines. Due to their inherent high fuel and economic performance, diesel engines are widely used as vehicle powerplants. The maximum total capacity of diesel engines is concentrated in freight and passenger vehicles and self-propelled agricultural machinery; in addition, the share of passenger cars with diesel engines is steadily growing. A significant increase in the scale of production and the rate of dieselisation will lead to further growth in the use of diesel fuel, which is limited in terms of oil refining and does not exceed 15–20% [1]. In addition, Ukraine is facing an acute shortage of domestically produced oil resources, which makes it difficult to use diesel engines on a large scale.

At the current stage of development of energy production for internal combustion engines (ICE), there is a need to reform the energy balance, namely, to transform it into one based on polyenergy, i.e. a system that uses several types of energy production sources [1, 2]. Among the aspects of energy use is the transition from using only traditional energy sources (light oil products) to alternative energy sources, which are obtained from sources with less limited raw materials or from renewable sources to expand the fuel base of wheeled vehicles.

An analysis of studies on the use of biodiesel fuels for transport diesel engines has shown that biodiesel has a number of disadvantages, namely: low volatility, increased density and kinematic viscosity, lower calorific value, increased coking ability, high cloud point and solidification, and increased surface tension coefficient. The above parameters have a significant impact on the efficiency of biodiesel use and worsen the environmental performance of the engine (due to the increased content of nitrogen oxides in the EG). In most of the analysed studies, it is noted that these shortcomings

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are caused by the mismatch of physical and chemical properties of biodiesel fuels compared to diesel fuel. At the same time, the analysed studies note that the presence of oxygen in the biodiesel molecule and high cetane number contribute to higher combustion efficiency [2, 3].

Improving the environmental performance of cars with modern diesel engines equipped with an electronic control system, adjustable gas turbine supercharging, exhaust gas recirculation (EGR) system and electronic crankshaft speed control system is possible by ensuring compliance with the requirements of regulatory documents through a systematic, phased transition from powering diesel engines with regular fuel to powering them with alternative fuels, namely by adding methyl esters of rapeseed oil (MERO) to regular petroleum diesel fuel (DF).

The use of blends of MERO and regular diesel fuel can improve the environmental performance of diesel and reduce mass emissions of harmful substances (HS) with exhaust gases. In view of this, it is important to study the impact of MERO additives to diesel fuel on the environmental, fuel and energy performance of modern vehicles.

2 Use of Alternative Fuels from Renewable Sources in Diesel Engines

Prerequisites for Using Fuels from Renewable Energy Sources

The increasing energy needs of humanity lead to an increase in energy consumption, which leads to their depletion and environmental pollution. It is known that heat engines are the main source of energy for vehicles. Recently, the need to save natural resources and preserve the environment while increasing the production of energy required to meet the needs of mankind has become an acute issue [1, 3, 4].

The largest amount of energy is produced by internal combustion engines (ICEs), which simultaneously consume the bulk of oil refining products and are the main source of chemical, mechanical, thermal, noise and other types of harmful environmental pollution. The most significant chemical pollution of the atmosphere is caused by harmful substances (HS) of exhaust gases (EG).

In terms of energy production from a minimum amount of fuel, the most suitable internal combustion engine is the diesel engine. Due to their high fuel and economic performance, diesel engines are widely used as vehicle powerplants. The maximum total capacity of diesel engines is concentrated in freight and passenger vehicles and self-propelled agricultural machinery, and the number of passenger cars with diesel engines is growing steadily.

The increased level of NO_x and particulate matter (PM) emissions into the environment is a disadvantage of diesel engines compared to spark ignition engines. The presence of the above-mentioned disadvantages of diesel engines makes it important to conduct research and implement measures aimed at reducing the concentration of

NO_x and particulate matter in exhaust gases while maintaining the existing level of fuel efficiency and, if possible, increasing it.

In the energy complex of developed countries, about 80% of the energy produced by power plants is obtained from ICEs [1]. The main share of ICE capacities is concentrated in road transport–60% and in the agricultural sector–25% [2].

Along with the increase in the production of ICEs, the demand for petroleum fuels is growing. In Ukraine, ICEs used in road transport and the agricultural sector consume about 16 million tons of petroleum-based fuels annually, 30% of which are diesel fuel [3].

In addition, it is predicted that in the near future, diesels will partially replace spark-ignition engines in trucks, city and intercity buses, and about half of passenger cars will also be equipped with diesels [4].

The implementation of research, the introduction of modern technologies and measures to improve fuel efficiency has made it possible to reduce diesel fuel consumption by 5–7% over the past twenty years [5].

However, despite significant achievements in improving fuel efficiency, the increase in production and dieselization rates will lead to further growth in the use of diesel fuel (DF), which can be produced by oil refining in limited quantities and does not exceed 15–20% [6]. In addition, Ukraine is facing an acute shortage of domestically produced oil resources, which complicates the widespread use of diesel. Domestic of oil and gas condensate production used for diesel fuel does not exceed 4 million tons per year [3, 6]. Even if the volume of oil refining is further doubled, imports of oil or oil products will still amount to about 80–90%.

The shortage of fuels derived from oil is causing increased interest in the use of new alternative fuels in ICEs, which are derived from sources with less limited resources or from renewable sources.

In recent years, a large number of foreign research centres of engine-building companies have been conducting research aimed at solving the problems of fuel economy and replacing traditional liquid hydrocarbon oil fuels with alternative fuels of non-mineral origin. Alternative fuels can be classified according to the following criteria:

- composition–alcohols, ethers, hydrogen fuels with additives;
- by aggregate state–liquid, gaseous, solid;
- in the volume of the main fuel, or as an additive to the regular fuel;
- by sources of raw materials–from coal, peat, shale, biomass, etc.

The most prospective alternative fuels are considered to be biofuels (BF) and plant-mineral mixtures (BF with mineral diesel) in different proportions.

In 2001, the European Commission identified three prospective alternatives to motor fuels: natural gas, biofuels and hydrogen. Each of these fuels could reach a level above 5% of total mineral fuel production in the motor fuel market by 2020.

The main factors that determine the need to replace petroleum motor fuels with fuels of biological (plant) origin are the following: environmental, economic and sanitary.

Passenger cars and buses equipped with diesel engines account for more than 9% of the emissions of the main HS [7]. More than 1000 different substances are present in the exhaust gases of ICEs, 200 of which have been identified [8]. On average, emissions from one diesel passenger car contain 2–4 g of toxic substances per kilometre travelled. The main feature of fuel combustion in a diesel engine is that this process occurs in a diffusion flow when liquid droplets enter it, which undoubtedly leads to the formation of a significant amount of soot (carbon) and polycyclic aromatic hydrocarbons due to the thermal decomposition of fuel molecules in a lack of oxygen.

In a diffusion flow, the most intensive combustion develops in the stoichiometric zone (at $\alpha \approx 1$) at the maximum combustion temperature, resulting in the intensive formation of nitrogen oxides NO_x. Therefore, one of the main harmful components of diesel EG is nitrogen oxides NO_x, the share of which in the total toxicity index can be more than 90% [6–8].

In addition, diesel fuel contains sulphur, which in the process of combustion in diesel, with an excess of oxygen, turns into sulphur oxides SO_2.

The modern energy transport system is a mono-energy system based on the use of one dominant energy source—oil. At the current stage of development of energy production for ICEs, there is a need to reform the energy balance, namely to transform it into one based on polyenergy, i.e. a system that uses several sources for energy production. The basis of polyenergy is the transition from using only traditional energy sources (light oil products) to using alternative energy sources, which are obtained from sources with less limited raw materials or from renewable sources.

These issues are most acute for the Ukrainian economy. Importing about 90% of oil in Ukraine not only reduces the production of motor petrol and diesel fuels, but also deteriorates their quality in the face of steadily rising fuel prices [4]. The constant increase in the cost of oil fuels leads to excessive costs for the main consumers of light oil products, and also has a negative effect on the economy of domestic agricultural producers.

Today, the issue of fuel "environmental friendliness" has acquired an independent significance due to the tightening of sanitary requirements for both fuels and their combustion products. These requirements are declared in international documents, which Ukraine also follows. Table 1 shows the environmental standards that modern fuels must meet, and Table 2 shows the emission standards for diesel vehicles [9].

One of the ways to solve the problem of expanding the energy base for diesel engines and partially resolving environmental and sanitary problems is to use fuels from renewable energy sources—first-generation fuels of plant origin, which include biodiesel (BD) and plant oil. In the future, with the improvement of biomass fuel production technology and reduction of production costs, the use of second-generation plant-based fuels may be possible.

Currently, fuels derived from renewable sources include plant oils (rapeseed, sunflower, peanut, soybean, etc.), esters, alcohols, biogas.

Table 1 Main environmental indicators of diesel fuels

Indicators	UNECE regulations, fuel standard according to EN 590–93	Euro 2, fuel standard according to EN 590–96	Euro 3, fuel standard according to EN 590–2000
Cetane number, not less than	45	49	51
Mass fraction of sulphur, %, not more than	0.3…0.5	0.050	0.035
Content of polycyclic aromatic hydrocarbons, %, not more than	Not regulated	Not regulated	11

**Table 2** Maximum permissible emissions for passenger cars with diesel engines

Normative document	Year of introduction of requirements		Maximum permissible emissions, g/km			
	Europe	Ukraine	Carbon monoxide CO	Nitrogen oxides NO_x	$HC + NO_x$	Particles PM
Euro – 1	1992	–	2.72(3.16)	–	0.97(1.13)	0.14(0.18)
Euro – 2	1996	2006	1.0	–	0.7	0.08
Euro – 3	2000	2013	0.64	0.50	0.56	0.05
Euro – 4	2005	2014	0.50	0.25	0.30	0.025
Euro – 5	2009	2016	0.500	0.180	0.230	0.005
Euro – 6	2014	2018	0.500	0.080	0.170	0.005

Production, Physical and Chemical Properties and Standards for Plant Oils and Fuels Based on Them

The first attempts to use plant oils as a motor fuel for diesel engines were made by Rudolf Diesel [4]. In 1900, at the World Exhibition in Paris, he demonstrated a diesel engine running on peanut oil. But as diesel engines were further developed, more attention was paid to fuels made from oil refining products. The depletion of mineral deposits and the need to replace exhaustible energy sources with renewable ones has led to a revival of interest in raw materials of plant and animal origin. The following can be used as raw materials for motor fuels: animal fat, wood and woodworking waste, agricultural and food processing waste, algae and other marine bioresources [10, 11].

Today, more than 30 countries produce liquid biofuels from various types of plant material. Among these biofuels are plant oils, their derivatives, bioethanol, biomethanol, biodimethyl ether, biomethyl tertiary butyl ether (bioMTBE), bioethyl

Fig. 1 Average estimated energy yield of BF per hectare of land for different crops under EU conditions [33]: 1–sunflower; 2–rapeseed; 3–wheat; 4–potato; 5–sugar beet
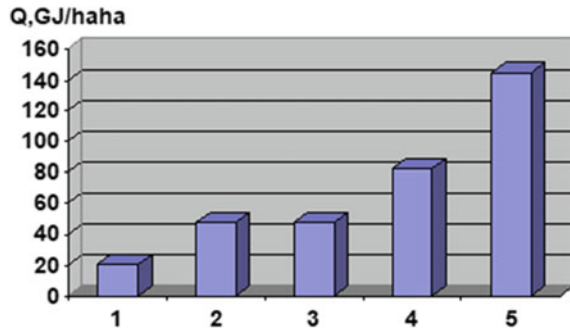
tertiary butyl ether (bioETBE), synthetic BF, biogas, and biohydrogen [12, 13]. It should be noted that under the same conditions of production of raw materials, alcohol fuels require less arable land than fuels based on plant oils (Fig. 1) [14].

At the same time, the physical and chemical properties of fuels derived from plant oils are closer to those of regular mineral diesel. Therefore, diesel engines are more suitable for use with plant oils and their derivatives.

The source of plant oils is oily plants that contain fats in their seeds or fruits.

There are several climatic zones where oilseeds are grown, which are the raw material for the production of oils and their esters. Rapeseed is grown in Western, Central and Eastern Europe, some parts of Asia (China, India), and Canada. The leading countries that grow soybeans are the United States, Brazil, Argentina and China. Sunflower is cultivated in Ukraine, Russia, Spain, Austria, the USA, and Canada. China, Japan, and Indonesia have significant raw material resources for producing peanut oil. Ukraine produces large volumes of sunflower and rapeseed.

The following types of oils are of the greatest industrial importance: legume (soybean), rapeseed, sunflower, palm, corn, castor, hemp, sesame, linseed, poppy, cottonseed, and almond. The global production of plant oils has reached 80 million tons per year [14]. The production of only four of them–soybean, rapeseed, sunflower and palm oils–amounted to 39.6 million tons per year [15].

A typical representative of plant oils is rapeseed oil (RO), which is obtained from rapeseed. Rapeseed is an annual plant of the cruciferous family. There are two varieties of rapeseed: spring and winter. For Ukraine, it is more expedient to produce RO from winter rapeseed. The scheme of rapeseed processing and production of fuel oil and motor fuels based on it is shown in Fig. 2 [16].

Methyl ester of rapeseed oil (MERO) is obtained as a result of direct esterification of fatty acids of RO with methyl alcohol (methanol) at a temperature of 80–90 °C in the presence of a catalyst, most often potassium hydroxide. The esterification of 1040 kg of RO and 144 kg of methanol produces 1 tonne of RO methyl ester and about 200 kg of glycerol (Table 3) [17].
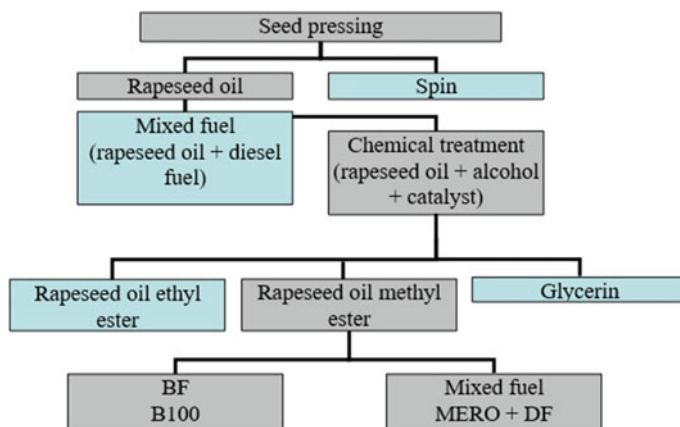
Fig. 2 Scheme of rapeseed processing and production of rapeseed oil and fuels

Table 3 Feedstock and products obtained in the production of one tonne of rapeseed oil methyl ester

Feedstock and processed products	Consumption, kg
Rapeseed seeds	3050
Rapeseed oil	1040
Methanol	144
Potassium hydroxide	19
Filter component	6
Pressed oilcake	1952
Glycerin	200

Plant oils are fats from the seeds or fruits of various plants, which are obtained by pressing or extraction using solvents. Plant oils generally consist (95–97%) of triacylglycerols, which are organic compounds, esters of glycerol, and mono- and diacylglycerols. Acylglycerols, in turn, contain molecules of various fatty acids bound to the glycerol molecule $C_3H_5(OH)_3$ [18, 19].

In terms of their chemical structure, fatty acid molecules differ from each other only in the content of hydrocarbon atoms and the level of saturation of the fatty acid, so the properties of plant oils are determined mainly by the content and composition of fatty acids that form triacylglycerols. Usually, these are saturated and unsaturated (with one to three double bonds) fatty acids with an even number of carbon atoms (mainly C16–C18). In addition, small amounts of fatty acids with an odd number of carbon atoms are present in plant oils (C15–C23).

Plant oils under normal conditions can be in a solid state, but more often they are oily liquids with increased density (usually $\rho = 900$–1000 kg/m^3) and viscosity ($v = 60$–100 mm^2/s at t $= 20$ °C, and $v = 30$–40 mm^2/s at t $= 40$ °C) and a relatively low auto-ignition temperature (Table 4) [13, 19–21]. Liquid plant oils, in turn, are

divided into those that dry out (linseed, hemp, tung), those that partially dry out (poppy, cottonseed, sunflower, rapeseed) and those that do not dry out (castor).

Fatty acids, which are the main component of plant oils, are high molecular weight oxygen-containing compounds with a hydrocarbon backbone. Therefore, all plant oils can be used as motor fuels. The low volatility and high viscosity of plant oils makes it impossible to use them in petrol engines. However, they can be successfully used as motor fuels for diesel engines [21–24].

Table 4 Physical and chemical properties of plant oils [21]

Physical and chemical properties	Oils							
	Rapeseed	Peanut	Sunflower	Soybean	Palm	Olive	Cotton	Castor
Density at 20 °C, kg/m^3	916	917	923	924	918	914	919	1069
Kinematic viscosity, mm^2/s at:								
20 °C	75.0	81.5	65.2	–	–	–	–	–
40 °C	36.0	36.5	30.7	32.0	–	–	–	–
100 °C	8.1	8.3	7.4	7.7	8.6	8.4	7.7	19.9
Cetane number	36	37	33	50	49	–	–	–
Amount of air required for the combustion of 1 kg of substance, kg	12.6	11.2	11.1	–	–	–	–	–
Heat of combustion, MJ/kg	37.3	37.0	37.0	36–39	37.1	–	–	–
Auto-ignition point, ºC	318	–	320	318	315	285	316	296
Freezing point, ºC	–20	–	–16	–12	+ 30	–12	–18	–27
Sulphur content, %	0.002	–	–	–	–	–	–	–
Content %, by weight:								
C	78.0	78.0	–	–	–	–	–	–
H	10.0	12.3	–	–	–	–	–	–
O	12.0	9.4	–	–	–	–	–	–
Acidity, mg KOH/100 ml of fuel	4.66	–	2.14	0.03	0.17	5.90	0.23	0.19
Coking point of 10% residue, %, not more than	0.40	–	0.51	0.44	–	0.20	0.23	–

A special feature of plant oils is the presence of a fairly large amount of oxygen (8–12%) in their composition. This leads to a decrease in their calorific value. Thus, the lower calorific value of plant oils is 36–39 MJ/kg compared to 42–43 MJ/kg of diesel fuels, which contain almost no oxygen in their composition. The presence of oxygen in the molecule of plant oils reduces their combustion temperature and significantly improves diesel efficiency and environmental performance. In many studies of diesel engines running on plant oils, a decrease in the smoke content of the EG and the content of products of incomplete combustion was observed [17].

The possibility of using plant oils as the main fuel for diesel engines is limited by increased soot formation–the deposition of coke on injector nozzles and other parts of the cylinder-piston group. Significant soot formation is caused by the presence of resinous substances and their increased ability to coke. While DF, according to the current DSTU, have a coking ability of 10% residue, not exceeding 0.3%, the coking ability of plant oils is 0.4–0.5%.

In addition, the disadvantage of plant oils used as fuel for diesel engines is the relatively high temperature of their clouding and solidification, caused mainly by the presence of unsaturated fatty acids in their composition (Table 5) [25, 26]. Plant oil fuels are characterized by their ability to biodegrade relatively quickly. Once they get into natural water bodies or soil, they are almost completely decomposed within a few weeks. In addition, plant oils differ from mineral diesel fuels in their low content of sulphur and polycyclic aromatic hydrocarbons [15, 26, 27].

A typical example of plant oils is RO, an oily brown liquid that turns light yellow after refining. Rapeseed oil is a mixture of mono-, di-, and triacylglycerols. It contains both saturated fatty acids—palmitic and stearic, and unsaturated fatty acids—oleic, linolenic, linolenic, eicosenic, and erucic (Table 5).

Table 4 shows the physical and chemical properties of average RO. The density of the RO is $\rho = 900\text{--}920\ kg/m^3$, the kinematic viscosity at 20 °C is $\nu = 70\text{--}90\ mm^2/s$.

The above data indicate that plant oils have physical and chemical properties that differ significantly from those of DF. Therefore, it is desirable to use refined products of plant oils in diesel engines—their refined products, ethyl and methyl esters of these oils. Physical and chemical properties of some of them are given in Table 6 [25, 27–29].

Table 5 Fatty acid content of average rapeseed oil [25]

Fatty acid	Chemical formula	Content, % (by weight)
Palmitic	$C_{16}H_{32}O_2$	4.8
Stearic	$C_{18}H_{36}O_2$	1.7
Oleic	$C_{18}H_{34}O_2$	43.7
Linoleic	$C_{18}H_{32}O_2$	20.9
Linolenic	$C_{18}H_{30}O_2$	8.5
Eicosenic	$C_{20}H_{38}O_2$	4.8
Erucic	$C_{22}H_{42}O_2$	15.6

**Table 6** Physical and chemical properties of fuels derived from plant oils [27]

Physical and chemical properties	Oil-based fuels					
	Sunflower oil refined	Soybean refined oil	Rapeseed methyl ester	Rapeseed ethyl ester	Soybean methyl ester	Palm oil methyl ester
Density at 20 °C, kg/m^3	920	923	877	895	884	870
Kinematic viscosity, mm^2/s at:						
20 °C	–	–	9.8	*	–	–
40 °C	34.4	31.2	5.2	*	4.1	4.5
Cetane number	40	27	51	–	46	62
The amount of air required for the combustion of 1 kg of a substance, kg	–	–	12.6	12.6	–	–
Heat of combustion, H$_u$, MJ/kg	–	–	37.8	36.8	–	40.1
Auto-ignition point, °C	202	220	230	–	141	174
Freezing point, °C	–20	–12	–21	–	–1	–
Sulphur content, % (by weight)	0.007	0.005–0.01	0.002	–	0.005–0.01	–
Content %, by weight:						
C	–	–	77.5	77.6	–	–
H	–	–	12.0	12.0	–	–
O	–	–	10.5	10.4	–	–
Coking ability of 10% residue, %, not more than	–	–	0.3	0.3	–	–

Notes "–" properties were not determined

The difference between the physical and chemical properties of plant oils and fuels based on them and those of mineral diesel fuels has an impact on the course of diesel engine operations. This primarily concerns the processes of fuel supply and the dynamics of mixture formation. These processes largely determine such physical properties of the fuel as density, viscosity, compressibility, surface tension.

Compared to diesel fuel, plant oils (rapeseed oil) have a higher density. Thus, while diesel fuel (DSTU 4840:2007) at a temperature of t = 20 °C has a density of ρ = 820–840 kg/m^3, RO has a density of ρ = 910 kg/m^3 [27]. RO almost does

Fig. 3 Dependence of density change on temperature: 1–RO; 2–MERO; 3–DF
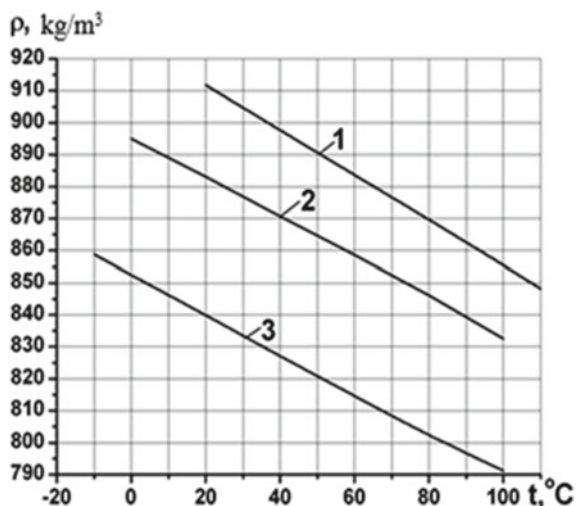
not differ from DF in the dependence of density change on temperature (Fig. 3) [28]. Esters produced on their basis have a lower density compared to plant oils. In particular, at a temperature of t = 20 °C, the density of RO (Fig. 3) is ρ = 910 kg/m^3, and that of MERO is ρ = 886 kg/m^3.

Plant oils are characterized by high kinematic viscosity, which exceeds the kinematic viscosity of standard diesel fuels by an order of magnitude. Under normal atmospheric conditions, the kinematic viscosity of DF "S" (summer) (ν = 3.5–4 mm^2/s) is one level lower than the kinematic viscosity of RO. Thus, in accordance with characteristic 1 (Fig. 4) [29], at t = 20 °C, the viscosity of the RO is ν = 75 mm^2/s [29]. At the same time, at higher temperatures, which are typical for fuel supply systems of transport diesel engines (at an ambient temperature of t = 20 °C, the fuel temperature in the fuel supply system is t = 40–60 °C [30]), the viscosity of the RO decreases sharply and at t = 40 °C is approximately ν = 37 mm^2/s (Fig. 4).

However, such kinematic viscosity values are too high, which makes it difficult to pump them through the fuel lines of the fuel supply system, organise the process of supplying and spraying plant oil in the diesel combustion chamber.

The list of biofuels with lower viscosity compared to RO includes products of their processing, namely MERO. In the production of plant oil esters, their esterification removes glycerol residues from acylglyceride molecules, which leads to a decrease in the kinematic viscosity of the resulting fuels. In particular, at a temperature of t = 20 °C, the kinematic viscosity of MERO is approximately ν = 10 mm^2/s (Fig. 4). This is significantly lower than the kinematic viscosity of plant oils, but two times higher than the kinematic viscosity of petroleum diesel fuels. An acceptable value of kinematic viscosity can be obtained by mixing MERO with a less viscous component, such as kerosene, diesel fuel.

The surface tension coefficient σ has a significant impact on the dynamics of fuel blending. Plant oils have a higher surface tension than diesel fuel. Under normal

Fig. 4 Dependence of
viscosity change on
temperature: 1–RO;
2–MERO; 3–DF
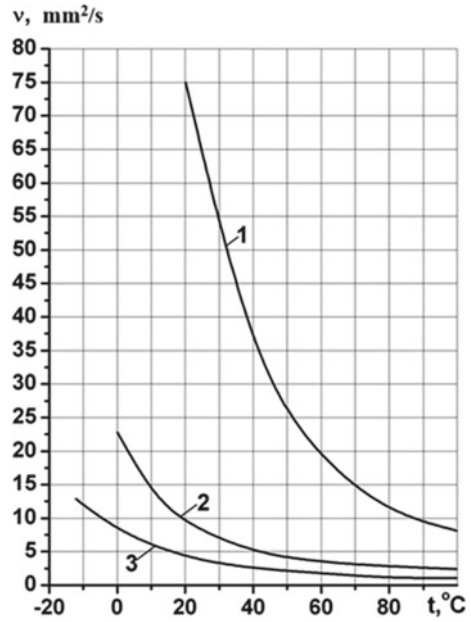
atmospheric conditions (t = 20 °C, p = 0.1 MPa), the surface tension coefficient of
DF is σ = 27.1 mN/m, RO σ = 33.2 mN/m, MERO σ = 30.7 mN/m (Fig. 5) [31].
According to the dependences shown in Fig. 5, it can be seen that the surface tension
coefficient of the presented fuels insignificantly depends on the temperature.

Fig. 5 Dependence of the
change in the surface tension
coefficient on temperature:
1–RO; 2–MERO; 3–DF
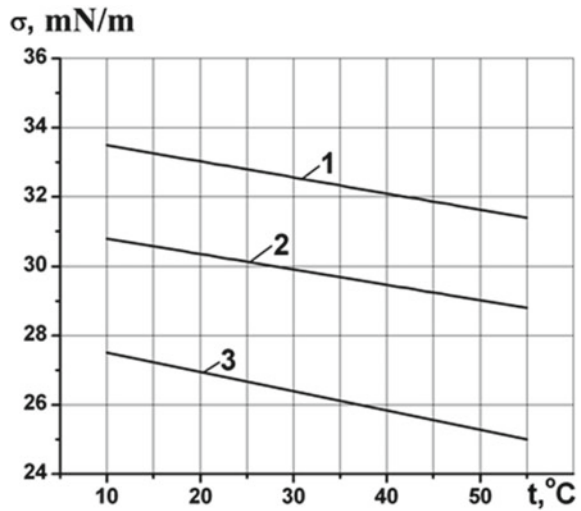
These features of the physical properties of plant oils and fuels based on them have a significant impact on the parameters of the fuel supply process, and, as a result, change the characteristics of the injection and spraying of these fuels, and, consequently, the processes of mixture formation and combustion [28–32]. The high values of density, kinematic viscosity, and surface tension coefficient of these fuels, which are fed into the combustion chamber by the standard diesel fuel supply system, cause an increase in their cycle supply and hourly consumption compared to diesel fuels in accordance with DSTU 4840:2007 [29].

The increased density of plant oils and fuels based on them causes a long-range fuel jet [33]. An increase in the length of the fuel jet worsens self-ignition (due to an increase in the ignition delay period) [33]. As a result, during the ignition delay period, the plant oil jet reaches the walls of the combustion chamber, part of the fuel that hits the walls does not burn completely, volumetric mixing is disturbed, piston rings lose mobility and engine oil dilution occurs.

At high kinematic viscosity and surface tension coefficient, the fuel plume opening angle decreases and the spray atomisation and fineness deteriorate, with an increase in the average droplet diameter. In addition, the increased surface tension of plant oils increases the heterogeneity of their spray. Higher values of density and kinematic viscosity of these fuels lead to an increase in the maximum injection pressure. The actual moment of injection start shifts towards an increase in the fuel injection advance angle. The above factors indicate the expediency of implementing measures that will improve the quality of fuel supply, spraying and mixture formation processes when a diesel engine runs on plant oils and fuels based on them.

One of the main conditions for normal operation of the engine when running on BF is its compliance with the standard. The standard for BF abroad is EN 14,214:2008 [34], and in Ukraine, DSTU 6081:2009 [35]. A comparison of these standards is given in Table 7.

Plant-based fuels, like oil, have different characteristics [36]. Whereas the physical and chemical properties of oil depend on the place of extraction, the characteristics of fuels of plant origin depend on geographical and climatic conditions, as well as on the variety and agronomic measures used in growing.

Despite the differences between the physical and chemical properties of plant oils and fuels based on them and those of diesel fuel, they are considered to be promising non-traditional fuels. This is due to the high environmental properties of fuels from plant oils and the renewability of raw materials for the production of these fuels. Therefore, research is being conducted on the adaptation of diesel engines when powered by the above fuels [36–38].

However, this approach to solving this issue requires significant changes to the design and regulation of diesel fuel supply system elements, which is unacceptable for diesel engines in operation.

The differences between the physical and chemical properties of MERO and the physical and chemical properties of regular diesel fuel have a significant impact on the energy, environmental and fuel economy performance of engines.

Taking into account the small volumes of biodiesel production, it is more appropriate and necessary for WV with diesel engines to adapt not diesel engines to

Table 7 Standards for biodiesel in Ukraine and Europe [35, 36]

Name of the indicator	DSTU 6081:2009	EN 14214:2003	Presented sample
Mass fraction of ethers, %, not less than	96.5	96.5	96.5
Density at 15 °C, kg/m³, within	860–900	860–900	887.5
Kinematic viscosity at 40 °C, mm²/s, in a range	3.5–5.0	3.5–5.0	5.5
Flash point, °C	120	101	183
Sulphur contents, mg/kg, not more than	10	10	110
Coking ability of 10% of the distillation residue, %, not more than	0.30	0.30	0.1
Cetane number, not less than	51	51	51
Ash content, % (mas.) not more than	0.02	0.02	0.005
Mass fraction of water: mg/kg, not more than %, not more than	500 0.05	500	1200 0.12
Content of mechanical impurities: mg/kg, not more than	24	24	80
Test on a copper plate (3 h at 50 °C)	Class 1	Class 1	Class 1
Oxidative stability at 110 °C, h, not less than	6.0	6.0	–
Acid number, mg KOH/100g, not more than	0.50	0.50	0.6
Iodine number, g of iodine /100 g, not more than	120	120	52.5
Mass fraction of linolenic acid methyl ester, %, not more than	12.0	12.0	–
Mass fraction of polyunsaturated methyl esters, %, not more than	1	1	–
Mass fraction of methanol, %, not more than	0.20	0.20	0.14
Mass fraction of monoglycerides, %, not more than	0.80	0.80	1.4
Mass fraction of diglycerides, %, not more than	0.20	0.20	0.6
Mass fraction of triglycerides, %, not more than	0.20	0.20	0.3
Mass fraction of free glycerol, %, not more than	0.02	0.02	0.01
Mass fraction of total glycerol, %, not more than	0.25	0.25	–

(continued)

Table 7 (continued)

Name of the indicator	DSTU 6081:2009	EN 14214:2003	Presented sample
Mass fraction of alkali metals:			
(Na + K), mg/kg, not more than	5.0	5.0	4.5
(Ca + Mg), mg/kg, not more than	5.0	5.0	4.5
Mass fraction of phosphorus, mg/kg, not more than	10	4	7.0

biodiesel fuels, but to prepare blended biodiesel fuels with the following physical and chemical properties that do not differ significantly from the physical and chemical properties of regular diesel fuel.

When using MERO as an additive to regular DF (hereinafter referred to as two-component biodiesel fuels), the kinematic viscosity increases with the increase in the volume fraction of MERO in the mixture. To prevent an increase in the kinematic viscosity of two-component biodiesel fuels, a component with a lower viscosity should be added (hereinafter referred to as three-component biodiesel). In this case, it is possible to expand the fuel base for diesel engines in operation.

The environmental performance of a diesel engine significantly depends on the physical properties of the fuel, which primarily include its density and viscosity [33].

Fuel viscosity is a direct factor influencing the operation of fuel delivery equipment, determining the internal friction of the fuel flow and thus hydraulic energy losses in the fuel delivery system. The degree of fuel throttling in the filling and cut-off holes of the fuel pump plunger sleeve, as well as in the nozzle channels, partly depends on the viscosity. With increasing viscosity, throttling increases when the plunger closes the filling hole of the sleeve, which causes an earlier start of fuel supply, and when it opens, it causes a later end of fuel supply, which leads to an increase in the cycle fuel supply. Due to the throttling of fuel in the storage and cut-off holes, the actual duration of the supply usually exceeds the geometric duration calculated by the moments when the holes are closed by the plunger edges. However, the main factor affecting the viscosity of the fuel supply cycle is the leakage (loss) of fuel through the gaps of the precision pairs of fuel supply equipment. Wear and tear of precision pairs of fuel delivery equipment also depends on the fuel viscosity. The lower limit of viscosity at which the lubricating ability of the fuel is ensured depends on the design features of the fuel equipment and its operating conditions. The higher the viscosity and density, the larger the droplets formed during spraying, and the longer the range of the fuel jet. At the same time, the quality of fuel spraying and evaporation deteriorates. Spray deterioration is also observed when injecting fuel with excessively low viscosity and density. In this case, a shortened fuel plume is formed, which does not cover the entire space of the combustion chamber, and not all the air charge is involved in the process of fuel oxidation.

The data under consideration indicate that the amount of fuel injected into the diesel combustion chamber depends on the fractional and group hydrocarbon composition of the fuels. With an increase in the boiling point of a fuel fraction, its density

and viscosity increase, while its compressibility decreases. High-boiling aromatic hydrocarbons are characterized by higher density and viscosity values. For example, diesel fuel of paraffinic naphthenic base (composition) obtained from West Siberian oil has a viscosity of $\nu_{20} = 3.5–4.0$ mm^2/s, and the same fractional composition of naphthenic aromatic base (composition) fuel from Sakhalin oil has a viscosity of $\nu_{20} = 5.5–6.0$ mm^2/s [36]. Changes in these properties also occur as a result of changes in fuel temperature. Due to the weighting of the fuel used, these three properties, complementing each other, lead to an increase in the cycle fuel supply and corresponding changes in the toxicity of the EG.

When studying the operation of the Detroit Diesel 60 series diesel engine in transient modes, it was noted that an increase in the density of the fuel used from 820 to 845 kg/m^3 is accompanied by an increase in soot emissions from 0.40 to 0.425 g/(kWh), i.e. by 8% [31]. This is due to the fact that an increase in fuel density leads to an increase in the mass cycle fuel supply, a decrease in the excess air coefficient α, an increase in diesel power, and a significant increase in specific soot emissions.

Other physical properties of fuels include their low-temperature properties, which are characterized by their pour point and cloud point, as well as their viscosity-temperature characteristics. Lowering the fuel temperature is accompanied by an increase in the cycle fuel supply and, as mentioned above, a corresponding change in the environmental performance of the diesel engine.

In general, the following patterns of influence of the physicochemical properties of fuels on the toxicity of EG diesel engines with direct injection and split combustion chambers can be noted [33]. Low NO$_x$ emissions are observed at low content of aromatic hydrocarbons in the fuel, which is characterised by lower density and viscosity, as well as a low boiling point of 96% of the fuel. Insignificant emissions of C$_m$H$_n$ are observed when using fuels with higher values of density, viscosity, CN and 96% boiling point. CO emissions and smokiness of EG increase with increasing aromatic hydrocarbon content, fuel distillation end temperature and decreasing EG.

Optimal values of the cetane number in the range of 55–60 and above are considered to be the best in terms of the total toxicity of EG. The highest (maximum) CNs are for fractions that boil in the range of 200–350 °C, those containing a high content of alkane hydrocarbons and a low content of aromatic hydrocarbons. An increase in the boiling point above 350 °C leads to a slight decrease of the CN, which is mainly due to the increased content of polycyclic aromatic hydrocarbons in these fractions.

Thus, it should be noted that optimisation of the physical and chemical properties of the fuels used is one of the effective ways to reduce the toxicity of EG. This is achieved both by improving the fuel parameters and narrowing their limits of change. Therefore, fuel producers need, on the one hand, to ensure that fuel specifications are in line with current standards, and, on the other hand, to improve fuel parameters that determine its quality and narrow the limits of their possible change.

The analysis of the influence of fuel properties on the toxicity of EG was carried out for diesel engines operating on standard diesel fuels. However, engines for transport and motor tractors can also be operated on fuels of other, non-mineral (petroleum) origin. Therefore, when choosing a fuel and adapting it for specific engine types, environmental performance can be significantly improved.

3   Assessment of Fuel Efficiency and Environmental Performance of the Vehicle in the European Driving Cycle Modes, When Running on Regular and Mixed Biodiesel Fuels

Automobile engines are mobile sources of environmental pollution operating in a wide range of load and speed modes that determine the conditions of vehicle movement in traffic. The main operating modes are: acceleration (deceleration), steady-state movement, engine braking (forced idling) and active idling. Thus, automotive engines operate, as a rule, in unsteady-state modes during vehicle operation, with successive cyclic transitions from one mode to another.

Therefore, the most accurate results, which fully take into account transient processes and individual characteristics of the engine and the vehicle as a whole, can be obtained by testing the vehicle on a simulator roller stand according to certain driving cycles.

To determine the level of emissions of harmful substances from the EG as accurately as possible, the vehicle must be tested under conditions that are as close as possible to real-world operating conditions. In contrast to road tests, tests on a roller simulator can be carried out in precise accordance with time-sensitive speeds, without the need to take into account actual traffic conditions. In this way reproducible and comparable vehicle test results can be obtained.

The aim of the modelling roller bench test is to determine the influence of the physical–chemical properties of mixed biodiesel fuels (two- and three-component) in order to optimize them to improve the fuel-economic and environmental performance of a diesel vehicle in operation equipped with an adjustable gas turbine supercharger, an EG recirculation system and an electronic crankshaft speed regulator.

Research Programme and Methodology

The programme of the study of conditional movement of a car on a simulating roller stand according to the European driving cycle includes the determination and comparative analysis of fuel consumption and the determination of mass emissions of harmful substances (carbon monoxide CO, hydrocarbons C_mH_n, nitrogen oxides NO_x, and particulate matter) during operation on the studied fuels:

– regular diesel fuel;
– two-component biodiesel fuel with a MERO content of 20%;
– three-component biodiesel fuel with a MERO content of 20%.

The following parameters were continuously recorded during the vehicle tests on the simulator: car speed V_C, instantaneous and total fuel consumption Gf, concentrations of carbon monoxide C_{CO}, hydrocarbons C_{CmHn}, nitrogen oxides C_{NOx} in

diluted EG and in diluted air. The mass of polluting particles G_{PM} was determined by gravimetric analysis.

The calculation method was used to determine the following: mass emissions per cycle of carbon monoxide G_{CO}, carbon dioxide G_{CO2}, hydrocarbons G_{CmHn}, nitrogen oxides G_{NOx} and particles G_{PM}.

The research was carried out in accordance with the methodology of the current standard DSTU UN/ECE R 83–05:2009 "Unified technical requirements for the approval of wheeled vehicles with regard to pollutant emissions depending on the fuel required for engines" [38]. The EU and EEC (European Economic Commission) test cycle—also called the European Driving Cycle—is carried out according to the programme shown in Fig. 6, which closely simulates the movement of cars in cities Urban Driving Cycle (UDC). In 1993, the cycle was supplemented by a suburban cycle with a speed of up to 120 km/h Extra Urban Driving Cycle (EUDC). Consisting of urban and suburban cycles, the new cycle is called NEDC (New Urban Driving Cycle).

In addition, the Euro 3 standard (2000) cancelled the preheating of the engine for 40 s before the start of the EG measurement (this cycle is called MNEDC—i.e. modified NEDC).

The city cycle consists of four identical parts, each lasting 195 s, which are completed without pauses. The stage is 4.052 km long, with a resulting average speed of 18.7 km/h. The maximum speed is 50 km/h.
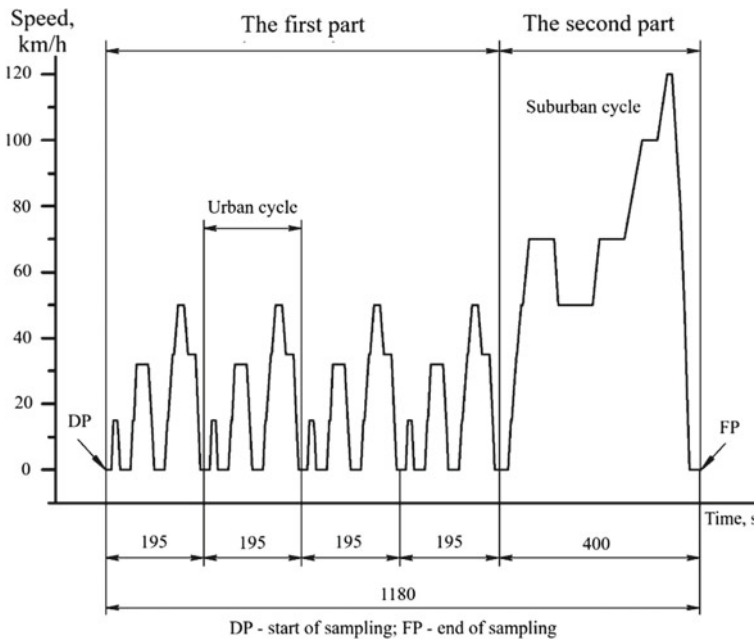

Fig. 6 Modified EU/ECC test cycle for cars and light trucks

Fig. 7　General view of the test setup

The country cycle is performed directly after the city cycle. The part of the country cycle lasts 400 s and the length of this stage is 6.955 km.

During the test, the EG is analyzed continuously or sampled into elastic containers using the Constant Volume Sampling (CVS) method. The mass emissions of C_mH_n are calculated based on the average values of concentrations of harmful substances in the EG, obtained either as a result of processing the data set of instantaneous values of concentrations of harmful substances in the EG, or on the average value of C_mH_n concentrations in diluted exhaust gases taken into an elastic container.

Tests to determine fuel and economic performance and mass emissions of harmful substances from the EG on a simulation roller stand in accordance with UNECE Regulation No. 83 were carried out on a production car Škoda Octavia 1.9Tdi (Fig. 7) (VIN TMBDG41U48B012562) equipped with a VAG ASV 1.9Tdi engine with adjustable gas turbine supercharging, an EG recirculation system, and an electronic crankshaft speed regulator. The technical characteristics of the Škoda Octavia 1.9Tdi are shown in Table 8.

Instruments and Equipment of the Research

A general view of the test setup with the Škoda Octavia 1.9Tdi is shown in Fig. 7.

The test vehicle is mounted with the drive wheels on rollers 3 (Fig. 8). In order to obtain the results of emissions of harmful substances from the EG on the simulation roller stand that correspond to road conditions, it is necessary to reproduce the forces of resistance, forces of change of inertial moment, rolling force and air resistance acting on the vehicle, which are reproduced on the rollers of the stand using an asynchronous DC motor. Braking devices provide the rollers with the necessary resistance, which depends on speed and load. Electric motors brake the rollers, and this force is overcome by the driving wheels of the vehicle. To simulate inertial mass, the test bench uses an electric flywheel mass simulator.

The change in braking load with speed and the required inertial moment reduced to the flywheel were determined with an accuracy of 0.4%.

Table 8 Brief technical characteristics of the Škoda Octavia 1.9Tdi

Option	Value
Unladen weight of the vehicle, kg	1300
Cargo weight, kg	100
The motor's moment of inertia,	0.15
The moment of inertia of the wheel	0.7
Dynamic wheel radius, m	0.317
Gear ratios of the transmission:	
–1 gear	3.778
–2 gear	2.063
–3 gear	1.348
–4 gear	0.967
–5 gear	0.769
–main gear	3.3389
Transmission efficiency	0.9

Fan 1, installed at a distance of 1 m from the car, simulated the oncoming air flow, while providing cooling of the engine radiator.

Gas sampling by the CVS method is carried out as follows: The vehicle exhaust gas in the tunnel 13 is diluted with air coming from the environment 12 through the filters 7 in a certain ratio, depending on the type of engine. The volumetric flow rate of the diluted EG must be the same, so the excess is pumped out by pump 8. This means that the addition of air is determined by the instantaneous flow rate of the EG. A constant amount of EG diluted with air was proportionally sampled throughout the test and collected in several elastic containers 5.

After completion of the driving cycle, the concentration of harmful substances in the tanks corresponds to the average concentration of the entire mixture of air and EG that was sampled. Based on the average concentrations of harmful substances in the EG and the volume of the diluted EG mixture, mass emissions of harmful substances were calculated.

It should be noted that dilution of the EG with air prevents condensation of water vapour contained in the EG, which significantly reduces the concentration of nitrogen oxides in the EG sampling tanks. In addition, dilution with air significantly minimizes the mutual reactions of EG components, primarily hydrocarbons.

The CVS method is characterized by the fact that in the course of the test:

- accounting for the actual volume of gas during testing;
- recording of all stationary and non-stationary operating modes;
- elimination of water vapour condensation.

Testing vehicles equipped with diesel engines. Since 1975, vehicles equipped with diesel engines have been tested using the CVS method. The CVS method was slightly
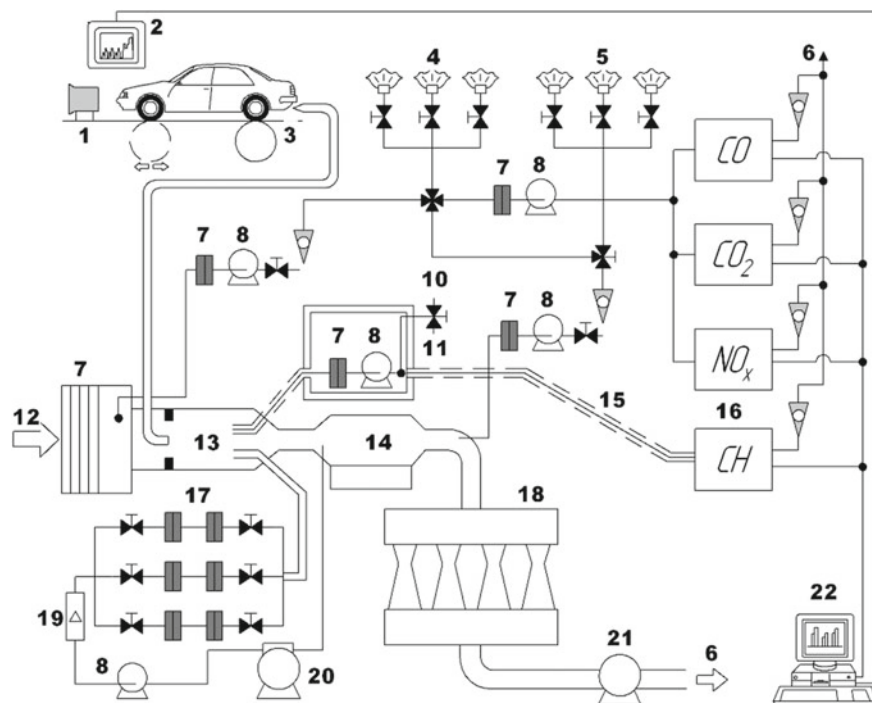
Fig. 8 Schematic of the test setup: 1–fan; 2–monitor for displaying the progress of the driving cycle; 3–rollers; 4–air sampling tanks; 5–LPG sampling tanks; 6–EG outlet; 7–filter; 8–vacuum pump; 9–heater; 10–valve for supplying the tare mixture; 11–valve for supplying "zero" (neutral) gas; 12–air supply; 13–tunnel for dilution of the gas; 14–heat exchanger/heater; 15–heated pipeline; 16–gas analysers; 17–filter; 18–venturi nozzles; 19–gas flow meter for particle detection; 20–air flow meter; 21–centrifugal vacuum pump; 22–computer for processing results

modified to test vehicles with diesel engines. Firstly, to avoid condensation of high-boiling hydrocarbons from the gas sample or to evaporate condensed hydrocarbons, the entire gas sampling system was heated to +190 °C.

In addition, the CVS method was modified to determine the particle content in the EG. For this purpose, a tunnel 13 (Fig. 7) was integrated into the measuring complex to crush the flow of gases with high internal turbulence (Reynolds number >40,000), which is equipped with appropriate filters 17 for particle selection.

The principle of measuring the concentration of harmful substances. In countries where the use of the CVS method has been incorporated into EG legislation, unified measurement methods are used to analyse EG components and harmful substances:

- measurement of CO and CO_2 concentrations by NDIR non-dispersive infrared analysers;
- measurement of NO_x concentration by CLD chemiluminescent instruments;
- determination of the mass of particles in the EG (by weighing the filters before and after sampling);

- measuring the concentration of total hydrocarbons C_mH_n by the flame ionisation method FID.

The AVL-Zollner roller simulator (Fig. 7) type RPL1220/12C23M17/APM150 (serial No. R1305) is designed to provide the required traction force and speed during the test, as provided for in the driving cycle programme. The main technical characteristics of the stand are shown in Table 9.

The fuel consumption during the test was determined by a dynamic liquid mass meter AVL LIST GmbH type 733S.18, which is designed to measure the mass of fuel consumed by a car engine (petrol, diesel fuel) in the range of mass flow rates from 0 to 150 kg/h with the largest mass of liquid passage of 1800 g, the maximum value of the relative error of measuring the mass of liquid in the weighing range from 50 to 1800 g according to the results of metrological studies does not exceed 0.4%.

The air flow rate measurement system was used as part of the universal particle emission analysis system "MT-010" (Fig. 9) with the limits of permissible relative error $\pm 1.5\%$ in the range of volume flow rate from 11.3 dm^3/min to 51.6 dm^3/min (total flow), and $\pm 2.5\%$ in the range of volume flow rate from 0.4 dm^3/min to 25.8 dm^3/min (sample flow). Channels for measuring the air volume flow rate of the CVS system "EMMS-CVS-010" (Fig. 10) with the limits of permissible relative error $\pm 2\%$.

Measurements of the volume content of carbon monoxide CO, carbon dioxide CO_2, hydrocarbons CmHn, methane CH_4, nitrogen oxides NOx and oxygen O_2 in the EG were carried out by the gas analytical complex MEXA-7400DEGR manufactured by Horiba Ltd (Japan) (Fig. 11), which includes gas analysers AIA-721 CO (order No. 6423004), AIA-722 CO/CO_2 (order No. 06420007), MRA-720 O_2 (order

Table 9 Technical specifications of the AVL-Zollner roller simulator

Parameter	Value
Maximum speed, km/h	200
Maximum pulling force, N	10,096
Weight of rotating parts, kg	1184
Minimum configurable weight of rotating parts, kg	454
Maximum adjustable weight of rotating parts, kg	5400
Drum diameter, mm	1219.2
Error in power measurement, %	<0.10
Error in speed measurement, %	<0.01
Acceleration measurement error, %	<1
Error in measuring mechanical losses, N	<5
Error in determining the time, ms	10
Error when setting a constant speed, %	<0.05
Error in setting the steady-state traction force, %	<0.2
Error when setting load simulation, %	<2
Error when setting the simulated moment of inertia, %	<1

Fig. 9 Emission analysis
system of particles
«MT-010»
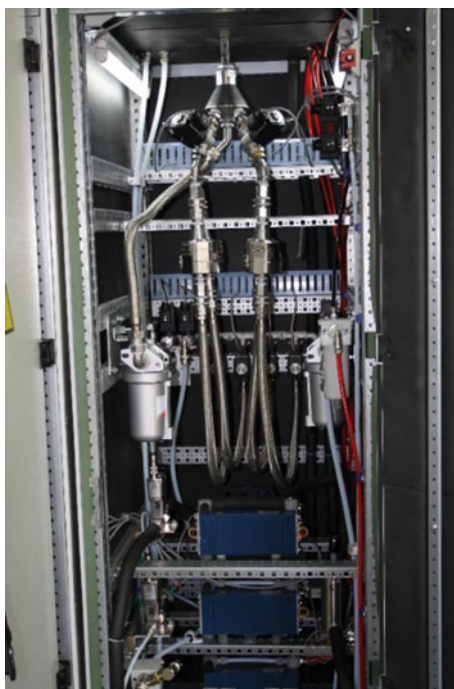
Fig. 10 Air volume flow
measurement system CVS
«EMMS-CVS-010»

Fig. 11 Gas analysing complex MEXA-7400DEGR

No. 29416005), and the OVN-728A unit (order No. 430148001), which houses gas analysers FIA-725 A.H.THC, CLA-755 A, H.NO/NO$_x$, and FIA-712HA. H.THC/CH$_4$.

The principle of operation of the devices for determining the concentrations of harmful substances in the EG is as follows: carbon monoxide CO and carbon dioxide CO$_2$—non-dispersive gas analyser with infrared absorption (NDIR); hydrocarbons C$_m$H$_n$—flame ionisation gas analyser calibrated by propane; nitrogen oxides NO$_x$—chemiluminescent gas analyser (CLA) with NO$_x$/NO converter.

The main metrological characteristics of the gas analytical complex are shown in Table 10.

The particle content was determined by the gravimetric method. The particles are captured by two step filters installed on the analysed gas flow line. The surface of the filters is made of a hydrophobic material that is chemically inert to the components of the gas (polytetrafluoroethylene). Before testing, the particulate filters are subjected to special treatment (temperature, humidity) in a dustproof chamber for 24 h (Fig. 11), and then weighed. After the test, the filters are subjected to a second special treatment and re-weighed. The weighing is carried out in a special chamber on a Sartorius SE2-F electronic balance (Fig. 12) with a maximum weighing limit of 2.1 g and a resolution of 0.0001 mg.

Table 10 Main metrological characteristics

Indicator to be determined (designation of the gas analyser)	Measuring range for volumetric content (%)	Measuring range interval	Permissible error	
			Absolute	Relative
CO (AIA-721 CO)	0–0.5	0–0.2% over 0.2%	±0.01% –	– ±5%
CO (AIA-722 O/CO$_2$)	0–12	0–0.6% over 0.6%	±0.03% –	– ±5%
CO_2 (AIA-722 O/CO$_2$)	0–20	0–10% over 10%	±0.5% –	– ±5%
C_mH_n (FIA-725 A.H.THC)	0–5%	0–0.02% over 0.02%	±0.001% –	– ±5%
CH_4 (FIA-712 HA.H.THC/CH$_4$)	0–0.25	0–0.02% over 0.02%	±0.001% –	– ±5%
NO_x (CLA-755 A, H.NO/ NO$_x$)	0–0.5	0–0.04% over 0.04%	±0.002% –	– ±5%
O_2 (MPA-720 O$_2$)	0–0.5	0–0.04% over 0.04%	±0.002% –	– ±5%

Fig. 12 Particle weighing chamber

Methodology for Calculating the Total Mass of Pollutant (Harmful) Substances Emitted

The determination of the mass of the i-th pollutant in grams per test is performed in accordance with the current standard [37].

The total mass of emissions of harmful substances is calculated by Eq. 1:

$$M_i = \frac{V_{mix} \cdot Q_i \cdot k_H \cdot C_i \cdot 10^{-6}}{d}, \tag{1}$$

where M_i–emitted mass of the i-th pollutant, g/test; V_{mix}–reduced to standard conditions (273.2 K and 101.33 kPa) volume of diluted EG, l/test; Q_i–density of the i-th pollutant, reduced to standard conditions (273.2 K and 101.33 kPa), g/l; k_H–coefficient that takes into account the effect of moisture. It is used only for calculating the mass of nitrogen oxides NO_x in EG; C_i–average value of the concentration of the i-th pollutant in diluted EGs, adjusted for the amount of the i-th pollutant contained in the air for dilution, mln^{-1}; d–distance conditionally travelled by the vehicle per cycle, km.

Bringing the volume of diluted EG to normal conditions. The volume of diluted EG is determined by the following relationship

$$V_{mix} = V \cdot k_1 \cdot \frac{p_b - p_i}{T_P}, \tag{2}$$

$$k_1 = \frac{273.2}{101.33} = 2.6961 \ \text{K} \cdot \text{kPa}^{-1}, \tag{3}$$

where V–is the volume of diluted EG (before adjustment), l/test; k_1–constant factor; p_b–barometric pressure in the test chamber, kPa; p_i–vacuum at the level of the air intake of the discharge pump, kPa; T_p–average temperature of diluted EG, K.

Calculation of the actual adjusted concentration of pollutants in the sampling chamber:

$$C_i = C_e - C_d\left(1 - \frac{1}{DF}\right), \tag{4}$$

where C_i–adjusted concentration of the i-th pollutant in diluted EG, mln^{-1}; C_e–measured concentration of the i-th pollutant in diluted EG, mln^{-1}; C_d–concentration of the i-th pollutant in the air to be diluted, mln^{-1}; DF–dilution coefficient.

The dilution factor is calculated according to the following formula:

$$DF = \frac{13.4}{C_{CO_2} + (C_{CmHn} + C_{CO}) \cdot 10^{-4}}, \tag{5}$$

where C_{CO2}–CO_2 concentration in diluted EG contained in the sampling chamber, %; C_{CmHn}–C_mH_n concentration of in diluted EG contained in the sampling chamber, mln^{-1}; C_{CO}–CO concentration in diluted EG contained in the sampling chamber, mln^{-1}.

The total mass of nitrogen oxides C_{NOx} in diluted EG is determined by formula (1). To correct the effect of moisture on the C_{NOx}, the following relationship was used:

$$k_H = \frac{1}{1 - 0.0329(H - 10.71)}, \tag{6}$$

where H–absolute moisture, g (water)/kg (air);

$$H = \frac{6.211 \cdot R_a \cdot p_d}{(P_B - P_d) \cdot R_a \cdot 10^{-2}}, \tag{7}$$

where R_a–relative moisture content of the ambient air, %; p_d–saturated water vapour pressure at ambient air temperature, kPa; p_B–atmospheric pressure in the room, kPa.

Features of determining the concentration of hydrocarbons C_mH_n. For vehicles equipped with diesel engines, the concentration of total hydrocarbons CmHn is determined as an average value during continuous analysis of diluted EG. When calculating the mass of hydrocarbons C_mH_n for diesel engines, the average integrated concentration value C_e is determined by the following dependence:

$$C_e = \frac{\int_{t_1}^{t_2} C_{CmHn} \cdot dt}{t_2 - t_1}, \tag{8}$$

where $C_{CmHn} \cdot dt$–integral of the dataset of instantaneous concentration values in the heated dilute EG during the test $(t_2 - t_1)$; C_e–average integrated value of the concentration of hydrocarbons C_mH_n in diluted EG, mln^{-1};

Determination of particle mass. Particle emissions M_p are calculated according to the following relationship (in our case, gas samples are taken outside the channel), g/km

$$M_p = \frac{(V_{mix} + V_{ep}) \cdot P_e}{V_{ep} \cdot d}, \tag{9}$$

where V_{mix}–volume of diluted EG under standard conditions (273.2 K and 101.33 kPa), l/test; V_{ep}–volume of EG that has passed through the particle trapping filters under normal conditions, l/test; P_e–mass of particles, g; d–distance conditionally travelled by the vehicle per cycle, km.

Test Results of the Škoda Octavia 1.9Tdi

The study of fuel efficiency and environmental performance of a car engine is carried out according to the MNEDC. The normalised parameters for the test cycle are: mass fuel consumption per cycle, g/km; mass emissions of harmful substances from the engine: carbon monoxide, hydrocarbons, nitrogen oxides, and particles, g/km [37].

Figure 13 shows the programme for changing the speed $V = f(t)$ in the modified European driving cycle and the actual change in the speed $Vy = f(t)$ of the car on the

simulation roller stand. Figures 14, 15, 16, 17 and 18 show examples of instantaneous values of fuel consumption $G_f = f(t)$ and concentration of harmful substances: carbon monoxide C_{CO}; hydrocarbons C_{CmHn}; nitrogen oxides C_{NOx} carbon dioxide C_{CO2} in diluted EG when performing the European driving cycle by a car running on regular fuel [38]. The results of tests with different types of fuels are summarised in Tables 11 and 12.

The consumption of regular diesel fuel during the test of the car on the modelling roller stand is 484.781 g/cycle, and according to the data obtained during the calculation on the mathematical model–481.68 g/cycle, which once again confirms the adequacy of the calculation of fuel consumption on the mathematical model.

As previously noted, the incommensurability of the quantitative results of mass emissions of HS with exhaust gases obtained by direct analysis and in diluted EG makes it possible only to qualitatively compare the results of their change.

Table 13 shows a comparison of the qualitative change (%) in mass emissions of HS with exhaust gases when operating on three-component biodiesel fuel (20% MERO) when calculated on a mathematical model and when testing a car on a simulation roller stand.

Table 13 shows that the pattern of change in mass emissions of carbon oxides, hydrocarbons, nitrogen oxides, particulate matter and total toxicity obtained from the results of the calculation on the mathematical model is practically the same as the pattern of change in mass emissions obtained during the test of the car on the simulation roller stand (Figs. 13, 14, 15, 16, 17 and 18).
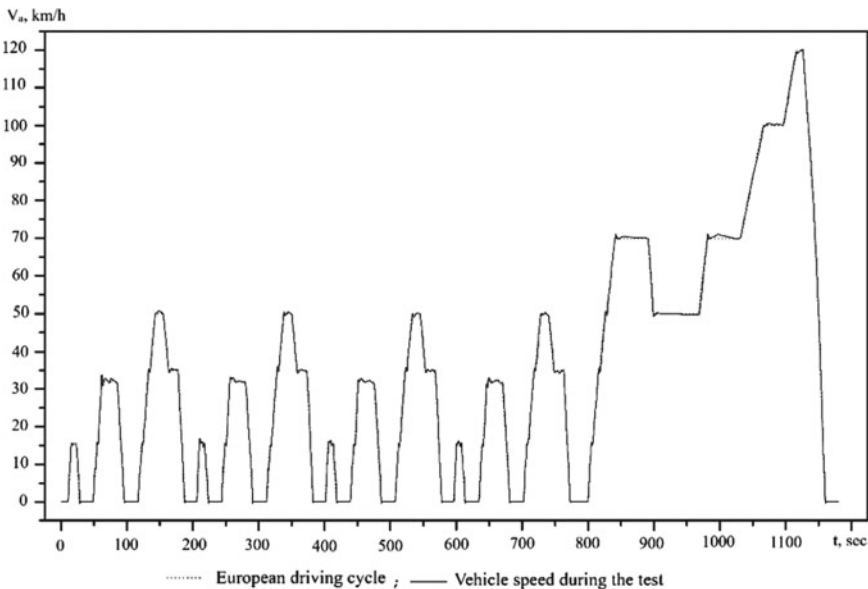
Fig. 13 Modified European Driving Cycle programme and actual change in vehicle speed
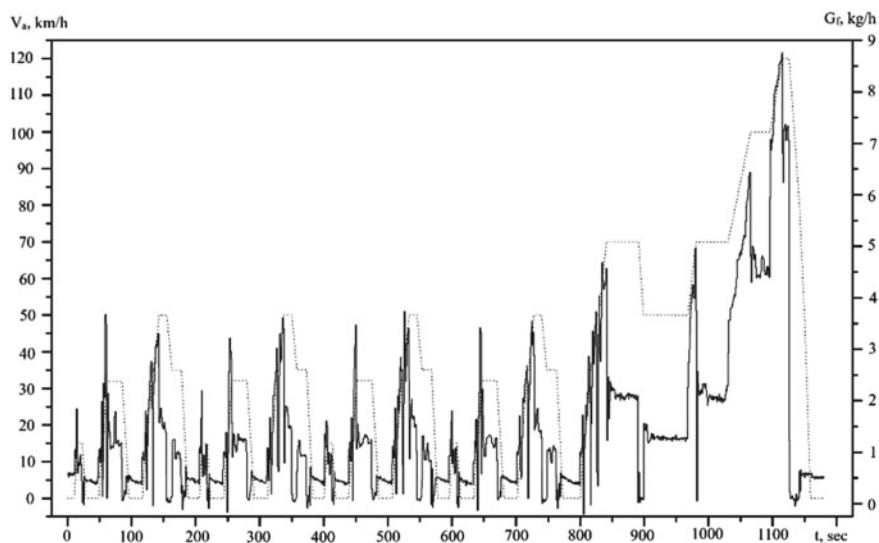
Fig. 14 Instantaneous fuel consumption of a car
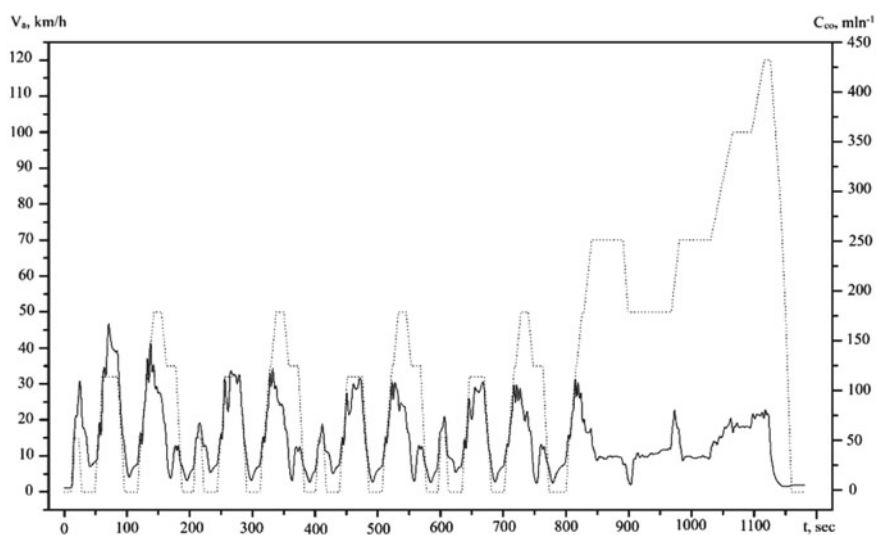
Fig. 15 Instantaneous concentration of carbon monoxide in dilute exhaust gases C_{CmHn}, mln^{-1}

The analysis of the results of car tests on a modelling roller stand under the conditions of the modified European driving cycle when running on regular and mixed biodiesel fuels shows that when the engine runs on biodiesel fuels, the consumption (g/cycle) increases by 4.6% when running on two-component biodiesel, and by 1.8% when running on three-component biodiesel. The fuels used in the research
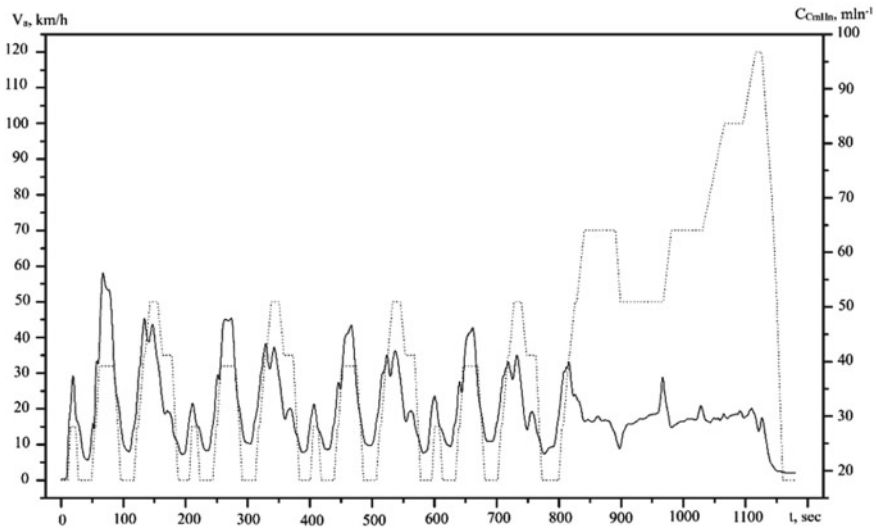
Fig. 16 Instantaneous hydrocarbon concentration in dilute exhaust gases
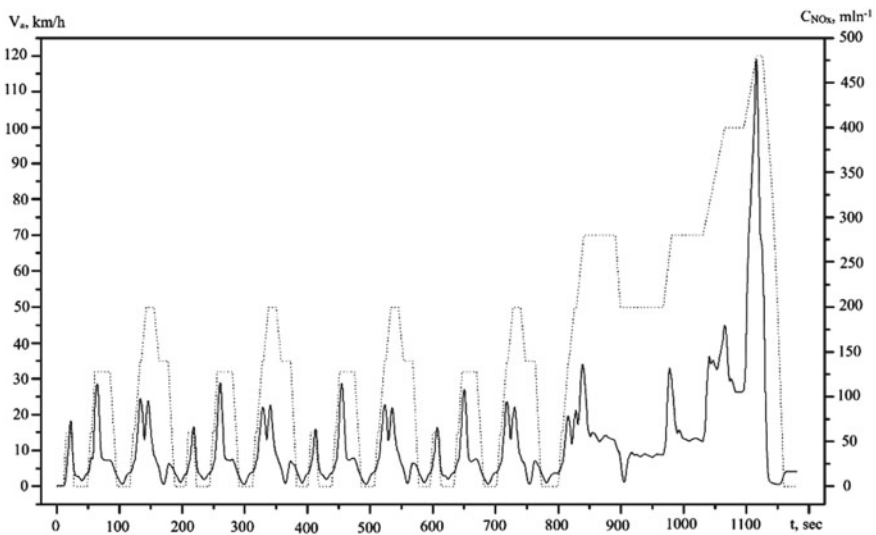

Fig. 17 Instantaneous concentration of nitrogen oxides C_{NOx} in diluted exhaust gases

have different lower heating values, so the quality of their heat use is assessed by the heat consumption (MJ/cycle) to perform equivalent work. Table 10 shows that when the engine runs on two-component biodiesel, there is a 2.12% increase in heat consumption compared to the heat consumed when running on regular diesel fuel to perform work in the driving cycle. When the engine runs on three-component
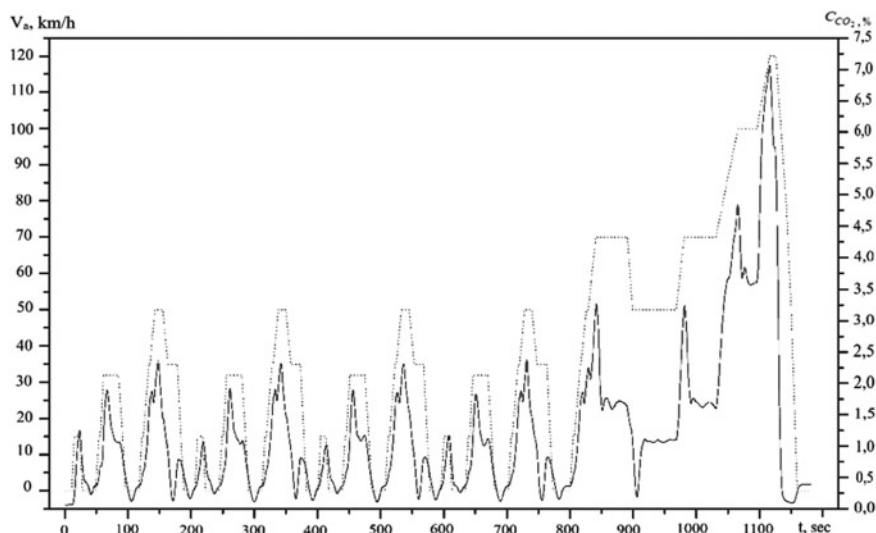
Fig. 18 Instantaneous concentration of carbon monoxide C_{CO2} in dilute exhaust gases

Table 11 Fuel consumption during testing of a car on a simulation roller bench in modified European driving cycle driving modes

Fuel	g/cycle	g/km	Change, %[a]	MJ/cycle	MJ/km	Change, %[a]
Regular diesel fuel	484.781	44.043	–	20.615	1.8729	–
2-component BF (20% MERO)	507.125	46.073	+4.6%	21.051	1.9125	+2.12%
3-component BF (20% MERO)	493.718	44.855	+1.8%	20.544	1.8674	−0.34%

[a] Change, %: + increase in fuel consumption or heat consumption; − decrease in fuel consumption or heat consumption

biodiesel fuel, there is a slight decrease in heat consumption (by 0.68%) to perform the same work.

Mass emissions of products of incomplete combustion: carbon monoxide G_{CO}, hydrocarbons G_{CmHn} and particles G_c. At the same time, mass emissions of nitrogen oxides G_{NOx} from the EG when the engine runs on two-component fuel (the kinematic viscosity of which is slightly higher) increase by 5.3% compared to mass emissions of nitrogen oxides G_{NOx} from the EG when the engine runs on regular DF. Mass emissions of nitrogen oxides G_{NOx} during operation on three-component biodiesel fuel are reduced by 6.2% (the kinematic viscosity of three-component fuels is equal to the kinematic viscosity of regular DF).

According to the test results, it was found that the total mass emissions of harmful substances from EG, reduced to CO, in the modified European driving cycle when

Table 12 Mass emissions of harmful substances during testing of a car on a simulator roller bench in modified European driving cycle driving modes

Mass of emissions of harmful substances	Fuel		
	Regular DF	2-comp. BF (20% MERO)	3-comp. BF (20% MERO)
G_{CO}, g/km	0.3568	0.2893	0.2808
		−18.9%[a]	−21.3%[a]
G_{CO2}[b], g/km	133.26	124.07	118.47
		−6.9%[a]	−11.1%[a]
G_{CmHn}, g/km	0.0854	0.0697	0.0687
		−18.4%[a]	−19.6%[a]
G_{NOx}, g/km	0.6095	0.6418	0.5717
		+5.3%[a]	−6.2%[a]
G_C, g/km	0.0421	0.0372	0.0365
		−11.8%[a]	−13.2%[a]
$G_{\Sigma CO}$, conv. g/kg	34.096	34.326	31.294
		+0.68%[a]	−8.22%[a]

[a] change, %: + increase in emissions; − decrease in emissions
[b] CO_2 is a non-toxic substance

Table 13 Relative change in emissions of harmful substances when testing a car on a simulation roller bench and calculating on a mathematical model when running on three-component biodiesel fuel (20% rapeseed oil methyl ester)

Type of research	Change in emissions compared to standard diesel fuel, %.*				
	CO (%)	C_{mHn} (%)	NO_x (%)	Particulate matter (%)	$G_{\Sigma CO}$ (%)
Calculation based on a mathematical model	−20.1	−21	−11.5	−8.8	−10.93
Tests on a simulated roller stand	−21.3	−19.6	−6.2	−13.2	−8.22

operating on two-component biodiesel fuel increase by 0.68%, and when operating on three-component fuel—decrease by 8.22% compared to standard diesel fuel.

4 Conclusions

1. The tests of the car on the modelling roller stand according to the modified European driving cycle, when running on two- and three-component biodiesel fuels, indicate that the mass emissions of incomplete combustion products are reduced: carbon monoxide G_{CO}; hydrocarbons G_{CmHn}; particles G_C. At the same time, the mass emissions of nitrogen oxides G_{NOx} rom the EG when the engine

runs on two-component fuel increase by 5.3% compared to the mass emissions of nitrogen oxides G_{NOx} from the EG when the engine runs on regular diesel fuel, and the mass emissions of nitrogen oxides G_{NOx} when running on three-component biodiesel fuel decrease by 6.2%.

2. Tests of a modern diesel car equipped with a regulated gas turbine supercharger, a EG recirculation system and an electronic crankshaft speed regulator showed that when the engine runs on three-component biodiesel fuel, mass emissions of the main harmful substances are reduced: carbon monoxide G_{CO} by 21,3%; total hydrocarbons G_{CmHn} by 19,6%; nitrogen oxides G_{NOx} by 6,2%; particles G_C by 13,2%; Improved efficiency of biodiesel use, reduced heat consumption by 2.46% to perform equivalent work compared to two-component biodiesel.

3. According to the test results, it was found that the mass emissions reduced to carbon monoxide in the modified European driving cycle when running on two-component biodiesel fuel increase by 0.68%, and when running on three-component fuel–decrease by 8.22% compared to regular diesel fuel.

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