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DETERMINING THE EFFECT OF SOY METHYL ETHER ADDITIVES TO COMMERCIAL DIESEL FUELS ON OIL CHANGE INTERVAL IN A 1.5 RENAULT DIESEL ENGINE, MODEL K9K

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This study explores viscosity-temperature characteristics of Castrol GTX RN-Spec 5W-30 engine oil and its oxidation resistance. The task addressed investigates the effect of adding SME to diesel fuels on the timing of oil changes in the engine.

The results showed that the maximum service life of Castrol GTX RN-Spec 5W-30 oil under specified conditions is 12 thousand km when operating on commercial diesel fuel. In the case of using mixtures of diesel fuel and 10, 20, and 50 vol. % SME, the maximum service life of cars before oil replacement according to viscosity-temperature characteristics is reduced from 9 to 6 thousand km, respectively.

The total base number (TBN) indicator of all experimental samples of engine oils reaches a critical value after a run of 9 thousand km. In general, the use of fuel mixtures with biodiesel based on soybean methyl ether in an amount of up to 50 vol. % does not require a significant reduction in the oil replacement period according to the TBN indicator.

The deterioration in the viscosity-temperature characteristics of Castrol GTX RN-Spec 5W-30 engine oil is explained by the fact that biodiesel fuel based on soybean methyl ether has a lower heat of combustion. The fuel mixtures do not have time to completely burn in the engine cylinders and, being washed away with the oil into the sump, partially dilute it.

The accumulation of biodiesel fuel in engine oil also contributes to a decrease in the alkaline number of Castrol GTX RN-Spec 5W-30 engine oil and accelerates its oxidation process.

The findings made it possible to move from general assumptions to specific regulations – reducing oil change intervals by 20–50% or introducing specialized engine oils.

The results of this work could be used in the field of car service to adjust the mileage limits before oil change when operating cars on biodiesel fuel

Keywords: alternative fuels, biodiesel, replacement terms, service life

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1. Introduction

Oil consumption in an engine significantly depends on its operating modes, the quality and type of fuel, as well as the operating conditions of the internal combustion engine (ICE). In an internal combustion engine, the operating conditions of the oil are extremely unfavorable: the combustion temperature reaches even above 2000°C, the engine crankshaft rotation speed can reach 6000 rpm. At these speeds, the piston must overcome the distance between the so-called dead centers of the cylinder 100 times per second with a speed of movement of up to 20 m/s, which requires the use of high-quality oils.

The choice of high-quality lubricant does not always provide high-quality protection of friction surfaces as the type and quality of fuel used in engines plays an important role.

Along with conventional types of commercial fuels, their alternative analogs are widely used. In particular, in [1, 2] the use of biodiesel fuel based on RME is proposed. The conversion of engines to diesel-hydrogen fuel is proposed in work [3]. In [4], the results from studying parameters of the DD15 diesel engine for the Sandvik LH514 loader in the process of using alternative fuels based on RME are reported. Experimental studies on a diesel engine operating on a mixture of diesel fuel and fusel oils are described in [5].

For gasoline engines, the use of pyrolysis gas [6] is proposed, as well as fuel made from Jerusalem artichoke [7] and biogas obtained from livestock waste [8].

Such a wide use of alternative fuels gives rise to a number of unsolved problems, in particular their impact on the quality indicators of motor oils and the timing of their replacement.

Therefore, studies aimed at identifying the impact of soybean methyl ether (SME) additives to commercial diesel fuels on the viscosity-temperature indicators of motor oil and its resistance to oxidation are relevant.

2. Literature review and problem statement

The results reported in [9] establish a relationship between oil change intervals and its quality, conditions, and operating modes of the engine. In [10] it was found that the service life of motor oil is also affected by the quality of the fuel used in the engines. However, the studies do not concern the use of biodiesel based on RME.

Research by scientists shows that oil change intervals also vary significantly depending on the region. For example, in China, 56.1% of car owners change their oil every 5000 km [11], in Europe – every 10000–30000 km [12], while in Mexico this interval is 10000 km for Mazda cars or 5000 km for Nissan cars [13]. For the most part, the cited studies are based on two characteristics – time and mileage, depending on which comes first, without considering the influence of other factors, including biodiesel additives.

In [14], the results of analyzing the physicochemical parameters of Castrol Edge 5W/30 motor oils and Castrol Magnatec 10W/40 semi-synthetic oil are reported. The exceeding of the limit values of such parameters as the degree of oxidation, water content, glycol content, total base number (TBN), total acid number (TAN) was established. However, the disadvantage of the study is that the oil was examined only after the expiration of its use period.

The authors of study [15] used samples of SAE 5W30 motor oil and analyzed the following parameters: viscosity, density, flash point, contamination with fuel and solids, degree of oxidation, dispersion ability. However, the data in the study relate to the use in the fuel supply system of commercial diesel fuel; therefore, they cannot be extended to biodiesel fuel.

In [16], research focused on the material compatibility of blends of methyl ester of karanja oil (biodiesel) with modern diesel engine equipment. It was found that blends of such biodiesel could be used in a CRDI engine without causing significant problems with engine durability or oil degradation. However, the study was conducted only for blends of diesel fuel and 20% karanja oil with a duration of 274 h, which is insufficient to detect the effect on oil degradation.

In [17], a comparison of the state of used diesel and gasoline engine oils was performed, focusing on nitration. The state of motor oil from diesel and gasoline vehicles was investigated and the exceeding of limit values of such parameters as oxidation, nitration, and residual content of amine antioxidants was established. However, the studies were conducted only for commercial gasoline and diesel fuels and therefore cannot be extended to other types of fuel.

Paper [18] showed that all used cars showed an increase in iron particles, increased silicon concentration, and an increase in nickel particles in the oil over 12,000 km. The disadvantage is that the authors used affordable low-carbon biofuel blends (B7 and E10).

In [19–21], the effects of using RME and B20 biodiesel on base oil aging and anti-friction performance were investigated. The results reported in [19] showed that using B20 biodiesel caused increased lead corrosion, fuel dilution and oxidation, and reduced oil viscosity. Findings from [20, 21] confirmed that RME biodiesel affects the degradation of motor oils and shortens their service life. A problematic component of studies [19–21] is that they were limited to the use of B20 biodiesel fuel, and the results do not take into account the post-warranty period of operation.

In [22], the obtained safflower methyl ester was mixed with diesel fuel in a ratio of 20% and 50% (vol.), and 100% SME was also used. However, the goal was to improve the environmental performance of the engine by coating the combustion chamber elements with chromium oxide by plasma spraying or layered graphene and MoS_2 [23]. These approaches are promising but they do not solve the issue of optimal oil change intervals.

In [24], a technology for obtaining biodiesel fuel based on soybean methyl ester (SME) is described. The main quality indicators of the resulting biodiesel fuel are established and the optimal composition in a mixture with commercial diesel fuel is proposed. This lays a basis for further research but does not answer the question of the influence of SME on the resource of motor oil.

In the considered literature, a sufficient number of studies on the influence of various factors on oil degradation have been reported. However, they lack generalized data on the degradation of engine oil when using biodiesel fuels RME, SME, B20 in the post-warranty period. There is no data on the optimal oil change intervals for engines running on biodiesel fuels, their compliance with manufacturers' recommendations, as well as the need for adjustment.

Thus, the basis for our study is the need for a scientifically based determination of the impact of biodiesel fuels on the resource of engine oil and the establishment of optimal intervals for its replacement, which could enable smooth engine performance throughout the entire period of operation.

3. The aim and objectives of the study

The purpose of our research is to establish a connection between the oil change intervals and the type of fuel used in the 1.5 Renault K9K diesel engine. This will make it possible to adjust the mileage depending on the volumetric content of SME-based biodiesel in diesel fuel.

To achieve the goal, the following tasks were set:

– to establish the influence of SME additives to diesel fuel on the change in density, kinematic viscosity, and viscosity index of Castrol GTX RN-Spec 5W-30 engine oil depending on the engine mileage;

– to derive experimental dependences of change in the flash point of Castrol GTX RN-Spec 5W-30 engine oil depending on its service life under the condition of using SME diesel fuel additives;

– to establish the influence of SME diesel fuel additives on the water content and change in the base number (TBN) of Castrol GTX RN-Spec 5W-30 engine oil depending on its service life.

4. The study materials and methods

The object of our study is the viscosity-temperature characteristics of Castrol GTX RN-Spec 5W-30 engine oil and its oxidation resistance.

The principal hypothesis assumes that the presence of biodiesel fuel residues in the experimental engine oil causes intensification of oxidation processes, which negatively affects the operational properties of the oil and can reduce the engine's service life.

Basic assumptions:

– Castrol GTX RN-Spec 5W-30 engine oil in its pure form has stable viscosity-temperature characteristics and sufficient oxidation resistance;

– biodiesel fuel residues may be in the crankcase of a diesel engine due to its incomplete combustion;

– biodiesel fuel residues are capable of entering into chemical reactions with engine oil, which can accelerate its degradation.

For simplicity, during the research, only the total mileage of cars was recorded and the possible influence of specific routes of their movement was discarded.

Sampling of oil for the study was carried out at the V.S.K. Renault Company, Ivano-Frankivsk (Ukraine), from November 2023 to November 2024.

All test vehicles were operated in the post-warranty period. The total mileage of the vehicles before the start of the tests did not exceed 145 thousand km. Table 1 gives specifications for the test vehicles before the tests.

Table 1

Technical characteristics of cars used in the study

No.	Model	Year	Engine capacity, l	Fuel type	Power, kW	Standard oil change interval, km*	Odometer readings, km
1	Renault Megane	2011	1.5	DF	80.9	10000	126000
2	Renault Megane	2011	1.5	DF + 10% SME	80.9	10000	132000
3	Renault Megane	2013	1.5	DF + 20% SME	80.9	10000	144000
4	Renault Megane	2011	1.5	DF + 50% SME	80.9	10000	135000

*Note: * – recommendations for Ukraine due to low quality diesel fuel.*

The vehicles used in this study were operated on fuel containing 10, 20, and 50% biodiesel by volume.

Before the start of the test, each vehicle was serviced and the engine oil was replaced with fresh Castrol GTX RN-Spec 5W-30 oil. The basic oil quality indicators according to the V.S.K. Renault Company are given in Table 2.

Table 2

Experimental quality indicators of Castrol GTX RN-Spec 5W-30 engine oil [25]

Indicator ID	Method	Units of measurement	Indicator value
1. Density of oil at 15°C	ASTM D4052	g/ml	0.855
2. Kinematic viscosity at 100°C	ASTM D445	mm^2/s	12
3. Kinematic viscosity at 40°C	ASTM D445	mm^2/s	73
4. Viscosity index	ASTM D2270	–	161
5. Pour point	ASTM D97	°C	–43
6. Flash point, PMCC	ASTM D93	°C	201
7. Sulphated ash	ASTM D874	% wt.	1.3
8. Total Base Number (TBN)	ASTM D2896	mgKOH/g	8.5

To assess the impact of SME biodiesel on oil aging, the mileage to mandatory oil change was divided into 5 parts during the tests. Then, periodic sampling was carried out every 3000 km with a small delay depending on possible operating conditions. Oil samples from each vehicle were taken with the engine warmed up to operating temperature (85–90°C) and cooled for a period of time not exceeding 2–3 min to limit possible particle deposition.

The oil samples were studied at the Laboratory of Automotive Operational Materials, Department of Automotive Transport, Ivano-Frankivsk National Technical University of Oil and Gas (Ukraine).

The density of motor oil was determined according to ASTM D4052 [26] with a maximum error of ±1%. To measure the density, we used an AON-1 hydrometer with a scale range of 820–880 kg/m^3, manufactured by PrAT "Skloprylad", Kyiv, V. Ivasyuka ave., 2G, Building 1 (Ukraine).

The viscosity of the motor oil was determined according to the ASTM D445 standard [27] with a maximum error of ±3%. To determine the viscosity, we used a set of VPZH-2 viscometers with capillary diameters from $(0.34 \text{ to } 4.5)\cdot 10^{-3}$ m manufactured by VAT "KHIMLABORREAKTIV", Brovary, Sich. Striltsiv str., 8 (Ukraine).

The kinematic viscosity of the oil (mm^2/s) was calculated from the following formula

$$\nu_t = c\tau, \tag{1}$$

where s is the viscometer constant, mm^2/s (taken from the manufacturer's passport); τ is the arithmetic mean oil flow time, s.

The viscosity index of motor oil was determined according to the ASTM D2270 standard [28]. According to the standard, the viscosity index of oil samples was calculated based on their kinematic viscosity at 40°C and 100°C.

The flash point was studied in accordance with the ASTM D93 standard [29]. According to this method, tests were performed on a manual Pensky-Martens device in a closed crucible with an accuracy of ±1%, manufactured by Koehler Instrument Company, Inc., New York, Sycamore Ave, Bohemia, NY 11716, (USA).

The water content in oil was studied using a Dean and Stark device manufactured by PrAT "Skloprylad", Kyiv (Ukraine). According to the methodology, 100 ml of oil is poured into a dry flask using a graduated cylinder, 100 ml of solvent is added using the same cylinder and mixed thoroughly. To prevent shocks and ejections of liquid during boiling, several glass capillaries are placed in the flask. The flask with the oil sample under study is heated so that 2...4 drops of condensate fall into the trap from the end of the refrigerator tube per second. Heating of the flask is stopped when the volume of water in the trap stops increasing and the upper layer of the solvent becomes transparent.

The water content in the oil in mass percent was calculated from the following formula

$$W_{mass} = \frac{\rho V_0 100}{V}, \tag{2}$$

where ρ is the density of oil at 15 °C, g/cm^3;

V_0 is the volume of water in the trap, cm^3;

V is the volume of the oil sample, cm^3.

The water content in oil in volume percent was calculated from the following formula

$$W_{volume} = \frac{V_0 100}{V}. \tag{3}$$

To assess the deterioration of engine oil quality under operating conditions, the alkaline number (TBN) was determined according to the ASTM D4739 standard [30]. This test method involves the determination of the alkaline components of lubricants by titration with hydrochloric acid in a mixture of isopropanol, toluene, chloroform, and water. This method makes it possible to record a decrease in the base number in the presence of almost all acids that can be found in the combustion zone.

In the process of studying TBN according to the ASTM D4739 standard, an automatic titrator GT-310 was used in the basic configuration with a glass pH electrode GTPH1B for acid-base titration. A silver chloride electrode GTRS10B (Ag/AgCl, 1…3 M LiCl, ethanol) was used for titration in non-aqueous solutions. All equipment was manufactured by Nittoseiko Analytech Co. Ltd, Japan. The discreteness of the burette dosing of the device 0.001 cm^3 corresponds to the established method of accuracy for measuring the volume of the titrant. The limits of permissible relative measurement error are ±2%.

5. Results of investigating the influence of soybean methyl ether additives on engine oil quality indicators

5. 1. Results of studies on changes in density, kinematic viscosity, and viscosity index of Castrol GTX RN-Spec 5W-30 oil

The results of determining the density of samples of Castrol GTX RN-Spec 5W-30 engine oil, which was operated on Renault Megane cars with a turbocharging system on diesel fuel, a mixture of diesel fuel and 10% vol. SME and a mixture of diesel fuel and 20% SME at a temperature of 15°C are shown in Fig. 1.

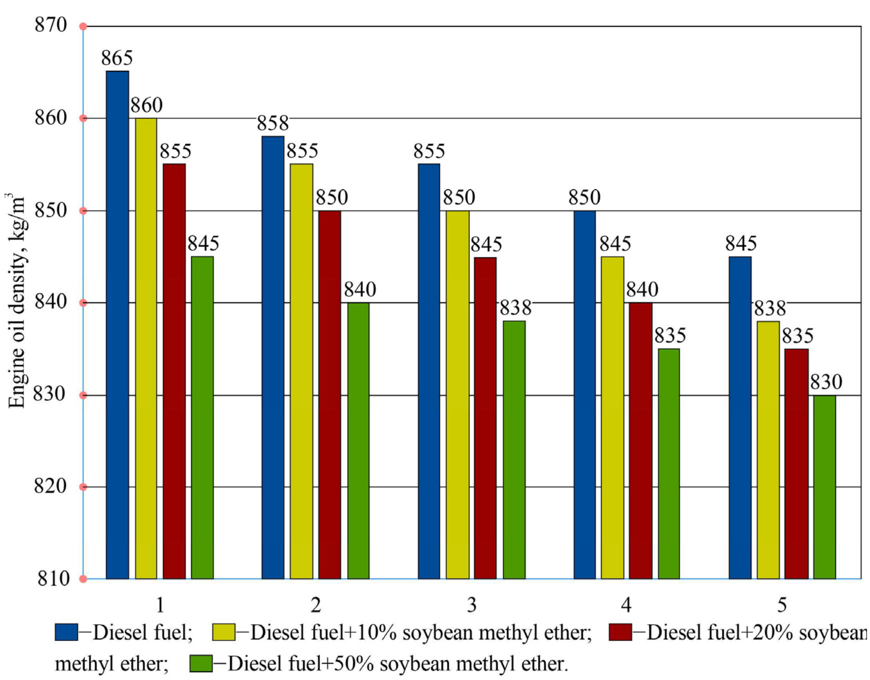

Fig. 1. Change in the density of Castrol GTX RN-Spec 5W-30 engine oil depending on the service life at a temperature of 15°C: vehicle mileage: 1 — 3 thousand km; 2 — 6 thousand km; 3 — 9 thousand km; 4 — 12 thousand km; 5 — 15 thousand km

According to the density indicator, Castrol GTX RN-Spec 5W-30 engine oil should be replaced when it drops below 850 kg/m^3. As shown in Fig. 1, the lowest dynamics of oil density decrease are observed when operating a Renault Megane car on commercial diesel fuel. Under such conditions, the oil should be replaced at 12 thousand km of mileage.

When operating cars on mixtures of diesel fuel and 10, 20, and 50% vol. SME, the maximum service life of cars before oil replacement is reduced from 9 to 6 thousand km, respectively.

Kinematic viscosity should enable reliable engine operation in a wide temperature range. High-quality oils should have low viscosity at low air temperatures to ensure easy engine start. And, accordingly, high viscosity at engine operating temperatures to enable high lubricating properties, that is, the viscosity should change little with temperature changes.

The results of our study on the change in kinematic viscosity and viscosity index of Castrol GTX RN-Spec 5W-30 motor oil during the use of biodiesel additives from 10 to 50% vol. are shown in Fig. 2–4. The maximum relative error in determining kinematic viscosity is ±3%.

The curves of changes in the viscosity of motor oil shown in Fig. 2, 3 are described by the following approximate dependences with coefficients of determination ranging from 0.993 and 0.997, respectively

$$\nu_t = -a \cdot L^2 - b \cdot L + c, \qquad (4)$$

where a, b, c are the experimental coefficients given in Table 3, determined by the least squares method;

L is the mileage of test cars, km.

Table 3

Experimental coefficients for equation (4)

Fuel type	Coefficient values		
	a	b	c
At an oil temperature of 100°C			
DF	0.008	0.0916	15.765
DF + 10% SME	0.0024	0.1759	15.482
DF + 20% SME	0.0024	0.1624	14.956
DF + 50% SME	$4 \cdot 10^{-16}$	0.2563	14.794
At an oil temperature of 40°C			
DF	0.0437	0.5976	101.2
DF + 10% SME	0.0635	0.1571	97.3
DF + 20% SME	0.0595	0.2119	95.9
DF + 50% SME	0.0159	1.4143	96.3

The results of our study on the kinematic viscosity and viscosity index of Castrol GTX RN-Spec 5W-30 oil, which was operated on Renault Megane cars with a turbocharging system on diesel fuel, a mixture of diesel fuel, and 10, 20, and 50% vol. SME (Fig. 2–4) indicate a decrease in its kinematic viscosity and viscosity index. Thus, the results of the study of oil samples from a car operated on diesel fuel show the limit values of the kinematic viscosity and viscosity index for 9 thousand km of mileage. A further increase in the car's mileage to 15 thousand km leads to a decrease in the viscosity index by 6.2% below the norm, which will lead to increased wear of friction pairs on the engine.

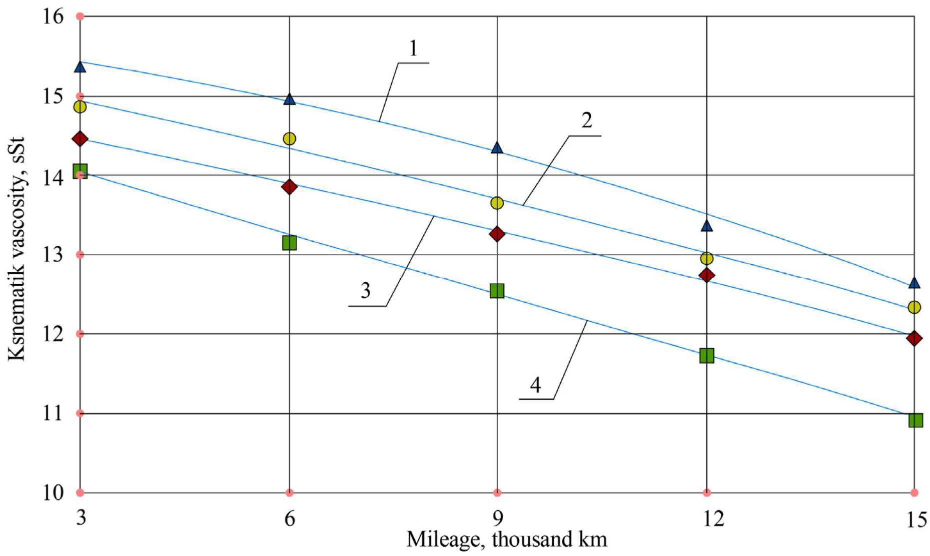

Fig. 2. Change in kinematic viscosity of Castrol GTX RN-Spec 5W-30 engine oil depending on the service life at a temperature of 100°C: 1 — engine operation on diesel fuel; 2 — diesel fuel plus 10% soy methyl ether; 3 — diesel fuel plus 20% soy methyl ether; 4 — diesel fuel plus 50% soy methyl ether

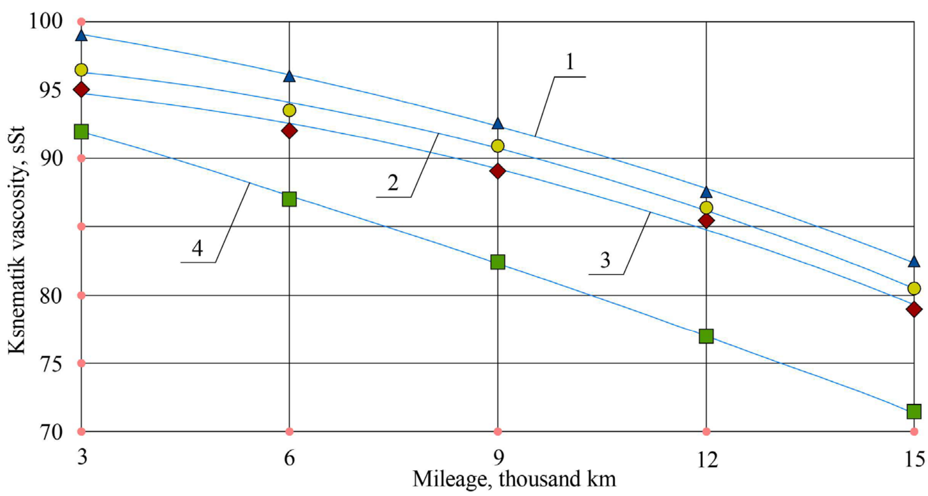

Fig. 3. Change in viscosity of Castrol GTX RN-Spec 5W-30 engine oil depending on the service life at a temperature of 40°C: 1 — engine operation on diesel fuel; 2 — diesel fuel plus 10% soy methyl ether; 3 — diesel fuel plus 20% soy methyl ether; 4 — diesel fuel plus 50% soy methyl ether

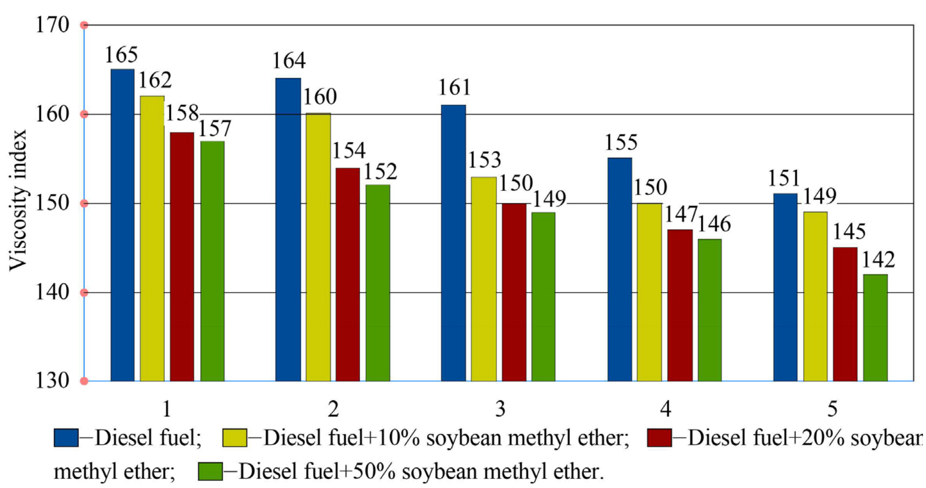

Fig. 4. Change in viscosity index of Castrol GTX RN-Spec 5W-30 engine oil depending on the service life: 1 — 3 thousand km; 2 — 6 thousand km; 3 — 9 thousand km; 4 — 12 thousand km; 5 — 15 thousand km

Under the condition of operation of Renault Megane cars on diesel fuel with the addition of 10, 20, and 50% vol. SME limit values of kinematic viscosity and viscosity index will be after 6 and 3 thousand km of run, respectively. And, therefore, in the process of using diesel fuel mixtures with a SME content of 10% vol. and more, it is necessary to reduce the oil service life by 40% compared to operation on commercial diesel fuel.

5. 2. Results of the study on a change in the flash point of Castrol GTX RN-Spec 5W-30 oil

The flash point characterizes the flammability of the oil product. It can also be used to determine the presence of low-boiling point impurities in fuel and lubricants. When fuel enters the engine oil during engine operation, its flash point decreases significantly, due to which the oil is liquefied and its consumption increases. For oils of the same viscosity class, for example, 10 mm^2/s at 100°C, a decrease in the flash point from 250°C to 218°C can cause oil overconsumption due to increased burnout for diesel engines by 10...15%.

The results of our study on the flash point of Castrol GTX RN-Spec 5W-30 oil are represented in the form of a graphical dependence in Fig. 5. The accuracy of measuring the flash point in a closed crucible on a manual Pensky-Martens device is ±1%.

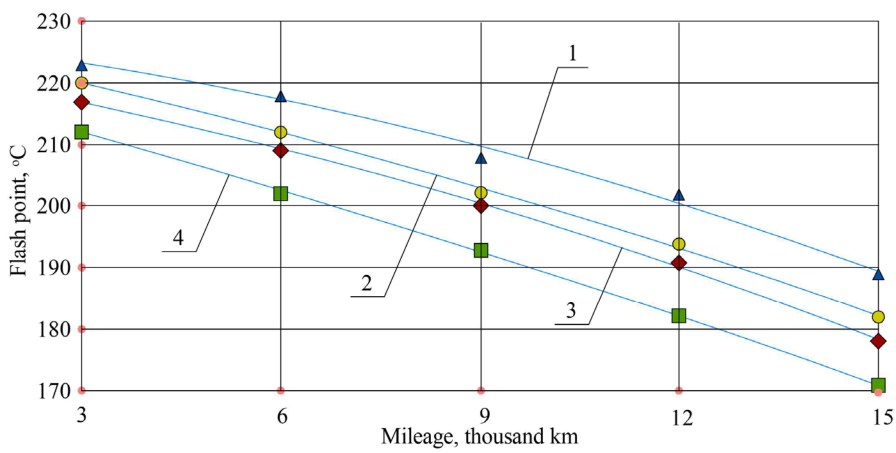

Fig. 5. Flash point of Castrol GTX RN-Spec 5W-30 engine oil depending on the service life: 1 – engine operation on diesel fuel; 2 – diesel fuel plus 10% soy methyl ether; 3 – diesel fuel plus 20% soy methyl ether; 4 – diesel fuel plus 50% soy methyl ether

The obtained curves of changes in the flash point of motor oil in Fig. 5 can be described by the characteristic equation (5) with determination coefficients ranging from 0.991 and 0.998, respectively

$$t_{fl} = -a_1 \cdot L^2 - b_1 \cdot L + c_1, \quad (5)$$

where a_1, b_1, c_1 are experimental coefficients given in Table 4, determined by the least squares method;

t_{fl} is the flash point of motor oil in a closed crucible, °C.

Table 4

Experimental coefficients for equation (5)

Fuel type	Coefficient values		
	a_1	b_1	c_1
DF	0.0952	1.0857	227.2
DF + 10% SME	0.0476	2.2762	227.2
DF + 20% SME	0.0794	1.7714	222.8
DF + 50% SME	0.0317	2.8286	220.6

For the experimental Renault Megane car, which operated on commercial diesel fuel for a mileage of 10 thousand km, according to Fig. 5, the flash point was observed to comply with the regulatory data in Table 2. An increase in the car's mileage to 15 thousand km leads to a decrease in the flash point below the regulatory one by 6%, which indicates dilution of the oil with unburned diesel fuel and will lead to an increase in its consumption for burnout, deterioration of lubricating properties.

During the operation of the Renault Megane car on fuel mixtures of diesel fuel and 10% vol. SME, the vehicle's maximum mileage in terms of the oil flash point is set at 9 thousand km. An increase in mileage to 15 thousand km on the specified fuel mixtures contributes to a decrease in the flash point by 9.5% below the regulatory one, which will lead to an increase in negative consequences for the engine compared to operation on commercial diesel fuel.

The results of investigating the operation of the Renault Megane car on fuel mixtures of diesel fuel and 20% vol. SME show that the maximum service life of the car in terms of the oil flash point is close to 9 thousand km, and an increase in mileage to 15 thousand km worsens this indicator by 11.4% below the standard.

The results of investigating the operation of the Renault Megane car on fuel mixtures of diesel fuel and 50% vol. SME show that the maximum service life of the car in terms of the oil flash point is close to 7 thousand km, and an increase in mileage to 15 thousand km worsens this indicator by 15% below the standard.

5. 3. Results of research on a change in the alkaline number of Castrol GTX RN-Spec 5W-30 oil

The harmful effect of water in oil is that at negative temperatures water freezes, causing increased mechanical wear, has a catalytic effect on the oxidation processes of oil, accelerates the rate of formation of low-temperature deposits. Water in oil can cause corrosion of ferrous metal parts and intensifies corrosion of bearing liners and other parts made of non-ferrous metals and alloys. When the temperature rises, in the presence of water, the oil foams, its loss increases, lubricating properties deteriorate and additives are washed out. The latter circumstance is the most dangerous. A relatively small amount of water (0.1...0.2%) is capable of decomposing more than half of the additives contained in the oil within a few days. Therefore, it is necessary to prevent atmospheric precipitation or other sources of water from entering the engine oil.

A study on the water content in Castrol GTX RN-Spec 5W-30 oil using a Dean and Stark device showed that for all operating modes of Renault Megane cars, the water content was in the range of 0.01 to 0.02 cm^3. This indicator is considered traces of water and does not have negative consequences for the engine.

Fig. 6 shows the results of determining the TBN alkaline number of used oil when the engine is running on diesel fuel and its mixtures with 10, 20, and 50% vol. biodiesel. The permissible relative error of TBN measurements was within ±2%. As soon as the alkaline additives are depleted beyond a certain limit, the lubricant no longer performs its function, and the engine is at risk of corrosion, sludge, and varnish formation. At this point, it is necessary to top up or replace the oil.

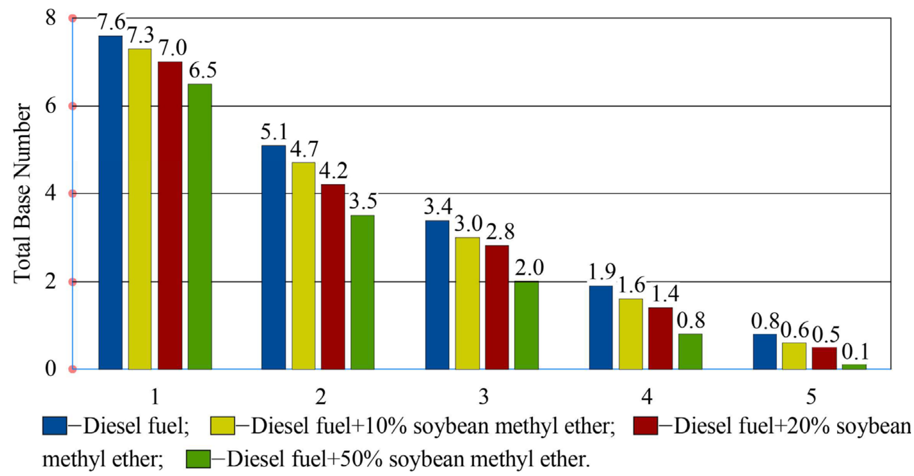

Fig. 6. Change in the total basic alkaline number of Castrol GTX RN-Spec 5W-30 engine oil depending on the service life: 1— 3 thousand km; 2 — 6 thousand km; 3 — 9 thousand km; 4 — 12 thousand km; 5 — 15 thousand km

According to the results from TBN studies, Fig. 6, it was found that the maximum service life of the oil according to this indicator is the same for all samples and is 9 thousand km. After this mileage, the TBN level is ≤ 2 mgKOH/g, which is critical for this indicator, and its further decrease causes the risk of corrosion, sludge, and varnish formation.

6. Discussion of results based on studying the influence of soybean methyl ether additives on engine oil quality indicators

dCi engines are a very complex mechanism in which many factors can affect the deterioration of the viscosity-temperature properties of the oil.

An increase in the volumetric content of SME additives in diesel fuel leads to an increase in the rate of decrease in density (Fig. 1), kinematic viscosity (Fig. 2, 3), and viscosity index (Fig. 4) of Castrol GTX RN-Spec 5W-30 engine oil. Moreover, it should be noted that these phenomena are also observed with an increase in the mileage of test cars. This is explained by the fact that biodiesel fuel (SME) has a lower calorific value and as a result, its overconsumption in the power system occurs. Such fuel mixtures do not have time to burn completely in the internal combustion engine cylinders and, being washed out with the oil into the sump, partially dilute it.

The decrease in the flash point of Castrol GTX RN-Spec 5W-30 engine oil (Fig. 5) with increasing service life is explained by the accumulation of unburned fuel in it, and the addition of SME accelerates this process. This can also be explained by the accumulation of unburned fuel in the oil.

Since the accumulated biodiesel in the oil contains an additional amount of oxygen, this contributes to a decrease in the base number (TBN) of Castrol GTX RN-Spec 5W-30 engine oil (Fig. 6) and accelerates its oxidation process.

Studies [31, 32] focus on fuel economy and protection of engine parts from wear through an individual approach to choosing oil for a specific engine. The experimental analysis of engine oil degradation allows for protection of engine parts from wear through a rational choice of its service life.

Works [33–35] propose adding additives and viscosity modifiers to the oil to improve the operational properties of the oil. The results of studies show that when using SME diesel fuel additives in an amount of 50%, it is impossible to completely restore the operational properties of the oil with additives.

In general, although there are recommendations for the optimal oil change interval for both diesel and gasoline vehicles [11–13], the use of fuel mixtures of commercial diesel fuels and SME in an amount of up to 50% vol. does not require a reduction in its service life according to the TBN indicator.

Therefore, the results of our study could be used by car owners to adjust the engine oil mileage before replacement, provided that biodiesel fuels are used in the fuel system. Compliance with the recommendations for oil change intervals proposed in our work will reduce the impact of biodiesel fuel on the engine resource.

However, the research had a number of limitations, namely urban operating conditions, seasonality of the research, and the use of one car model. Therefore, further studies should significantly expand car models and car operating conditions.

The disadvantages of our study include the use of test cars with an engine with a Common Rail power supply system; therefore, in the future, the research should be extended to diesel engines of other modifications.

7. Conclusions

1. In the oils that we have studied, a decrease in the density of the engine oil was observed during operation, so the maximum service life according to this indicator is 12 thousand km when operating on commercial diesel fuel. In the case of using SME biodiesel additives with a volume fraction of 10, 20%, these terms are reduced to 9 thousand km. According to the viscosity indicators of Castrol GTX RN-Spec 5W-30 oil during operation in Renault Megane cars with a turbocharging system on diesel fuel, a mixture of diesel fuel and 10% vol. SME and a mixture of diesel fuel and 20% SME, a decrease in its kinematic viscosity and viscosity index was established. Thus, the results of research on oil samples from a car that was operated on diesel fuel show the limit values of kinematic viscosity and viscosity index after 9 thousand km of run, an increase in the car's run to 15 thousand km leads to a decrease in the viscosity index by 6.2% below the norm, which will lead to increased wear of friction pairs on the engine. Under the condition of operation of Renault Megane cars on diesel fuel with the addition of 10 and 20% vol. SME, the limit

values of kinematic viscosity and viscosity index will be after 6 and 3 thousand km of run, respectively.

2. The results of research on the flash point of oil from a Renault Megane car that was operated on commercial diesel fuel after a run of 10 thousand km meet the standards for Castrol GTX RN-Spec 5W-30 motor oil. Increasing the car's mileage to 15 thousand km leads to a decrease in the flash point below the standard by 6%, which indicates dilution of the oil with unburned diesel fuel and will lead to an increase in its consumption for burnout, deterioration of lubricating properties. When using fuel mixtures of diesel fuel and 10% vol. SME, the limit mileage of the car in terms of the oil flash point is set to 9 thousand km.

3. The results of our study on the water content in Castrol GTX RN-Spec 5W-30 oil selected from Renault Megane test cars showed its content in the range from 0.01 to 0.02 cm^3. This content is considered traces of water and will not lead to negative consequences for the internal combustion engine. The total base number (TBN) for all test samples of motor oils acquires a critical value at a mileage of 9 thousand km, where TBN $\leq$ 2 mgKOH/g. Further reduction in TBN increases the risk of corrosion of metal engine parts and the formation of varnish deposits.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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Authors' contributions

Vasyl Melnyk: Conceptualization, Investigation, Supervision, Project administration; **Maria Hnyp:** Formal analysis, Writing – original draft, Writing – review & editing; **Ihor Zakhara:** Methodology, Visualization, Funding acquisition; **Ivan Mykytii:** Software, Validation.

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