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Evaluation of the antiwear properties of timely changed engine oils

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The article presents the results of tests, replaced according to the vehicle manufacturer's recommendations, of engine oils. The sample of engine oils in service came from spark-ignition and compression-ignition vehicles used in urban or mixed mode. During their collection, the type of drive unit, the mileage of the car and the number of kilometers the oil was used for were recorded for each sample (this was the main criterion for differentiating samples). In addition, a control group of samples consisting of fresh oils of the same viscosity grade and distributed by the same producer was set up to observe changes in the parameters of individual lubricants after the operating period. The first part of the empirical study consisted of determining the physico-chemical properties of the lubricants, i.e.: kinematic viscosity, density and water content. The second part involved anti-wear tests using a T-02U tribometer. The use of the tribometer made it possible to record the anti-wear parameter, i.e. moment of friction, and also the load imposed on the friction node, as a result of which it was possible to calculate the friction force and friction coefficient. The research was complemented by an analysis of worn surfaces of the friction node on a microscope. The tests carried out can be used for predictive purposes, in terms of assessing the condition of a lubricant subjected to an operating process in an internal combustion engine.

Key words: *combustion engines, viscosity, density, water content, wear*

1. Introduction

It is estimated that approximately 23% of total energy consumption worldwide is related to friction. The negative effects can be reduced by using lubricants. The use of such measures, among others, can reduce the aforementioned energy consumption by 40% in the long term and by 18% in the short term [10]. In addition to its primary function – lubrication – engine oil also has the task of dissipating heat, among other things. Protection in the broadest sense also includes preventing corrosion and cleaning the interior of the engine from wear products by accumulating wear products and transferring them to the filter [17].

As the lubricant is used, its parameters change [24], which is associated with a loss of protective properties. This is influenced by the thermal oxidation process [23], which determines the darkening of the fluid and an increase in its viscosity. The products of this process contribute to the formation of viscous fractions, which can cause blockages in filter cartridges. Too low viscosity, on the other hand, can be caused by the penetration of fuel or coolant into the oil [16]. The properties of the lubricating oil are also affected by aspects such as the presence of worn particles of drive unit components, soot or exhaust gas [20]. Observing the dynamics of changes in the physico-chemical properties of engine oils can provide information about possible damage to the unit.

Because of the variable nature of lubricant viscosity during the exploitation process, researchers often refer to it. The article [13] focused on the study of viscosity changes depending on the mileage of the vehicle sampled. The experiment was conducted on oils from compression-ignition (CI) and spark-ignition (SI) engines. The analysis of the results showed that, based on this parameter for the group of oils from CI engines, it is possible to estimate the approximate mileage at which an oil change is necessary. An attempt to capture the correlation between lubricant viscosity and wear resistance of sliding nodes was made in his work by Ryniewicz [19]. He performed viscosity tests over a wide temperature range for engine oils differing in viscosity class and manufacturer. The results show that despite the same oil designation according to SAE classification, viscosity characteristics differ between samples from different manufacturers. These differences are particularly apparent in the non-catalog range for measurements at 40 and 100°C. Another paper focusing on viscosity is that of Ghannam [9]. In this case, used and fresh oil samples were juxtaposed. This approach allowed a conclusion to be drawn regarding the difference in viscosity characteristics created due to the type of power unit. Viscosity is sensitive to the lubricant's degree of wear and tear and the way it is used, which provides a reasonable basis for using this value as an indicator during research dedicated to engine oils.

The driving style of the driver influences the condition of the engine oil. The lack of smoothness of the drive unit, understood as city traffic, as well as often starting the engine at low temperatures can result in the accumulation of water in the engine. This results in an emulsion that is characterized by a higher viscosity and therefore does not lubricate the engine as effectively as fresh oil [14]. Another adverse effect of water in the lubricant is the increased danger of corrosion of system components [8]. In his work, Jakubiec [14], based on processes occurring during operation, provides a set of methods useful in assessing the properties of engine oils. One of the proposed parameters is the determination of water content in a sample following ASTM D 95. An alternative is to use the Karl Fischer coulometric titration method, which was used by Jędrychowska in her work [15]. In a subsequent paper [22], a team of researchers focused on the diagnostics of a drive unit based on lubricant properties. One of the parameters determined was the water content, which after the test exceeded the permissible limit, which the authors considered as a reason for immediate lubricant replacement. The frequent use of water content in engine oil as an indicator of irregularities related to the operation of a drive unit, and as a parameter conditioning the reduced suitability of a lubricant to protect cooperating elements, motivates its use when analysing the impact of the value of this parameter on the antiwear characteristics of the system.

As the lubricant is used, the content of wear products from the system also increases. Such contaminants contribute to an increase in the density of the substance [23]. As presented in the article [24], increased density can be an indicator of progressive oxidation of the sample. As studies available in the literature [21] show, there is an apparent correlation between lubricant density and lubricant viscosity. This translates directly into lubricant properties in terms of friction as well as wear. This parameter can successively be used to determine the relationship between the properties of fresh and degraded oils. Such an approach was presented in their work by Landowski and Baran [17]. One type of engine oil (5W30) – fresh and used – was tested. The methodology included a comparison of three parameters with each other, which were density, viscosity and viscosity index. Based on the results, the authors conclude that the observed changes can be used as an indicator to determine the condition of the drive unit.

In addition to focusing on the properties of the lubricant, it is worth deepening the analysis by performing tests using the kinematic node that the oil protects. Machines that enable such tests are tribometers. [18]. One of the most commonly used tribometers is the T02-U four-ball tribometer. The work of Farhanah [7] was dedicated to testing engine oils of the same SAE viscosity class (10W30) from three different manufacturers. During the experiment, the temperature (40, 70, 100°C) and speed were changed stepwise. As the results show, despite the identical designation of the lubricants, they exhibit different lubricating properties. A different approach, a comparison of two groups of oils – synthetic and mineral – is presented in the paper [21].In addition to recording the basic physicochemical properties of the engine oils, the authors examined them using a T02-U tribometer. Through correlation analysis, it was proven that the frictional properties of lubricants are influenced by their viscosity. This conclusion is only possible if the analysis is extended to include wear testing. Another application of the four-ball tester in the analysis of the properties of petroleum products was the work of [11]. In this study, the effect of carbon black, on the tribological properties of engine lubricants was investigated. The result of the study was one of the conclusions indicating engine oil as having better antiwear properties than base oil.

The purpose of this study is to obtain data to develop an assessment of the condition of a lubricant subjected to service in a combustion engine. Most of the literature sources are based on the analysis of the physico-chemical parameters of fresh or used oils, or of the wear tests. Some of the tests involve artificial contamination of samples with wear products. In the present study, the focus will be on lubricants subjected to operation under real conditions, i.e. in an internal combustion engine. It is hoped that the juxtaposition of data from physico-chemical and tribological tests will contribute to the knowledge of changes in the properties of lubricants that have been subjected to service. The paper consists of four chapters. The first contains a literature review related to the issue under consideration. The second describes the methodology of the research carried out. Another, the third, is designed to present the results of the empirical research. The last chapter contains a summary and conclusions of the analysis.

2. Methodology

The experiments carried out are part of a planned comprehensive study of the effects of lubricant properties on the system in which they operate and on the components they protect from wear. Figure 1 shows in yellow the scope of the work envisaged in the current section, the results of which are described in the article, while grey shows further experiments related to the extension of the analysis.

The empirical research consisted of two parts. The first involves testing lubricants for their physico-chemical properties. This included measuring the viscosity, density and water content of fresh and used oil samples. Carrying out wear tests using a T02-U tribometer (four-ball machine) formed the second part of the laboratory tests.

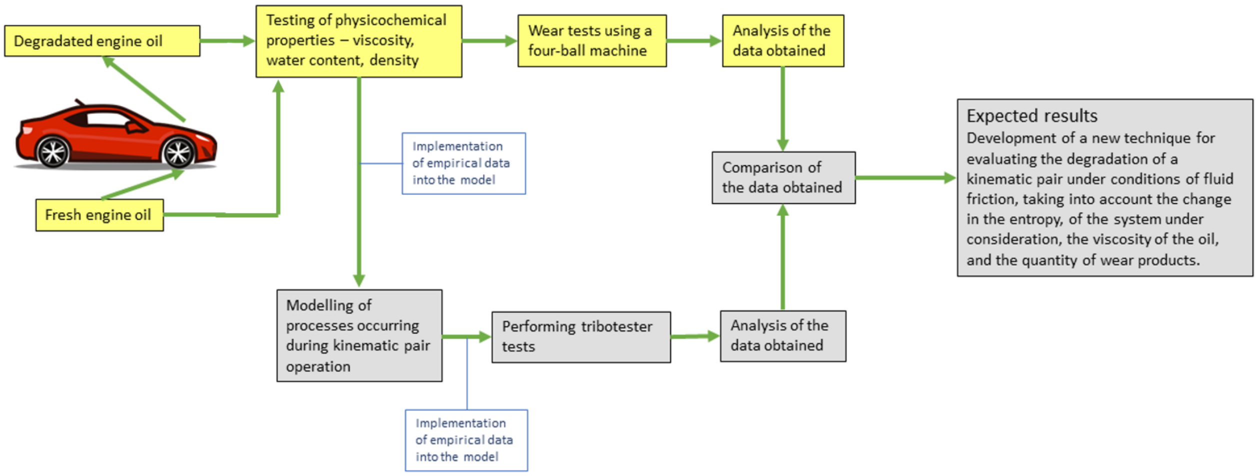


Fig. 1. Scheme of planned research

2.1. Research object

Table 1 shows eleven selected used oil samples, which were assigned fresh oil samples characterised by the same viscosity class and manufacturer (attention was also paid to the additives contained in the oil). During the collection of used oil samples, data related to the characteristics of the drive unit and its mileage was extracted. In addition, to simplify the determination of the samples, each sample was marked with an individual laboratory number, which is recorded in the first column of the table. The viscosity of the prepared samples was determined using an automatic mini AV-X viscometer. Measurements were carried out at temperatures of 40°C – under EN ISO 3104:2020 [5] – and 75°C. The higher measurement temperature provided a reference point for tribological tests, which were performed at the same temperature.

For the determination of the water content of the samples, the testing methodology was based on EN ISO 12937:2000 [3]. The Cou-Lo Aquamax KF apparatus was used for the tests. Samples for the test were fed at 1 cm^3.

The density of the samples was determined using a standardised areometer with a range of 0.8–1.0 $g \cdot ml^{-1}$. The tests were carried out taking into account the lubricant density test temperature given in EN ISO 3675:1998 [6]. Analogous to the viscosity measurement, due to tribological testing, the second density determination test was carried out at 75°C.

The tribological process test was performed following EN ISO 20623:2018 [4]. Another document that specifies the test conditions is ASTM D 4172-94 (Method B) [1]. The test time was 3600 s. The spindle speed was 1200 rpm, the node was loaded with a force of 392 N. The temperature of the lubricant was 75°C. The balls from the kinematic node were visually inspected and measured using a microscope (HUVITZ HRM 300). According to the standard, the diameter of the wear marks formed on the lower balls was measured for each test performed and the average wear diameter was determined from these.

Following the empirical tests, an analysis of the data obtained was carried out and the correlation between the physicochemical and tribological properties of the tested engine oils and their effect on the state of the kinematic junction was determined.

3. Results

A mileage index was used to compile the data, which takes into account both the P_P vehicle mileage and the P_O oil mileage. It was calculated from the equation:

$$W_P = 1 - \frac{P_O}{P_P} \qquad (1)$$

where: W_P – mileage index [-], P_O – oil mileage [km], P_P – vehicle mileage [km].

This approach makes it possible to take into account both performance variables that characterise the test group. If the W_P value is close to zero, it can be concluded that the sample came from a low mileage vehicle. As this indicator increases and approaches a value equal to 1, it can be assumed that the vehicle has a lower operating potential (the operating parameters of the vehicle may be worse than those of a new vehicle).

3.1. Results of physico-chemical tests

The data obtained from the physico-chemical tests were ranked according to the adopted split concept concerning the W_P index (table 2). The oil that had the lowest mileage index is 0w30 distributed by the Volkswagen Group. The sample was characterised by the fact that it was taken from a new car and the oil change interval was within the manufacturer's recommended interval. By comparing the results of this sample with fresh oil from the control group, it can be seen that the viscosity and density parameters are similar. The fresh oil showed a 5% increase in viscosity, which was 58.96 cSt at 40°C and 19.86 cSt at 75°C (a 3% increase). For density, the values were 0.835 $g \cdot ml^{-1}$ for 15°C and 0.815 $g \cdot ml^{-1}$ for 75°C.

The next in line sample is the 5w30 grade oil distributed by Selenia. In this case, the viscosity of the used oil dropped by 37.3% (viscosity measurement at 40°C) and for 75°C the viscosity decreased by 28.3%. When comparing the density measurements of fresh and used oil, they increased slightly. For the 15°C test, it was an increase of 1.2%, and for 75°C only an increase of 0.6%. The same trend of decreasing or increasing density and viscosity was shown by another lubricant with a viscosity grade of 5W40 (Total). The viscosity values in the used oil decreased by 23.6% (at the lower test temperature) and 20.2% (at the higher test temperature). For density, there was an increase of 1.7% and 1.2% for the 15°C and 75°C measurement temperatures, respectively. Another sample showing the same trend is oil with a viscosity grade of 5W30 (Shell). The decrease in viscosity values in this case did not exceed 1% for both temperatures. In contrast, the density of the oil in service increased by 1.8% for both temperatures.

Table 1. Data on operating conditions of used oil samples

Engine oil				Vehicle			
#sample number	Manufacturer	Viscosity class SAE	Oil mileage [km]	Type of fuel to power the engine	Engine capacity [dm^3]	Nominal motor power [kW]	Car mileage at oil drain [km]
1	Fanfaro	5W30	12,650	Gasoline +LPG	1.4	63	362,211
2	Mobil	5W30	14,141	Gasoline	1.6	85	91,635
3	Shell	5W30	5,481	Gasoline	1.2	57	110,007
4	Total	5W40	7,734	Gasoline	1.6	120	60,631
5	Fanfaro	5W30	11,452	Gasoline +LPG	1.6	63	157,473
6	Selenia	5W30	14,998	Diesel	1.6	77	101,021
7	Shell	5W30	5,002	Gasoline	1.0	57	52,333
8	Mobil	10W40	6,500	Gasoline	1.6	72	330,041
9	Fanfaro	5W30	5,159	Diesel	2.5	88	196,427
10	Total	5W20	5,126	Gasoline	1.5	110	112,927
11	Volkswagen	0W30	15,000	Gasoline	1.0	95	15,000

Table 2. Physico-chemical test results sorted by mileage index

#sample number	Viscosity class SAE	W_P	μ_{40} [cSt]	μ_{75} [cSt]	δ_{15} [g·ml^{-1}]	δ_{75} [g·ml^{-1}]	Water content [μg·cm^{-3}]
11	0W30	0.00	61.97	20.44	0.850	0.810	845.14
2	5W30	0.845	70.50	22.10	0.865	0.825	643.15
6	5W30	0.851	34.07	12.04	0.860	0.825	316.46
4	5W40	0.872	61.84	20.22	0.865	0.825	740.85
7	5W30	0.904	58.20	19.29	0.855	0.815	993.16
5	5W30	0.927	54.61	17.30	0.860	0.820	1877.26
3	5W30	0.950	63.92	20.44	0.855	0.815	2124.42
10	5W20	0.954	41.40	13.93	0.855	0.820	895.86
1	5W30	0.965	61.42	19.17	0.855	0.815	825.31
9	5W30	0.973	58.35	18.47	0.855	0.815	1180.19
8	10W40	0.980	86.72	24.75	0.870	0.830	1088.63

Sample number 5, in the viscosity test run, showed a decrease in viscosity of approximately 11% for both temperatures relative to the fresh oil sample from the control group. The density measured for the dependent samples at 15°C was unchanged, while at 75°C it increased by less than 1%. A sample of oil in use with a viscosity grade of 5W20 (Total) relative to the oil in the control group showed a decrease in viscosity of 10.0% (at 40°C) and 7.7% (at 75°C). There was an increase of 0.5% in density at 15°C and a decrease of 0.6% at 75°C.

A sample of the oil 5W30 (Fanfaro) after viscosity testing at the lower temperature showed a 0.1% increase in viscosity, and a 1.1% increase for the higher temperature. Comparing the density measurements, it was found that the values at the lower temperature differed by 0.5%, while there was no change at the higher temperature. The last lubricant sample distributed by the same manufacturer and the same viscosity class (#9), with a different mileage index, showed decreases in viscosity relative to fresh oil of 4.8% for both temperatures. The density measurement at the lower temperature also showed a decrease (by 0.6%), while the measurement at 75°C was the same for both used and fresh oil.

A trend line was drawn for the ranked data, showing the relationship between the results obtained during the physico-chemical tests and the mileage index. In this way, four characteristics were obtained, which show that the trend in these parameters is similar. The mileage index of the analysed data was in the range of 0.84–0.99. From Fig. 2a, it can be determined that there is a decrease in oil viscosity in the range of 0.84–0.88. In the range 0.88–0.92, the values are lowest and then there is an increase until the W_P index value is close to 1.

Analogous ranges can be determined for the density test carried out. The middle limit denoting the range of the lowest density values of the samples is shifted slightly towards higher values and is in the range of 0.9–0.94 W_P.

When analysing the graphs presented, a characteristic point can be seen that stands out from the rest of the data, this being the point describing the viscosity measurement at 40°C for the 5W30 oil (Selenia). Such a low value for this parameter may be since the drive unit of the vehicle from which the sample came was subjected to a flushing during the lubricant change.

When analysing the results obtained from testing the water content of in-service oil samples, no correlation was found between this data and the value of the mileage index.

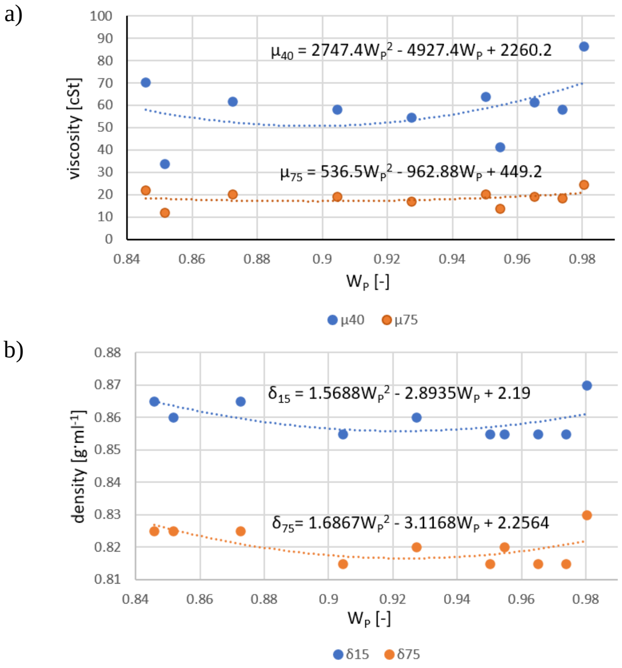


Fig. 2. Comparison of viscosity (a) and density (b) test results with trend lines

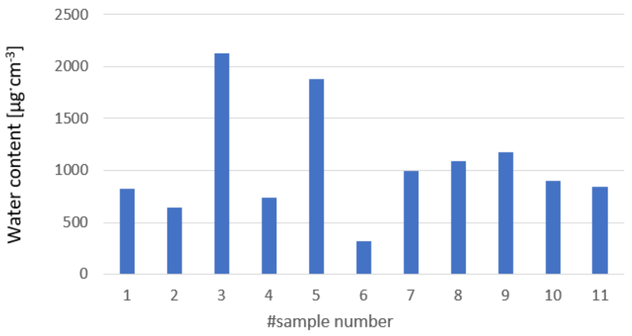


Fig. 3. Water content in samples

3.2. Results of tribological tests

The T02-U four-ball tester used in this part of the study made it possible to record test parameters such as the actual force acting on the kinematic node and the actual friction torque. These parameters were recorded at a frequency of 1 Hz. In order to take into account the load on the node and the torque acting on it, the coefficient of friction μ was calculated for each test, according to the following equation:

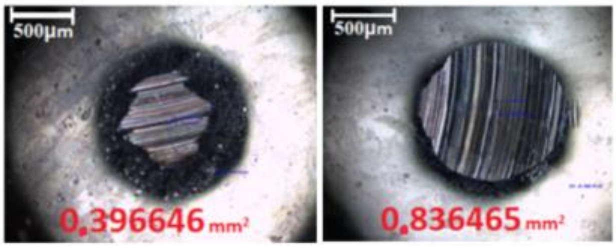
$$\mu = \frac{M_f}{r \cdot F}, \tag{2}$$

where: μ – coefficient of friction [-], M_f – friction torque [Nm], F – load on the kinematic node [N], r – constant moment arm of 0.15 m.

The tests on the four-ball tester consisted of three test runs for one lubricant, one hour each. The variation in time of the coefficient of friction for each sample is shown in Fig. 4. The average coefficient of friction characterising the sample was then calculated for this run.

After each test, the lower balls were visually inspected using a microscope to determine the average area of the wear mark. The data thus prepared were ranked in the same way as the results of the tribological tests (Table 3). The standard for the determination of wear traces assumes the measurement of trace diameters on the three lower balls of the kinematic node. For each ball, the measurement should be carried out twice – once along the wear traces and the second across them.

The wear marks obtained from the tests showed heterogeneity in terms of shape. Some of them were irregular (Fig. 5a), while others were close to a circle (Fig. 5b). For this reason, the diameter calculated according to the standard was not used to determine the area of the wear mark, but the image analysis methodology was used to calculate the area. This approach enabled a more accurate determination of the contact area between the lower balls (A_e – for used oil samples, A_f – for fresh oil samples) and the ball placed in the spindle of the tribometer.



(a) (b)

Fig. 5. Example microscopic images of signs of wear

By placing the points corresponding to the mean wear trace area on the graph as a function of W_P, it was found that the trend line describing the change in mean wear trace area (Fig. 6) shows similar properties to the trend lines determined for viscosity and density. It decreases slightly in the range 0.83–0.85 W_P. In the range of 0.85–0.91 it is at a constant value (lowest). Once the W_P exceeds 0.91, the trend line manifests an increasing trend.

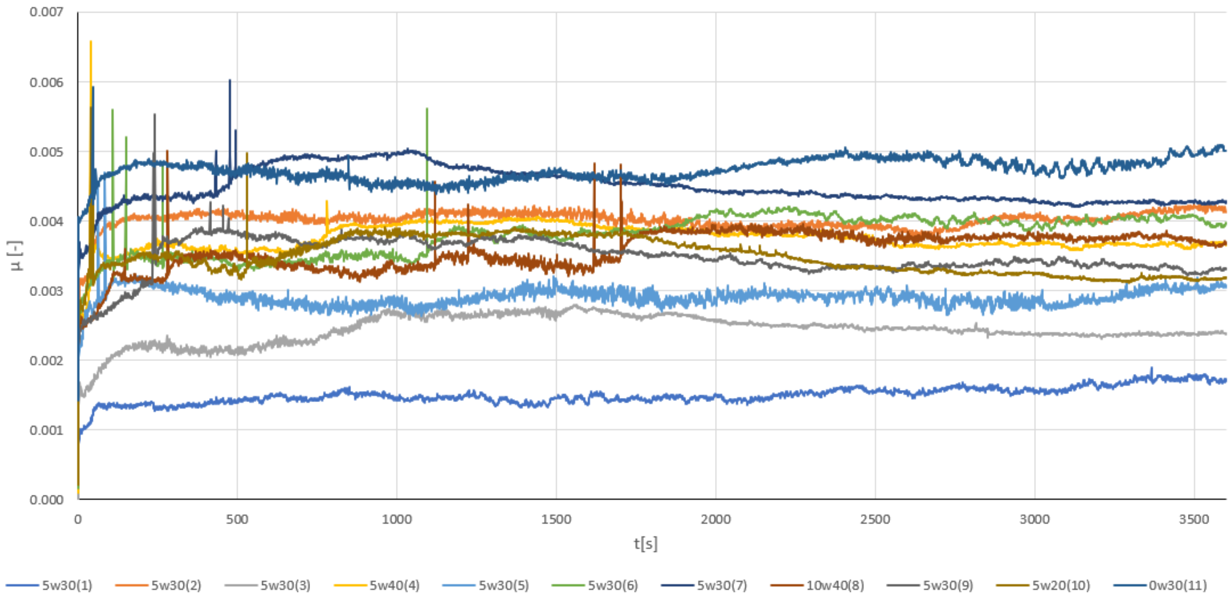


Fig. 4. The μ factor for all used oil samples

Table 3. Results of tribological tests ranked by mileage index

#sample number	Viscosity class SAE	W_p	μ	A_e [mm^2]	A_f [mm^2]	$\frac{A_e}{A_f}$
11	0W30	0.00	0.268	0.782631	0.234429	3.33
2	5W30	0.845	0.228	0.669358	0.405792	1.64
6	5W30	0.851	0.218	0.611117	0.318869	1.91
4	5W40	0.872	0.216	0.974916	0.200990	4.85
7	5W30	0.904	0.256	0.552152	0.220804	2.50
5	5W30	0.927	0.167	0.850034	0.166564	5.10
3	5W30	0.950	0.141	0.614777	0.220804	2.78
10	5W20	0.954	0.197	0.938673	0.202223	4.64
1	5W30	0.965	0.084	0.471683	0.166564	2.83
9	5W30	0.973	0.199	0.541008	0.166564	3.24
8	10W40	0.980	0.207	0.1073030	0.260796	4.11

The trend line drawn for the data describing the friction coefficient as a function of the mileage index did not show the same characteristics. In this case, in the range 0.84–0.87 there was an increase in the trend line. In the range 0.87–0.95, there was a decrease. This was followed by an increase once again once the run rate exceeded 0.95. Although this trend line does not show the same characteristics over the entire range as those determined previously, it is worth noting that it also shows an increase after crossing a relatively high run rate.

When analysing the data collected, it is important to note the differences in the field of wear marks obtained in the tests of used and fresh oils. In each case, the wear traces when testing fresh lubricants are smaller. When calculating the relationship between the field of the wear pattern obtained from testing fresh and in-service oils, it can be seen that the traces of the second oil group are larger from 1.6 to more than 5 times.

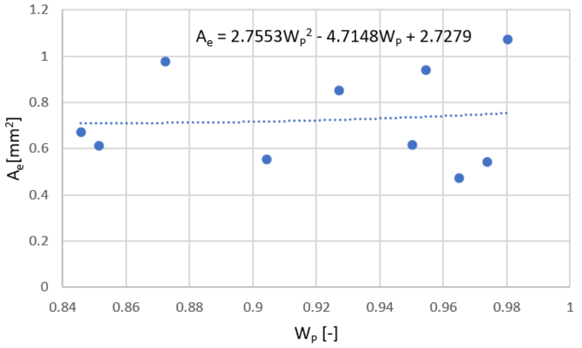


Fig. 6. Field of wear marks in relation to the mileage index

The coefficient of friction μ, calculated on the basis of the applied force and friction torque, was in most cases greater for the used oil than for the fresh oil. Only samples of oils produced by Fanfaro are inconsistent with this relationship. Due to this fact, attention was paid to the friction torque that was recorded during the test. It turns out that for all three lubricants subjected to operation, it was lower compared to the oil in the control group. Because of the dependence of the friction coefficient on the friction torque, this translated into an inverse relationship between the operated and fresh oils.

4. Conclusions

In this paper, aspects of lubricant condition assessment were developed. Based on the collected data, a synergistic W_P mileage index was determined, taking into account vehicle mileage and engine oil mileage. This enabled the research group to be ordered according to the criterion of operating conditions.

As the test results show, as the mileage index value approaches 1 (which can be defined by the near-critical condition of the drive unit), viscosity and density also increase. For proper lubrication of the drive unit, the parameters should be within the appropriate range and not increase excessively. It can therefore be concluded that, in the case of an engine in critical condition, these properties will be so high that the lubricant will not provide adequate protection for the system components. As mentioned in the introduction of the paper, the increase in these parameters may be due to excessive accumulation of wear products. In the case of water content, it was found that there was no correlation between the adopted W_P index. The values recorded during the tests for used oils were in the range of 316–2125 $\mu g \cdot cm^{-3}$. Such a large discrepancy in results could be influenced by such aspects as the moment of oil change (hot or cold engine), the method of operation (e.g. frequent engine start-up and driving over short distances) or the water content of fresh oil fed into the system.

The relationships between the assumed W_P index and the density measured at 15°C and 75°C in the form of trend lines are similar in shape. This can be inferred from the similar coefficients of the trendline equation. In the case of the trend line describing the viscosity relationship at 40°C and 75°C and the W_P index, the discrepancy between the trend line coefficients is noticeably different. The coefficients take on a value several times greater for the trend line plotted for the viscosity measurement at 40°C.

The loss of lubricating properties by oils taken from high-mileage engines is also confirmed by tribological tests carried out. Several times larger areas of wear marks (from 1.6 to more than 5 times) in the case of testing with used oil than with fresh oil testify to less protection for the mating parts. It should be noted that in all tribological tests carried out with fresh oil, the field of the wear mark was always smaller than that of the corresponding used oil of the same viscosity grade and distributed by the same manufacturer. By comparing the wear marks of the lower balls of the four-ball tester with each other when testing a group of oils operated according to the mileage indicator, it can be deduced that, with the drive unit approaching a critical state, the wear marks will also be larger, and thus, just as in the case of the comparison with fresh oils, the engine components will be more exposed to wear.

The microscopic examination carried out showed irregular wear marks on the lower balls of the four-ball apparatus. This result may be due to the formation of lubrication channels at the lower ball – upper ball interface, which prevents the components from fully pressing against each other. It should be noted that the validity of this statement is supported by the fact that when irregularly shaped wear marks were obtained during the test, a friction torque was recorded at a very low level, at times not exceeding 0.1 Nm.

Nomenclature

A_e	area of the wear mark on the lower ball of the four-ball tester for used oil [mm^2]
A_f	area of the wear mark on the lower ball of the four-ball tester for fresh oil [mm^2]
F	kinematic node load [N]
M_f	friction torque [Nm]
P_O	oil mileage [km]
P_P	vehicle mileage [km]

r	friction torque arm [m]
SAE	Society of Automotive Engineers
t	time [s]
W_P	mileage index [-]
μ	coefficient of friction [-]
μ_{40}	viscosity at 40°C [cSt]
μ_{75}	viscosity at 75°C [cSt]
δ_{15}	density at 15°C $[g\cdot ml^{-1}]$
δ_{75}	density at 75°C $[g\cdot ml^{-1}]$

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