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# Assessment of oil change intervals in urban buses based on the selected physicochemical properties of used engine oils

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*The paper presents the results of the analysis of selected physicochemical parameters of engine oils after their use. The oils were obtained both from urban buses belonging to the fleet of a municipal transport company in Lublin, Poland but also from the city of Pardubice in the Czech Republic. Five samples of 10W40 semi-synthetic oil and four samples of 5W30 synthetic oil were tested. Kinematic viscosity at 40°C and 100°C, oxidation, nitration, sulfonation, total acid number (TAN), total base number (TBN), remaining antiwear additives, water content and glycol content, were assessed using infrared spectroscopy (FTIR). The tests were performed on the basis of the ASTM E2412-10 standard. The article also presents the exceedance of the limit values results for the selected parameters. The results of the research can be used in optimizing the engine oil change interval so that the decision to replace the oil is justified both in economic and technical terms, taking into account the need to maintain the service life of the bus.*

Key words: *degradation, engine oil, oil change, urban buses, FTIR*



## 1. Introduction

One of the biggest challenges that we are currently facing is climate change and the environmental problems which are associated with it. Public transport has a significantly more beneficial impact on nature and the environment than individual transport. The arguments for using public transport often focus on cost, accessibility, and environmental impact. To convince more people to change their communication habits, transport companies must offer high-quality transport services, increasing their availability and monitoring the costs associated with it.

Many processes are responsible for the proper maintenance of the vehicle, oil change being one of them [2]. During operation, engine oil ages and absorbs many contaminants. The oil aging process is affected by the process of its oxidation, nitration, contamination by fuel, and gases blown through during circulation in the engine, as well as polymerization under the influence of heat. All this leads to a deterioration in its quality. Finally, all this lead to the oil properties being insufficient, and the user's decision to continue to drive on it may start to cause engine problems. Therefore, it must be periodically replaced.

The engine oil change intervals (OCI) dictated by the vehicle manufacturers are based on a predetermined number of kilometers driven or a specified period of operation. This vehicle maintenance strategy is called preventive maintenance, and it aims to reduce the frequency and number of failures of a given device. The application of this strategy is based either on the experience of people employed in maintenance positions or on the recommendations of original equipment manufacturers (OEM). The problem with successfully implementing this type of strategy is achieving optimal (OCI) because vehicles operate in different environments, and due to their actual operating conditions, they may require different OCI. Whereas relying on the experience of people dealing with maintenance in the company creates problems for the company at a time when there is a high turnover among employees and various strategies for determining the optimal oil change date are mixed [1].

Predictive maintenance, also known as condition-based maintenance (CBM), is the second maintenance strategy option. This type of strategy is more expensive to implement than preventive maintenance due to the need to employ specialized staff with appropriate knowledge as well as to invest in appropriate measuring equipment. The CBM strategy is based on the registration and control of the obtained data, their thorough analysis using computer tools, as well as on the detection of trends of changes. Then, according to the CBM, the information obtained from the condition monitoring process is the basis for deciding the need for maintenance. The fact is that there are certain signals, symptoms or conditions before the equipment failure occurs. Therefore the motivation to use this type of strategy is to know in advance those symptoms that may indicate the occurrence of a specific failure [16, 17]. In general, maintenance decision-making in a CBM strategy is based on a real-time assessment of equipment conditions, which is ultimately expected to reduce costs by minimizing maintenance needs [14]. The oil condition monitoring process can provide in two ways: online and offline. The online process takes place when the equipment is in working condition (operational state), while the offline process takes place when the equipment is not working. To determine the optimal OCI and diagnose the lubricated system without disassembly, quick and precise analysis of the lubricant is extremely important. An effective oil analysis program often relies on offline oil analysis performed in laboratories where all properties of the oil are analyzed.

The operating conditions of a given device equipped with a combustion engine are important in the context of its maintenance, but looking through the prism of reliability and vehicle life, the properties of the oil with which it is lubricated are also of great importance [13]. The type of engine oil and its current condition affect not only the performance parameters of the engine but also its wear and emissions [6]. Taking into account the different chemical compositions of engine oil and the irregular influence of external factors on the aging process, it is impossible to draw up a general schematic representation (model) of oil quality changes occurring during operation [5, 21]. Therefore, it is important to estimate the moment when the oil loses its functions and reaches the operational limit state.

Attempts to detect most changes in the operating parameters of oils during actual operation are difficult. A similar situation (during oil exploitation) takes place in the case of an attempt to indicate the moment when the oil reaches the limit values of its physicochemical properties. In the literature devoted to the problems of determining the limit values of lubricating oil parameters, we encounter attempts to determine acceptable changes in selected physicochemical properties of the oil, a parameter considered representative of the aging process, a package of parameters relating to the properties of the oil or the concentration of chemical agents. The most frequently chosen parameters to represent qualitative changes are kinematic viscosity (KV) at 40 and 100°C, oxidation, nitration and sulfonation, TAN and TBN, fuel content, soot content, susceptibility to foaming or content of elements [4, 11, 18, 20]. Therefore, to assess the condition of engine oil correctly, it is important to know the limit values of the tested parameters and the current values of the given coefficients. These pieces of information allow us to make the right decision – whether the used engine oil is still usable or not.

The research aimed to check whether the decision made by bus owners to change the oil, dictated by the specified service mileage of the vehicle recommended by the manufacturer, was optimal due to the number of exceedances of limit values. The paper presents the results of research on selected physicochemical properties of engine oils after a period of operation, which are important from the point of view of proper engine operation. The oils come from fleets of buses of various age structures and different operating conditions. Specific parameters were selected for the analysis and assessment of the operating properties of the tested oils because they characterize the oil aging process that takes place during operation, and are the basis for determining its suitability for further use [3, 7, 10, 12].

## 2. Materials and methods

The research material consisted of motor oils obtained during a standard oil change from two municipal transport companies, one from the city of Lublin, and the other, from the city of Pardubice in the Czech Republic. The oils come from 2 producers and differ in the SAE viscosity class: engine oils obtained from Pardubice have a viscosity class of 5W30, while oils obtained from Lublin have a viscosity class of 10W40. The key physicochemical properties of new engine oils are shown in Table 1.

Engine oils obtained from replacement were grouped by manufacturers, and then the given code names were applied: PU01-04 and OP01-05. 9 samples of used engine oils from 6 city buses of different manufacturers with various levels of mileage, were used in the research. During the sampling, the overall mileage of the bus (ODO) and the distance on oil interval were recorded. Buses of different age structures, and various technical solutions of diesel engines, were selected for the tests. The research material collected from the public transport company in Pardubice comes from one bus – Iveco Urbanway 12 and relates to four consecutive OCI. In the conducted research, the life of the oil, understood as the mileage of the bus recommended by the manufacturer, in which engine safety and work efficiency are ensured, was important. In the case of the PU 5W30 synthetic oil group, that period was set at 50,000 km, and in the case of OP 10W40 semi-synthetic oil at 60,000 km. Table 2 presents data on the buses used in the research.

Table 1. The key physicochemical properties of new engine oils

| Parameter | Unit | Oil code | |
|---|---|---|---|
| | | OP from Lublin, Poland | PU from Pardubice, Czech Republic |
| Viscosity class, SAE | – | 10W40 | 5W30 |
| Quality class, ACEA | – | E4, E7 | E4, E6, E7 |
| KV@100°C | $mm^2/s$ | 14.67 | 9.93 |
| KV@40°C | $mm^2/s$ | 86.5 | 58.14 |
| TBN | mg KOH/g | 10.57 | 9.45 |
| TAN | mg KOH/g | 0 | 0.84 |
| Oxidation | Abs/0.1 mm | 0.13 | 0.23 |
| Nitration | Abs/0.1 mm | 0.04 | 0.10 |
| Sulfonation | Abs/0.1 mm | 0.2 | 0.23 |

The ERASPEC OIL apparatus manufactured by Eralytics was used in the research to analyze specific physicochemical parameters of engine oils after their use. The device is based on the Fourier Transform Infrared (FTIR) spectroscopic method, and it is in full compliance with ASTM, DIN, and JOAP methods. Analyzes were performed following ASTM E2412-10 infrared standard. The chemical structures of fresh and used engine oils are examined by comparing their FTIR spectra. The levels of individual bands for used oils were determined not directly from their spectra, but from differential spectra, i.e. spectra resulting from a mathematical operation: spectrum of used oil minus the spectrum of fresh oil. The parameters indicated in the introduction (i.e. KV@40°C and KV@100°C, oxidation, nitration, sulfonation,, TAN and TBN, remaining anti-wear additives (AW), water and glycol content) were chosen because they allow to show oil degradation as a result of bus operation. Triplicate tests were carried out for all oils, and then the result was averaged.

Changes in the parameters of the oils taken from the buses were compared to the parameters of fresh oils, which are listed in Table 1. Moreover, in order to determine the limit values, the values obtained for fresh oils were the reference point.. The literature analysis showed disparities in the determination of threshold values of indicators of the engine oil condition. The assessment of the current condition of the engine oil was made, based on the limit values adopted and presented in Table 3.

Table 2. Technical data and mileage of the tested buses

| Oil group | Item | Bus model | Code of the sample | Bus ODO [km] | Distance on oil interval [km] | Engine/oil pan capacity [liter] |
|---|---|---|---|---|---|---|
| PU SAE 5W30 | #1 | Iveco Urbanway 12 | PU01 | 51,394 | 51,394 | Iveco Cursor 9/34 |
| | #2 | Iveco Urbanway 12 | PU02 | 95,195 | 43,801 | |
| | #3 | Iveco Urbanway 12 | PU03 | 146,496 | 51,301 | |
| | #4 | Iveco Urbanway 12 | PU04 | 197,961 | 51,465 | |
| OP SAE 10W40 | #1 | Autosan Sancity M12LF | OP01 | 170,178 | 60,500 | Iveco Cursor 78 EEV/22 |
| | #2 | Merc.Benz Connecto 18 | OP02 | 667,290 | 64,683 | OM 470/35 |
| | #3 | Merc.Benz Connecto 18 | OP03 | 678,258 | 64,162 | |
| | #4 | Merc.Benz Connecto 18 | OP04 | 732,678 | 63,347 | |
| | #5 | Merc.Benz Connecto 12LF | OP05 | 1,038,973 | 61,131 | OM 936/29 |

Table 3. Limit values of oil parameters adopted in the tests

| Parameter | Unit | Limit values | | | | |
|---|---|---|---|---|---|---|
| | | based on the literature | | | | Established in this study |
| | | [8] | [10] | [15] | SAE J300-2015 | |
| KV@100°C | $mm^2/s$ | – | ±15% | ±15% | 5W – min 9.3; max < 12.5<br>10W – min 12.5; max < 16.3 | ±15%<br>5W – min 8.4; max 11.4<br>10W – min 12.5; max 16.9 |
| KV@40°C | $mm^2/s$ | ±15% | – | ±15% | – | ±15%<br>(5W) – min 49.4; max 66.9<br>(10W) – min 73.5; max 99.5 |
| TBN | mg KOH/g | < 30% | < 30% | < 30% | – | < 30%<br>(5W) – max 7.4<br>(10W) – max 6.6 |
| TAN | mg KOH/g | – | – | 6 mg KOH/g | – | +2.5 mg KOH/g |
| oxidation | Abs/0.1 mm | > 1.0 | > 0.15 | > 0.4 | – | > 0.4 |
| nitration | Abs/0.1 mm | > 1.0 | > 0.15 | > 0.4 | – | > 0.4 |
| sulfonation | Abs/0.1 mm | > 1.0 | > 0.20 | > 0.4 | – | > 0.4 |
| Water content | wt% | > 0.3 | > 0.2 | | | > 0.2 |
| Glycol content | wt% | > 0.3 | > 0.08 | | | > 0.3 |

To graphically present the distribution of the statistical feature of the results obtained for each of the analyzed variables, box charts for two oil groups were used. Measurements were made in triplicate. The obtained results were statistically analyzed using the Statistica 13 software package. The graphical form of the presentation of the results enabled the observation of the location, shape, and distribution of the empirical feature under examination. The charts include the following items: tested values (outliers and extremes); the median, and a box containing the quartile range (quartiles – 25th and 75th percentile).

## 3. Results and discussion

This section presents the most important results regarding the oil quality, degradation, and contaminant content parameters observed at the time of oil change after the specified period of oil life. In the end, a summary of exceedances of the limit values of individual oil parameters for the tested groups was introduced in Table 4.

When analyzing the test results (Fig. 1), it was observed that in three samples from the PU synthetic oil group, the limit value of the KV@40 parameter was exceeded. Exceeding the lower limit is visible, which can lead to a lack of protection of the friction mechanisms. In the case of the sample marked PU_03, a decrease of 30% was recorded, which is twice the limit value. Greases with the wrong viscosity for the application can cause, among other things, increased metal-to-metal contact, friction, wear, and increased oil loss in service [19]. Only in the case of oil change in the sample marked PU_02, the change compared to fresh oil was 12%, and the limit of the lower boundary of the value set at –15% was not exceeded. It is worth noting that in this particular sample, the oil was changed at 43,801 km, which is about 7,000 km earlier than in the other three. To maintain engine lubrication conditions at an appropriate level, this may be one of the arguments for the company to reduce the OIC to the level of 40,000 km. Analyzing the position of the box plot, the minimum of the non-outliers was 40.44 $mm^2/s$, the maximum of the non-outliers was 50.89 $mm^2/s$, and the median was 45.06 $mm^2/s$. No extreme values were recorded in this case. The data is not scattered, and the data plot looks symmetrical.

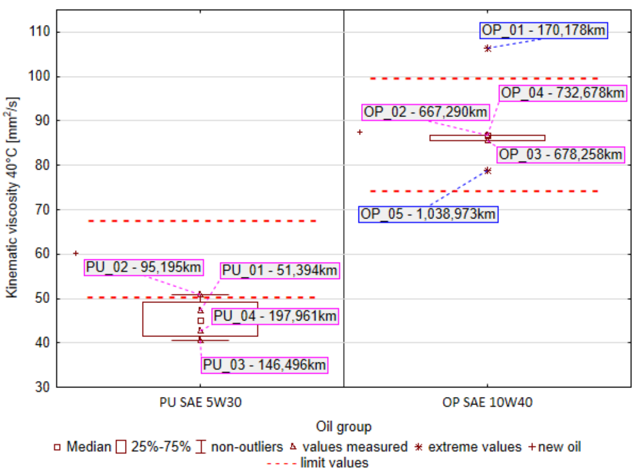


Fig. 1. Measurement of KV@40 in engine oil samples

In the case of the OP semi-synthetic oil group, only in one case, specifically in the OP_01 sample (bus after 170,178 km), the maximum viscosity value was exceeded, which may be the basis for excluding the oil from further use due to significant difficulties in oil distribution and, as a result, the possibility of insufficient lubrication of the moving parts of the mechanism. Compared to the viscosity determined for fresh oil, the viscosity of OP_01 increased by 23%. The remaining samples from this group, compared to the new oil, did not exceed 10% of the difference in values, and in three cases the changes did not even exceed 1.5% of the difference. A fact worth noting, in this case, is that a decrease of 8% compared to the new oil was recorded in the case of the bus with the highest operating mileage of 1,038,973 km, while the case of exceeding the maximum viscosity value was recorded in the vehicle with the lowest operating mileage in the entire tested oil group. Meanwhile, when analyzing the position of the box plot, the minimum of non-outliers was 85.47 $mm^2/s$, the maximum was 86.77 $mm^2/s$, and the median was 86.73 $mm^2/s$. Two extreme values were recorded, including one outside the limits set for this parameter. The data is scattered, and the shape of the graph, indicates a right-sided asymmetry.

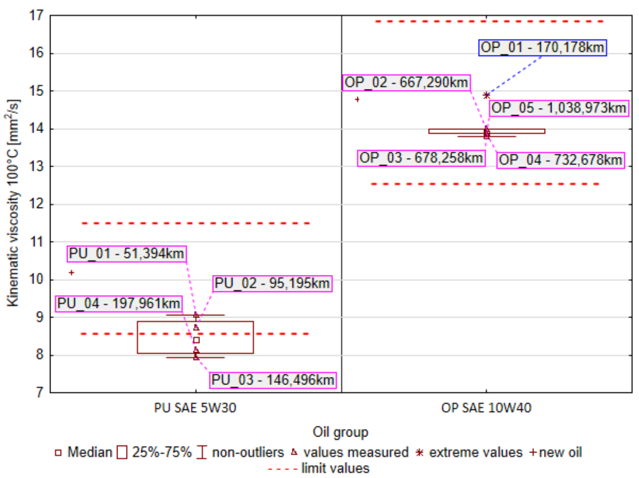


Fig. 2. Measurement of KV@100 in engine oil samples

The graph in Fig. 2 shows that the KV@100°C in a significant number of oil samples (7/9) was within the specified limits, which proves that the oils still met the criteria for a given parameter. Near the lower limit of the parameter, a sample marked as PU_02 was observed (a decrease of 12% compared to fresh oil). Looking at the results of the samples belonging to the OP semi-synthetic oil group, it was observed that all of them were within the prescribed limits. On the other hand, two samples of synthetic PU oil exceeded the lower limit value of the parameter, these were samples PU_03 after 51,301 km of operating mileage on oil (a decrease of 20% compared to fresh oil) and PU_04 after 51,465 km of mileage on oil (a decrease of 18%). From the point of view of viscosity classification according to SAE J300-2015, the measured viscosity for these samples, was fitted in the lower viscosity class (20). In addition, the analysis also showed a tendency to decrease the viscosity with the increase in the overall operating mileage of the tested bus. Oils operating at extremely high temperatures can begin to thermally crack. High temperatures can break/break oil molecules into smaller particles, resulting in a loss of fluidity. According to Macian et al. [9], fluctuations of this parameter are due to two reasons, firstly, due to variable thermal loads of the engine, with the process of base oil oxidation, and the second reason can be seen with the addition of a viscosity index improver to the oil recipe, which, together with the aging of the oil under the influence of high shear conditions and high temperatures encountered during normal engine operation cause a decrease in oil viscosity. According to the research results of Sejkorova et al. [12] KV@40 and KV@100°C of oils obtained from city buses did not exceed the tolerance of ±20% to the fresh oil.

Analyzing the position of the box plot for the PU synthetic oil group, the minimum of the non-outliers was 7.93 $mm^2/s$, the maximum of the non-outliers was 9.07 $mm^2/s$, and the median was 8.42 $mm^2/s$. No extreme values were recorded, the data is not dispersed, and the data graph looks symmetrical. Whereas, when analyzing the position of the box plot for the OP semi-synthetic oil group, the minimum of the non-outliers was 6.67 $mm^2/s$, the maximum of the non-outliers was 8.6 $mm^2/s$, and the median was 8.1 $mm^2/s$. One extreme value was recorded, the data is dispersed, and the shape of the data plot, again as in the first case, indicates a right-sided asymmetry.

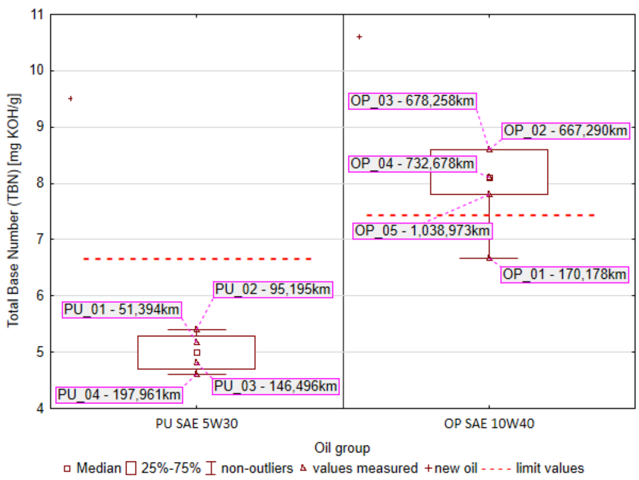


Fig. 3. Measurement of TBN in engine oil samples

TBN is the number of alkaline additives found in the oil to counteract the effects of acids entering the oil from combustion and other sources, and the TAN is a measure of this acidification. The results of the determination of the base number in the analyzed oils are shown in Fig. 3. All samples from the PU synthetic oil group exceeded the determined limit value set as a 30% decrease compared to the new oil. A trend of TBN loss was observed with the increasing mileage of the bus. All samples had similar TBN losses – with the average value being around 47%. The lowest decrease in TBN (at 43%) was observed for the PU_02 sample, which had an OCI 7,000 km less than the other three. This may be another argument for the company to reduce the OCI by 10,000 km. Similar observations regarding the size of changes were presented by Wolak [18], where the average of changes in the case of passenger cars operated mainly in urban conditions was 50% compared to new oil. Macian et al. [9] analyzing OCI in city buses also noticed a 50% decrease in TBN.

Analyzing the results of TBN measurements in samples of used OP semi-synthetic oil, it was found that four out of five samples were within the specified limits and did not fall below the adopted minimum limit of 7.4 mg KOH/g in this case. In one OP_01 sample, a value lower than the established minimum was obtained, where its value was 6.67 mg KOH/g (decrease by 37% compared to new oil).

Analyzing the position of the box plot for the PU synthetic oil group, the minimum of the non-outliers was 4.6 mg KOH/g, the maximum of the non-outliers was 5.4 mg KOH/g, and the median was 5 mg KOH/g. No extreme values were recorded, the data is not dispersed, and the data graph looks symmetrical. Meanwhile, when analyzing the position of the box plot for the OP semi-synthetic oil group, the minimum of the non-outliers was 6.67 mg KOH/g, the maximum of the non-outliers was 8.6 mg KOH/g, and the median was 8.1 mg KOH/g. No extreme values were recorded, the data is scattered, and the shape of the data plot in this case, indicates a left-sided asymmetry.

During the combustion process, sulfur turns into sulfur dioxide, which in combination with water present in the exhaust gas becomes aggressive sulfuric acid. The higher the alkaline reserve, the longer it takes for acidic products to form in the oil.

The analysis of the TAN in the tested oils showed that in all the analyzed samples from both groups of oils, the limit value was not exceeded. It is worth noting that the higher TAN values were in the group of PU synthetic oil with a viscosity grade of 5W30. In this case, there is also a tendency to increase the TAN content with the increase in the vehicle's operational mileage. A similar conclusion was drawn by Chmielewski [4], where changes in selected physicochemical properties in the registered tests of engine oils from medium-duty trucks confirm the thesis about the correlation of the value of the observed parameter with the mileage of the vehicle. Two samples showed values very close to the limit value – PU_03 (2.25 mg KOH/g) and PU_04 (2.29 mg KOH/g). The results of determining the TAN in the analyzed oils are shown in Fig. 4.

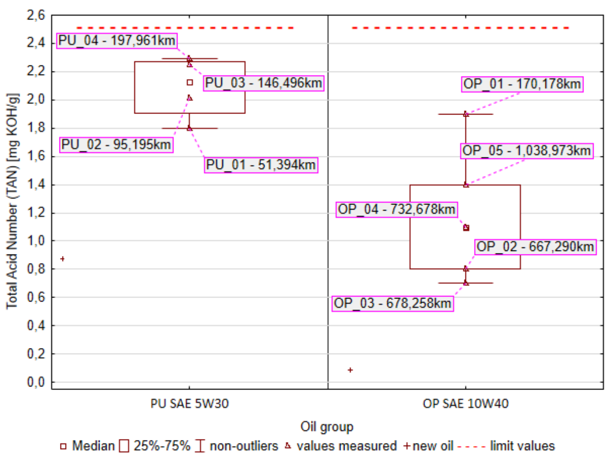


Fig. 4. Measurement of TAN in engine oil samples

Analyzing the position of the box plot for the PU synthetic oil group, the minimum of the non-outliers was 1.8 mg KOH/g, the maximum of the non-outliers was 2.29 mg KOH/g, and the median was 2.13 mg KOH/g. No extreme values were recorded, the data is not dispersed, and the shape of the data plot, in this case, indicates a left-sided asymmetry. Whereas, when analyzing the position of the box plot for the OP semi-synthetic oil group, the minimum of the non-outliers was 0.7 mg KOH/g, the maximum of the non-outliers was 1.9 mg KOH/g, and the median was 1.1 mg KOH/g. No extreme values were recorded, the data is scattered, and the shape of the data plot, in this case, indicates a right-sided asymmetry.

The degree of oxidation of the oil in the tested samples is shown in Fig. 5. Oxidation is a natural process that occurs during oil exploitation. A too-high degree of oxidation of the oil causes degradation of the oil, loss of its lubricating properties, and reduction of corrosion protection. None of the analyzed oils exceeded the established critical oxidation value of 0.4 Abs/0.1 mm. The highest degree of oxidation was recorded in the group of PU_03 oil (146,496 km of the total mileage of the bus), which was 0.32 Abs/0.1 mm. It is worth noting that the observed degree of oxidation in the case of PU_03 (0.32 Abs/0.1 mm) and PU_04 (0.31 Abs/0.1 mm) had an impact on exceeding the limit value of the viscosity parameter both at 40 and 100°C. The lowest value was observed in the OP oil group, in which the OP_05 sample (1,038,973 km of the total mileage of the bus), showed the value of this parameter at the level of 0.16 Abs/0.1 mm. Analyzing the results in terms of their percentage change, measuring fresh oil as a reference in the case of the OP semi-synthetic oil group, the average value was – 35%, while in the case of the PU synthetic oil group – 28%. The highest percentage change was 66% for sample OP_01. The percentage changes observed in the conducted studies are at lower levels than in the work of Macian et al. [9], where the observed changes reached the order of 120%, and in the case of CNG-powered buses even over 160%.

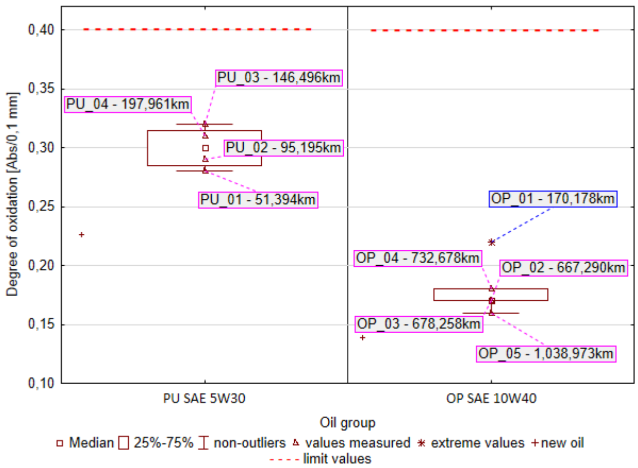


Fig. 5. Measurement of oxidation in engine oil samples

Analyzing the position of the box plot for the PU synthetic oil group, the minimum of the non-outliers was 0.28

Abs/0.1 mm, the maximum of the non-outliers was 0.32 Abs/0.1 mm, and the median was 0.3 Abs/0.1 mm. There are no extreme values recorded, the data is not dispersed, and the shape of the data graph looks symmetrical. Meanwhile, when analyzing the position of the box plot for the OP semi-synthetic oil group, the minimum of the non-outliers was 0.16 Abs/0.1 mm, the maximum of the non-outliers was 0.18 Abs/0.1 mm, and the median was 0.17 Abs/0.1 mm. One extreme value was recorded, the data is scattered, and the shape of the data plot, in this case, indicates a left-sided asymmetry.

As a result of the fuel combustion process in internal combustion engines, nitration products are formed. Excess oxygen is the main cause of most nitration products. Nitration is the process by which the oil reacts with nitrogen oxides ($NO_x$) to form deposits. The products of this process are oil sludge and other deposits formed on the metal parts of the engine, as a result of which the oil degrades, loses its lubricating properties, and reduces corrosion protection. The established limit value of the nitration degree of 0.4 Abs/0.1 mm was not exceeded in any of the analyzed samples. However, the highest value was observed in the PU synthetic oil group, in which the PU_04 sample showed the value of this parameter at the level of 0.143 Abs/0.1 mm. The lowest degree of nitration was observed in the OP oil group in the OP_03 oil sample (0.081 Abs/0.1 mm), which was taken from the bus after the oil exploitation mileage of 64,162 km. The oil nitration degree is shown in Fig. 6.

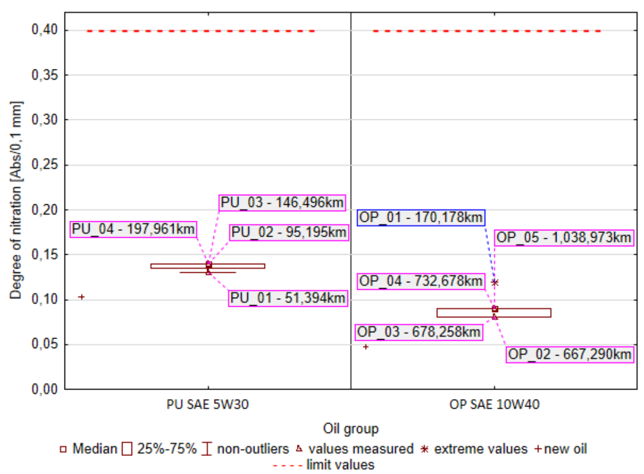


Fig. 6. Measurement of nitration in engine oil samples

The reaction of sulfur (mainly in the fuel) with oxygen results in a process called sulfonation. The products of this process are harmful deposits formed inside the engine, as well as sulfuric acid, which in turn is formed as a result of the reaction of sulfur oxides with water resulting from the combustion process. As with oxidation and nitration, excessive oil sulphonation leads to poor lubrication, deposits, sludge build-up, loss of corrosion protection, and it is an indication of an oil change. The established sulfonation threshold value was not exceeded in any of the tested samples, which proves that good-quality fuel was used in both cases. The highest value was recorded in the OP_01 semi-synthetic oil group, which amounted to 0.296 Abs/0.1 mm. However, the lowest value was also observed in the OP oil group, in which the OP_03 sample showed the value of this parameter at the level of 0.248 Abs/0.1 mm. The results of the degree of sulfonation are shown in Fig. 7.

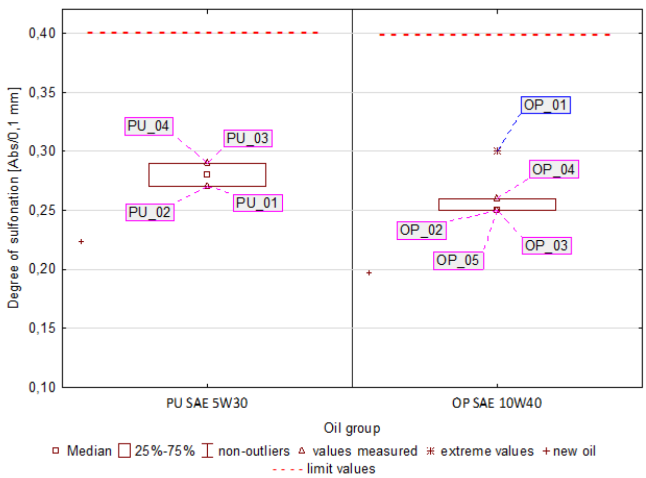


Fig. 7. Measurement of sulfonation in engine oil samples

Lubricants are refined with additives that improve the specific parameters of the oil or grease, and during operation, these additives are subject to wear. The degree of wear of individual additives, such as antioxidants or AW additives during operation, in conjunction with other tests, allows us to determine the intervals for replacing the lubricant in the friction node. Initially, phosphate AW additives break down and form a protective film by bonding to metal surfaces and through oxidative mechanisms. When analyzing the test results, it was observed that only three of them had more than 50% of the remaining content of AW additives – these were samples from the group of semi-synthetic oils OP_05, OP_03, and OP_02. Meanwhile, all samples from the PU synthetic oil group had less than 40% of AW additives during the oil change. The lowest values were observed in two cases OP_01 and OP_04 where these samples no longer had any of AW additives. The remaining content AW additives in the tested oils is presented in Fig. 8.

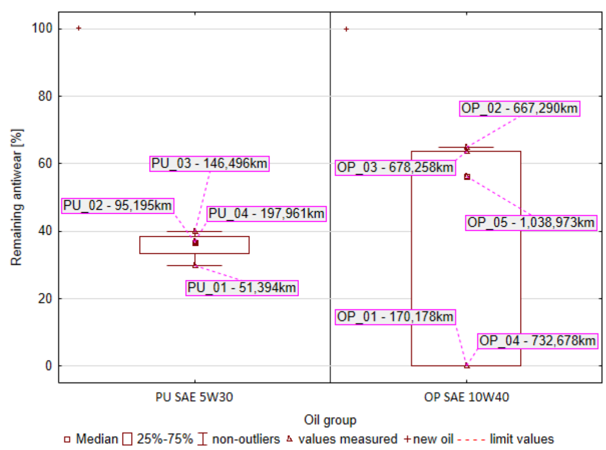


Fig. 8. The remaining content of AW additives in engine oil samples

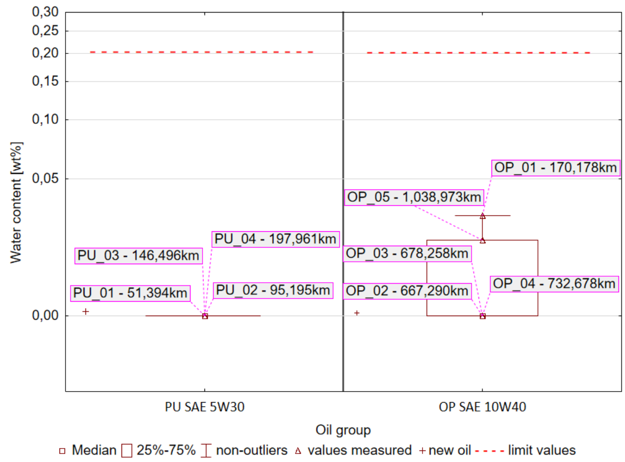


Fig. 9. Measurement of water content in engine oil samples

Figures 9 and 10 show the content of oil impurities in the form of water and glycol in the tested oils. Water is one of the most unfavorable contaminants in any type of service oil. This leads, among others, to oil degradation, and poor corrosion protection. Water in engine oil can cause, for example, condensation of some additives in the form of deposits or hydrolysis of detergents. The presence of too much water may indicate leaks in the cooling system. When observing the graph, no water content was observed in the tested oils, only a trace percentage of water was observed in the OP_01 (0.03 wt%) and OP_05 (0.02 wt%) samples. Referring to Raposo et al. [11], in 10 standard (12 m) city buses, similar percentages of water content oscillating around 0.1wt% were observed.

Figure 10 shows the glycol content in the tested oils. There should be no traces of glycol in the engine oil at all, its presence indicates a defect in the engine's tightness (crack of the head or wear of the head gasket). The presence of glycol leads to oil contamination, sludge and varnish build-up, and potential engine failure. In all tested cases, the limit value for this parameter was exceeded, which may indicate the poor condition of the tested engines.

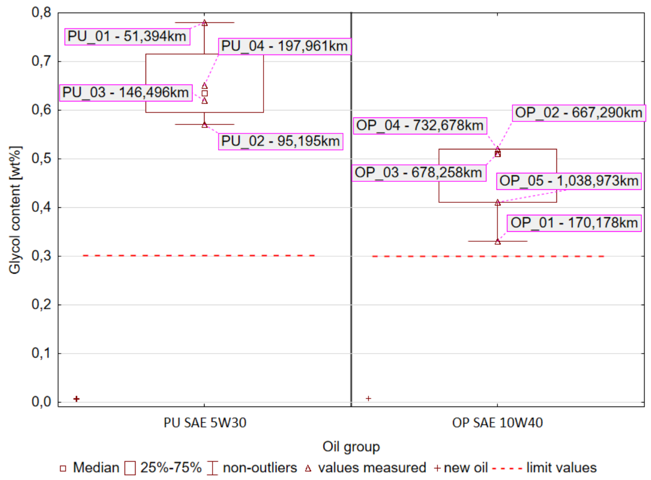


Fig. 10. Measurement of glycol content in engine oil samples

The test results of individual oil parameters for the tested groups are presented in Table 4. When analyzing all the tested samples and the number of exceedances of the limit values for the tested parameters, it was observed that in two cases there were two exceedances, in one case there were three exceedances, and in three cases as many as four exceedances were recorded. It should be emphasized that the OP semi-synthetic oil group fared better in the study, in which in three out of five cases only one exceedance of the

Table 4. The test results of individual oil parameters for the tested groups: summary

| Engine oil | Code of the sample/Bus model | Bus ODO [km] | Distance on oil interval [km] | KV@40°C | KV@100°C | oxidation | nitration | sulfonation | TAN | TBN | remaining AW | water content | glycol content | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | **15** |
| OP SAE 10W40 | OP1/Autosan Sancity M12LF | 170,178 | 60,500 | X | √ | √ | √ | △ | △ | X | X | √ | X | **4/10** |
| | OP2/Merc.Benz Connecto 18 | 667,290 | 64,683 | √ | √ | √ | √ | √ | √ | √ | √ | √ | X | **1/10** |
| | OP3/Merc.Benz Connecto 18 | 678,258 | 64,162 | √ | √ | √ | √ | √ | √ | √ | √ | √ | X | **1/10** |
| | OP4/Merc.Benz Connecto 18 | 732,678 | 63,347 | √ | √ | √ | √ | △ | √ | √ | X | √ | X | **2/10** |
| | OP5/Merc.Benz Connecto 12LF | 1,038,973 | 61,131 | √ | √ | √ | √ | √ | √ | △ | √ | √ | X | **1/10** |
| **Total** | | | | **1** | **0** | **0** | **0** | **0** | **0** | **1** | **2** | **0** | **5** | |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| PU SAE 5W30 | PU1/Iveco Urbanway 12 | 51,394 | 51,394 | X | √ | √ | √ | √ | √ | X | √ | √ | X | **3/10** |
| | PU2/Iveco Urbanway 12 | 95,195 | 43,801 | △ | △ | √ | √ | √ | √ | X | √ | √ | X | **2/10** |
| | PU3/Iveco Urbanway 12 | 146,496 | 51,301 | X | X | △ | √ | △ | √ | X | √ | √ | X | **4/10** |
| | PU4/Iveco Urbanway 12 | 197,961 | 51,465 | X | X | △ | √ | △ | √ | X | √ | √ | X | **4/10** |
| **Total** | | | | **3** | **2** | **0** | **0** | **0** | **0** | **4** | **0** | **0** | **4** | |

Legend: √ Normal Lubricant △ To watch X Danger limit values for the tested parameters was recorded. The highest number of exceedances was recorded for the percentage of glycol in the oil, where it turned out that all the tested samples exceeded the limit value. Another parameter in which the limit values were exceeded was the total alkaline number, where all samples from the PU synthetic oil group did not fall within the set limits. In addition, only one sample from the same group did not exceed the limit value of oil viscosity at 40°C. There were no exceedances of limit values in such oil parameters as: TAN, oxidation, nitration and sulfonation, and water content.

## 4. Conclusions

When assessing the condition of used lubricating oils after actual operation, it is necessary to analyze as many parameters as possible. After determining the limit values of individual parameters based on fresh engine oil, the number of exceedances in the used oil samples needs to be checked. Oils no longer fulfill the functions assigned to them if any value reaches its limit, thus giving a diagnostic signal for its replacement. As a result of the conducted tests of selected physicochemical properties of two groups of used engine oils, the nature of their changes and the frequency of exceeding the previously established limit values were determined.

Exceedances were found in KV@40°C (44%) and 100°C (22%), the remaining content of AW additives (22%), TBN (56%) and glycol content (100%). The obtained results did not provide a clear answer to the question of whether the mileage since the last oil change – commonly used to determine the interval between oil changes – is the most reliable criterion. The fact is that, in more than 67% of the samples tested, more than one exceedance was detected. However, when we are guided by the size of these exceedances and the parameter that has been exceeded, the assessment no longer seems unambiguous.

In the case of the OP oil group, buses marked with the symbols OP_1 and OP_4, due to the zero content of AW additives, should be subjected to further in-depth observations, including elementary analysis, to analyze the potential excessive wear of the engine. It is also recommended to limit exceeding the OCI set by the manufacturer.

On the other hand, in the PU oil group, the case of a bus marked with the code PU_2 – where the oil was collected within 7,000 km shorter than the manufacturer's deadline, may constitute a recommendation for the vehicle maintenance program. Reducing the OCI in this case, indicates potential benefits to the condition of the engine and its components, which in turn can reduce maintenance costs as well as reduce downtime and repairs.

These types of tests require at least several oil change cycles, so they must be spread over time. Own experience and publications indicate that single replacement cycles do not reflect the actual state of oil quality in the context of its degradation. In consultation with the public transport company, a two-year research cycle was developed. This will allow the analysis of a minimum of two oil changes, which will allow for a more accurate determination of the condition of the oil.

The presented research should be treated as a pilot study, aimed at showing the problem related to determining the optimal OCI. The authors, are currently in the process of carrying out extended research with a larger number of vehicles and analyzed parameters, as well as an analysis of the specificity of bus operation, which will increase the chance for effective verification of oil change standards proposed by manufacturers.

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## Nomenclature

| | |
|---|---|
| AW | anti-wear additives |
| CBM | condition-based maintenance |
| FTIR | Fourier transform infrared |
| KV | kinematic viscosity |
| OCI | oil change interval |
| ODO | odometer (overall mileage of vehicle) |
| TAN | total acid number |
| TBN | total base number |

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