

Forum on Innovative Technologies and Management for Sustainability, ITMS'2016, 28-29 April  
2016, Panevėžys, Lithuania

## Tribo-diagnostics as an indicator and input for the optimization of vehicles preventive maintenance

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### Abstract

The importance of using proper oil analysis is not always entirely clear to all users. There is a strategy that shows when it is necessary to change the oil. The oil might be used to indicate when and where the failure occurs in a vehicle. In other words, an oil analysis can reduce the severity of failures. . Most often, oil analysis program combines the continuous attention to oil and the vehicles condition. By combining the instrumental methods of tribotechnical diagnostics (FTIR spectrometry, atomic emission spectrometry, particles analysis with the use of a laser analyzer) it was found that engine oil change intervals should be optimized to maximize the efficiency of engines and extend their lifetime. Changing the engine oil specified by the manufacturer of the buses is relatively conservative, does not reflect the operating motor conditions, fuel quality and individual driving habits and ambient conditions.

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Peer-review under responsibility of the Kaunas University of Technology, Panevėžys faculty of Technologies and Business

*Keywords:* Tribotechnical diagnostics; engine oil; instrumental methods; FTIR spectrometry; atomic emission spectrometry; laser analyzer

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### 1. Introduction

Ideally, modern maintenance would be based on the real condition of machines. The condition monitoring of machinery can be anything from simple visual inspection to continuously functioning real-time condition monitoring systems.

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Oil analysis is a significant part of a condition-based maintenance, because the oil tells us about the history of the machine since the last oil change.

Lubrication oils are during their operation in the lubrication system of an engine exposed to high temperatures, pressures and contamination by undesired materials from outside. These factors cause troubles with the operational quality of oils and materials of mechanical components of a lubrication system. The origin of degradation products and the contamination of oil from outside cause the additives to decrease [1,2]. The resilience of oil to these processes defines its degree of life-cycle.

One of the methods of the non-dismantling technical diagnostics which uses the lubrication oil as a source of information about the processes and the mechanical changes in machinery mechanisms, is a tribotechnical diagnostics (TTD). Its function is to discover, evaluate and identify the occurrence of foreign substances in the lubricant and further monitor the effects and the results of lubricant degradation process during the operation. For the TTD to be valid, it is essential to perform the lubricant analysis fast, correctly and accurately [3,4,5,6].

The tribotechnical diagnostics fulfils the following objectives:

- a) to observe conditions and wornness of machines and equipment in order to determine the occurrence of metal particles in lubricants where the magnitude of measured values is important,
- b) to determine lubricants useful lifetime by specifying the level of their devaluation, the products of thermal and oxidation processes as well as external contaminants. The increased amount of contaminants in oil not only means that the lubricated parts are worn off more, but also that the sediments which may clog oil holes and grooves of the machines have been formed. ,
- c) to determine optimum regular intervals for oil exchange [7].

An efficient oil analysis programme is often based on an off-line oil analysis, performed in laboratories where all oil properties are analyzed. However, there are more and more requirements for real-time oil analysis data to support the maintenance decisions. Numerous continuously measuring on-line/in-line oil analysis sensors are commercially available. Conductometric sensors have been fabricated by applying imprinted polymers as receptors for monitoring engine oil quality in [8]. When evaluating the condition of automotive engine oil, the oil's viscosity is one of the most important parameters. Using microacoustic viscosity sensors, an oil-viscosity measurement can be performed on-board [9]. Wang [10] examined road tests of an oil condition sensor and sensing technique. The newly designed sensors were installed in three vehicles and tested on the road. The test results indicated that the degradation of engine oil could be divided into three stages: (1) good, (2) rapid increase in the total acid number (TAN), and (3) rapid increase in viscosity [11]. Various sensor principles of the on-line monitoring of thermal aging of engine oils are considered in Agoston et al [12]. Capone et al [13] deal with the application of a gas sensors array to detect defects in fuel system and contamination in engine oil. Zhan et al [14] made the operational approach to a bar-type engine oil cooler. However, these sensors often measure one property only.

Physico-chemical instrumental control methods have been developed extensively in recent years. These methods enable us to determine not only the actual state of an operated oil charge, but also determine the type of friction and wear of machinery lubricated by oil. This is performed on the basis of abrasion particle characteristics (the number, chemical composition, a structure, surface texture, morphological characteristics and so on). The methods used for this purpose are the infrared spectroscopy with Fourier transform (FTIR spectroscopy) [15-18] and electrochemical methods [19].

With the development of the FTIR spectrometry, software equipment of spectrometers got improved by adding highly demanding mathematic-statistical (chemo-metric) methods that allow to compress the extensive matrix of spectral data, to create regression calibration models for predicting the quality parameters of lubricants and fuel and, as the case may be, to classify the petrochemical samples into one of several (two or more) groups based on the similarity of their variables. A lot of consideration is given to the possibility of using the FTIR spectrometry as an alternative method for checking the oils and fuel in literature [20-23].

Another group of methods allows us to monitor the process and the amount of wear of components that are lubricated by the appropriate lubricant. These methods are suitable for determining the concentration of abrasion metals, describing their morphology and dividing into classification classes according to size, and also for determining e.g. contaminants from filtration materials (they are namely emission spectrometry, analyzer of particles and ferrography) [3,4,5,24-30]. The obtained analytical data provide both the diagnostic information and the prognostic information – i.e. they allow us to predict disrepair situations and prevent their occurrence.

Kumbár et al say [2] that the current evaluation of the quality of automotive engine oil can be sufficiently expressed by dynamic viscosity oils, the analysis of wear metals by emission spectrometry and detection and monitoring of the quantity, type and size of wear debris by analyzer of particles. Similar conclusions may be found in [31] and [32].

## 2. Experimental

### 2.1. Diagnosed objects

The samples of engine lubrication oil were continuously collected from various types of buses which vary according to a type and a model year (table 1). New engine oil was added when necessary to the original charge during the operation of the buses. Sampling intervals ranged from about 5 000 to 10 000 km. Elementary operating methods were performed in the laboratory of a transport company to determine the presence of water, dirt and relative dynamic viscosity.

Table 1. The technical specification of the buses and the operated oil chargers

Bus marking	SOR B 9,5	IrisBus CityBus 18M	Karosa Axer
Type of engine		diesel - supercharged	
The number of cylinders	6	6	26
Year of manufacture	2000	2002	2003
Oil charger volume [l]	12	25	38
Recommended interval of oil change [km]	15	40	40
Mileage of engine with oil charge [Mth]	14	50	50
Engine oil marking	OMW Truck LD SAE 15W/40	OMW Truck FE Plus SAE 10W/40	OMW Truck FE Plus SAE 10W/40

By combining the instrumental methods of tribotechnical diagnostics (FTIR spectrometry, atomic emission spectrometry, analysing the particles using a laser analyzer), we analysed the relations between the degradation processes which occur during the motor oil operation and the characteristics of the process of operational wear of engine parts where this oil is applied.

### 2.2. Experimental Methods used

#### FTIR spectrometry

The infra-red spectrometry is one of the optical methods of molecular spectrometry that uses the spectral range delimited by wavelengths of 0.78–1,000  $\mu\text{m}$ , i.e. wavenumbers from 12,800 to 10  $\text{cm}^{-1}$ . The most commonly used one is the middle infra-red (MIR) area of 4,000–400  $\text{cm}^{-1}$ . The principle of the method is the absorption of infra-red radiation when passing through a sample where the vibration or vibration-rotation energy states of a molecule change depending on changes of its dipole moment. The analytical output is the band absorption spectrum which is a graphical representation of a functional dependency of energy, usually expressed in percent of transmittance or in units of absorbance.

The level of the engine oils wear can be determined using the differential spectroscopy for the spectra of the original oil and the degraded one. Therefore, it is possible to determine the relative content of oxidizing, nitrating and sulphatising products, the content of water, fuel and cooling liquid, the level of anti-oxidizing additives reduction, and so on [16].

Infrared spectra were recorded on a Nicolet IS10 spectrometer (Thermo Scientific) in the spectral range of 650–4000  $\text{cm}^{-1}$ , with the resolution of 4  $\text{cm}^{-1}$  and with the scan number 32 by means of the ATR technique (ZnSe crystal).

### *Atomic Emission Spectrometry*

The emission spectrometry is one of the optical methods of atomic spectrometry. It uses the radiation emitted by free excited atoms or by elements in gaseous state for determining the element composition of samples in solutions as well as solid samples. The principle of the atomic emission spectrometry (AES) is to register photons that come into existence due to passes of valency electrons from higher energy levels to lower ones.

Tribotechnical diagnostics use the methods of AES to determine the degree of wear of friction pairs, the concentration of additives in a lubricant and the concentration of contaminants [5,25,26,29]. By regular monitoring the concentration of abrasion metals in the oil, optimum preventive maintenance processes can be set and, hence, the reliability of the device can be increased.

Chosen abrasion metals and contaminants were evaluated on spectrometer Spectroil Q100 (Spectro Inc., USA).

### *Analysis on Particle Counters*

The device that works on the principle of counting the particles in conjunction with the analysis of their shape is LaserNet Fines (LNF). The LNF detects particles larger than 5  $\mu\text{m}$  using laser and advanced software for an image analysis. The outlines of images of the analysed particles in the 20–100  $\mu\text{m}$  range are based on the algorithms of neural network methods.

The information about the captured particles is used for evaluating the current state of wear of the given system and can be observed directly on the screen of the LNF control computer.

The evaluation of the wear mode of the most exposed friction surfaces of the engine was realized by the particle analyzer LNF Q200 Laser Net Fines (Spectro Inc., USA)

## *2.3. Experimental Results*

The aim of the analysis of the engine oils from the buses was to consider whether the change in setting replacement intervals (in two buses the replacement interval was prolonged by 10 000 km, in one case it was shortened by 10 000 km) made on the basis of the results of elementary operating methods is optimal. Due to the limited size of the paper the analysis results are processed in detail only for the bus IrisBus CityBus 18 M. The results for other buses are shown in [4].

The first sample was taken when the mileage of the bus was 423 963 km. This articulated bus had been ridden on suburban routes. It had been used almost daily.

The spectral record in Fig. 1 demonstrates the penetrative decrease in antiwear and antioxidation additive based on ZnDDP (zone area 1050–950  $\text{cm}^{-1}$  and 690  $\text{cm}^{-1}$ ) after the mileage 23 828 km. This corresponds to a half replacement interval contrary to the interval given by the producer of the bus. The depletion of additives of this type can affect significantly the occurrence of increased wear of engine parts. The replacement of oil is recommended every time the decrease in anti-wear and antioxidant additives is about 80 %.

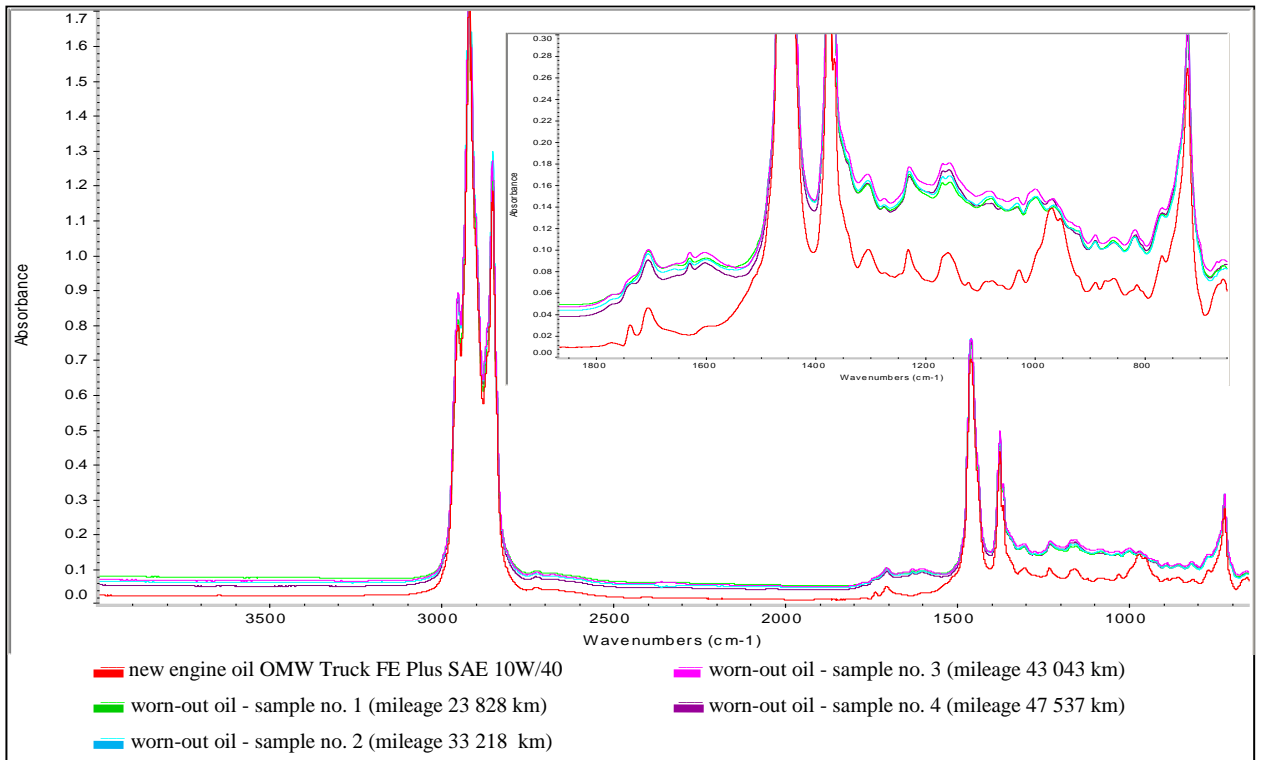


Fig. 1. The spectra of the operated oil charges in the bus after separate samplings

The quality of oils after a certain mileage was mainly marked by soot particles and aging products which is accompanied by oil darkening (the shift of the base line of the spectrum to higher values of absorbance in  $2000\text{ cm}^{-1}$ ). Some authors state [33] that higher temperature causes the formation of insoluble particles and more intensive oil carbonisation. .

Soot is formed by almost pure carbon and in some cases it is hard with sharp edges. That is why its higher concentration in engine oil causes increasing viscosity which later results in the increased wear of the engine. During pumping and circulation the polluted oil may occur (due to the flow of soot particles) and can cause abrasive wear on the metal surfaces. .

The limit concentration of soot in oil of 3 % wt. is used for older types of engines [34]. But modern engine oils replaced after longer intervals are made from hydrocracked based oil. These oils withstand higher load by soot without significant influence on the properties of the engine oil compared to a conventional solvent-refined base oils group I [34]. Of course this also very much depends on the used additive of the base oil and the dispersant effectiveness.

The fuel contaminates the oil charge (Fig. 1 zone with the peak of  $816\text{ cm}^{-1}$ ). Since the presence of fuel decreases oil viscosity and soot increases it, significant change in relative viscosity was not detected by a rotational viscometer.

The oil has a very good oxidation resistance, because the absorbance related to the oxidation of hydrocarbons did not increase in the range of  $1710\text{ cm}^{-1}$ , i.e. the content of oxidation products containing the C=O bond in a carbonyl group did not increase.

The interval of  $1610\text{--}1630\text{ cm}^{-1}$  which occurred in the samples is without operational risk. This area is associated with oil nitration which occurs due to the reaction of oil with nitrogen oxides from combustible gases. The increased content of nitrogen oxides may be caused by improper fuel/air mixture ratio in the combustion chamber. The range of nitrides in the FTIR spectrum indicates excessive wear of piston group, namely the leaks of piston rings.

The concentration of the elemental composition of wear metals and contaminants was monitored by AES with a rotating disk electrode. As shown in Fig. 2, in almost all oil charges the concentration of wear metals and contaminants changed when compared to the original values in the new oil.

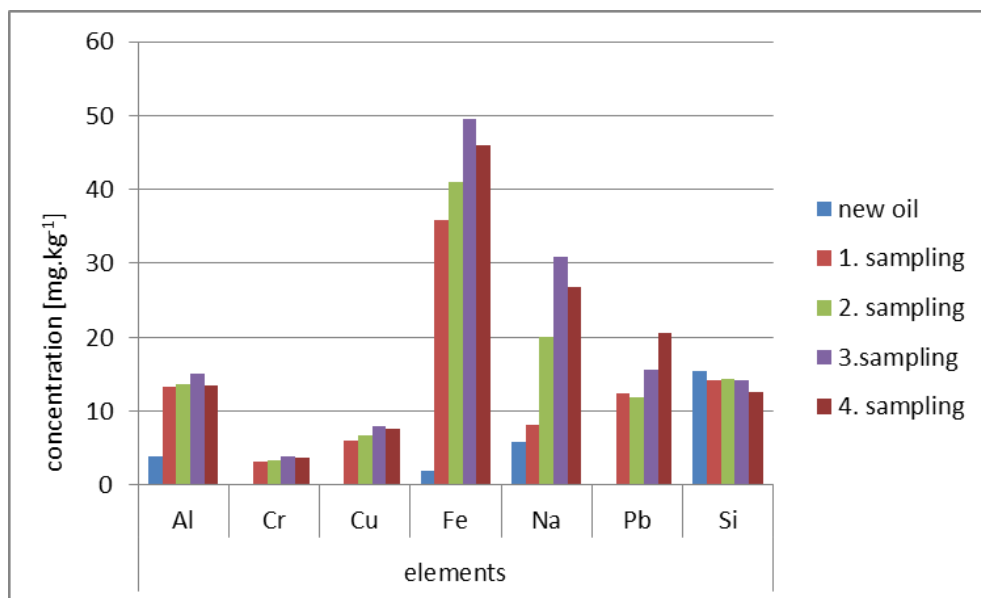


Fig. 2. The concentration of wear metals and contaminants in the oil of the operated bus

It is apparent from Fig. 2 that the increased growth of the content of wear metals *Fe* and *Pb* was identified in all oil charges. At the third sample the concentration of  $Fe=50 \text{ mg.kg}^{-1}$  reached the threshold of increased wear. The boundaries of increased wear were also reached by the concentration of  $Pb=15 \text{ mg.kg}^{-1}$  for the sample no. 4. The concentration of *Cu*, which may indicate wear of bearings, did not acquire the values higher than  $30 \text{ mg.kg}^{-1}$  in any analysed oil sample. This limit is given as the lower limit on increased wear. The concentration of *Al* (the source may be bearing or cylinder head wear, for example) did not reach the value of  $25 \text{ mg.kg}^{-1}$  which is the limit on the increased wear. Fig. 2 shows that a sudden increase in the concentration of wear metals occurred at sample no. 2 (about in the mid of a replacement interval). This shows that the result is consistent with the conclusions of FTIR spectrometry - in this sample a marked decrease in antiabrasion additive was found. .

Dust silicate particles did not get into the oil charge. Increase in *Na* could signalize the penetration of cooling liquid (coolant containing various sodium salts as an inhibitor of corrosion) into the oil charge. But this was excluded by performing FTIR spectrometry and simple operational test detecting the presence of water. Given that the sampling no. 2 and 3 was conducted during a winter season, it can be concluded that *Na* comes from the road salt which was used for treating winter roads.

When performing the analysis of the particle counter LNF it was found that although additional oil of 5.4l was put into the engine, this action did not provide significant increase in oil lubrication quality. Some parts of the engine showed signs of fatigue processes and increased wear processes which portend a possible accident. (Table 2).

Table 2. Results of the particle counter analysis LNF Q200

THE SAMPLE NUMBER	THE NUMBER OF PERTICLES				
	cutting wear	damage wear	fatigue wear	non-metallic particle	unclassified particle
1	6,2	15,4	52,3	18,5	0
2	1,5	6,2	33,9	12,3	0
3	1,6	0	25,6	6,4	1,5
4	69,4	35,5	673,3	313,3	3,2

Adhesive wear particles which range from 15 to 50  $\mu\text{m}$  (the particles of cutting and damage wear - Table 2, 3) were produced significantly since the manufacturer of the bus recommended the extension a replacement interval. .

Table 3. The results of classification of particles according to size

THE SAMPLE NUMBER	THE NUMBER OF PARTICLES ACCORDING TO SIZE				The total number of particles
	5–15 [ $\mu\text{m}$ ]	15–25 [ $\mu\text{m}$ ]	25–50 [ $\mu\text{m}$ ]	50 and more [ $\mu\text{m}$ ]	
1	8 894	168	48	3	9 113
2	8 637	68	37	6	8 748
3	16 686	77	6	3	16 772
4	26 386	1 718	589	42	28 735

There was a damage to the engine of the bus IrisBus CityBus 18 M; right in this case the replacement interval was prolonged by about 7500 km. Step increase in large particles (mainly those of the size ranging from 15 to 50  $\mu\text{m}$ ) might be considered to be a portent of unfavourable friction conditions. These particles were identified as particles connected with fatigue (fatigue wear often occurs at valve tappets [33]) and abrasive processes depending on their shape characteristics. Damage particles were also identified (Table 3).

### 3. Conclusion

The practical application of the TTD instrumental methods to oil samples taken from the buses proved that the generally recommended boundary values of abrasion metal concentration are not always sufficient when it comes to judging the course of wear of the engine since each engine is specific and is operated in different conditions. Another reason is that the AES is not sensitive enough to detect the particles larger than 5  $\mu\text{m}$ . In order to judge the course of wear of the engine, it is necessary to have the data about the size-related composition and distribution of abrasion particles available; this can be achieved by analysing the particles using a laser analyser.

However, when interpreting the results of particle analysis it is also necessary to take into consideration the time intervals of sampling, re-filling the oil during operation and the efficiency of its filtering. The presence of oil ageing products (sludge and sediments) and the products of imperfect combustion of fuel and mechanical impurities (especially the abrasion from the wear of metal materials and dust particles from outside) is undesirable because it increases the wear and failure rate of the engine. Most often, oil analysis program combines the continuous attention to oil and disruptions groups of vehicles. The required contribution is indeed useful, but should not be considered significant in comparison with other objectives. Maintenance strategy based on the state defines the philosophy of a proactive maintenance which should be the real basis for the oil analysis program.

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