Motor oil degradation during urban cycle road tests

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Abstract: Several civilian vehicles in China operate in urban traffic conditions and have their motor oil changed every 5,000 km. This study investigates the variations in oil properties after servicing at 5,000 km, based on systematic road tests (including a repeated test, a parallel test, and a new vehicle test). The physicochemical properties, changes in components, oxidation stability, detergent-dispersant performance, and tribological properties of motor oils were analyzed. The results showed that the total acid number (TAN) of oils increased with the operation mileage, by up to 1.41 mgKOH/g. The total base number (TBN) decreased after the road tests were completed, and the decrease was less than 44.6%. The kinematic viscosity (KV) of most oils decreased initially and then stabilized in the middle stage, before starting to increase later in the experiment. The change in KV at 100 °C was less than 15.96%. The oxidation onset temperature (OOT) of the oils diminished gradually with the operation mileage. All OOT values of the used oils were higher than 210 °C. A spot test indicated that the used oils retained their detergent-dispersant performance to an appropriate extent. The four-ball wear scar diameters and friction coefficient of the used oils did not increase significantly after the road tests were completed. This study can serve as a reference for end-users when changing motor oils.

Keywords: motor oil; urban vehicles; oil degradation; road test; oil analysis

1 Introduction

Motor oil provides wear protection, thermal management, and corrosion inhibition functions that are critical to engine performance and longevity [1, 2]. Regardless of the oil type used, the quality declines during use because of degradation and/or contamination [3, 4]. Therefore, motor oil must be changed to counter degradation and contamination, and to maintain the quality necessary to protect the engine [5, 6]. A rapid increase in the number of vehicles has increased the demand for motor oil. There were about 250 million automobiles in China

up to June 2019, and about 200 million of those automobiles were private vehicles. The requirement for gasoline motor oil in China is near one million tons every year [7]. Even though some new-energy vehicles have appeared, most vehicles are still running on fossil fuels. Petroleum-powered vehicles cannot be completely replaced within a short time, which indicates that the demand for motor oil will not diminish. The use and drainage of a large amount of motor oil as a consumed petroleum resource has increased preventive maintenance costs and necessitated stringent measures to ensure environmental protection [8, 9]. According to the

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study, one gallon of lubricating oil has potential to contaminate one million gallons of drinking water [10]. Oil drain intervals that are too long will increase engine wear and the likelihood of engine damage. Therefore, a reasonable oil-change time is important to the economy and people's livelihoods.

The oil maintenance schedule in China is very different from that of other developed countries. Researchers from Mercedes-Benz AG and Shell International Petroleum Co. [11] studied oil-change intervals in Europe from the 1950s to the 1990s. The oil drain interval of Europe in the 1970s was 5,000 km and increased to 15,000 km in the 1990s. The General Motors Corporation maintenance schedule for gasoline-fueled passenger vehicles and light trucks recommends that the engine oil should be drained every 12,000 km or 12 months, barring severe operating conditions [12]. The oil maintenance in China is more frequent than that in Europe and USA. Presently, approximately 56.1% of civilian vehicle models are recommended for an oil change at 5,000 km, according to our study on the oil-change mileage of 278 models of civilian vehicles in China, as recommended by original equipment manufacturers (OEMs). Even for motor oil and vehicles imported from the Europe or USA, the oil-change interval is shortened when they are used in China. The reasons may include the operation condition, environmental factors, gasoline quality, and end-user's opinion on oil maintenance. Severe traffic jams may occur in cities owing to the high number of civilian vehicles. The sulfur content in Chinese gasoline is higher than in Europe and the US, which influences the exhaust emissions and oil degradation. In addition, the end-user's opinion on motor oil maintenance affects the oil-change mileage. Many drivers consider changing the oil frequently is better for their vehicles.

Several experiments on monitoring the motor oil condition were conducted in Europe. Wolak and Zajac [13] used two Fourier transform infrared spectroscopy (FTIR) devices to test the oils in three gasoline and three diesel engines. The physicochemical properties (degree of oxidation, degree of nitration, degree of sulfonation, basic number, and percentage content of additives) were used to assess the quality

of lubricating oils. The study did not provide an exhaustive answer, but it did show the potential of predicting oil-change intervals using a FTIR method.

Raposo et al. [14] studied diesel engine oil in urban buses and proposed a model to predict maintenance interventions. An oil analysis to monitor the oil condition examined the antifreeze, appearance, fuel, content of water, soot, nitration, oxidation, sulfation, viscosity, viscosity index, total base number (TBN), wear metals, and particles. A proposed model based on mathematical and statistical methods can provide oil-change intervals for buses. The study helped extend the oil-change interval of some models of buses from 20,000 to 25,000 km.

Gołębowski et al. [15] studied two types of engine oils used in 17 different passenger vehicles, which included 13 diesel engines, 3 gasoline engines, and 1 gasoline + liquefied petroleum gas engine. Physicochemical parameters including the degree of oxidation, degree of nitration, degree of sulfonation, water content, glycol content, TBN, total acid number (TAN), and kinematic viscosity (KV) at 40 and 100 °C of fresh and used oils, operated from 10,000 to 30,000 km, were analyzed and compared with the limit values. The results showed that an exceedance of KV measured at 40 °C was particularly striking for both synthetic and semisynthetic oils. In 14 samples (out of 17 tests), at least one exceedance of the limit value was observed. As the study was conducted via off-road testing, the operating conditions of the experimental oils were not clear. Thus, the study did not provide an unequivocal answer to a specific question: Why did engine oil at mileages of 16,000 and even 24,000 km not show any limit value exceedances, and for some mileages of 10–13,000 km exhibited exceedance for more than one parameter?

As mentioned in Section 1, the recommended oil-change interval in Europe is different from that in China. The experimental mileages in Refs. [14, 15] were from 10,000 to 30,000 km, which were higher than the mileage in our experiments (approximately 5,000 km). European scholars are still carrying out studies to determine whether it is possible to extend the oil-change interval. Thus, oil-change internal analysis for passenger vehicles in China is

necessary.

Similarly, some key physicochemical parameters (TAN, TBN, KV, degree of oxidation, nitration, and sulfation) were analyzed in our study to monitor the oil condition. The experimental vehicles, oils, and operating conditions were different from those of the abovementioned studies. Five gasoline-engine vehicles were used in several on-road tests under urban city conditions to study the oil degradation. The oxidation stability, detergency, dispersancy, and tribological properties of the motor oils during the road tests were systematically analyzed. More comprehensive parameters of oils were analyzed in an attempt to determine the accuracy of the oil condition; this can provide end-users with useful information regarding motor oil maintenance.

2 Experimental

All of the experimental vehicles were operated under urban traffic conditions. The experimental vehicles and motor oils are listed in Table 1. Experiments 1-1 and 2-1 were conducted with two civilian vehicles of the same model, with the same synthetic oil and test time. Experiments 3-1, 3-2, and 3-3 were tests repeated using the same mineral oil. Experiments 4-1 and 4-2 were repeated using the same synthetic oil. Experimental vehicle 5-1 was new. 92-Research

Octane Number (RON) gasoline was used in the experimental vehicles. The vehicles were equipped with an on-board diagnostic (OBD) system that can obtain real-time operation information including the engine operation time, mileage, fuel consumption, average speed, and idle ratio.

An oil sample of about 15 mL was collected from the crankcases approximately every 30 days. No fresh oil was poured to refill the crankcase during the experiments. The average distances within 30 days of experimental vehicles 1–5 were 658.8, 540.9, 1160.6, 971.6, and 793.7 km, respectively. The relative changes in the oxidation, nitration, sulfation, and phosphate content were evaluated using the Integra software with an infrared spectrometer (NICOLET iS10, Thermo Fisher Scientific, USA), with American Society for Testing Material (ASTM) E2412-10 as a reference. The infrared absorbance spectrum of each oil sample was acquired, covering a range of 550–4,000 cm^{-1} . The features in the infrared spectrum indicative of the components of interest (oxidation, nitration, sulfation, and phosphate content) were measured. The difference between the infrared spectra of used oil and fresh oil can be calculated with Integra and can illustrate the changes in the component contents.

The TAN, TBN, and KV of the oil samples were tested using the ASTM D974-2014, ASTM D2896-88,

Table 1 Experimental vehicles and motor oils.

No.	Experimental vehicle	Engine capacity (L)	Vehicle age (years)	Motor oil	Oil drain mileage (km)
1-1	Nissan Teana	2.5	2	Shell Ultra API SL, SAE 5W-30 synthetic oil	7,816
2-1	Nissan Teana	2.5	2	Shell Ultra API SL, SAE 5W-30 synthetic oil	6,419
3-1	Hyundai Verna	1.4	5	API SL, SAE 5W-20 mineral oil, special for Hyundai	5,396
3-2	Hyundai Verna	1.4	5	API SL, SAE 5W-20 mineral oil, special for Hyundai	5,002
3-3	Hyundai Verna	1.4	5	API SL, SAE 5W-20 mineral oil, special for Hyundai	5,062
4-1	Buick Regal	2.0	0.5	API SN, SAE 5W-30 synthetic oil, special for GM	5,020
4-2	Buick Regal	2.0	0.5	API SN, SAE 5W-30 synthetic oil, special for GM	4,938
5-1	Fengshen AX7	2.0	New	API SN, SAE 5W-40 synthetic oil, special for Fengshen	5,291

and ASTM D445-2009 standards as references, respectively. To determine the TAN, the oil sample was dissolved in a mixture of toluene and isopropyl alcohol containing a small amount of water and a standard alcoholic base solution to the endpoint indicated by the color change of added p-naphtholbenzein solution. To determine the TBN, the oil sample was dissolved in a mixture of petroleum ether and glacial acetic acid solution to the endpoint, which was indicated by the color change of a mixture of p-naphtholbenzein and methanol solution. The KV was measured using the flow time and calibration constant of the viscometer under a certain temperature.

The oxidation onset temperature (OOT) of motor oil was determined by pressure differential scanning calorimetry (PDSC, NETZSCH HP 204, Germany) with ASTM E2009-02 as a reference. The test oil sample in an aluminum container and an empty reference aluminum container was heated at a specified constant heating rate (10 °C/min) in an oxygen (100 mL/min, 3.5 MPa) environment. The heat flowing out of the specimen was monitored as a function of temperature until the oxidative reaction was manifested by heat evolution on the thermal curve. The OOT measurement was initiated upon reaching the exothermic reaction and measuring the extrapolated onset temperature.

A blotter spot test was used to evaluate the detergency and dispersancy of the motor oil using ASTM D7889-13 as a reference. At room temperature and with no wind, a drop of oil was placed in the center of a piece of quantitative filter paper (Shuang Quan, Hangzhou Xinhua, China), which was put on a plastic cup to hang the center of the filter paper in the air. After the oil drop diffused in the filter paper for 2 h, two or three oil rings formed on the filter paper. The detergency and dispersancy were evaluated by checking the color and size of the oil spot.

The tribological properties of the fresh oils and used oils were investigated with a four-ball tester (YIHUA, China) with ASTM D4172 as a reference. Three 12.7-mm-diameter steel balls were clamped together and covered with the motor oil for evaluation. A 12.7-mm-diameter steel ball, referred to as the top ball, was pressed with a force of 147 N into the cavity formed by the three clamped balls,

to achieve three-point contact. The temperature of the test motor oil was maintained at 20 °C, and the top ball was rotated at 1,200 rpm for 30 min. The average size of the scar diameters worn on the three lower clamped balls was used to evaluate the anti-wear performance of the test oil. The friction coefficient (COF) was obtained using a force sensor.

3 Results and discussion

3.1 Operation status of experimental vehicles

The operation status of the experimental vehicles, acquired using the OBD systems, is presented in Fig. 1. As shown in Fig. 1(a), the speed of the experimental vehicles varied mainly from 0 to 40 km/h, and the average speed was 20.1 km/h. The idle ratio was mainly 10%–40%. Most of the idle ratio was higher than 10% as presented in Fig. 1(b). Figures 1(c) and 1(d) show the single operation time and single operation mileage (a single operation time/mileage is from starting to switching off the engine), respectively. Approximately half of the single operation time was less than 20 min, and approximately 90% of the single operation mileages were less than 30 km.

According to Fig. 1, the experimental vehicles had the characteristics of low operation speed, high idle ratio, and short operation time and mileage, which are typical urban traffic conditions. The average speed (20.1 km/h) of the experimental vehicles was consistent with the average speed of major cities in China (19.893 to 27.031 km/h) provided by the Amap company. Thus, the experimental vehicles can be taken as typical cases for studying the operation status of civilian vehicles in major cities in China.

3.2 Component changes and physicochemical properties of experimental oils

Motor oil contacts with oxygen and operates under elevated temperatures. Thus, the oxidation of motor oil is unavoidable. Fuels and lubricating oil often contain sulfide, nitrides, and other corrosive components [16]. Aging of motor oils is often caused by strong acidification from combustion products

Fig. 1 Operation status of experimental vehicles: (a) average speed, (b) idle ratio, (c) single operation time, and (d) single operation mileage.

(SO_x and NO_x), which are absorbed by motor oils. This causes corrosion, harm to the engine, waste of the neutralization reserves of the oil, and a reduction in the lifetime of the oil [17]. The relative change values of the oxidation, nitration, sulfation, and phosphate content tested with the Integra reflected the degradation and additive consumption of the motor oil.

Changes in the components of the oil samples were evaluated using Integra; the results are shown in Fig. 2. As Figs. 2(a)–2(c) show, all oxidation, nitration, and sulfation values of the tested motor oils increased with the operation mileage, and the phosphate content decreased with a prolongation of the experiments (Fig. 2(d)). The oxidation, nitration, and sulfation values increased rapidly, while the phosphate content decreased rapidly during the initial period of the experiment. This was caused by mixing with residual oil and the dissolution of residues from the previous oil. The phosphate content changed during parallel tests with the same vehicle model (1-1 and 2-1), repeated test with mineral oil (3-1,

3-2, and 3-3), and repeated test with synthetic oil (4-1 and 4-2). These had good repeatability, indicated that the consumption of anti-wear components during road tests repeated well. Experimental vehicle 5-1 was new and operated its first 5,291 km. The component change characteristics of motor oil 5-1 were similar to those in the other road tests. All oxidation, nitration, and sulfation values of the used oils were lower than the warning limit (1.0 A/0.1 mm) reported in Ref. [18].

TAN is considered an important indicator of oil quality, specifically in terms of defining oxidation and the extent of acidic contamination of the used oils [17, 19]. The TAN of the used motor oils is presented in Fig. 3. The TAN increased with the operation mileage. The increases (from experiment 1-1 to 5-1) were 1.41, 1.26, 0.99, 0.55, 0.43, 0.50, 0.85, and 1.29 mgKOH/g, respectively. There are no uniform warning limits for oil quality evaluation. Different investigators may suggest different limits for a given oil analysis measurement. This study considered a TAN > 7 mgKOH/g as the warning

Fig. 2 Component change characteristics of experimental motor oils: (a) oxidation value, (b) nitration value, (c) sulfation value, and (d) phosphate content.

Fig. 3 TAN of experimental motor oils.

limit, and $\text{TAN} > 15 \text{ mgKOH/g}$ was observed in a short-trip service without engine failure [20]. According to the criteria for changing gasoline engine oil in China (GB/T 8028-2010) [21], the warning limit for oil-change is an increase in $\text{TAN} > 2 \text{ mgKOH/g}$. The variations of TAN during the road tests were in the range of the reported literature and criteria of China. As the oxidation value and TAN were

related to oxidative degradation, the trend of the oxidation value (Fig. 2(a)) and TAN (Fig. 3) was similar. The oxidation value and TAN increased gradually with the operation mileage. The oxidation value of experiment 1-1 increased rapidly at 6,891 km of road test, which was consistent with the change characteristic of TAN.

TBN represents the additive alkalinity reserve in oil, which can neutralize acid products occurring during combustion. The TBNs of experimental oils are presented in Fig. 4. The TBN value of fresh oil decreased after the road tests were completed. The warning limits of TBN in different studies are not always the same. Timotijevic et al. [19] considered that the TBN decreased by 75% as the critical value for changing oil. Another study held that a $\text{TBN} < 2 \text{ mgKOH/g}$ was the warning limit. Chinese standards state that motor oil needs to be changed while $(\text{TBN} - \text{TAN}) < 0.5 \text{ mgKOH/g}$ [21]. The variation of TBN in experiment 3-2 was largest at -44.6% . The change in TBN for all experimental oils fulfilled the requirements of engine protection.

Fig. 4 TBN of experimental motor oils.

KV is a vital indicator of motor oil. A viscosity that is too low or too high can affect the oil performance [16, 22]. Suggested warning limits of KV varied from investigator to investigator. Timotijevic et al. [19] insisted that a change in KV at 100 °C should be in the range of −10% to 20%. Another study proposed that the warning limit is an increase (> 35%) in KV at 100 °C [20]. Chinese standards related to motor oil need to be changed when the KV at 100 °C is beyond $\pm 20\%$ [21]. The KV at 100 °C of fresh oils and used oils are shown in Fig. 5. The KV of experiments 1-1, 2-1, 3-2, and 3-3 decreased initially, then became steady in the middle stage, and started to increase later in the experiment. The shearing stress of engine parts, oil oxidation, light components of fresh oil evaporation, and fuel or soot contamination results in the changes in KV of motor oil in urban vehicles. The change in KV at 100 °C during the road tests (from experiments 1-1 to 5-1) was −6.32%, −0.26%, 4.23%, 2.75%, 0.46%, −15.96%, −15.21%, and −1.01%, respectively. No

Fig. 5 KV at 100 °C of experimental oils.

changes in KV at 100 °C of the used oil reached the warning limit.

Oxidation stability is one of the most important parameters of lubricating oil to evaluate the service life at high temperatures and in extreme applications. The more resistant a lubricant is to oxidation, the lower its tendency to form deposits, sludge, and corrosive byproducts in industrial applications [23–25]. The changes in oxidation stability in eight road tests are illustrated in Fig. 6. The oxidation stability of different experimental vehicles decreased with the operation mileage. The change characteristics of antioxidants corresponded to changes in the oxidation value in Fig. 2(a). The OOT values of the used oils were higher than 210 °C. This suggested that the oxidation stability of the used oils still fulfilled the requirement.

Detergency and dispersancy are properties that allow oil to suspend and carry away pollutants from diverse sources such as soot from combustion, metallic particles from wear, corrosion of mechanical parts, and insoluble products resulting from the aging of oil. The blotter oil spot method is an efficient way to evaluate the detergency and dispersancy properties of motor oils [26, 27]. The oil spot test for used oils is presented in Fig. 7. The color of the oil spot images was light and evenly graduated. The oil ring in the exterior oil spot image was bright, and the deposition ring of the center oil spot image was not obvious. The used oils still retained good detergency and dispersancy properties.

3.3 Tribological properties

Tribological properties are a fundamental performance

Fig. 6 OOT of experimental motor oils.

Fig. 7 Spot images of experimental oils.

measurement of motor oil and can reflect the lubrication and anti-wear property directly [28, 29]. The average COF and wear scar diameter (WSD) of fresh and used oils are shown in Figs. 8 and 9, respectively. As Figs. 8 and 9 indicate, the average COFs and WSDs of the used oils were greater than those of fresh oils concerning oil degradation. The average COFs of fresh oils (from experiments 1-1 to 5-1) were 0.0757, 0.0757, 0.0810, 0.0810, 0.0810, 0.0840, 0.0840, and 0.0802, respectively. The average COFs of the used oils (from experiments 1-1 to 5-1) were 0.0798, 0.0765, 0.0910, 0.0820, 0.0850, 0.0900, 0.0862, and 0.0868, respectively. The WSDs (Fig. 9) of fresh oils (from experiments 1-1 to 5-1) were 0.253, 0.253, 0.247, 0.247, 0.247, 0.244, 0.244, and 0.244 mm, respectively. The WSDs of the used oils (from experiments 1-1 to 5-1) were 0.268, 0.262, 0.273, 0.254, 0.279, 0.290, 0.282, and 0.263 mm, respectively. The change in the average COF and average WSD of motor oils in eight road tests was less than 12.35% and 18.85%, respectively. The COF and four-ball WSD did not increase significantly after the road tests.

In general, the changes in TAN, TBN, and KV at

Fig. 8 COF of experimental oils.

Fig. 9 Wear scar diameter of experimental oils.

100 °C and the oxidation value, nitration value, and sulfation value of all used oils fulfilled the requirement reported in the literature and/or criteria of China. PDSC results and a blotter spot test suggested that the used oils operated for approximately 5,000 km retained good oxidation stability and detergent-dispersant performance. The four-ball WSD and COF of used oils did not increase significantly after the road tests.

According to the studies by Raposo et al. [14] and Gotębiowski et al. [15], it is not easy to determine an accurate oil-change mileage in time. This can be attributed to the various types of oils and engines, complicated operating conditions, numerous testing indicators, and nonuniform limit values for the same indicator. Even though oil analysis always needs a long experiment time, oil analysis, especially when combined with road tests, remains an effective method to study the oil degradation level. This study provides some experimental data for scholars to study the change characteristics of oil deterioration, and also provides end-users some information on oil maintenance.

4 Conclusions

The study researched motor oil degradation based on road tests and provided test data for end-users and researchers. The conclusions are as follows:

1) The variations in the TAN, TBN, and KV of used oils operated for approximately 5,000 km are within the range of the current Chinese standards and agree with those of previous studies. The oxidation, nitration, and sulfation values of used

oils do not exceed the warning limits reported in the literature. The used oils still possessed good oxidation stability and detergent-dispersant performance. Four-ball WSD and COF of used oils did not increase significantly after the 5,000 km road tests. The change characteristics of motor oil serviced in a new vehicle exhibited no obvious difference from that in older vehicles.

2) The results of this study focused on a limited number of civilian vehicles and typical urban traffic conditions. In future studies, more vehicles, oil types, and operating conditions will be taken into consideration. This might make it possible to verify the appropriateness of the oil-change standards proposed by OEMs.

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