Friction **8**(1): 95–106 (2020) ISSN 2223-7690
https://doi.org/10.1007/s40544-018-0248-0 CN 10-1237/TH

RESEARCH ARTICLE

Motor oil condition evaluation based on on-board diagnostic system

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Received: 06 February 2018 / Revised: 26 June 2018 / Accepted: 22 September 2018

Abstract: The condition of the motor oil in civilian cars is difficult to monitor; hence, we propose a method to evaluate the degree of degradation of motor oil using an on-board diagnostic (OBD) system. Three civilian cars and four motor oils (containing mineral oils and synthetic oils) were subjected to five groups of road tests under urban traffic and high-way conditions. The operation information, oil service time, mileage, engine operation time, idle time of the engine, and number of start-ups of the engine were obtained using the proposed OBD system. Physiochemical properties and changes in the components of motor oils during road tests were analyzed in laboratory. The theoretical model of the comprehensive indicators of driving parameters and oil properties were established. The proposed method was successfully applied to different cars, motor oils, and operating conditions in road tests. All the theoretical models had high accuracy and precision. Herein, we provide a method to monitor the oil condition with real-time driving parameters and provide a reference for end users to change their motor oil reasonably.

Keywords: motor oil; oil condition evaluation; on-board diagnostic system

1 Introduction

Motor oil is an essential part of fuel-based vehicles. It provides wear protection, thermal management, and corrosion inhibition functions that are crucial for operation of the vehicle [1–3]. Regardless of the type of oil used in vehicles, degradation and/or contamination under complicated working conditions cannot be avoided [4–6]. Therefore, the motor oil must be changed to meet the normal working requirement. Although certain new energy vehicles have been developed, fuel-based vehicles continue to dominate the vehicle market. Fuel-based vehicles cannot be completely replaced in a short period of time. Excessively lengthy oil drain intervals increase wear in the engine and the likelihood of engine damage. If the intervals are too short, unnecessary preventive maintenance costs, energy wasting, and environment pollution are caused [7–10]. Study also shows that draining the motor oil too frequently may lead to a high concentration of additives in the oil. This can cause a reaction with the lubricant-surface and result in excessive wear [11]. Hence, a reasonable oil change interval is necessary for energy conservation, environment protection, and maintain cost saving.

Generally, there are two methods to determine the oil change interval. One method is sending oil samples to a laboratory to analyze the properties of the oil to determine whether the oil still meets certain criteria. The aforementioned oil analysis method can accurately

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determine the properties of oil; however, the long testing time and high cost limits its application [12–15]. Another more widely used method to change motor oil is based on the mileage or service time recommended by the original equipment manufacturers (OEM). As end users can easily monitor the miles that the vehicle has driven between oil change intervals, the recommended oil change interval has become widely accepted [16]. The recommended mileage that the OEM suggests for oil change intervals is based on various levels of severity of operation, which are rarely seen by consumers. It is impossible for the OEM to anticipate all operations of a user and list different oil drain intervals for each of them. In particular, most vehicles are used for more than one kind of operation. Hence, it is not easy to determine an optimum mileage for accurately changing motor oil [17−19]. Some scholars and OEMs attempt to use sensor technology to determine the oil life. Wang et al. [20] proposed a real-time sensor system that measures engine parameters and applies a special algorithm to indicate the oil drain interval. Jun et al. [21] applied the principal component analysis method to estimate the quality of vehicle engine oil based on oil viscosity indicators and certain engine operation parameters. General Motors has implemented an oil life monitoring system by monitoring the oil temperature and contaminations, and a penalty factor and engine speed are combined to simulate different operation speeds [22–26]. The application of such sensors and algorithms are limited due to cost, complexity, and limited utility of sensors and the errors caused by the algorithms. Jan Kral et al. [27] studied the features and qualities of 13 oil samples recommended for replacement by the onboard computer. The properties of kinematic viscosity, total base number, the amount of soot, oxidizing and sulphating products, water, fuel and glycol contamination, and high antioxidant presence were measured. The results did not correspond with the conclusions recommended by onboard computers.

Oil degradation is closely related to the operating conditions. The working load in the operation state and the idle state is different, which affects the working pressure of the engine oil. Frequently stopping and starting the engine results in continual oil temperature changes. Driving for short trips may cause unburned fuel and/or water to come into motor oil, which can reduce the viscosity and cause excessive wear of engine. Thus, it is necessary to establish the relation model between operation parameters and oil properties for scientifically determining motor oil change interval.

In this paper, a method to establish the theoretical model of operation parameters and oil properties based on road tests in urban traffic and high-way conditions was proposed. The theoretical model can directly reflect the change characteristics of motor oil properties with the operation parameters. This can be used to predict oil degradation in real-time based on the operation parameters of cars. This method can reduce the testing time and increase the accuracy for evaluating the oil change interval compared to the traditional laboratory oil analysis and stipulated operation mileage or service time, which helps change motor oil more economically and effectively.

2 Experimental details

The experimental cars and engine oils were tabulated in Table 1. The experimental cars include a 10 years old car (Experimental car No. 1), a 5 years old car (Experimental car No. 2), and a new car (Experimental car No. 3). All the experimental engines were port fuel injection-based and naturally aspirated. All the experimental cars were equipped with an on-board diagnostic (OBD) system. The OBD system was originally designed for monitoring emissions and fault diagnosis using a large number of sensors. The system can provide real-time operation information and trouble codes [28]. The OBD system has a connector for end users to access the diagnostic data. In this study, WiFi adapters are plugged into the OBD connector of cars, and the data can be manipulated using a cell phone application. Real-time engine operation time (EOT), mileage (MIL), service time (ST), engine idle time (EIT), and number of start-ups (NBS) were acquired using the OBD system and the cell phone application.

Oil samples were collected from the crankcase approximately every 30 days. Oil should be collected after the experimental cars stopped about half an hour. Collection via a vacuum tube inserted into the dipstick opening (sample a centimeter or two above the bottom of the oil pan). Sampling from the mid portion of the oil is preferable since the top and bottom portions are more likely to be contaminated, and

Table 1 Experimental cars and motor oils.

No.	Experimental cars	Displacement (L)	Motor oils	Oil change mileage (km)	Oil service time (d)
1-1	Citroen Triomphe	2	API SL, SAE 5W-40 mineral oil special for Citroen engine	5723	410
1-2	Citroen Triomphe	2	API SL, SAE 5W-40 mineral oil special for Citroen engine	3883	165
2-1	Hyundai Verna	1.4	Havoline, API SL, SAE 5W-30 mineral oil	6317	165
3-1	Buick Regal	2	API SN, SAE 5W-30 synthetic oil, special for GM	4938	147
3-2	Buick Regal	2	Castrol Edge Professional SAE 5W-30 synthetic oil	6471	154

the mid portion is more likely to represent what is flowing through the lubrication system. The component changes of oxidation, nitration, sulfation, zinc dialkyldithiophosphate (ZDTP) of oils were tested using the Integra software of infrared spectrometer (NICOLET iS10, Thermo Fisher Scientific, US). Total acid number (TAN) of oil samples were tested with reference to the ASTM D974-2014 standard [29]. The oxidation onset temperature (OOT) was determined using differential scanning calorimeter (NETZSCH HP 204, Germany) with reference to the ASTM E 2009-02 (the heating rate was 10 °C/min, the oxidation pressure was 3.5 MPa, the flow rate of oxidation was 100 mL/min) [30].

3 Results and discussion

Experiment No. 1-1 was taken as an example to demonstrate the details of the analysis and modeling process. The driving parameters and oil properties of Experiment No. 1-1 are given in Table 2. The driving parameters, ST, MIL, EOT, ITE, and NBS, obtained using the OBD system can completely represent the operation state of the cars in the experiment. The physicochemical properties (TAN and OOT) and component changes of experimental oil (oxidation, nitration, sulfation, and ZDTP relative change values) directly reflect the motor oil degradation degree.

As shown in Table 2, the motor oil in Experiment No. 1-1was effective to 410 days and the experimental was driven for 5723 km. The engine worked for 255.90 h and the idle time was 54.73 h. The engine was started 545 times. The TAN of the new oil was 2.17 mgKOH/g, which increased to 3.95 mgKOH/g after the experiment was concluded. The OOT value of the oil decreased from 243.7 to 198.9 °C during

Table 2 Driving parameters and oil properties of Experiment No.1-1.

Driving parameters					Oil properties					
ST (d)	MIL (km)	EOT (h)	ITE (h)	NBS	TAN (mgKOH/g)	OOT (°C)	Oxidation (A/0.1mm)	Nitration (A/0.1mm)	Sulfation (A/0.1mm)	ZDTP (A/0.1mm)
0	0	0.00	0.00	0	2.17	243.7	0.00	0.00	0.00	0.00
47	769	36.77	6.73	82	2.29	232.1	0.05	0.05	0.04	–0.07
76	1390	62.30	10.96	135	2.42	224.5	0.06	0.07	0.06	–0.09
109	2013	88.90	16.59	196	2.80	220.0	0.08	0.10	0.08	–0.11
139	2424	105.27	20.39	232	2.93	216.6	0.09	0.12	0.10	–0.12
170	2862	124.43	24.58	269	3.11	213.3	0.10	0.14	0.11	–0.12
200	3333	145.13	29.02	313	3.26	212.3	0.11	0.17	0.12	–0.12
230	3858	169.37	34.32	360	3.44	209.3	0.12	0.20	0.14	–0.13
269	4226	182.93	37.19	389	3.53	208.5	0.14	0.22	0.15	–0.13
296	4587	199.10	41.09	423	3.62	204.1	0.13	0.23	0.16	–0.13
327	4918	212.02	43.57	449	3.66	202.1	0.14	0.25	0.17	–0.13
356	5054	220.05	45.73	465	3.72	201.0	0.14	0.26	0.17	–0.13
387	5405	236.55	49.60	502	3.83	199.7	0.14	0.26	0.16	–0.14
410	5723	255.90	54.73	545	3.95	198.9	0.15	0.30	0.19	–0.14

the road test. After the oil was used for 410 days, the oxidation, nitration and sulfation relative change values were 0.15 A/0.1mm, 0.30 A/0.1mm and 0.19 A/0.1mm, respectively. The multifunctional additive ZDTP relative change value was -0.14 A/0.1mm. Four steps were applied by the proposed method to establish the theoretical model of operation parameters and oil properties.

The detailed description of every step of the analysis method is provided below.

Step 1: Data pre-processing.

The units and dimensions of the factors were different, and therefore, the original data obtained by the OBD system and the laboratory need processing before analysis. The average and initial values divided by original data are commonly used to pre-process data. In order to establish a theoretical model for oil degradation prediction, the initial value method was considered more suitable for this study. Some initial values of the factors (driving parameters, oxidation, nitration, sulfation, and ZDTP value) were 0, which cannot be considered as a dividend. Thus, the driving parameters and oil properties of the road test in 47 days were considered as the initial value. The result of pre-processing the data of driving parameters and oil properties is illustrated in Table 3.

Step 2: Comprehensive indicator calculation.

This study attempted to establish a theoretical model between the comprehensive variation of driving parameters and the oil properties under different periods. The initial sequence was defined as the reference sequence X_0. The data in the subsequent experiment were defined as the comparability sequence X_i.

The absolute variation represented the change degree of the two groups of data. The change degree of the driving parameters and oil properties can be calculated with Eq. (1). The comprehensive indicator γ_i was calculated with Eq. (2) for modeling data.

$$\Delta_i(k) = \left| x_i(k) - x_0(k) \right| \tag{1}$$

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\frac{1}{\Delta_i(k)} \tag{2}$$

where $x_0(k)$ is the element of the reference sequence, $x_i(k)$ is the element of the comparability sequence, $\Delta_i(k)$ is the absolute variation of $x_i(k)$ and $x_0(k)$, and n is the number of the elements. The driving parameters are considered as an example to present the details of the calculation process. The X_0 and X_1 (in Table 3) values were presented as follows.

X_0 (k) = [$x_0(1)$, $x_0(2)$, $x_0(3)$, $x_0(4)$, $x_0(5)$] = [1.0000, 1.0000, 1.0000, 1.0000, 1.0000]

X_1 (k) = [$x_1(1)$, $x_1(2)$, $x_1(3)$, $x_1(4)$, $x_1(5)$] = [1.6170, 1.8075, 1.6943, 1.6285, 1.6463]

Table 3 Processed data of driving parameters and oil properties for Experiment No. 1-1.

	Driving parameters					Oil properties					
	ST	MIL	EOT	ITE	NBS	TAN	OOT	Oxidation	Nitration	Sulfation	ZDTP
X_0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
X_1	1.6170	1.8075	1.6943	1.6285	1.6463	1.0568	0.9673	1.2000	1.4000	1.5000	1.2857
X_2	2.3191	2.6177	2.4177	2.4651	2.3902	1.2227	0.9479	1.6000	2.0000	2.0000	1.5714
X_3	2.9574	3.1521	2.8629	3.0297	2.8293	1.2795	0.9332	1.8000	2.4000	2.5000	1.7143
X_4	3.6170	3.7217	3.3840	3.6523	3.2805	1.3581	0.9190	2.0000	2.8000	2.7500	1.7143
X_5	4.2553	4.3342	3.9470	4.3120	3.8171	1.4236	0.9147	2.2000	3.4000	3.0000	1.7143
X_6	4.8936	5.0169	4.6062	5.0996	4.3902	1.5022	0.9018	2.4000	4.0000	3.5000	1.8571
X_7	5.7234	5.4954	4.9750	5.5260	4.7439	1.5415	0.8983	2.8000	4.4000	3.7500	1.8571
X_8	6.2979	5.9649	5.4147	6.1055	5.1585	1.5808	0.8794	2.6000	4.6000	4.0000	1.8571
X_9	6.9574	6.3953	5.7661	6.4740	5.4756	1.5983	0.8707	2.8000	5.0000	4.2500	1.8571
X_{10}	7.5745	6.5722	5.9845	6.7949	5.6707	1.6245	0.8660	2.8000	5.2000	4.2500	1.8571
X_{11}	8.2340	7.0286	6.4332	7.3700	6.1220	1.6725	0.8604	2.8000	5.2000	4.0000	2.0000
X_{12}	8.7234	7.4421	6.9595	8.1322	6.6463	1.7249	0.8570	3.0000	6.0000	4.7500	2.0000

According to Eq. (1), the absolute variation can be calculated as

Δ_1 = [|1.6170-1.000|, |1.8075-1.0000|, |1.6943-1.0000|, |1.6285-1.0000|, |1.6463-1.0000|] = [0.6170, 0.8075, 0.6943, 0.6285, 0.6463].

γ_1 can be obtained with Eq. (2) as

$$\gamma_1 = \frac{1}{5}\sum_{k=1}^{5}\frac{1}{\Delta_1(k)} = \frac{1}{5}\times\left(\frac{1}{0.6170}+\frac{1}{0.8075}+\frac{1}{0.6943}+\frac{1}{0.6285}+\frac{1}{0.6463}\right) = 1.4875$$

With the same method, the γ_i of the driving parameters and oil properties in different periods can be calculated (in Table 4).

Step 3: Establishing the theoretical model.

After the comprehensive indicators of driving parameters and oil properties were calculated, the theoretical model of driving parameters and oil properties was established. As shown in Fig. 1, the theoretical model of the comprehensive indicators of driving parameters and oil properties was y = 6.2677x + 0.7334, where x is the comprehensive indicator of the driving parameters and y is the comprehensive indicator of oil properties. The R square of the theoretical model was 0.997, which indicated the theoretical model represent the relation of data well ($R^2 = \frac{\sum_{i=1}^{n}(\hat{y}_i-\bar{y})^2}{\sum_{i=1}^{n}(y_i-\bar{y})^2}$, where $\hat{y}_i$ is the calculated value of theoretical model, $\bar{y}$ is the average value of the actual test value, and y_i is the actual test value).

According to the criteria for changing gasoline engine oil of China (GB/T 8028-2010), oil should be changed when the increment of the TAN of motor oil reaches 2 mgKOH/g. Thus, the motor oil used in Experiment No. 1-1 needs to be changed when the TAN increases to 4.17 mgKOH/g. The oil properties of TAN reached 4.17 mgKOH/g, which can be considered as the limiting value for draining the motor oil. As shown by the development trend of oil properties in Fig. 2, the OOT, oxidation, nitration, sulfation, and ZDTP values were 197.4 °C, 0.16 A/0.1 mm, 0.34 A/0.1 mm, 0.20 A/0.1 mm, and −0.15 A/0.1 mm, respectively, when the TAN reached 4.17 mgKOH/g. The limiting comprehensive indicator of oil properties can be calculated with Eqs. (1) and (2), and it was found to be 1.6098. The limiting comprehensive indicator of the driving parameters was 0.1398, as calculated with the above established model. This suggests that the motor oil should be drained when the comprehensive indicator of driving parameters decreases to 0.1398.

Table 4 Comprehensive indicators of driving parameters and oil properties.

Time (days)	Driving parameters	Oil properties	Time (days)	Driving parameters	Oil properties
76	1.4875	10.1925	269	0.2348	2.3436
109	0.6967	4.8481	296	0.2106	2.0690
139	0.5103	3.7639	327	0.1938	1.9480
170	0.3969	3.1109	356	0.1838	1.8887
200	0.3207	2.8722	387	0.1681	1.7963
230	0.2644	2.4642	410	0.1540	1.7229

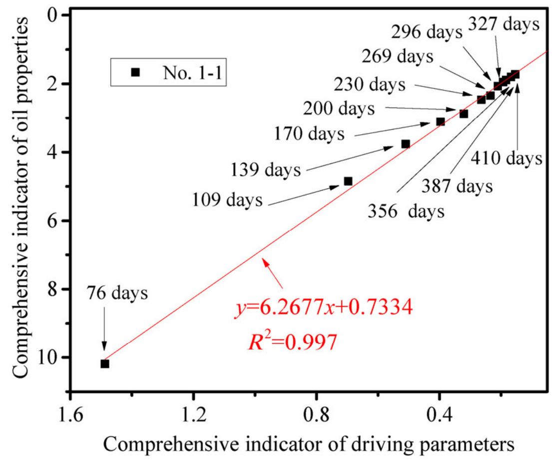

Fig. 1 Theoretical model for experiment No. 1-1.

The road test for Experiment No. 1-2 was carried out with the same oil, experimental car, and the driver as used for Experiment No. 1-1. The average operation mileage per day for Experiment No. 1-2 (23.53 km/day) was larger than that for Experiment No. 1-1 (13.96 km/day). The driving parameters and oil properties are tabulated in Table 5. The oil used in Experiment No. 2-1 serviced 165 days, and the experimental cars operated 3883 km with 327 engine starts and stops. The engine operated for 165.70 h, with 32.57 h in the idle state. After the road test was completed, the TAN of the experimental oil increased from 2.14 to 4.64 mgKOH/g; the OOT value decreased

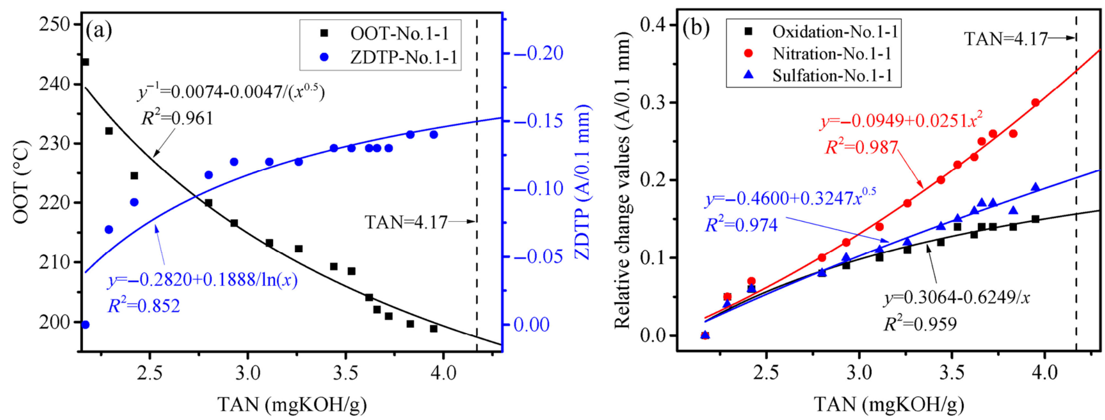

Fig. 2 Trend of oil properties for Experiment No. 1-1. (a) OOT and ZDTP; (b) oxidation value, nitration value and sulfation value.

Table 5 Driving parameters and oil properties for Experiment Nos. 1-2 and 2-1.

No.	Driving parameters					Oil properties						
	ST (d)	MIL (km)	EOT (h)	ITE (h)	NBS	TAN (mg KOH/g)	OOT (°C)	Oxidation (A/0.1mm)	Nitration (A/0.1mm)	Sulfation (A/0.1mm)	ZDTP (A/0.1mm)
1-2	0	0	0.00	0.00	0	2.14	243.7	0.00	0.00	0.00	0.00
	30	592	23.78	4.63	43	2.53	232.8	0.05	0.09	0.05	–0.04
	62	1264	53.90	10.48	105	2.87	223.4	0.06	0.12	0.03	–0.06
	90	2056	86.10	17.85	166	3.09	218.5	0.10	0.18	0.10	–0.08
	120	2664	112.50	22.23	212	3.83	215.4	0.11	0.21	0.12	–0.10
	153	3547	150.70	29.61	301	4.46	209.5	0.13	0.25	0.15	–0.11
	165	3883	165.70	32.57	327	4.64	209.0	0.14	0.27	0.16	–0.11
2-1	0	0	0.00	0.00	0	1.63	233.0	0.00	0.00	0.00	0.00
	19	1125	34.37	7.46	73	1.78	223.5	0.04	0.06	0.04	–0.04
	48	2911	92.53	20.15	173	2.03	212.6	0.05	0.10	0.07	–0.06
	79	3886	134.10	28.05	265	2.12	209.5	0.05	0.12	0.07	–0.09
	108	4848	172.78	36.88	350	2.29	206.9	0.07	0.16	0.10	–0.09
	137	5628	197.07	41.00	411	2.39	205.6	0.08	0.18	0.12	–0.12
	156	6317	222.67	45.56	462	2.45	205.4	0.09	0.20	0.13	–0.10

from 243.7 to 209.0 °C; and the oxidation, nitration, sulfation, and ZDTP relative change values were 0.14 A/0.1 mm, 0.27 A/0.1 mm, 0.16 A/0.1 mm, and –0.11 A/0.1 mm, respectively. The driving parameters and oil properties of 30 days were considered as the reference sequence. The theoretical model was established with the method proposed above (Fig. 3). The theoretical model of the comprehensive indicators of driving parameters and oil properties of Experiment No. 1-2 was $y = 8.2795x + 0.7161$, where x is the comprehensive indicator of the driving parameters and y is the comprehensive indicator of the oil properties. The R square of the theoretical model was 0.999, which suggested that the theoretical model has high precision. The theoretical models for both Experiment Nos. 1-1 and 1-2 were high accuracy linear models.

The development trend of the oil properties of Experiment No. 1-2 (Fig. 4) can be determined with a similar method as that used for the Experiment No. 1-1. The OOT, oxidation, nitration, sulfation, and ZDTP values were 211.4 °C, 0.13 A/0.1 mm, 0.24 A/0.1 mm, 0.14 A/0.1 mm, and –0.11 A/0.1 mm, respectively, when the TAN reached the criterion for oil change (2.14 mgKOH/g). The limiting comprehensive indicator

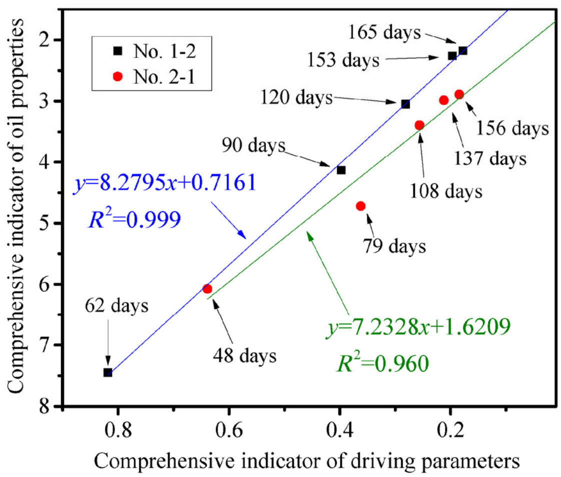

Fig. 3 Theoretical models for Experiment Nos. 1-2 and 2-1.

of the oil properties and driving parameters were 2.4670 and 0.2115, which indicated that the motor oil should be drained when the comprehensive indicator decreased to 0.2115. The established theoretical model has high precision even though the road test exceeded the limiting comprehensive value; this also demonstrated that the proposed method has good reliability.

Experiment No. 2-1 was carried out using Havoline mineral motor oil. The driving parameters and oil properties are presented in Table 5. Experiment No. 2-1 took 156 days, and the experimental cars operated for a total of 6317 km. The engine operated for 222.67 h, of which 45.56 h were in the idle state. The engine started 462 times during the experiment. The TAN of the oil used in Experiment No. 2-1 increased from 1.63 to 2.45 mgKOH/g. The OOT value of the used oil was 205.4 °C, which decreased by 27.6 °C, compared to that for the new oil. The Integra results of the used oil show that the oxidation, nitration, sulfation, and ZDTP relative change values were 0.09 A/0.1 mm, 0.20 A/0.1 mm, 0.13 A/0.1 mm, and −0.10 A/0.1 mm, respectively. The driving parameters and oil properties of 19 days were considered as the reference sequence. The theoretical model (Fig. 3) for Experiment No. 2-1 was $y = 7.2328x + 1.6209$, where x is the comprehensive indicator of driving parameters, and y is the comprehensive indicator of oil properties. The R square of the theoretical model was 0.960, which indicated that the linear model has high accuracy for representing the data.

The development trend of the oil properties for Experiment No. 2-1 (as shown in Fig. 5) suggested that the OOT, oxidation, nitration, sulfation, and ZDTP values were 199.5 °C, 0.15 A/0.1 mm, 0.42 A/0.1 mm, 0.27 A/0.1 mm, and −0.16 A/0.1 mm, respectively, when the TAN reached the criterion for oil change (3.63 mgKOH/g). The limiting comprehensive indicator of the oil properties (1.8854) and the driving parameters (0.0366) can be calculated with Eqs. (1) and (2). The motor oil needs to be changed while the comprehensive indicator decreases to 0.0366.

Synthetic oil was also studied in this work. The oil used in Experiment No. 3-1 was synthetic oil, specially designed for GM engines. The oil used in Experiment No. 3-2 was the Castrol Edge Professional SAE 5W-30 synthetic oil. Two groups of experiments were carried out with the same experimental car and driver. The driving parameters and oil properties for Experiment Nos. 3-1 and 3-2 are presented in Table 6. The oil used in Experiment No. 3-1 serviced 147 days and the experimental car operated 4938 km. The engine of the experimental car operated for 202.00 h, and it was in the idle state for 43.44 h. The increment of TAN

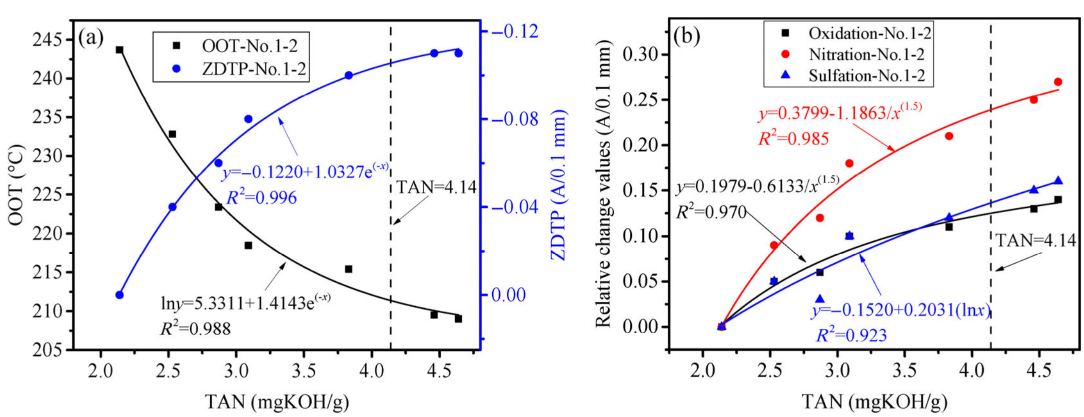

Fig. 4 Trend of oil properties for Experiment No. 1-2. (a) OOT and ZDTP; (b) oxidation value, nitration value and sulfation value.

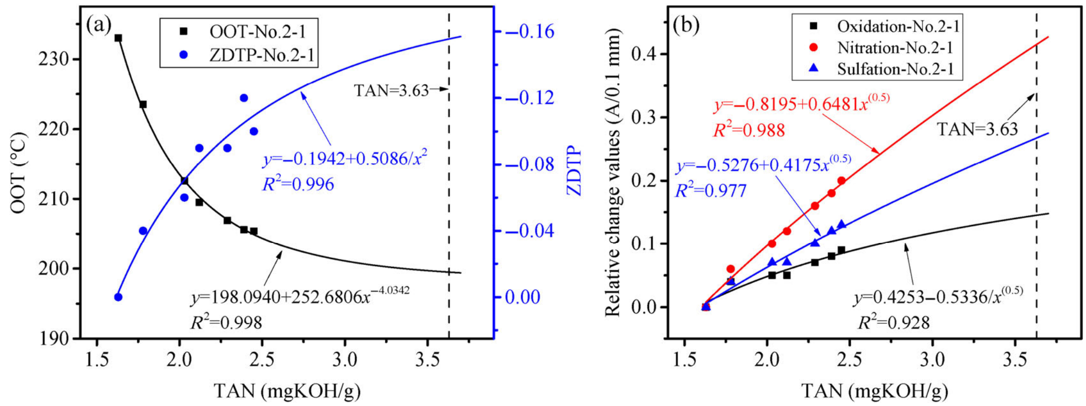

Fig. 5 Trend of oil properties for Experiment No. 2-1. (a) OOT and ZDTP; (b) oxidation value, nitration value and sulfation value.

Table 6 Driving parameters and oil properties for Experiment Nos. 3-1 and 3-2.

No.	Driving parameters					Oil properties				
	ST (d)	MIL (km)	EOT (h)	ITE (h)	NBS	TAN (mgKOH/g)	OOT (°C)	Oxidation (A/0.1mm)	Nitration (A/0.1mm)	Sulfation (A/0.1mm)
3-1	0	0	0.00	0.00	0	1.69	256.0	0.00	0.00	0.00
	23	695	36.90	7.80	66	1.74	242.9	0.03	0.04	0.03
	54	1880	82.90	15.81	141	1.99	236.4	0.04	0.07	0.04
	83	2609	129.72	25.84	209	2.28	230.6	0.06	0.10	0.07
	114	4118	167.22	35.33	285	2.47	225.3	0.06	0.11	0.07
	143	4821.	198.00	42.63	347	2.50	221.6	0.08	0.16	0.10
	147	4938	202.00	43.44	356	2.54	220.4	0.10	0.17	0.11
3-2	0	0.	0.00	0.00	0	1.55	239.7	0.00	0.00	0.00
	25	544	21.50	4.40	51	1.62	236.2	0.03	0.05	0.02
	59	986	36.73	7.64	85	1.67	233.7	0.05	0.07	0.03
	93	4552	100.98	15.86	175	2.12	226.3	0.08	0.12	0.04
	123	5710	134.95	22.54	236	2.24	224.5	0.10	0.14	0.05
	154	6471	171.48	31.19	311	2.34	222.0	0.11	0.17	0.06

for the Experiment No. 3-1 oil was small, increasing from 1.69 to 2.54 mgKOH/g; the OOT decreased from 256.0 to 220.4 °C; and the oxidation, nitration, and sulfation relative change values were 0.10 A/0.1 mm, 0.17 A/0.1 mm, and 0.11 A/0.1 mm, respectively. The driving parameters and oil properties for 23 days were considered as the reference sequence. The theoretical model (as shown in Fig. 6) for Experiment No. 3-1 was y =12.4997x + 0.2813, where x is the comprehensive indicator of the driving parameters and y is the comprehensive indicator of the oil properties. The R square of the theoretical model was 0.997, which suggested that the theoretical model was reliable and accurate. The trend of oil properties of No. 3-1 experiment (Fig. 7) illustrated the OOT value, oxidation value, nitration value, and sulfation value were 210.0 °C, 0.20 A/0.1mm, 0.38 A/0.1mm, and 0.27 A/0.1mm, respectively, when the TAN reached to criterion for oil changing (3.69 mgKOH/g). The limiting comprehensive indicator of oil properties (1.7389) and driving parameters (0.1166) can be calculated with Eqs. (1) and (2). The motor oil need to be changed while the comprehensive indicator decrease to 0.1166.

The oil in Experiment No. 3-2 serviced for 154 days and the experimental car operated for 6471 km. The engine started 311 times during the 171.48 h of operation time, of which the idle time was 31.19 h.

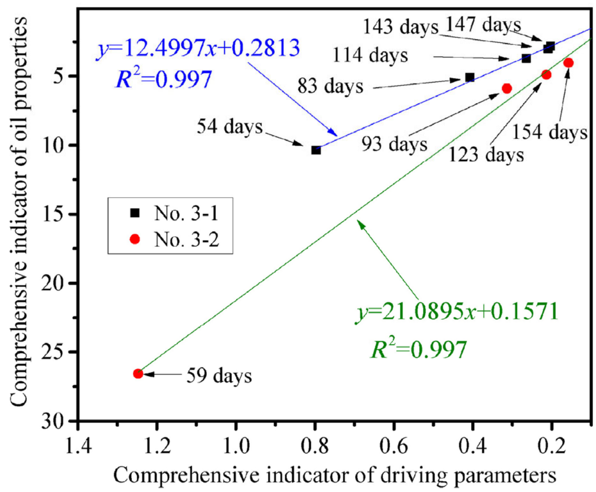

Fig. 6 Theoretical models for Experiment Nos.3-1 and 3-2.

The TAN of Experiment No. 3-2 oil increased from 1.55 to 2.34 mgKOH/g, and the OOT decreased from 239.7 to 222.0 ℃. After the experiment was completed, the oxidation, nitration, and sulfation relative change values were 0.11 A/0.1 mm, 0.17 A/0.1 mm, and 0.06 A/0.1 mm, respectively. The driving parameters and oil properties of 25 days were considered as the reference sequence. The theoretical model (Fig. 6) of Experiment No. 3-2 was $y = 21.0895x + 0.1571$, where x is the comprehensive indicator of the driving parameters and y is the comprehensive indicator of oil properties. The R square of the theoretical model was 0.997, indicating that the theoretical model represented the data well.

The development trend of the oil properties for Experiment No. 3-2, as shown in Fig. 8, indicates that the OOT, oxidation, nitration, and sulfation values are 216.1 ℃, 0.15 A/0.1 mm, 0.23 A/0.1 mm, and 0.09 A/0.1 mm, respectively, when the TAN reaches the criterion for oil change (3.55 mgKOH/g). The limiting comprehensive indicator of oil properties (2.6808) and driving parameters (0.1197) can be calculated with the Eqs. (1) and (2). The motor oil needs to be changed when the comprehensive indicator decreases to 0.1197.

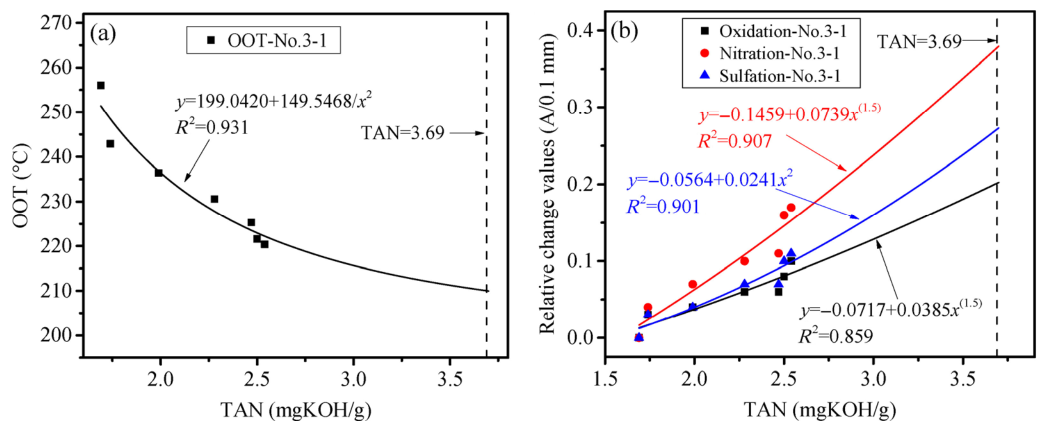

Fig. 7 Trend of oil properties for Experiment No. 3-1. (a) OOT; (b) oxidation value, nitration value, and sulfation value.

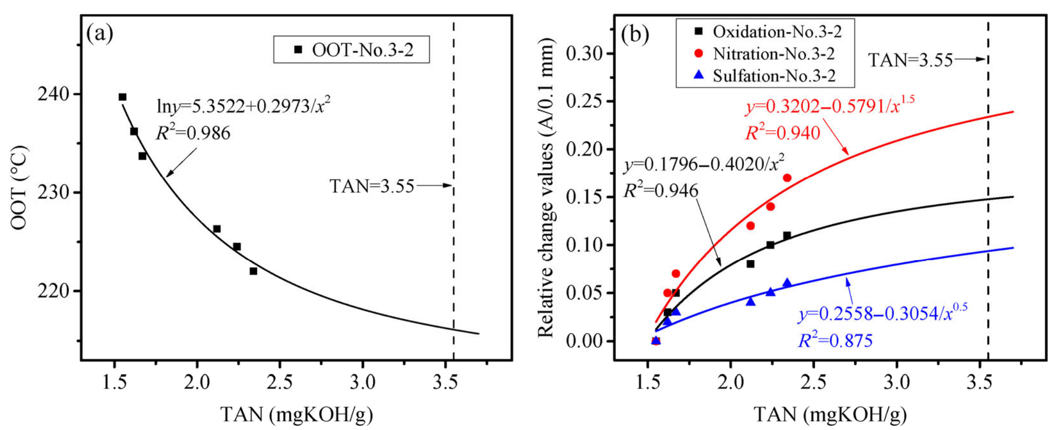

Fig. 8 Trend of oil properties for Experiment No. 3-2. (a) OOT; (b) oxidation value, nitration value, and sulfation value.

As per the operation information and oil properties presented in Tables 2, 5, and 6, the OOT values of synthetic oils were larger than 220 °C after the oils serviced more than 4938 km and 6471 km, which was higher than that for mineral oils (approximately 200 °C). It is suggested that the oxidation stabilities of the experimental synthetic oils were better than those of mineral oils. The increments of the TAN of synthetic oils were smaller than that of the mineral oils, which indicated the advantages of the synthetic oil in reducing the production of acid products. The experimental synthetic oils have better comprehensive performance than the experimental mineral oils.

The average speed and idle ratios of the experiments are shown in Fig. 9. Since the Experiment Nos. 1-1, 1-2, 2-1, and 3-1 were conducted under urban traffic conditions, the average speeds for these experiments were 22.36 km/h, 23.43 km/h, 28.37 km/h, and 24.45 km/h, respectively. Experiment Nos. 1-1, 1-2, 2-1, and 3-1 have the characteristics of high idle ratios and low operation speeds, which are typical urban traffic conditions. The average speed for Experiment Nos. 1-1, 1-2, 2-1, and 3-1 were consistent with the average speeds of civilian cars in China's major cities (approximately 20–27 km/h). The Experiment No. 3-2 was carried out under urban and highway traffic conditions; the average speed for this experiment was 37.74 km/h, and the idle ratio was 18.2%. The average speed was higher and the idle ratio was smaller compared with those suitable for urban traffic conditions. All R-square values of the established theoretical models were larger than 0.96, which suggested that the proposed method used to establish the theoretical model between the driving parameters and oil properties had high accuracy and precision in both experimental mineral oils and synthetic oils under urban traffic and highway conditions.

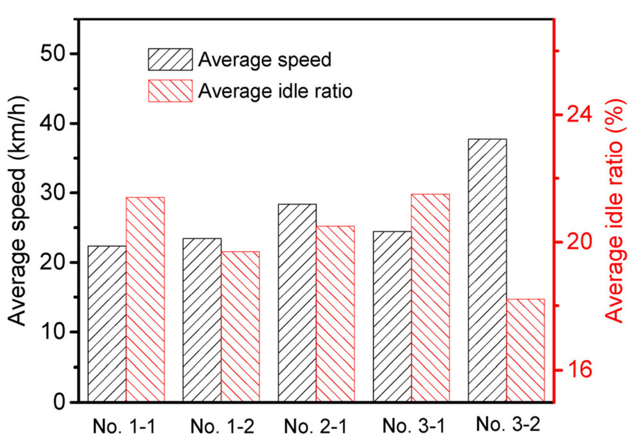

Fig. 9 Average speed and average idle ratio of the experiments.

4 Conclusions

This study was based on 41 oil samples in three experimental cars during the 575 days of road tests. The conclusions were as follow:

1) A method was proposed to establish the theoretical models of the comprehensive change characteristics of the driving parameters and oil properties. The proposed method has high accuracy and precision for both mineral and synthetic oils under urban traffic and highway conditions. The proposed method can help realize real-time oil condition monitoring with operation parameters obtained by the OBD system.

2) The results of the road tests in this study verified that the synthetic oils have better ability to restrain the increase of acid products and decrease oxidation stability compared to that of mineral oils. The oil change interval can also be appropriately extended by using the synthetic oil.

Acknowledgements

The authors are grateful for the financial support from the National Natural Science Foundation of China (No. 51575402).

References

[1] Klowak M, Gracyalny G. Engine oil recirculation system for extended maintenance interval. U.S. Patent 20150053505,

Feb. 2015.

[2] Wei L, Duan H T, Chen S, Jia D, Qian X Z, Cheng B X, Liu J F, Li J. A field test method to quantitatively determine oxidation stability of gasoline engine oil. *Lubricat Sci* **30**(2): 57–64 (2018)

[3] Kader M K, Ramani T, Jacobs T J. Effect of extended idle on oil degradation rates of heavy-duty vehicles. *Int J Heavy Veh Syst* **22**(3): 193–212 (2015)

[4] Yüksek L. Optimization of the oil drain interval of non-phosphorus and non-ash engine oil. *Ind Lubr Tribol* **68**(4): 497–507 (2016)

[5] Langfitt Q, Haselbach L. Coupled oil analysis trending and life-cycle cost analysis for vessel oil-change interval decisions. *J Mar Eng Technol* **15**(1): 1–8 (2016)

[6] Zhu X L, Zhong C, Zhe J. Lubricating oil conditioning sensors for online machine health monitoring–a review. *Tribol Int* **109**: 473–484 (2017)

[7] Holmberg K, Erdemir A. Influence of tribology on global energy consumption, costs and emissions. *Friction* **5**(3): 263–284 (2017)

[8] Qian X Z, Xiang Y L, Shang H F, Cheng B X, Zhan S P, Li J. Thermal-oxidation mechanism of dioctyl adipate base oil. *Friction* **4**(1): 29–38 (2016)

[9] Puckace J A, Redmon J J, Fitzgerald H, Ismail O K. Method of determining optimal change interval for a functional fluid. U.S. Patent 20130046433, Feb. 2013.

[10] Gulzar M, Masjuki H H, Varman M, Kalam M A, Zulkifli N W M, Mufti R A, Liaquat A M, Zahid R, Arslan A. Effects of biodiesel blends on lubricating oil degradation and piston assembly energy losses. *Energy* **111**: 713–721 (2016)

[11] Youngk R D. Automobile engine reliability, maintainability and oil maintenance. In *Proceedings of Annual Reliability and Maintainability Symposium. 2000 Proceedings. International Symposium on Product Quality and Integrity*, Los Angeles, CA, USA, 2000: 94–99.

[12] Ahmed N S, Nassar A M, Abdel-Hameed H S, El-Kafrawy A F. Preparation, characterization, and evaluation of some ashless detergent/dispersant additives for lubricating engine oil. *Appl Petrochem Res* **6**(1): 49–58 (2016)

[13] Timotijevic Z, Bacevac S, Corsi S. Evaluation of oil drain interval for buses in urban traffic with respect to local operating conditions. In *Proceedings of World Tribology Congress*, Torino, Italy, 2013.

[14] Rudnick L R. Summary of lubricant standard test methods and some product specifications. In *Lubricant Additives*: *Chemistry and Applications*. Rudnick L R, Ed. Bosa Roca: CRC Press, 2003: 599–616.

[15] Thom R, Kollmann K, Warnecke W, Frend M. Extended oil drain intervals: Conservation of resources or reduction of engine life. *SAE Trans* **104**(4): 706–718 (1995)

[16] Mesgarpour M, Landa-Silva D, Dickinson I. Overview of telematics-based prognostics and health management systems for commercial vehicles. In *Proceedings of the 13th International Conference on Transport Systems Telematics*, Katowice-Ustroń, Poland, 2013: 123–130.

[17] Sejkorová M, Hurtová I, Glos J, Pokorný J. Definition of a motor oil change interval for high-volume diesel engines based on its current characteristics assessment. *Acta Univ Agric Silvic Mendelianae Brun* **65**(2): 481–490 (2017)

[18] Mamgbi R, Cerny J, Barifaijo E. Time of Exploitation and Detergency Properties of Low Saps Engine Oil. *Nafta-Gaz* **69**(1): 57–65 (2013)

[19] Sharma B K, Stipanovic A J. Development of a new oxidation stability test method for lubricating oils using high-pressure differential scanning calorimetry. *Thermochim Acta* **402**(1–2): 1–18 (2003)

[20] Wang J C, Whitacre S D, Schneider M L, Dringenburg D H. System and method for determining oil change interval. U.S. Patent 6,253,601, Jul. 2001.

[21] Jun H B, Conte F L, Kiritsis D, Xirouchakis P. A predictive algorithm for estimating the quality of vehicle engine oil. *Int J Ind Eng Theory Appl Pract* **15**(4): 386–396 (2008)

[22] Schwartz E S, Smolenski D J, Wisehart A J, Nguyen T N. Automatic engine oil change indicator system. U.S. Patent 4742476, May 1988.

[23] Schwartz E S, Smolenski D J, Keersmaekers J D, Traylor C M, Wallo G J. Automatic engine oil change indicator system. U.S. Patent 4847768, Jul. 1989.

[24] Mc Donald J E, Schwartz E S, Hamparian N, Jacek M, Stempnik J M, Fletcher S J. Oil life monitor for diesel engines. U.S. Patent 6327900, Dec. 2001.

[25] Schwartz S E. A model for the loss of oxidative stability of engine oil during long-trip service, Part I: Theoretical considerations. *Tribol Trans* **35**(2): 235–244 (1992)

[26] Schwartz S E. A model for the loss of oxidative stability of engine oil during long-trip service, Part II: Vehicle measurements. *Tribol Trans* **35**(2): 307–315 (1992)

[27] Kral Jr J, Konecny B, Kral J, Madac K, Fedorko G, Molnar V. Degradation and chemical change of longlife oils following intensive use in automobile engines. *Measurement* **50**: 34–42 (2014)

[28] Siegel J, Bhattacharyya R, Deshpande A, Sarma S. Vehicular engine oil service life characterization using On-Board Diagnostic (OBD) sensor data. In *Proceedings of 2014 IEEE*

SENSORS, Valencia, Spain, 2014: 1722–1725.
[29] US-ASTM. ASTM D974–2014 Standard test method for acid and base number by color-indicator titration. ASTM, 2014.
[30] ASTM International. ASTM E2009–02 Standard test method for oxidation onset temperature of hydrocarbons by differential scanning calorimetry. West Conshohocken, PA: 19428-2959 ASTM International, 2002.

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