# Effect of Engine Oil on Fuel Consumption and Durability of Heavy-Duty Vehicle

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## 1 Introduction

### 1.1 Fuel Economy Standards

Improving fuel economy has been a key focus across the automotive industry since many years ago. For heavy-duty commercial vehicles, they accounted for 36% of oil consumption and GHG emissions from the transportation sector in 2010, and the benefits from minor gains in fuel economy can lead to significant savings for fleets as well as owners and operators. Setting heavy-duty vehicle (HDV) efficiency standards is significantly more challenging, because HDV fleets are extremely diverse in terms of vehicle size and configuration as well as usage patterns.

Governments have driven the improvement of diesel engine fuel economy in transportation through tightening legislation all over the world. These legislations began to be implemented in 2014–2015; the percentage reduction in limits of fuel consumption is 10–20%. It is expected that stricter limits of fuel consumption will be implemented by 2020 (Table 1).

### 1.2 Oil Specifications

The development trend of diesel engine oil specification also reflects the effect of diesel engine oil on fuel consumption. The need for diesel engine fuel economy

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**Table 1** Global comparison of fuel economy/GHG standards for heavy-duty vehicle [1]

| Country/ Region | Target year | Vehicle type | Regulation type | Energy saving | Next phase |
|---|---|---|---|---|---|
| USA | 2014 | GVW > 3.86 t | GHG/Fuel efficiency | 6–23% | 2020 (Phase 2) |
| Canada | 2014 | GVW > 3.86 t | GHG/Fuel efficiency | 6–23%[a] | 2020 (Phase 2) |
| China | 2014 | GVW > 3.5 t | Fuel consumption | 10.5–14.5%[b] | 2019 (Phase 3) |
| Japan | 2015 | GVW > 3.5 t | Fuel economy | 12.1–12.2%[c] | 2020 (Phase 2) |
| EU | – | – | GHG | – | 2016–2017 |
| India | – | – | Fuel efficiency | – | 2018–2019 (Phase 1) |

[a]Implemented beginning with MY2014, $CO_2$ emission reductions ranging from 6 to 23% in the MY2017 timeframe (as compared to a MY2010 baseline)
[b]Compared to the limits with Phase 1
[c]Improvement over 2002 performance

improvement resulted in the establishment of API's proposed category 11 (PC-11) program which aimed at establishing a new standard to ready it for the market in 2016. European Automobile Manufacturers Association (ACEA) is also considering the introduction of similar requirements in the future specification update. Compared with other means of reducing fuel consumption, the use of energy-saving engine oil presents a high performance/price ratio (Table 2).

## 1.3 Measurement Methods

There are three measurement methods for fuel consumption: simulating calculation method, chassis dynamometer method, and proving ground test. Typical examples of light-duty vehicle (LDV) drive cycles on chassis dynamometer include the Environmental Protection Agency (EPA) Federal Test Procedure 75 (FTP-75) [3], the New European Drive Cycle (NEDC), the Japanese JC08 Cycle, and the Worldwide harmonized Light vehicles Test Cycles (WLTC); examples of HDV

**Table 2** Specification of diesel engine oil and the deed of fuel economy improvement

| Specification | ACEA future specification | PC-11 [2] |
|---|---|---|
| Characteristic | Series E is considering to introduce a specification of HTHS <3.5 to meet the need of fuel economy improvement | CK-4: high HTHS ($\geq$3.5 mPa s)<br>FA-4: low HTHS (2.9–3.2 mPa s): fuel economy improvement |

drive cycles include the Urban Dynamometer Driving Schedule (UDDS), the European Transient Cycle (ETC), the Japanese JC05 Cycle, and the World Transient Vehicle Cycle (WTVC) on chassis dynamometer. Proving ground test doesn't have a fixed drive cycle, with SAE J 1321 as an example.

### 1.3.1 Fuel Economy Measurement Cycle (Chassis Dynamometer Method)

Measurement cycle is a scientific and practical method to evaluate the influence of engine oil on fuel consumption. The cycle of fuel economy measurement is mostly carried out by means of emission measurement cycle. Every government establishes the measurement cycle according to every real-world driving condition, and there is a big difference between different cycles as shown in Table 3.

China heavy-duty vehicles measurement cycle (C-WTVC) which adjusts accelerations and decelerations is based on the World Transient Vehicle Cycle (WTVC). Drive cycle is the reference and foundation of fuel economy measurement. It is effective to evaluate the influence of engine oil on the fuel consumption by establishing a practical and reasonable measurement cycle which is in the fixed dynamic condition.

### 1.3.2 Proving Ground Test

American SAE J1321 is a test method for fuel consumption by the actual operation of vehicles. SAE J1321 testing involves at least a control vehicle and a test vehicle which are identical. After selecting the representative route, "weigh tanks" for accurate gravimetric measurement of fuel or fuel flow meter is used to calculate fuel consumption (Table 4).

As mentioned previously, it is found that fuel economy measurements carried out on the chassis dynamometer with fixed measurement cycle show good reproducibility; however, test results have deviation due to the difference between measurement cycle and real-world driving conditions. Proving ground test is more similar to the real-world driving conditions; however, if scientific and reasonable test methods are not specified clearly, it is difficult to distinguish between test reproducibility and experimental error. Because of the difference between China and other countries of geographical positions and urban traffic situations, it is of great significance to establish drive cycle in accordance with the real-world driving

**Table 3** Selected operating parameters by test cycle [2, 3]

| Test cycle | WTVC | Japan JE05 | US UDDS | US Manhattan cycle |
|---|---|---|---|---|
| Running time (s) | 1800 | 1800 | 1060 | 1090 |
| Average speed (km/h) | 41.00 | 26.94 | 30.40 | 11.00 |
| Maximum speed (km/h) | 87.6 | 88.0 | 93.3 | 40.9 |

**Table 4** SAE J1321 [4]

| Item | Requirement |
|---|---|
| Vehicle | Test vehicle + Control vehicle |
| Test route selection | Long-haul operation >64.4 km |
| | Other operation 30% of the tank capacity or 22.7 L fuel consumption, greater |
| Vehicle test speed | Representative of the average operation |
| Cargo weight | Representative of the fleet operations |
| Driver selections | Sufficiently skilled and excellence of test procedure conduct |
| Fuel measuring | Portable weigh tank method or flow meter method |
| Test accuracy | 1% |

conditions in China to differentiate fuel efficiency benefits from oil to oil. The test cycle is carried out by the equipment with good test precision, the vehicle is driven on a proving ground test track, and the test conditions are relatively controllable.

## 2 Data Acquisition System and Measuring System

Before establishing drive cycle, the vehicle was instrumented with data acquisition systems for recording multiple key parameters; the collected data was processed, analyzed, and combined to create drive cycle. The cycle was assessed to be representative of the real driving condition of EMS vehicle in Beijing. Before measuring fuel consumption on proving ground test, the vehicle was instrumented with fuel consumption measuring system for monitoring fuel consumption in real-time and driver aid device, etc.

### *2.1 Data Acquisition System*

The data acquisition system was installed at the corresponding position of the vehicle, and sufficient key parameters were collected such as GPS data, CAN data, oil temperature data, and atmospheric temperature data. The data acquisition system is mainly divided into three parts: the Sierra part, the temperature acquisition part, and the SOMAT part. Circuit connection of data acquisition system is shown in Fig. 1.

### *2.2 Fuel Consumption Measuring System*

The fuel consumption rate is the mass of the fuel consumed by the engine for per 1 kW effective power in 1 h. Brake specific fuel consumption (BSFC) is commonly

**Fig. 1** Circuit connection of data acquisition system

used as a measure of how efficiently a given amount of fuel is being converted by the engine into a specific output torque [5]; the unit is g/(kW h). By accurately measuring the fuel flow rate, engine output torque, and engine speed, BSFC can be recorded.

$$\mathrm{BSFC} = \frac{\gamma}{\mathrm{Pe}} = \frac{\gamma}{\omega \cdot \tau} \tag{1}$$

Pe is the power produced in watts where (kW)
$\gamma$ is fuel consumption in grams per second (g/s)
$\tau$ is engine output torque in newton meters (Nm)
$\omega$ is engine speed in radians per second (rads/s)

### 2.2.1 Fuel Consumption Measurement Device

The fuel supply system was designed and improved to accurately measure fuel consumption. Coriolis mass flow meter was an independent fuel consumption measurement device; the advantage was mass flow rather than volume flow which needs calculation as temperature changes. The flow accuracy was 0.1%, and the repeatability was better than 0.05%; the calibrated Coriolis mass flow meter was to measure the fuel flow rate from 0.24 to 300 kg/h. Figures 2 and 3 show the interior structure and the installation position of Coriolis mass flow meter.

### 2.2.2 Engine Output Torque Measurement Device

The torque transducer in engine output torque measurement device was suitable for measuring the torque of the long-term continuous high-speed rotating components. On account of engine output torque being generated by rotation, the non-contact torque transducer was long-term maintenance free. The torque transducer consisted of two separate parts: the rotor and the stator. The rotor comprised the measuring

**Fig. 2** Interior structure of Coriolis flow meter

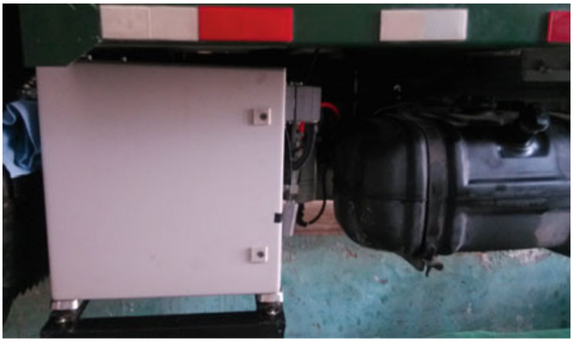

**Fig. 3** Installation position of Coriolis flow meter

body and the signal transmission elements. The rotor electronics generated the bridge excitation voltage and transmitted the measuring signal to the evaluation unit (stator) and was located at the outer circumference of flywheel, and the stator electronics was located at the flywheel cover. The installation positions of the rotor and the stator are seen in Figs. 4 and 5.

#### 2.2.3 Engine Speed Measurement Device

Engine speed is monitored by and accessible from the vehicle J1939 Control Area Network Binary Unit System (CANBus). This system is the broadcast serial bus standard for connecting electronic control units (ECUs) to send and receive messages to control the vehicle's electronic systems [6].

### *2.3 Driver Aid Device*

The control box of driver aid device was installed in cab, and the tablet of driver aid device which was connected to the control box via Ethernet was mounted on the

**Fig. 4** Installation positions of the stator


**Fig. 5** Installation positions of the rotor

windscreen, as shown in Figs. 6 and 7. The driver drove the vehicle in accordance with drive cycle shown on the screen and voice prompt.

After installation of the data acquisition systems, raw data from over 10 km of driver operation was collected through a computer connected to the SOMAT part and was analyzed to detect the correlation of various parameters. According to the correlation of various parameters and the driver's driving experience, by adjusting the parameters of data acquisition systems, the data acquisition systems could operate normally and the vehicle was in a best running state to give reliable results.

**Fig. 6** Installation positions of control box of driver aid device

**Fig. 7** Tablet of driver aid device

## 3 Drive Cycle Development

With the development of urbanization and logistics industry, the inter-city logistics industry has developed rapidly, and statistics show that the sales of HDV increase year by year. Beijing is the most typical city in China which has a relatively well-developed road network and large population density, and road traffic in Beijing is characterized by more traffic jams, longer vehicle retention time, and more express roads, etc. Therefore, selected vehicle was a FAW J6F configuration, and selected operation conditions were EMS logistics fleets in Beijing. To comprehensively generate road condition in Beijing, the test vehicle was given to EMS logistics fleets that used it on normal logistics delivery routes in Beijing urban and suburb.

First of all, multiple key parameters, which was about 3047 km in urban and 15504 km in suburb, were generated from the test vehicle during its normal operation, and the specific route is shown in Fig. 8. The multiple key parameters were processed, analyzed, and calculated by mathematical statistics. Based on these statistics, a drive cycle of EMS vehicle in Beijing shown in Fig. 9 was established; the characteristics of the drive cycle of EMS vehicle in Beijing are seen in Table 5. The drive cycle consisted of two distinct parts: part 1 to simulate urban operation and part 2 to simulate suburb driving.

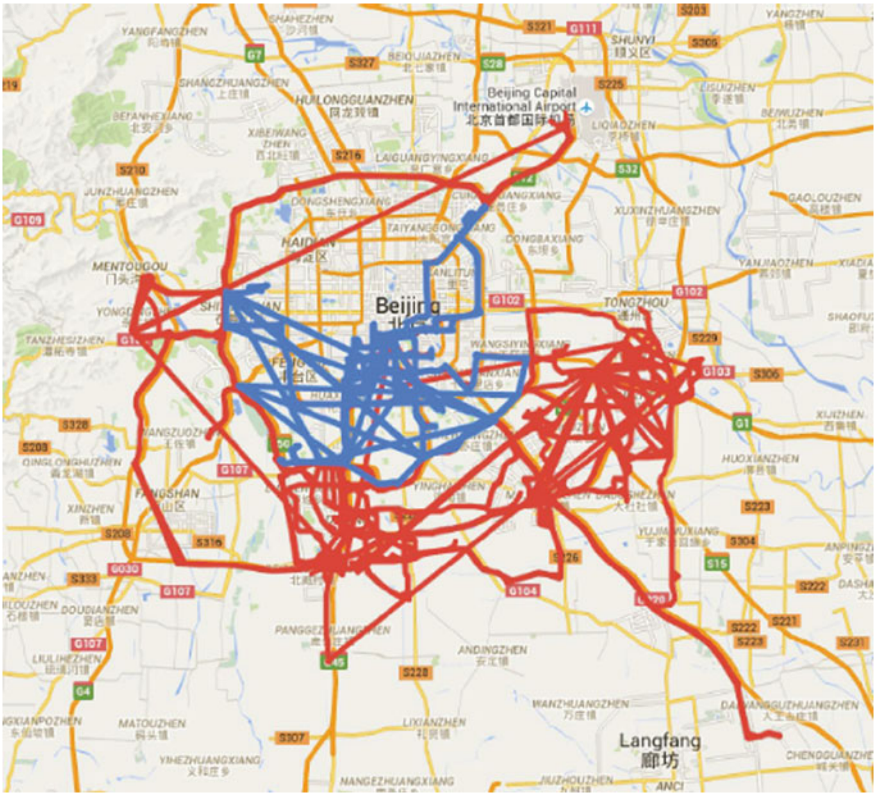


Fig. 8 Specific route of EMS vehicle

## 4 Fuel Consumption Measurement

In order to investigate fuel economy, tests on chassis dynamometer and proving ground were implemented on a FAW J6F to compare the fuel consumption of the candidate oil 5 W-30 diesel engine oil (using Lubrizol fuel economy formulation) with that of the reference oil CI-4 15 W-40 diesel engine oil.

### *4.1 Chassis Dynamometer Test*

Chassis dynamometer test of fuel consumption was performed according to GB/T 27840-2011 "Fuel Consumption Test Methods for Heavy-Duty Commercial Vehicles," using C-WTVC drive cycle.

An engine oil fuel economy evaluation test of the candidate oil relative to the reference oil was undertaken on chassis dynamometer at China Automotive

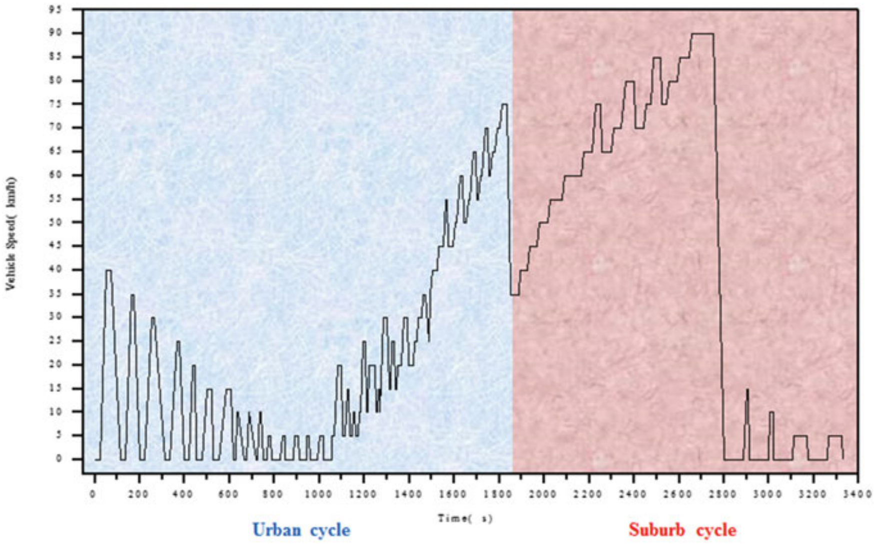


**Fig. 9** Drive cycle of EMS vehicle in Beijing

**Table 5** Characteristics of the drive cycle of EMS vehicle in Beijing

| Condition | Urban | Suburb | Total |
|---|---|---|---|
| Total time (s) | 1803 | 1562 | 3365 |
| Idle time (s) | – | – | 23.3 |
| Distance (km) | 9.8 | 18.8 | 28.7 |
| Average speed (km/h) | 19.6 | 43.4 | 30.7 |
| Maximum acceleration ($m/s^2$) | – | – | 0.35 |
| Maximum deceleration ($m/s^2$) | – | – | 1.67 |
| Proportion (%) | 64 | 36 | 100 |

Technology and Research Center (CATARC), which should be able to accurately simulate the vehicle road resistance, accelerating and decelerating condition, equivalent inertia, etc. During the test, data acquisition system also collected the data (Fig. 10).

The result showed a clear differentiation between the averages of fuel consumption in L/100 km with a total of 3.8% fuel saving on the candidate oil compared to the reference oil.

## 4.2 *Proving Ground Test*

The proving ground test was carried out at proving ground under the Ministry of Transport from July 2015 to November 2015. The selected track field was a high-speed circuit, as shown in Figs. 11 and 12 (Table 6).

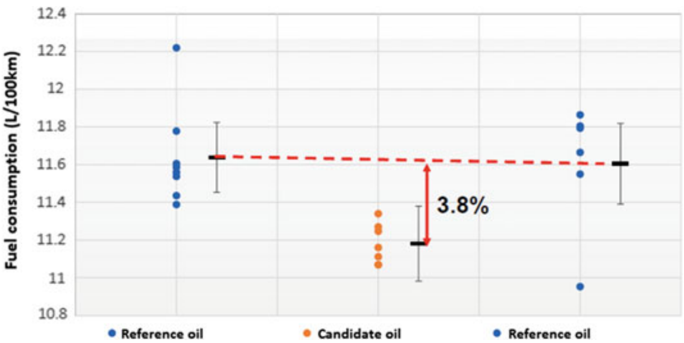


**Fig. 10** Results of chassis dynamometer method test

**Fig. 11** Proving ground under the ministry of transport


**Fig. 12** Vehicle running on high-speed circuit

The un-laden weight of FAW J6F is 2.8 tons, and laden weight is 4.5 ton. Barrels of oil and water were added as a temporary solution to increase the weight. The laden FAW vehicle was tested with the drive cycle of EMS vehicle in Beijing on the proving ground under the Ministry of Transport. The candidate oil showed a total of 1.7% less BSFC compared to the reference oil in total drive cycle. Comparison of the corrected BSFC data can be found in Fig. 13.

**Table 6** Test cycle number of proving ground test

| Sample | Effective test cycle number | Invalid test cycle number | Total test cycle number |
|---|---|---|---|
| Reference oil | 20 | 2 | 22 |
| Candidate oil | 20 | 9 | 29 |
| Reference oil | 24 | 25 | 59 |

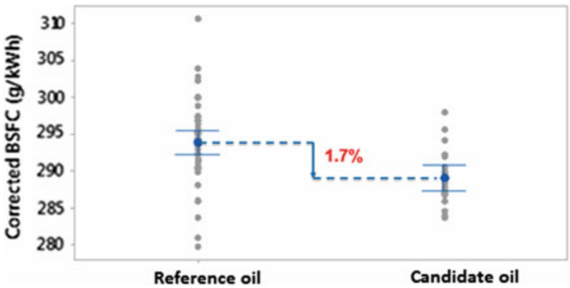


**Fig. 13** Corrected BSFC data (total cycle)

It can be seen in Figs. 14 and 15 that using the candidate oil relative to the reference oil, 2.5% BSFC could be saved in urban cycle of the EMS vehicle drive cycle in Beijing; the candidate oil measured 1.5% improvement over the reference oil in suburb cycle of the drive cycle.

The drive cycle of EMS vehicle in Beijing was required to differentiate the fuel economy benefits from oil to oil while remaining representative of the real-world data recorded. The candidate oil showed a decrease of 1.5–2.5% BSFC compared to the reference oil.

## 5 Field Test

The field test began from August 2015; the test vehicle information is in Table 7. Before the test, the vehicle had driven more than 110,000 km. The engine was flushed twice with the candidate oil to minimize the contamination from the used

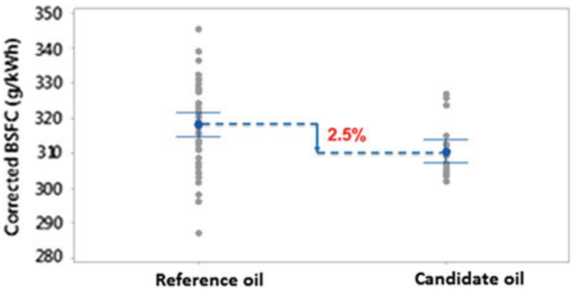


**Fig. 14** Corrected BSFC data (urban cycle)

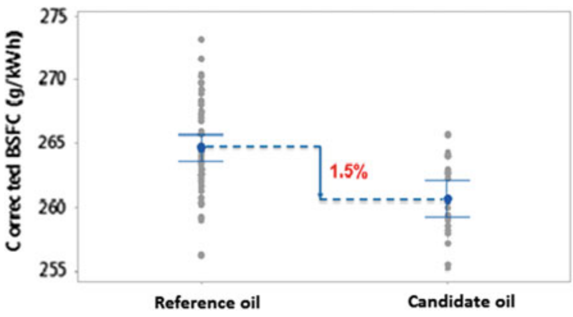


**Fig. 15** Corrected BSFC data (suburb cycle)

**Table 7** Test vehicle information

| Information | |
|---|---|
| Vehicle number | 吉H39367 |
| Engine style | CA4DD1-15E4R |
| Vehicle style | FAW J6F, platform truck |
| Initial mileage | 112,603 km |
| Carrying capacity | Usually 7 t–8 t, occasionally more than 10 t |
| Running route | Rural road in Yanji, cement paving road |

oil. During the test, 200 ml oil sample was taken for analysis. When it reached 150,000 km, the engine was taken back to FAW R&C to disassemble for measurement (Fig. 16).

## 5.1 *Oil Sample Analysis*

### 5.1.1 Viscosity

The viscosity of used oil is influenced by oxidation, light component evaporation, fuel dilution, water contamination, and mechanical shear. From Fig. 17, it was found that the viscosity changed slightly with the mileage increase, and it did not exceed the limited value of GB/T 7607-2010. The oil could still provide good lubricating protection.

### 5.1.2 TAN & TBN

The oil property can be influenced by low and high temperatures, and the oxidation of oil usually leads to TAN increasing and TBN decreasing. As is shown in Fig. 18,


**Fig. 16** Field test vehicle

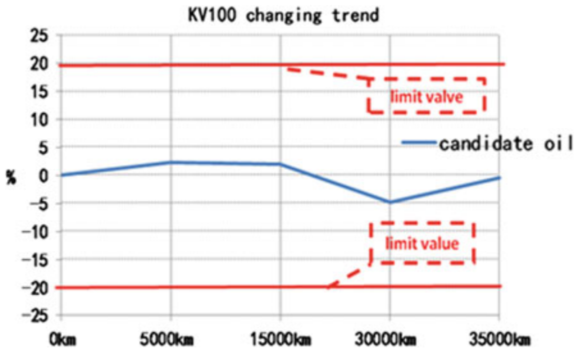


**Fig. 17** Viscosity changing trend at 100

TAN increased slightly with the mileage increasing while TBN decreased; neither of them exceed the limited value of GB/T 7607-2010. The oil could still provide good acid neutralization ability.

### 5.1.3 Oxidation, Nitration, and Sulfonation

The oil aging extent can be reflected by oxidation, nitration, and sulfonation. As is shown in Fig. 19, oxidation, nitration, and sulfonation increased slightly with the mileage increasing.

### 5.1.4 Metallic Element

Iron in the engine oil mainly comes from wear of cylinder and piston ring, copper comes from liner and bearing, and aluminum comes from piston and bearing. Silicon mainly comes from contaminant of dust from the external environment. As is shown in Figs. 20, 21, 22, and 23, it was found that iron, copper, aluminum, and silicon increased with the mileage increasing, which did not exceed the limited value of GB/T 7607-2010. The oil could still provide good anti-wear ability.

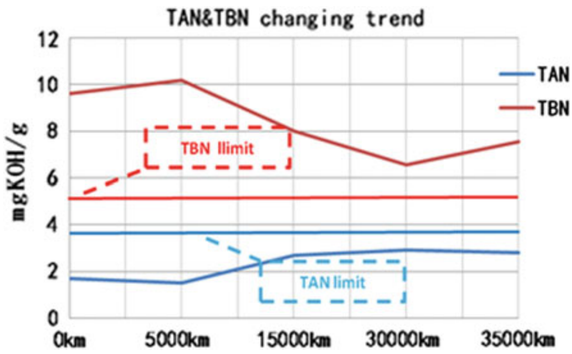


**Fig. 18** TAN & TBN changing trend

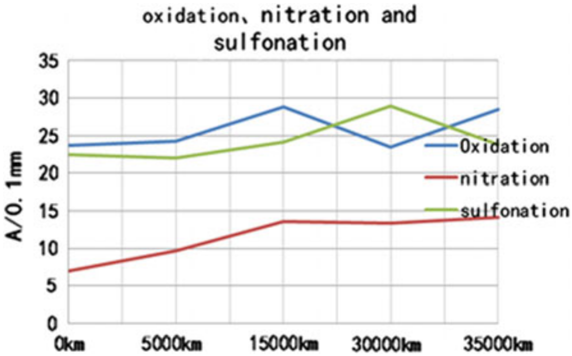


**Fig. 19** Oxidation, nitration, and sulfonation changing trend

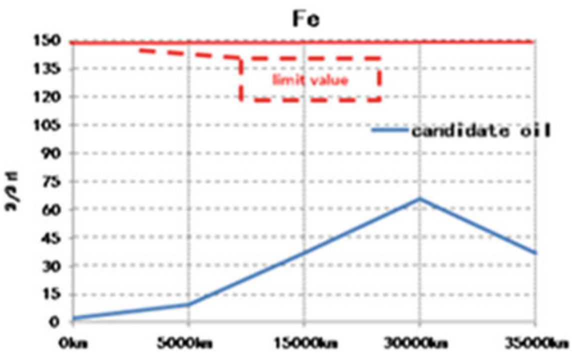


**Fig. 20** Iron content

## 5.2 *Engine Disassemble*

Figures 24, 25, 26, 27, 28, and 29 are pictures of the disassembled engine. Carbon deposition on the head of piston was normal, reticulate pattern of cylinder was good, and there was no severe polishing. The wearing area of the middle part of the

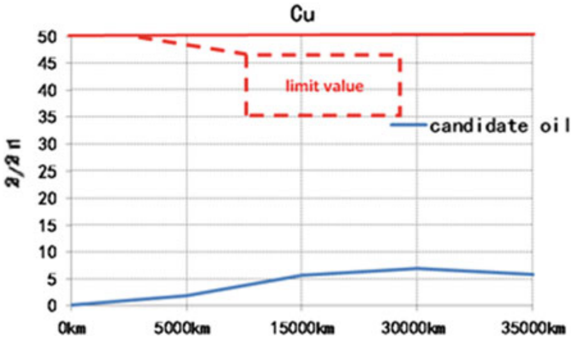


**Fig. 21** Copper content

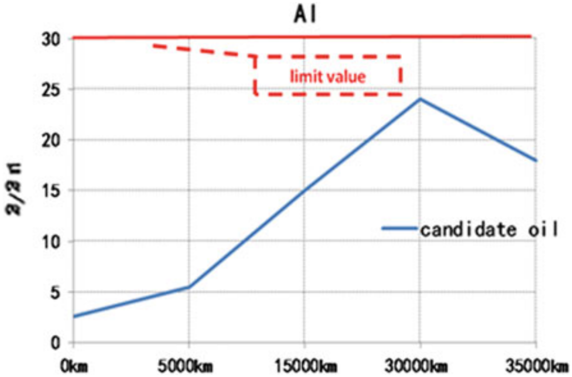


**Fig. 22** Aluminum content

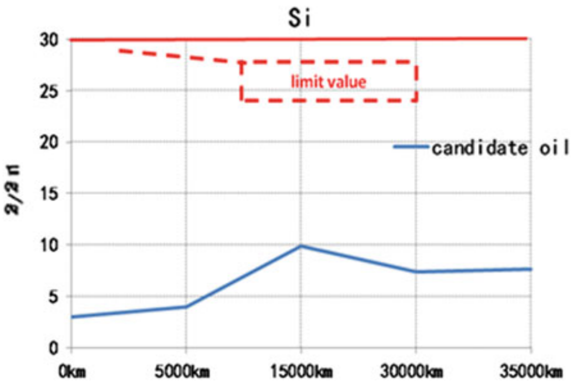


**Fig. 23** Silicon content

first piston ring was 80–90%; the second piston ring was 75–80%. The lower bearing of the main bearing had obvious wear due to the worst lubricant condition; two upper bearings of connecting rod had obvious wear; the rest of wearing components were good. In view of the 150,000 km running mileage, the result was acceptable.

**Fig. 24** Piston

**Fig. 25** Reticulate pattern of cylinder

**Fig. 26** First piston rings

**Fig. 27** Second piston rings

**Fig. 28** Main bearings

**Fig. 29** Connecting rod bearings

## 6 Conclusions

Based on the analysis of the test results, the following conclusions can be drawn:

Compared with the reference oil CI-4 15 W-40 diesel engine oil, the candidate oil 5 W-30 diesel engine oil (using Lubrizol fuel economy formulation) had the certain fuel efficiency benefits. The result of chassis dynamometer test showed a clear differentiation between the averages of fuel consumption in L/100 km with a total of 3.8% less fuel consumed on the candidate oil compared to the reference oil.

Using the drive cycle of EMS vehicle in Beijing, the proving ground test showed that the candidate oil showed a decrease of 1.5–2.5% BSFC compared to the reference oil.

During the field test, the low-viscosity candidate oil provided good lubricant protection. The oil monitoring result showed that the oil properties were normal. The inspect result of the disassembled engine was acceptable. Due to the long-running mileage of the vehicle before the test and the changing of oil, it was difficult to determine the real reason for engine wear. More research work and tests need to be carried out.

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