Published 10/08/2017
Copyright © 2017 SAE International
doi:10.4271/2017-01-2346

0W-16 Fuel Economy Gasoline Engine Oil Compatible with Low Speed Pre-Ignition Performance

Hong Liu, Jiajia Jin, and Hongyu Li
Sinopec Lubricant Co., Ltd

Kazuo Yamamori, Toyoharu Kaneko, and Minoru Yamashita
Toyota Motor Corp

Liping Zhang
Toyota Motor Engineering & Mfg NA Inc.

ABSTRACT

It has been long established fact that fuel economy is a key driving force of low viscosity gasoline engine oil research and development considered by the original equipment manufacturers (OEMs) and lubricant companies. The development of low viscosity gasoline engine oils should not only focus on fuel economy improvement, but also on the low speed pre-ignition (LSPI) prevention property. In previous LSPI prevention literatures, the necessity of applying Ca/Mg-based detergents system in the engine oil formulations was proposed. In this paper, we adopted a specific Group III base oil containing Ca-salicylate detergent, borated dispersant, Mo-DTC in the formulation and investigated the various effects of Mg-salicylate and Mg-sulfonate on the performance of engine oil. It was found that Mg-sulfonate showed a significant detrimental impact on silicone rubber compatibility while the influence from Mg-salicylate remains acceptable. The newly developed 0W-16 engine oil in this paper showed 1.0% fuel economy improvement (FEI) compared to typical GF-5 0W-20 engine oil. In addition, adequate fuel economy retention property of the 0W-16 engine oil was demonstrated in the ageing process. This newly developed engine oil also passed LSPI test and all of the bench and engine tests required by GF-5, which implied that this oil could provide good protection for engines.

CITATION: Liu, H., Jin, J., Li, H., Yamamori, K. et al., "0W-16 Fuel Economy Gasoline Engine Oil Compatible with Low Speed Pre-Ignition Performance," *SAE Int. J. Fuels Lubr.* 10(3):2017, doi:10.4271/2017-01-2346.

1. INTRODUCTION

The evermore stringent regulations on exhaust emission and fuel consumption prompt the continuous upgrading of engine oil. As shown in Table 1 [1], similar to the trends in EU, US and Japan, the fuel economy limit in China will be lowered from 6.9L/100km in 2015 to 5.0L/100km. Thus, automakers and oil companies are focusing more on devising new strategies to improve the fuel economy of vehicles.

On the one hand, fuel economy improvement is achieved by the downsized design of engines and the introduction of turbocharger to engines. However these designs may cause the abnormal pre-ignition phenomenon in the engine at low speed also known as low speed pre-ignition (LSPI) [2], which leads to extreme heavy-knocking and consequentially, results in severe engine damage. On the other hand, engine oil is playing a greater role in improving fuel economy of vehicles for its lower cost compared to other fuel saving strategies. From the Stribeck curve presented in Fujimoto et al.'s article [3], it shows that fuel economy improvement can be achieved by lowering the friction coefficient in both boundary and hydrodynamic lubrication conditions through the introduction of friction modifier and lower viscosity of engine oil[4,5,6].

For low-viscosity engine oils, LSPI prevention property should be taken into consideration. Fujimoto et al. (2012) introduced an empirical equation about the relationship between LSPI frequency and the elements content in engine oil as shown in equation (1) in their previous study [2].

$$\text{LSPI frequency} = 6.59 \times \text{Ca}[\text{Wt.\%}] - 26.6 \times \text{P}[\text{Wt.\%}] - 5.12 \times \text{Mo}\,[\text{Wt.\%}] + 1.69 \qquad (1)$$

According to this equation, calcium content in engine oil should be decreased. In order to maintain the deposit control capability, magnesium-based detergents are usually added to engine oil formulations. According to another study [7], Kaneko et al. (2016) found that Mg-sulfonate detergent-based formulations resulted in a higher friction coefficient compared to Ca-salicylate-based

Table 1. Projected FE limits for new vehicles

Counties /Region	2015	2020	2025	Degree of Reduction -2020	Degree of Reduction -2025
	Limits	Limits	Limits		
China	6.9L/100km	5.0L/100km	—	5.5%	—
EU	130g/km (5.2L/100km)	95g/km (3.8L/100km)	75g/km (3.0L/100km)	5.4%	4.2%
America	36.2mpg (6.5L/100km)	44.8mpg (5.3L/100km)	54.5mpg (4.3L/100km)	3.7%	3.4%
Japan	16.8km/L (5.9L/100km）	20.3km/L (4.9L/100km)	—	3.3%	—

formulations, which implied a detrimental impact on the fuel economy of vehicles. This negative impact was counter balanced by the introduction of borated dispersant. Nevertheless Kaneko et al.'s study did not probe the different influence of Mg-salicylate and Mg-sulfonate on the engine oil performance.

Based on all of the above, this paper would like to probe the various effects of Mg-salicylate and Mg-sulfonate on the performance of engine oil, and developed new 0W-16 low viscosity engine oil compatible with low speed pre-ignition performance, which also passed all of the bench and engine tests required by GF-5.

2. STRATEGY OF LOW-VISCOSITY ENGINE OIL DEVELOPMENT

In the development of the oil, fuel economy improvement is the most essential criteria being focused on. Hence, viscosity index improver (VII) with better friction reduction and viscosity-temperature properties was selected primarily.

For more attention would like to be paid to the various effects of Mg-salicylate and Mg-sulfonate on the all-round performance of engine oil, including fuel economy, we adopted a specific Group III base oil containing specific Ca-salicylate detergent, borated dispersant, Mo-DTC in the formulation. Finally, we conducted LSPI test and the entire bench and engine tests required by GF-5 on the developed oils and guaranteed well durability property of the newly-developed oil.

3. TEST METHODS

A high frequency reciprocating rig (HFRR) and mini-traction machine (MTM) were used in the evaluation of three selected viscosity index improver (VII). A viscosity index improver with better friction reduction property will be chosen in the formulation.

3.1. Mini-Traction Machine (MTM)

MTM works as a screening test method for measuring friction and wear behavior of lubricants in both boundary friction and hydrodynamic friction condition. The friction coefficient curves of three 0W-16 candidate oils were tested by MTM with different PMA VIIs. The test conditions are shown in Table 2.

Table 2. MTM test conditions

Mini-traction Machine	
Materials	AISI 52100 steel ball and disk
Sliding rolling ratio	50%
Load	30N
Contact pressure	1.0Gpa
Speed	10~3000mm/s
Test duration	6sec/step
Temperature	80℃

3.2. High Frequency Reciprocating Rig (HFRR)

High-frequency reciprocating rig, as described in ASTM D6079-99, is usually used to evaluate the lubricity of diesel fuels, while it is also used to check the performance of low viscosity lubricants. In this paper, HFRR was adopted to check the friction reduction properties of the selected VIIs, as a supplementary of MTM test. The test conditions are shown in Table 3.

Table 3. HFRR test conditions

HFRR	
Stroke	1mm
Load	400g
Temperature	100℃
Reciprocating frequency	50Hz

3.3. Engine Fuel Economy Test

Fuel economy improvement was evaluated using a 2ZR-FE, 1.8L, linear 4-cylinder engine with roller rocker arm type valve train system [2]. The test procedure was consisted of 9 typical engine conditions with different engine speeds, loads, oil temperatures and coolant temperatures, and each condition was assigned a weighting factor according to their contribution to the fuel consumption. The final fuel consumption was calculated by the amount of fuel consumption multiplied by corresponding weighting factors. In order to avoid the fluctuation caused by different engine tests, the engine fuel economy test of the GF-5 0W-20 reference oil was conducted prior to and after the test of the candidate oil. Final fuel economy improvement index was achieved with the normalized fuel consumption of candidate oil dividing the average fuel consumption of the reference oil.

3.4. Fuel Economy Retention Test

The ageing process of candidate oil and reference oil was conducted in a 2ZR-FE engine as described in previous study [3] to check the fuel economy retention property of the candidate oil. Each test cycle is divided into 5 stages characterized with different duration, engine speeds, loads, oil temperatures and coolant temperatures. Then fuel economy engine test was carried out for aged candidate oil and reference oil as described in part 3.3.

3.5. LSPI Engine Test

LSPI frequencies were tested in the prototype engine as described in previous study [2]. The specification of the engine used in LSPI test is shown in Table 4.

Table 4. Test engine specifications

Engine	Prototype
Air Intake System	Turbocharged
Fuel System	Direct Injection (Lateral)
Number of Cylinder	L-4
Fuel Quality	98 RON

3.6. Oil/Silicone Rubber Compatibility Test

Oil/silicone rubber compatibility is a significant property for the application of engine oil. Oil/silicone rubber compatibility test was conducted as described in ASTM D7216. After immersing silicone rubber test specimen in oil conditioned to 150 °C for 560 hours continuously, their tensile strength, hardness and change in volume were measured and compared with reference oil.

3.7. Seq. IIIG Engine Test

The deposit control capability, viscosity retention capability and valve-train anti-wear property of engine oil was investigated in Seq. IIIG engine test which was conducted on General Motors 3800 Series II V6 gasoline engine as described in ASTM D7320. The testing apparatus is shown in Figure 1. Seq. IIIG engine test conditions are shown in Table 5.

Figure 1. Seq. IIIG testing apparatus

Table 5. Seq. IIIG engine test conditions

Parameter	IIIG
Test Length	100 hours
Oil Level Block	20 hours
New Oil Additions (Total)	1888 ml
Speed	3600 rpm
Load	250 Nm
Oil Temp.	150℃
Coolant Temp.	115℃
Inlet Air Temp.	35℃

4. RESULTS AND DISCUSSION

4.1. MTM Evaluation

VII plays an important role in the characterization of viscosity-temperature property of engine oils. In order to select an appropriate VII with best fuel economy property, 0W-16 candidate oil was blended with 3 different kinds of PMA VII, which is known for its viscosity optimization capability and shear stability improvement property. The typical physical and chemical properties of selected VIIs are shown in Table 6. Three test oils are designated as Oil-1, Oil-2 and Oil-3, the compositions of which are shown in Table 7. Friction coefficients of 3candidate oils were tested by MTM. The test results are shown in Figure 2.

Table 6. Physical and chemical properties of selected VIIs

Sample Name	Molecular Weight	SSI	KV100（typical value）
PMA1	（4×10^5）max	＞30	350 mm^2/s
PMA2	（3×10^5）max	5max	900 mm^2/s
PMA3	（3×10^5）max	5max	1300 mm^2/s

*SSI was tested by the standard methods described in ASTM D 6278 (30 cycles)

Table 7. Formulation and properties of the test oils

SAE	0W-16		
No.	Oil-1	Oil-2	Oil-3
VM	PMA1	PMA2	PMA3
Base Oil	Group III （Base Oil A）		
Detergent	Ca-salicylate & Mg-sulfonate		
Dispersant	Dispersant 1		
MoDTC	MoDTC-1		
Others	ZnDTP, Anti-oxidants, PPD		
KV100	6.62 mm^2/s	6.42 mm^2/s	6.17 mm^2/s
HTHS150	2.3 mPa·s	2.3 mPa·s	2.3 mPa·s

As shown in Figure 2, with the increase of test speed, lubrication condition in the test changed from boundary lubrication to hydrodynamic lubrication. It can be concluded from Figure 2 that Oil-2 and Oil-3 demonstrates good friction reduction property when compared with Oil-1, especially in boundary lubrication condition where metal-to-metal contact occurred.

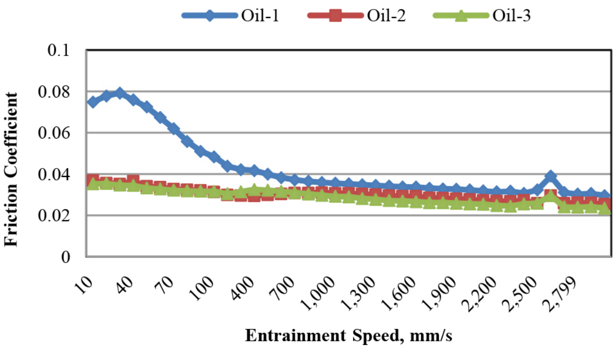

Figure 2. MTM test results

4.2. HFRR Evaluation

Besides MTM test, 3 candidate oil samples (Oil-1, Oil-2, and Oil-3) were also tested by HFRR. Friction coefficients and wear scar diameters can be achieved in HFRR test. The results are shown in Figure 3 and Table 8.

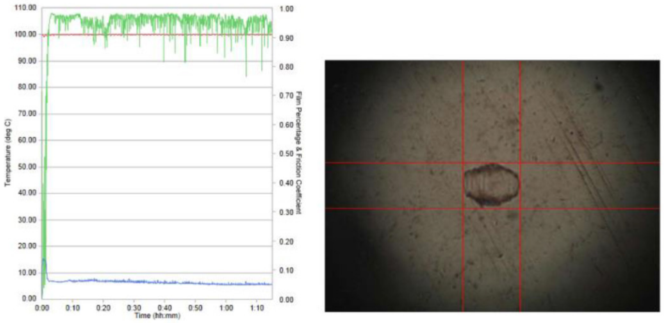

Figure 3-1. HFRR test result of Oil-1

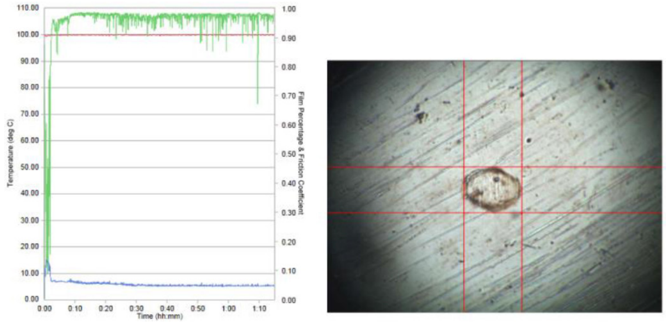

Figure 3-2. HFRR test result of Oil-2

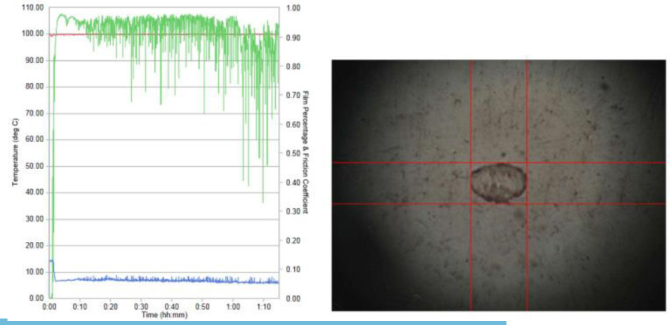

Figure 3-3. HFRR test tesult of Oil-3

Table 8. HFRR test results

	Oil-1	Oil-2	Oil-3
Friction Coefficient	0.06	0.05	0.06
Wear Scar Diameter（X-axis）	176 um	177 um	171 um
Wear Scar Diameter（Y-axis）	140 um	141 um	127 um
Wear Scar Diameter (In average)	158 um	159 um	149 um

As shown in Figure 3 and Table 8, Oil-2 demonstrates a slightly lower friction coefficient comparing to Oil-1 and Oil-3. When compared by wear scar diameter, Oil-3 shows a better anti-wear property. Combined with the results in MTM test, Oil-3 demonstrated good friction reduction and anti-wear properties, which may imply a better fuel economy improvement potential. Hence, PMA3 was chosen as the VII in the final formulation.

4.3. LSPI Engine Test

LSPI frequencies were tested in prototype engine lubricated by 0W-20 engine oil A with the same additive package as Oil-3 described in Table 7. In this part, we also investigated the influences of Mg-sulfonate and Mg-salicylate on the LSPI frequency, the formulations are shown below. (See Table 9).

Table 9. Formulation and properties of the test oils

SAE	0W-20	
No.	Oil-A	Oil-B
VM	PMA3	
Base Oil	Group III Base oil A	
Detergent	Ca-salicylate & Mg-sulfonate	Ca-salicylate & Mg-salicylate
Dispersant	Dispersant-1	
MoDTC	MoDTC-1	
Others	ZnDTP, Anti-oxidants, PPD	

LSPI engine test results are shown in Figure 4. As demonstrated in Figure 4, both of the two 0W-20 engine oils with additive packages shown in Table 9 show good LSPI prevention property as LSPI frequency are almost zero during the 100 hours engine test (equivalent to 10,000 miles). From equation (1), it can be found that 0W-16 engine oil adopting the same additive package would achieve the same or better LSPI prevention performance.

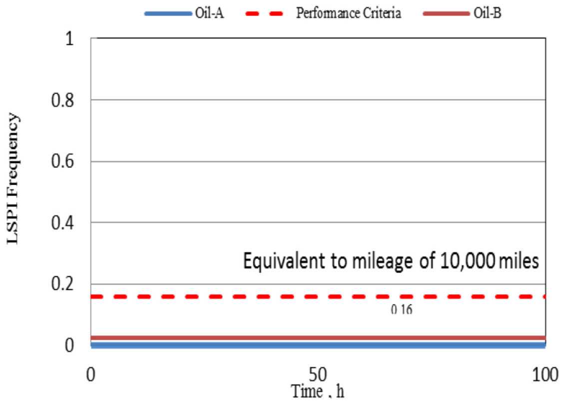

Figure 4. The results of LSPI engine test

4.4. Engine Fuel Economy Test

In order to investigate the various effects of Mg-salicylate and Mg-sulfonate on the all-round performance of engine oil, two test oils were blended with selected PMA 3 and specific Ca-salicylate detergent, borated dispersant, Mo-DTC and Group III base oil in the formulation as shown in Table 10.

Table 10. Formulation and properties of the test oils

SAE	0W-16	
No.	Oil-3	Oil-4
VM	PMA3	
Base Oil	Group III Base oil A	
Detergent	Ca-salicylate & Mg-sulfonate	Ca-salicylate & Mg-salicylate
Dispersant	Dispersant-1	
MoDTC	MoDTC-1	
Others	ZnDTP, Anti-oxidants, PPD	
KV100	6.17 mm^2/s	6.21 mm^2/s
HTHS150	2.3 mPa·s	2.3 mPa·s

Fuel economy engine tests were performed on Oil-3 and Oil-4, with typical GF-5 0W-20 engine oil being the reference oil. The fuel economy engine test results of fresh candidate oils and reference oil are shown in Figure 5.

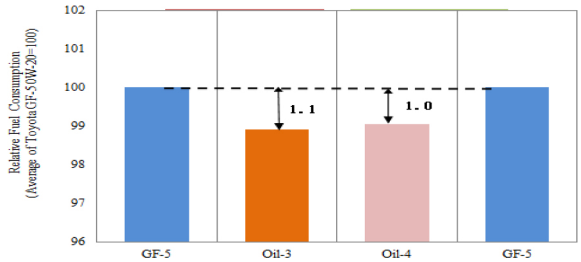

Figure 5. Test results of engine fuel economy test

From Figure 5, we may conclude that Oil-3 demonstrates better fuel economy improvement property when compared with Oil-4, which accounted for 1.1% and 1.0% improvement respectively comparing with typical GF-5 0W-20 reference oil.

4.5. Engine Fuel Economy Retention Test

After an ageing process, fuel economy retention performance of the candidate oil samples and the reference oil sample were examined. The test results are shown in Figure 6. From Figure 6, we can see that aged Oil-3 shows 1.0% fuel economy improvement as compared to aged typical GF-5 0W-20. For candidate Oil-4, aged Oil-4 showed 1.0% fuel economy improvement over the aged typical GF-5 0W-20 engine oil. The slight decrease in fuel economy improvement was observed for Oil-3 with Mg-sulfonate, which may be attributed to the consumption of detergents by the acidic oxidative products during the ageing process. Oil-4 with Mg-salicylate detergent showed a good fuel economy retention property which may result from the anti-oxidation property of Mg-salicylate. Fuel economy retention test demonstrated that both newly developed 0W-16 engine oils showed adequate fuel economy retention performance after an ageing process.

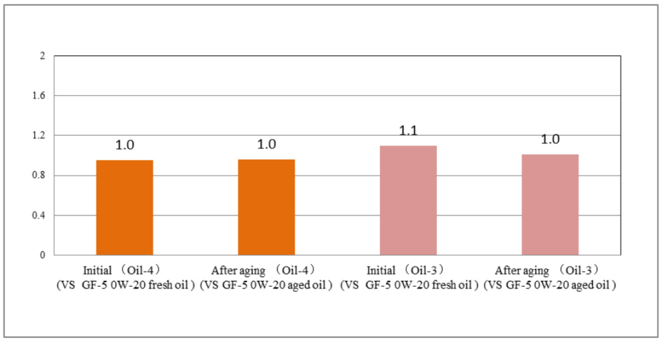

Figure 6. Test results of engine fuel economy retention test

4.6. Oil/Silicone Rubber Compatibility Test

Oil/silicone rubber compatibility test was conducted for Oil-3 and Oil-4 as shown in Table 10. Test results are shown in Table 11.

Table 11. Test Results of Oil/Silicone Rubber Compatibility Test

VQM-1	Limits	Oil-3	Oil-4
Volume / %	-5～40	23.5	28.33
Hardness / pts	-30～10	-18	-21
Tensile strength /%	-50～5	-76.2	-43.9

From Table 11, it is shown that the change of tensile strength of VQM-1 immersed in Oil-3 with Mg-sulfonate did not meet the requirement from ILSAC, while the change of tensile strength of VQM-1 immersed in Oil-4 with Mg-salicylate met the requirement. From these oil/silicone rubber test results, it can be concluded that Mg-sulfonate showed a significant detrimental impact on silicone rubber while the influence from Mg-salicylate remained acceptable. The specific reason of this phenomenon will be studied in subsequent researches in the future.

4.7. Seq. IIIG Engine Test

Seq. IIIG engine test was conducted for Oil-4, which already had passed oil/silicone rubber compatibility test. The results of Seq. IIIG engine test are shown in Table 12.

Table 12. Test results of Seq. IIIG engine test

Sequence IIIG（ASTM D7320）	Criterion	Results
Kinematic viscosity increase at 40℃	150 (max)	77.6%
Average weighted piston deposits, merits	4.0 (min)	4.08
Hot stuck rings	None	None
Average cam plus lifter wear	60 (max) µm	50.4 µm

We may find that Oil-4 exhibited good deposit control capability, viscosity retention capability and valve-train anti-wear property from the results of Seq. IIIG engine test.

Besides Seq. IIIG engine test, other bench and engine tests required by GF-5 were conducted to Oil-4. The newly-developed engine oil Oil-4 passed all of them.

5. CONCLUSIONS

In this paper, 0W-16 fuel economy gasoline engine oil compatible with low speed pre-ignition (LSPI) performance was developed. Viscosity index improver (VII) with good friction reduction and viscosity-temperature properties was selected from MTM and HFRR test.

Investigation was emphatically conducted on the various effects of Mg-salicylate and Mg-sulfonate on the all-round performance of engine oil. We found that Mg-sulfonate showed a significant detrimental impact on silicone rubber, while the influence from Mg-salicylate remained acceptable.

All in all, we have developed a new 0W-16 engine oil that showed 1.0% fuel economy improvement (FEI) as compared to typical GF-5 0W-20 engine oil. At the same time, even after an ageing process, the new 0W-16 engine oil demonstrated adequate fuel economy retention property. The newly developed engine oil also passed LSPI test and all of the bench and engine tests required by ILSAC GF-5. Therefore, sufficient evidences are present to validate the ability of the new 0W-16 engine oil which is capable to provide good fuel economy improvement and engine protection.

REFERENCES

1. “Projected FE Limits for New Vehicles”. Ministry of Industry and Information Technology of the People’s Republic of China, accessed January 26, 2015. http://www.miit.gov.cn/n1146285/n1146352/n3054355/n3057585/n3057589/c3616982/content.html
2. Fujimoto, K., Yamashita, M., Hirano, S., Kato, K. et al., "Engine Oil Development for Preventing Pre-Ignition in Turbocharged Gasoline Engine," *SAE Int. J. Fuels Lubr.* 7(3):869-874, 2014, doi:10.4271/2014-01-2785.
3. Fujimoto, K., Yamashita, M., Kaneko, T., Hirano, S. et al., "Development of ILSAC GF-5 0W-20 Fuel Economy Gasoline Engine Oil," SAE Technical Paper 2012-01-1614, 2012, doi:10.4271/2012-01-1614.
4. Shan Tianliang and Qu Hongjie. 2010. “Improving Energy Efficiency by Using Engine Oil”. Paper presented at Fuels and Lubricants Committee of SAE-China, Proceedings of the Fourteenth Annual Meeting. Lanzhou: Fuels and Lubricants Committee of SAE-China,: 159-162.
5. Taylor R I, Coy R C. “Improved Fuel Efficiency by Lubricant Design: A Review”. *ARCHIVE Proceedings of the Institution of Mechanical Engineers Part J Journal of Engineering Tribology* 1994-1996 (vols 208-210), 2000, 214(1):1-15.
6. Chen Shangshan. “Lubrication and Resource Conservation”. *Resource Conservation Technology of Vehicle Transportation*, 1995 (2): 47-50.
7. Kaneko, T., Yamamori, K., Suzuki, H., Onodera, K. et al., "Friction Reduction Technology for Low Viscosity Engine Oil Compatible with LSPI Prevention Performance," SAE Technical Paper 2016-01-2276, 2016, doi:10.4271/2016-01-2276.

CONTACT INFORMATION

Liu Hong
No.6 West Road of Anning Zhuang, Haidian District
Beijing, P.R. China, 86-10-62941011

DEFINITIONS/ABBREVIATIONS

FEI - Fuel Economy Improvement

MTM - Mini Traction Machine

HFRR - High Frequency Reciprocating Rig

VII - Viscosity Index Improver

VI - Viscosity Index