

Development of ILSAC GF-4 0W-20 Gasoline Engine Oil

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ABSTRACT

This paper describes the development of a 0W-20 engine oil designed to meet the ILSAC GF-4 engine oil standard beginning on July 31st, 2004.

The GF-4 engine oil standard stipulates upper limits for phosphorus and sulfur content in oil to prevent poisoning of exhaust system components. The new standard has also generated concerns that the reformulated oil will accelerate wear of engine parts. Each additive in the newly developed oil has been selected to improve anti-wear performance. In addition, the contribution of kinematic viscosity and HTHS viscosity to engine motoring friction has been verified, and the molecular weight of the viscosity index improver has been optimized to achieve GF-4's the higher fuel economy requirement.

The newly developed engine oil was evaluated in GF-4 standard tests and was confirmed to meet GF-4 performance.

1. Introduction

The demand to cut down the environmental impact of automobiles has increased in recent years. Engine oil must be optimized to minimize this impact. Generally, environmentally friendly engine components can only be applied at the factory. This is not the case with engine oil. With advanced engine oils, additional environmental benefits can be achieved in existing engines. Honda has focused on reducing the environmental impacts of its engines through improvements in fuel economy. Honda has achieved this in part by developing engine oils that enhance engine fuel economy performance^{(1),(2)}.

In 1994, US automobile manufacturers (GM, Ford and Daimler-Chrysler) and the Japan Automobile Manufacturers Association (JAMA) started the International Lubricant Standardization and Approval Committee (ILSAC). The objective of ILSAC is to maintain the quality of oil in the marketplace and improve oil's effect on engine fuel economy and performance. As shown in Fig. 1, ILSAC standards have been revised synchronously with the US emission and fuel economy regulations.

The US Environmental Protection Agency (EPA) has issued guidelines related to the performance of engine oil. The new ILSAC approved GF-4 engine oil standards introduction begins July 31, 2004, and is applicable to 2005-model year vehicles⁽³⁾. The most important changes in the new GF-4 standards in comparison to the current GF-3 standards are the improvement of catalyst compatibility by strengthening the element content standards for phosphorous and sulfur in engine oil, high temperature oxidation stability, and fuel efficiency⁽⁴⁾. Honda has developed an engine oil that meets the new standards.

Model Year		94	95	96	97	98	99	00	01	02	03	04	05	06	07	
US regulation	Federal Emission	Maskie Act			Tier1 100k mile				LEV			Tier2 120k mile				
	California	LEV1 100k mile									LEV2 120k mile					
	LDV	27.5mpg														
	CAFE	LDT	20.7mpg													
														21.0	21.6	22.2
Engine oil standard	ILSAC	GF-1			GF-2			GF-3			GF-4					
	API	SH			SJ			SL			SM					
	Catalyst compatibility	Phosphorus	0.12%max			0.10%max							0.06%min 0.08%max			
		Sulfur	Not required										0.5%max ^{*1} 0.7%max ^{*2}			
	High temp. oxidation	Test	Sequence III-E					Sequence III-F					Sequence III-G			
		W.P.D ^{*3} Min. limit	Not required					4.0P					3.5P			
		Viscosity increase	375%max at 64hrs			64hrs max to 375%			275%max at 80hrs			150%max at 120hrs				
	Fuel efficiency	Test	Sequence VI			Sequence VI-A			Sequence VI-B							
		Min. limit ^{*4}	2.7%			1.4% ^{*5} Not required ^{*6}			2.0% ^{*5} 1.7% ^{*6}			2.3% ^{*5} 2.0% ^{*6}				

^{*1}; 0W-20, 5W-20, 0W-30, 5W-30

^{*2}; 10W-30

^{*3}; Weighted Piston Deposit (Merit rating)

^{*4}; 0W-20, 5W-20

^{*5}; after 16hrs aging

^{*6}; after 96hrs aging

Fig. 1 US emissions/FE regulations and engine oil standards

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2. Development Goals

The two points below were the main development goals of the new GF-4 compliant engine oil.

- (1) Compliance with standards for Phosphorous content (More than 0.06%, less than 0.08%) and Sulfur content (Less than 0.5%)
- (2) Improvement of fuel economy performance

Phosphorous and sulfur are elements included in additives used in engine oil. The upper and lower limits according to the standards restrict the type, and content of the additives. Figure 2 shows the limits of sulfur and phosphorus allowed in the GF-3 and GF-4 standards. Figure 2 also shows the North American market average values for phosphorous and sulfur content under the GF-3 standard.

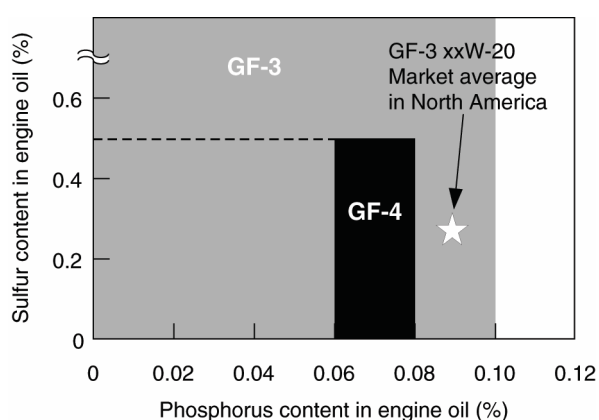


Fig. 2 Standard limits and xxW-20 market average for phosphorus and sulfur content in engine oil

The GF-4 standards place more importance on phosphorous content than sulfur content. In this development, the appropriate phosphorous content and sulfur content in engine oil were studied, and the improvement of the fuel economy performance of engine oil was investigated.

3. Study of Engine Oil Specifications

Base oil (B/O), detergent inhibitors (DI) and viscosity index improvers (VII) were selected to satisfy fundamental performance requirements of engine oil. The fundamental performance requirements include friction reduction, cooling, sealing, anti-rust, detergency and power transmission characteristics. Each of these items were studied individually.

3.1. Base Oil

American Petroleum Institute (API) categorizes base oil into five groups (Table 1)⁽⁵⁾. Group I to III are mineral oils obtained by the distillation and refining of crude oil, while Group IV and V are synthetic oils. Mineral oils are further sub-divided according to the proportions of sulfur content, saturates, and viscosity index. In the past Honda has used Group III oil. Group III oil was also investigated during this development.

Table 1 API base oil interchange guidelines

Base oil category	Sulfur [%]	Saturate [%]	Viscosity index
Gr.I	0.03 <	and/or < 90	80 to 120
Gr.II	≤ 0.03	and 90 ≤	80 to 120
Gr.III	≤ 0.03	and 90 ≤	120 ≤
Gr.IV	All polyalphaolefins (PAOs)		
Gr.V	All others not included in Gr.I,II,III or IV		

3.2. Detergent Inhibitors

Various additives are used in engine oil to satisfy fundamental performance requirements. Table 2 shows the functions, typical chemicals, phosphorous, and sulfur content (if existing) of various kinds of additives. Compared to sulfur, phosphorous is limited to a few kinds of engine oil additives, extreme pressure agents, and in oxidation inhibitors. Currently, phosphorous-type extreme pressure agents are almost never used. Organometallic compound zinc dithiophosphate (ZnDTP) is used in practically all engine oils as an extreme pressure agent because of its performance and availability. ZnDTP also has the property of anti-oxidation, and is a prominent additive. Reducing the phosphorous content to meet the new GF-4 standards requires nothing but reducing the ZnDTP content. Thus, it is necessary to find the method to compensate the reduced ZnDTP.

Table 2 Typical engine oil additives

Additive	Function	Typical chemicals	Phos-phorus	Sulfur
Extreme pressure agents	Anti-wear Anti-seizure	Organometallic compound type (Zinc dithiophosphate)	✓	✓
		Sulfur type		
		Phosphorus type	✓	
		Chlorine type		
Oxidation inhibitors	Chain reaction stop	Phenol type		
		Amine type		
	Peroxide decomposition	Organometallic compound type (Zinc dithiophosphate)	✓	✓
		Sulfur type		✓
Detergent-dispersant additives	Detergency	Sulfonate type		✓
		Salicylate type		
		Phenate type		
	Sludge dispersancy	Amin type		
		Imide type		
Friction modifiers	Friction reduction	Organometallic type		✓
		Ester type		
Viscosity index improvers	Viscosity adjustment	Polymethacrylate		
		Olefin copolymer		
Carrier oils	Solvent of additives	Mineral oil		✓
Others				

The effects of ZnDTP content, specifically anti-wear performance were investigated. Also the effects of phosphorous content in the current GF-3 engine oil on the cam wear of valve train were studied by carrying out a test with and without molybdenum dithiocarbonate (MoDTC), which is a friction modifier (FM). The results of the test are shown in Fig. 3 and the test conditions in Table 3.

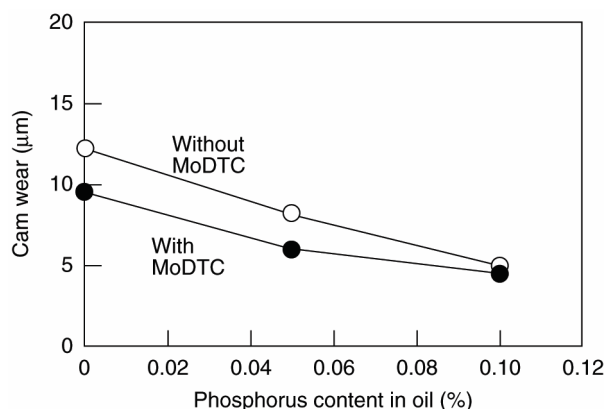


Fig. 3 Cam wear level in Honda valve train wear test

Table 3 Valve train wear test conditions

Engine	L4, 2.2L, MPI
Valve train	SOHC, 4valve, Slide-type
Engine speed [rpm]	2000 / 0
Oil temperature [°C]	90 - 95 / 20 - 30
Water temperature [°C]	80 - 90 / 15 - 25
Test duration [cycle]	300

ZnDTP prevents wear and seizure by generating a phosphate film formed by the chemical reaction between its decomposition product and the metallic surface⁽⁶⁾. When MoDTC is added, it is assumed that MoS₂ is formed on the rubbing surface due to the decomposition of ZnDTP and itself. As a result, friction reduction and anti-wear/anti-seizure performance become more effective^{(7), (8)}. Although the wear due to the reduction of ZnDTP can be prevented to a certain extent using MoDTC, the amount of wear increased. However, for a treatment in which MoDTC is added, it was estimated that a performance equivalent to or better than the current performance could be obtained within the range of acceptable levels of phosphorous contents of GF-4 by making more effective use of MoDTC. On the other hand, detergent-dispersant additives, particularly ashless dispersant, reacts with ZnDTP and also affects the generation of MoS₂. In this development, optimization of the detergent-dispersant additives increases the generation of MoS₂ on the rubbing surface, and attempts to prevent wear and to reduce friction. The Schwingung Reibung Verschleis (SRV) test was carried out^{(9), (10)} on the current GF-3 oil and a study oil obtained by changing its detergent-dispersant additives. The test conditions are shown in Table 4.

The binding energy of molybdenum compound on the surface of the disk specimen was measured using X-ray photoelectron spectrometer (XPS). The results of comparison of the measured results are shown in Fig. 4⁽¹¹⁾.

The binding energy of MoS₂ (229eV) was confirmed to be stronger than that of oil with GF-3 specifications because of the optimization of the detergent-dispersant additives. The MoS₂ molecules generated on the surface are estimated to have increased.

Table 4 SRV test conditions

Pin	Diameter [mm]	15
	Length [mm]	22
	Material	DIN 100Cr6
Disk	Diameter [mm]	24
	Thickness [mm]	6.9
	Material	DIN 100Cr6
Temperature [°C]		80
Load [N]		200
Frequency [Hz]		50
Sliding distance [mm]		1.0
Test duration [min]		20

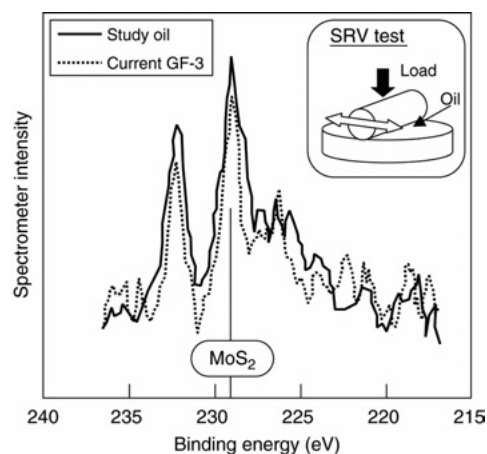


Fig. 4 XPS analysis in SRV test

3.3. Viscosity Index Improvers

Engine friction may be broadly classified into frictional resistances, pumping, and stirring resistance under reciprocating sliding condition. The former is affected to a large extent by high temperature high shear (HTHS) viscosity, while the latter is affected to a large extent by kinematic viscosity. To study the fuel economy of the engine oil, the effects of HTHS and kinematic viscosity on the engine friction were verified. Engine friction was taken as the friction during motoring, and three engine speeds most often used at actual driving condition were selected. Table 5 shows the test engine specifications.

Table 5 Test engine specifications

Engine	L4, 2.0L, MPI
Bore × Stroke [mm]	86.0 × 86.0
Valve train	DOHC, 4valve Roller-type rocker-arm Chain-driven
Compression ratio	9.7

The contribution of each kind of viscosity to the overall engine friction is as shown in Fig. 5. At temperatures below 80 °C, the effect of kinematic viscosity increased, while at temperatures above 80 °C, that of the HTHS viscosity increased. It is evident from the above that a moderate balance between the HTHS viscosity and kinematic viscosity is necessary to reduce the engine friction effectively. With HTHS viscosity constant (2.6 mPa·s) at 150 °C, the molecular weight of viscosity index improver was varied and the HTHS viscosity and kinematic viscosity at 60 °C, 80 °C and 100 °C were examined. As shown in Fig. 6, each viscosity characteristic has an opposite tendency to the molecular weight of viscosity index improver. Thus, the molecular weight with which the optimum viscosity setting can be obtained was selected.

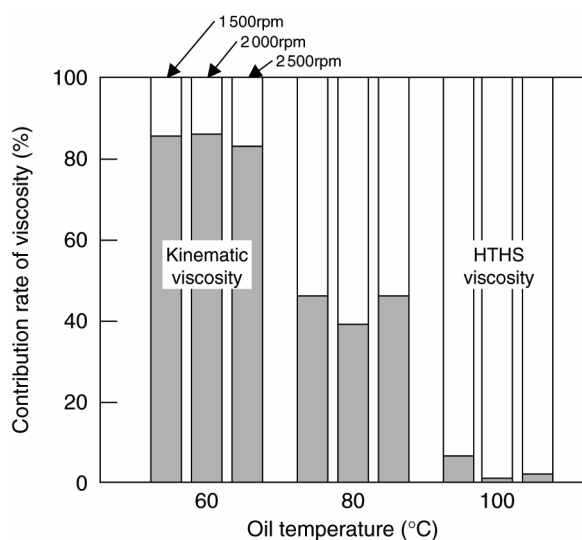


Fig. 5 Contribution of viscosity to engine motoring friction

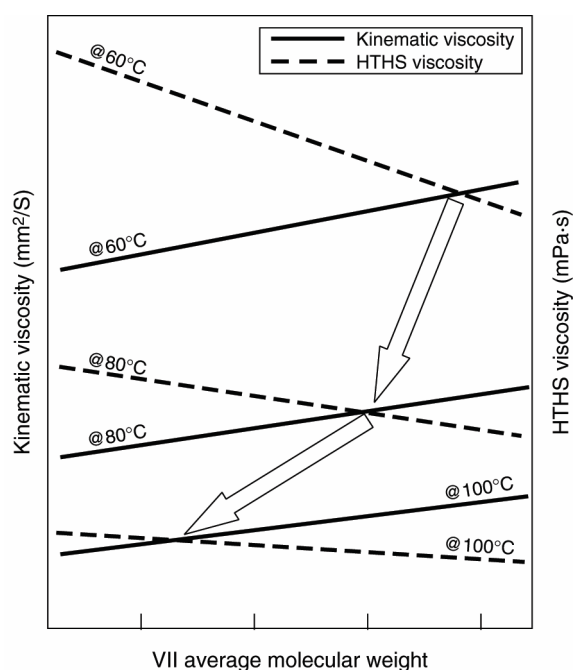


Fig. 6 Viscosity characteristic by VII molecular weight

4. Results Confirming the Performance

From the results of the study above, the test oil (prototype GF-4 oil) was experimentally blended and its performance was confirmed. The oil specifications are shown in Table 6. As reduction in phosphorous content concerns high temperature oxidation stability, anti-wear and fuel economy performance, these confirmed results are described below.

Table 6 Properties of test engine oil

		Current GF-3 oil	Prototype GF-4 oil
Formulation (DI)		A	B
Base oil		Gr.III	Gr.III
Viscosity grade		0W-20	0W-20
Kinematic viscosity [mm²/s]	40 [°C]	34.8	33.4
	100 [°C]	7.85	8.02
HTHS viscosity [mPa·s]	150 [°C]	2.6	2.6
Phosphorus [%]		0.10	0.08
Sulfur [%]		0.30	0.25
Viscosity index improver		PMA-A	PMA-B
Friction modifier		MoDTC-A	MoDTC-B

4.1. High Temperature Oxidation Stability

The high temperature oxidation stability of test oils was evaluated by the Indiana Stirring Oxidation Test (ISOT). Figure 7 shows the test results and Table 7 the test conditions of the current GF-3 oil and the prototype GF-4 oil. It is clear that the prototype GF-4 oil prevents the viscosity increase due to high temperature oxidation compared to the current GF-3 oil.

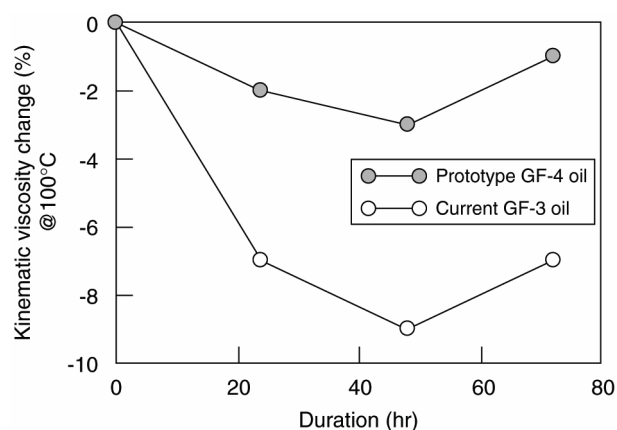


Fig. 7 Kinematic viscosity change in ISOT

Table 7 ISOT test conditions

Method	Based on JIS K 2514		
Oil volume [ml]	250		
Oil temperature [°C]	175		
Catalyst	Copper and Iron		
Test duration [hr]	24	48	72

4.2. Anti-wear Performance

Valve train wear test in the Honda engine described earlier and Sequence IV-A valve train wear test (ASTM D 6891) specified in the GF-4 standards were used to evaluate the anti-wear performance. The results of the valve train wear test using the Honda engine are shown in Fig. 8. The test conditions are the same as those in Table 3. The Sequence IV-A valve train wear test results are shown in Fig. 9 and the test conditions are given in Table 8. In all tests, prototype GF-4 oil showed better results in comparison to the current GF-3 oil.

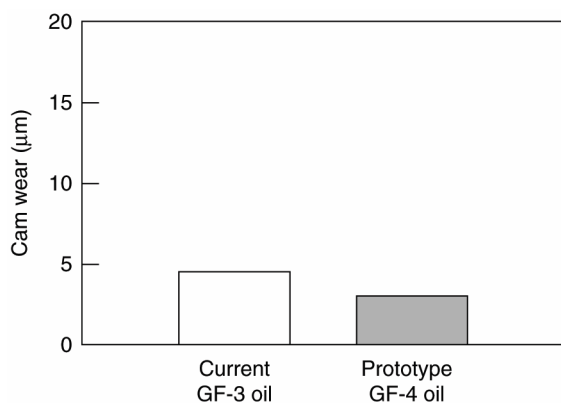


Fig. 8 Comparison of cam wear level in Honda valve train wear test

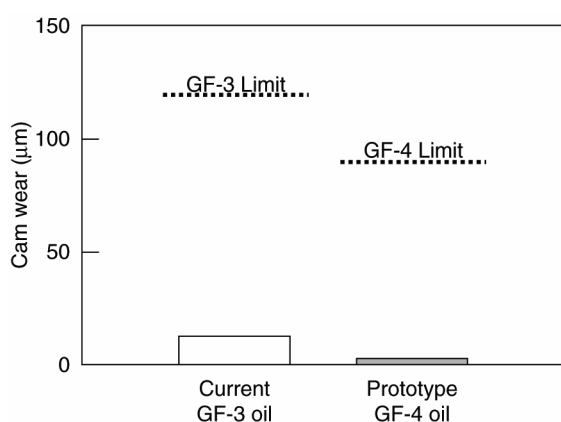


Fig. 9 Comparison of cam wear in Sequence IV-A

Table 8 Sequence IV-A test conditions

Engine	Nissan KA24E, L4, 2.4L	
Stage	I	II
Stage duration [min]	50	10
Engine speed [rpm]	800	1500
Engine torque [N·m]	25	25
Oil temperature [°C]	50	60
Water temperature [°C]	50	55
Test duration [cycle]	100	

4.3. Fuel Economy Performance

Figure 10 shows the results of 10.15-mode fuel economy test in a vehicle equipped with a typical Honda engine. The specifications of the vehicle are given in Table 9. Figure 11 shows the fuel economy improvement (FEI) by the Sequence VI-B fuel economy test (ASTM D 6837) specified in the GF-4 standards. The conditions of the test are given in Table 10. In these tests, fuel economy was confirmed to improve in the prototype GF-4 oil over the current GF-3 oil. Also the prototype GF-4 oil met the FEI standards in the 0W-20 category of GF-4.

Table 9 Japanese 10.15 mode test conditions

Engine	L4, 2.0L, MPI
Valve train	DOHC, 4valve, Roller-type
Vehicle	Domestic production model
Test mode	Japanese 10.15

Table 10 Sequence VI-B test conditions

Engine	Ford modular, V8, 4.6L				
Aging stage	I		II		
Stage duration [hr]	16		80		
Engine speed [rpm]	1500		2250		
Engine power [kW]	15.39		23.10		
Oil temperature [°C]	125		135		
Water temperature [°C]	105		105		

Test stage	1	2	3	4	5
Engine speed [rpm]	1500	800	800	1500	1500
Engine power [kW]	15.39	2.18	2.18	15.39	15.39
Oil temperature [°C]	125	105	70	70	45
Water temperature [°C]	105	95	60	60	45

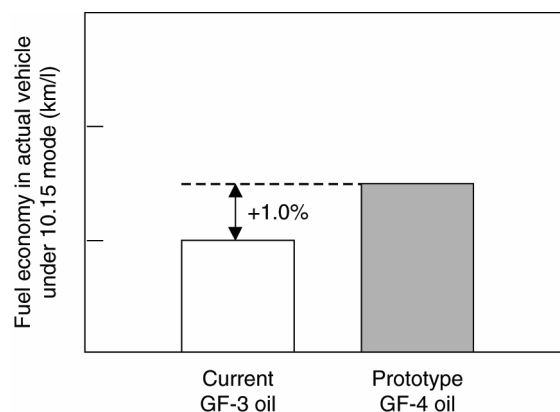


Fig. 10 Fuel economy improvement in Japanese 10.15 mode test

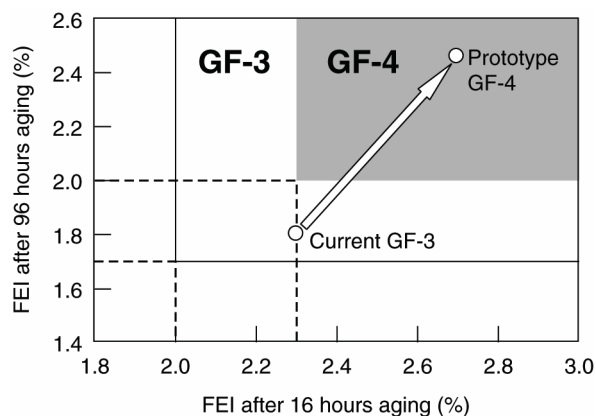


Fig. 11 Fuel economy improvement in Sequence VI-B

5. Conclusion

The researchers arrived at the following conclusions through the development of 0W-20 fuel economy gasoline engine oil conforming to the new GF-4 standards:

- (1) By selecting MoDTC and detergent-dispersant appropriately to compensate for extreme pressure agent ZnDTP, wear could be prevented.
- (2) The contribution of kinematic viscosity and HTHS viscosity on engine friction varies with the temperature. It was found that optimizing the molecular weight of viscosity index improver was an effective method to reduce friction.
- (3) The prototype oil blended based on this knowledge met the GF-4 standards and improved the actual fuel economy by 1%.

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