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1.INTRODUCTION

Environmental concerns are the most significant subjects to be tackled going into the 21st century. The pollution from vehicle exhaust emissions is a major problem, but countries such as the U.S, Japan and Europe now regulate these emissions have regulations to control these emissions[1]. In Japan, following the control for gasoline vehicles, both short- and long-term regulations were established for diesel vehicle emissions to be carried out in two steps. Currently, the short-term regulations are being carried out as the first step. Stricter long-term regulations will be implemented successively starting with light-duty vehicles in and after 1997.

To cope with the exhaust emission regulations is the most important technical theme facing for the Japanese vehicle manufacturers and each of them is making efforts for technical improvement. Concerning fuels, the sulfur content in the diesel fuel will be reduced to 0.05 mass% starting in 1997 to respond to the long-term regulation.

The substances controlled by the diesel engine exhaust emission regulation are NOx, CO, THC, and PM . Among them, NOx and PM trade off with each other, and the technology for reducing them at the same time is considered to be the most significant subject for the future .One of the most effective techniques of reducing NOx is exhaust gas recirculation (EGR). This method is now being in some of the light-duty diesel vehicles.

To meet the regulations expected to be much tighter in the future, consideration is being given to increasing the amounts of exhaust gases to be recirculated and adopting this method in heavy-duty trucks and buses in addition to light-duty vehicles. But in the case of the diesel engine, which is required to be highly durable and reliable, there is the concern that the engine oil may deteriorate and various parts of the engine may be worn by the effects of EGR [2)~5)].

The effects of EGR on diesel engine oil was investigated by doing engine tests and studying the countermeasures. This paper discusses the results of the investigation and studies.

2.Test

2.1 Test engine and operation conditions

4.2 L naturally aspirated direct injection diesel engine with an EGR system was used for the test. The engine specifications are shown in Table 1. For the operation mode, Japanese 13 was used. This mode is considered to be correlated with field operation. This cycle was repeated continuously for 400 hours. The details of the operating conditions are shown in Table 2. The coolant temperature was controlled with in 59±1℃. The engine oil temperature, which was not controlled, ranged from 45 to 90 ℃. The engine oil and the oil filter were kept unchanged during 400 hours test.

Table 1. Engine Specifications

Engine Type	L-4.4cycle Diesel Natural aspiration
Combustion type	Direct Injection
Displacement	4.2L
Bore × Stroke m/m	108×115
Compression ratio	18.0
Maximum Output kW/min	96/3200
Maximum Torque Nm/min	304/1800

Table 2 Test Operation

Test Mode	13-mode
Test duration (h)	400
Cooling water temperature(℃)	58~60
Engine oil temperature(℃)	45~95
Exhaust pressure (Pa)	1333

Step No	Time	Speed (min^{-1})	Output(kW)
1	12'18"	650	0
2	2'13"	1280	7
3	1'37"	1280	15
4	12'18"	650	0
5	1'44"	1920	11
6	3'50"	1920	22
7	2'28"	2560	29
8	1'55"	2560	43
9	4'37"	1920	34
10	3'18"	1920	45
11	2'57"	1920	53
12	2'13"	2560	57
13	8'32"	1920	3

The EGR rate was 0% for the modes No. 1 and 4 (idling) of the 13 modes and ranged from 10 to 50% for the other modes. The details of the test conditions are shown in Table 2. As a result, NOx was reduced to a half to a third of the level of NOx for the diesel engine without EGR.

2.2 Test fuels and engine oils

In order to investigate the effects of the sulfur content in the diesel fuels shown Table4, three types of diesel fuels were used : one containing 0.5 mass% sulfur, which was available in and before 1992 ; another containing 0.2 mass% sulfur, which is currently available ; and still another containing 0.05 mass% sulfur, which will be put on sale in the market from 1997.

To investigate the effects of EGR on engine oil and study the countermeasure ,several oils consisting of various types of base oils and additives were tested. The properties of the engine oils are shown in Table 3. Solvent refined base oils were used for oil A, B, and C, a very high viscosity index base oil refined by hydrocracking was used for oil D, and a synthetic oil (PAO) was used for oil E.

dditives were added to meet the API CC to CF-4 grade of each oil. To investigate the effects of dispersancy, the authors used four types of dispersants: ⓐ, ⓑ, ⓒ, and ⓓ. The dispersant ⓐ has the dispersancy equal to CC grade, and the dispersant ⓑ has the dispersancy equal to CD grade.

The dispersants ⓒ and ⓓ have the dispersancy equal to CF-4 grade. In the dispersants ⓒ and ⓓ, ⓓ has higher dispersancy than ⓒ.

The test conditions are shown in Table 4.

Table 4 Test conditions

RUN	1	2	3	4	5	6	7
EGR	without	with	←	←	←	←	←
Sulfur content in Diesel Fuel %	0.4	0.2	←	0.05	←	←	←
Engine Oil	A	B	C	B	C	D	E

3. Test results

3.1 Effects of EGR on the engine oil

3.1.1 Effects on the viscosity

The deterioration of the engine oil due to application of EGR will show an increase of the insolubles due to the contamination of soot from the combustion chamber into the engine oil and a decrease of the total base number due to the sulfuric acid generated from the combustion of the sulfur contained in the diesel fuel.

The amounts of the insolubles in this test are shown in Fig. 1, and the viscosity increase tendency is shown in Fig. 2. The figures show that the amounts of the insolubles increase by EGR. The viscosity tends to increase when EGR is applied (runs 2 to 7) as compared to when the run without EGR (run 1).

In the runs 2 to 7, with EGR, the viscosity increase was remarkably larger in the runs 2 and 4 than in the other runs. In the runs 2 and 4, the dispersant had the dispersancy equal to CD grade. In order to investigate the effects of the dispersancy, the distribution of the particle diameter in the oil was measured.

The results are shown in Fig.3. The figure shows that the average diameter of the particles in the oil with high dispersancy is smaller than and suggests that the oil dispersancy affects the viscosity increase.

The engine oil deterioration resulting from oxidation is also considered to affect the viscosity increase. Therefore, the oil deterioration in the run 2 was compared with that in the run 7, in which the viscosity increase was small and a synthetic oil was used as the base oil.

Table .3 Properties of test oils

Oil	A	B	C	D	E
SAE Viscosity Grade	30	30	10W-30	10W-30	10W-30
API	CC	CD	CF-4	(CF-4)	(CF-4)
Base Oil	Solvent Refined base oil	←	←	Very High Viscosity Index base oil	Synthetic oil (PAO)
Viscosity Index Improver	0	0	1	1/3	0
Dispersant	ⓐ	ⓑ	ⓒ	ⓓ	ⓓ
Kinematic viscosity (mm2/s) @40℃	93.68	102.0	67.55	68.12	68.72
@100℃	10.82	11.53	10.19	10.55	10.36
Viscosity Index	99	100	136	143	137
HTHS Viscosity(mPa.s) @150℃	3.27	3.58	3.12	3.25	3.31
CCS Viscosity (mPa.s) @-20℃	-	-	3350	3350	3010
Total Acid Number (mgKOH/g)	2.26	2.10	2.66	2.66	2.66
Total Base Number (mgKOH/g) (HCL)	7.23	10.4	10.5	10.6	10.6
Total Base Number (mgKOH/g) (PCA)	8.33	13.0	13.3	12.1	12.1
Sulfated ash contend (mass%)	1.09	1.66	1.64	1.64	1.64
Elements(mass%) Ca	0.28	0.45	0.42	0.42	0.42
Zn	0.10	0.11	0.12	0.12	0.12
P	0.09	0.09	0.10	0.10	0.10
N	0.02	0.04	0.10	0.05	0.04

The drain oil was dialyzed in each of both runs with a rubber membrane and the infrared absorption spectrum of the dialyzed oil was measured. The results are shown in Fig. 4.

Between the runs 2 and 7, there is no difference observed in absorption of 1720 cm-1, which shows the engine oil deterioration due to oxidation.

Therefore those results show that the oxidation of base oils is not a major cause of viscocity increase in those tests .Furthermore , the viscosity increase may be affected by the amounts of insolubles. In this test, the insolubles were evaluated based on the insoluble heptane content separated by an ultracentrifuge (40,000 G). The tendency was observed that the amount of the insolubles in the runs 5 to 7, which used oils with high dispersancy, was smaller than in the other runs. This tendency was possibly ascribable to the fact that the diameter of the particles in the runs 5 to 7 was smaller, which is shown also by the measurement results of the particle diameter distribution, and that such particles were not able to be aggregated by a centrifugal force of 40,000 G. The centrifugal force was increased to 250,000 G, and the result was the amount of the insolubles collected increased to approx. 10 mass% as compared with the amount when centrifugal force was 40,000G. The amount of soot is considered to be almost constant.

The above results make it clear that the viscosity increase caused by the increased insolubles due to the application of EGR can be restrained to some extent by increasing the dispersancy of the oil.

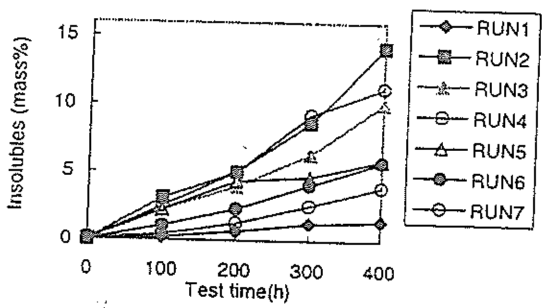

Fig.1 Coagulated heptane insoluble(40000G) in 13-mode test

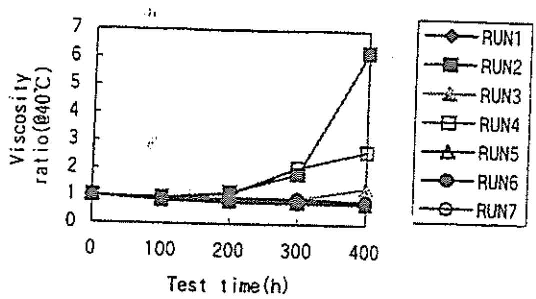

Fig.2 Viscosity ratio in 13-mode test

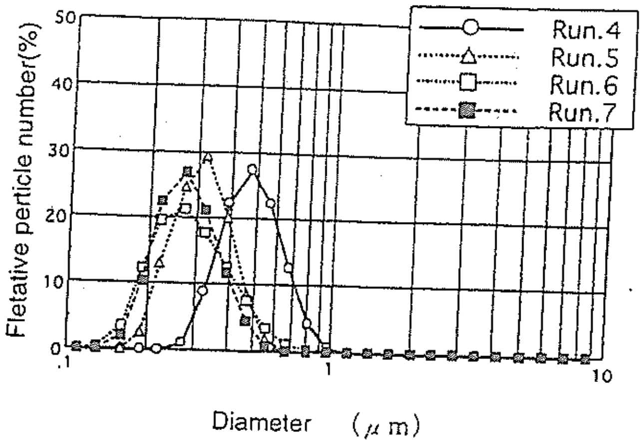

Fig.3 The particle diameter distribution of drain oils

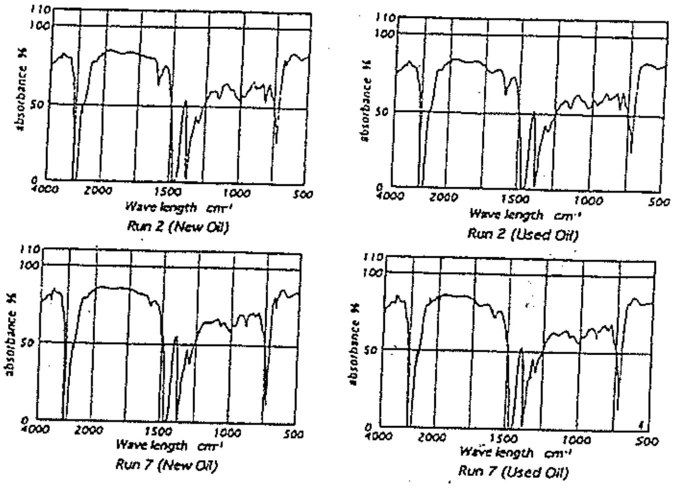

Fig 4. IR spectrum of the dialyzes oils

3.1.2 Effects of EGR on the total base number

The decrease of total base number of test oils are shown in Fig. 5. Run 1, in which the diesel fuel containing 0.4 mass% sulfur was used and EGR was not applied was compared with the runs 2 to 7, in which EGR was applied and the diesel fuels containing 0.2 mass% and 0.05 mass% sulfur were used. The results show that the difference in the content of sulfur in diesel fuel is exactly the difference in total base number decreases. When the diesel fuel containing 0.05 mass% sulfur was used, the total base number decreased less than when the diesel fuel containing 0.2 mass% sulfur was used. Because the amount of sulfur contained in diesel fuel will be reduced to 0.05mass% from the Fall of 1997 in Japan , the decrease in total base number by the application of EGR is considered to be a level which will not pose problems.

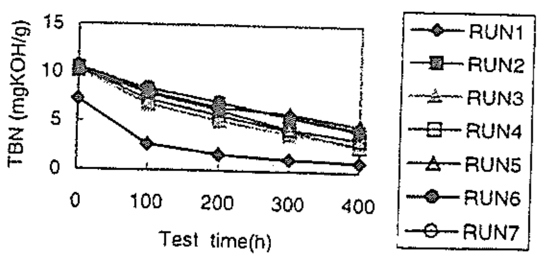

Fig5.TBN in 13-mode test

3.1.3 Effects of EGR on detergency

To study the effects of EGR on detergency of the engine oil, the detergency of the oil on the oil pan sludge, TGF, and the piston cleanliness was investigated.
The test results are shown in Fig.6 and 7. The comparison between with EGR and without EGR shows the tendency of more sludge on the oil pan and also TGF when EGR is applied. These adverse effects on the detergency may be due to the increase in amounts of the soot which gets into the engine oil from the combustion chamber by EGR.
The sludge deposits in the oil pan are larger in the runs 2 and 4 (when oil B was used). The result is better when oils C, D, and E, which have higher dispersancy than oil B, were used (runs 5 to 7).
This result shows that, it is effective to improve the dispersancy of the oil in order to keep the oil pan clean, therefore, we believe it is necessary to use engine oils having higher detergency and dispersancy for diesel engines with EGR.
The effect of oil dispersancy on TGF was not so remarkable as compared with oil pan sludge. There were cases where the result was worse with the oil of higher dispersancy than with the oil of lower dispersancy.
When oils B and C were compared in the tests which used diesel fuel containing 0.2 mass% sulfur and diesel fuel containing 0.05 mass% sulfur, the TGF ratio was lower, for the oil B, which had lower dispersancy. There was no correlation found between TGF and dispersancy.
For the effect of the fuel on TGF, comparison was made between the runs 2 and 4, in both of which the same type of oil (oil B) was used, and between the runs 3 and 5, in which oil C was used. The comparison shows the TGF ratio is lower in the runs 4 and 5, where the diesel fuel containing 0.05 mass% was used.
Reducing the sulfur content in diesel fuel tends to lower the TGF ratio.
The amount of a viscosity index improver is considered to have an effect upon increasing the TGF.
The viscosity index improver is a polymer. If its amount are large, then the coking deposits will be large in the top groove, where the temperature is relatively high, and the TGF will increase.
The relationship between TGF and the amount of the viscosity index improver are shown in Fig. 8. It shows that a correlation exists between the amount of the viscosity index improver and TGF. The TGF ratio was lower in the case of the oil D (run 6) and oil E (run 7), each of which contained less amounts of viscosity index improver than in the case of the oil C (run 5), which was likewise a 10W-30 oil.
From the above fact, it is considered effective for lowering the TGF to reduce the amount of the viscosity index improver in the oil in addition to reducing the amount of sulfur in the fuel. Also, it will be necessary to improve the dispersancy of the oil to ensure the detergency of the oil for the oil pan sludge at the same time.

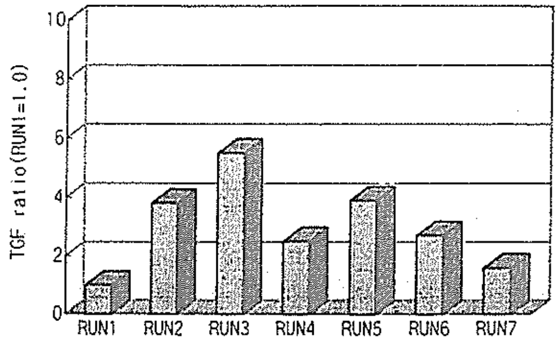

Fig.6 TGF in 13-mode test

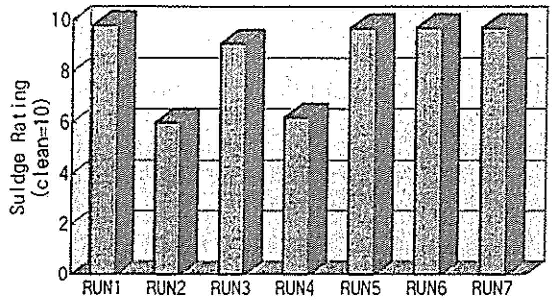

Fig.7 Sludge rating of the oil pan after tests

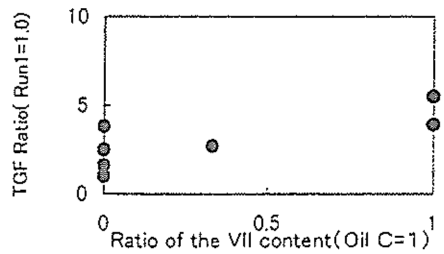

Fig.8 Relationship between TGF and VII content

3.1.4 Effects of EGR on the top ring wear

There are many reports on the subject regarding the increase of the top ring wear when EGR is applied [2), 3)].
The top ring wear in this test is shown in Fig. 9. The top ring wear was larger when the diesel fuel containing 0.2mass% sulfur was used and EGR was applied (runs 2 and 3) than when EGR was not applied.
When all the test results were considered, no wear difference caused by the oil was recognized. The sulfur content in the fuel rather than the oil performance had a greater influence on the top ring wear.
From this fact, it is considered that, if the diesel fuel containing 0.05 mass% sulfur is used, it will reduce the top ring wear. For the top ring wear, corrosion will be a larger factor than the amount of soot caused by the application of EGR. Engine operating conditions also have a large effect on corrosion and we plan to continue studies on corrosion in the future.

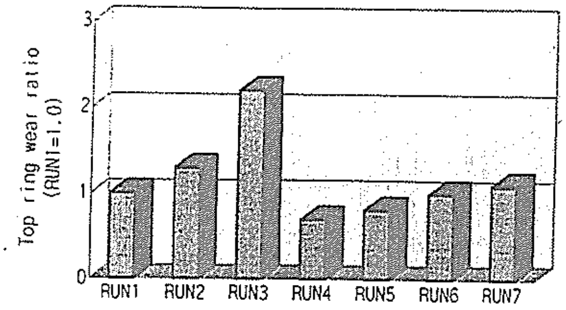

Fig.9 Top ring wear in 13-mode test

3.1.5 Effects of EGR on the valve train wear

Several papers have discussed the effects of EGR on the valve train wear of overhead camshaft (OHC) diesel engines but very few have discussed the effects of EGR on the valve train wear of overhead valve (OHV) diesel engines[3), 5),8)].

The cam wear is shown in Fig. 10. The cam wear was larger in the runs 3 and 5 (where oil C was used) than in the runs 2 and 4 (where oil B was used).

The oils B and C differed in dispersancy and viscosity grade. The 10W-30 viscosity grade will continue to be a major grade of the diesel engine oil in the future from the points of cold startability and fuel economy. Therefore, the oil formulation for improving the ability of the 10W-30 oil to decrease the valve train wear was studied.

To decrease the valve train wear, it is necessary to keep an oil film on the sliding surface of the cam and the tappet. For this purpose, it is considered necessary to increase the high temperature high shear viscosity (HTHS viscosity) of the oil, that is, to increase the base oil viscosity by using a base oil having a high viscosity index.

There is also the view that high-molecular viscosity index improvers adversely affect the valve train wear [9)]. Considering this point, a study was also done on reducing the amount of viscosity index improver to be added.

Oil D is blended with a very high viscosity index base oil and containes viscosity index improver in the amount of which was reduced to one third of the amount for oil C. Oil E was adjusted to a 10W-30 oil without adding a viscosity index improver by using the synthetic oil PAO. Oils D and E both have higher HTHS viscosity than oil C. The effect of higher HTHS viscosity was verified in the runs 6 and 7, where the cam wear was lower than in the run 5.

The above result showed that increasing HTHS viscosity and reducing the amount of viscosity index improver are effective for preventing the valve train wear.

The relationship of the cam wear and HTHS viscosity is shown in Fig. 11, and the relationship with the soot in Fig. 12. The results show that both factors probably contributed to the cam wear. Therefore, a multivariate statistical analysis based on the cam wear and soot content and HTHS viscosity was conducted.

As a result, the standard regression coefficient (absolute value) for HTHS viscosity was 0.711, which was higher than 0.419, the standard regression coefficient for the soot content. From the above result, it was revealed that the valve train wear due to soot (insolubles) caused by EGR can be restrained by making HTHS viscosity and the amount of viscosity index improver appropriate.

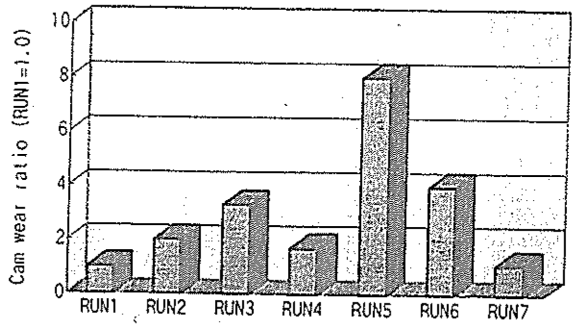

Fig.10 Valve train wear in 13-mode test

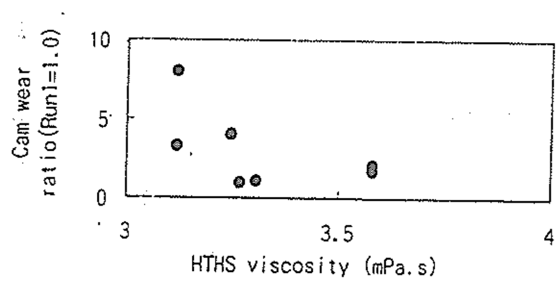

Fig.11 Relationship between cam wear and HTHS viscosity

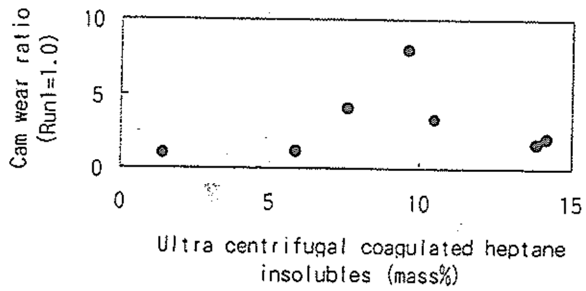

Fig.12 Relationship between cam wear and ultra centrifugal coagulated heptane insolubles

3.2 Effects of the sulfur content in the diesel fuel on the engine oil and the engine parts.

Using the diesel fuel containing 0.05 mass% sulfur, which will also be available in Japan in and after the Fall 1997, the authors performed testing to investigate the effects of EGR on the engine oil deterioration, the detergency of the oil, and the wear of engine parts. The test results showed that use of the diesel fuel containing 0.05 mass% sulfur tends to reduce the decrease of the

total base number (Fig. 5), reduce TGF (Fig. 6), and reduce the top ring wear (Fig. 9) and the bearing (Fig. 13).

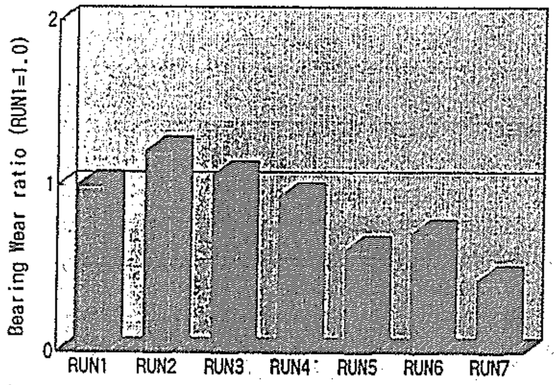

Fig.13 Bearing wear in 13-mode test

4. Summary

(1) Effects of EGR on the engine oil

- The application of EGR promotes the increase of the amount of insolubles and the increase of the viscosity. The decrease of the total base number is eased to a level which will not pose problems by reducing the sulfur content in the fuel.
- The detergency of the engine oil tends to decrease while the top ring wear and the valve train wear tends to increase.

(2) Countermeasures

- Improving the dispersancy of the oil prevents of the viscosity increase and improves the detergency of the oil.
- The valve train wear can be reduced by increasing HTHS viscosity and by decreasing the amount of viscosity index improver.
- For increasing the HTHS viscosity and decreasing the viscosity index improver amount, it is effect to use a very high viscosity index base oil or a synthetic oil as the base oil.
- The ring wear and TGF tend to be reduced by reducing the sulfur content in the diesel fuel.

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