

Extended Oil Drain Performance Capabilities of Diesel Engine Oils

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ABSTRACT

This paper describes the results of a comprehensive field-testing program conducted in modern low-emission heavy-duty diesel engines to evaluate the extended oil drain capabilities of several diesel engine oils of varying performance levels. The data generated in the 59-truck trial, which was conducted over a two to three year period, provide support for extension of engine oil drain intervals when a premium mineral diesel oil is used rather than a fighting-grade mineral diesel product. The field trial results also document the performance of a premium fully synthetic engine oil at four times conventional oil drain intervals. Engine inspections conducted after 500,000 test miles confirm that the extension of oil drain intervals with premium diesel engine oils has no negative impact on engine durability. In addition to the extended oil drain interval performance, the fully-synthetic SAE 5W-40 oils evaluated were found to provide approximately a 3% reduction in fuel consumption relative to conventional SAE 15W-40 mineral oil based products in the applications tested.

INTRODUCTION

In recent years, it has become increasingly important to operators of large fleets operating heavy-duty diesel engines to reduce their operating expenses. One of their objectives is to cut costs from their businesses by extending the mileage or time between scheduled servicing of the vehicles. By extending the service intervals, particularly of engine oil and oil filters, they can not only save costs on the purchase and disposal of oil and filters, they can also reduce the downtime of the vehicle. The potential problem with extending oil drain intervals is that all oils may not be capable of protecting vital engine components when oil drains are extended. This is especially true with today's

emission controlled engine designs, which lead to more severe operating environments for the engine oil. This could lead to greatly increased repair expenses if engine durability and/or reliability were adversely affected. Another area of concern for fleet operators is fuel consumption, as fuel costs are one of the highest operating expenses incurred by fleets. Small improvements in fuel consumption can bring significant savings to a fleet's overall operating budget.

The objective of the work described in this paper was to evaluate the extended oil drain capabilities of several diesel engine oils of varying performance levels in actual field operation in modern low-emission heavy-duty diesel engines. Extended service oil filters were also evaluated during the trial.

TEST OILS

Four test oils were used in the evaluations. The oils were selected to represent a wide range of performance levels within the requirements of the latest API heavy-duty diesel engine oil category, CG-4. While the oils chosen all meet API CG-4 requirements, they ranged from a standard oil just meeting the requirements to a premium, fully synthetic oil that far exceeds the requirements. Details of the four test oils are as follows (the oils were color coded for the test program):

Blue Oil is the standard reference oil for the testing. It is a fighting grade mineral diesel engine oil that does not provide alkalinity reserve beyond the requirements for standard recommended drains and service as defined by API CG-4.

Red Oil is a premium mineral diesel oil which is designed to exceed the requirements of API CG-4. This is accomplished with a balanced additive system to provide reserve alkalinity and exceptional piston deposit

severe service, typical of extended drains.

Silver Oil is a premium, fully synthetic diesel oil designed to far exceed the performance requirements of API CG-4. This oil is designed to take advantage of the beneficial properties of synthetic base fluids combined with a well balanced additive system to provide excellent reserve alkalinity and wear protection under the very severe operating conditions expected with greatly extended drain intervals. The beneficial properties of synthetic base fluids and advantages for oils formulated with such base fluids for heavy-duty diesel engines have been described previously [1-4].

White Oil is also a premium, fully synthetic diesel oil. White Oil is a modified version of Silver Oil designed not only to exceed API CG-4 but also the newly proposed API CH-4 category required for engines designed to meet 1998 U.S. emissions requirements.

Typical inspection properties of these oils are included in Table 1.

TEST ENGINES/FLEETS

In total, 59 heavy-duty diesel engines were tested during the trial at four locations in the U.S. and Canada. Two engine types were used in the trial, which represent a range of engine horsepower common for today's over-the-road trucking fleets. All the engines were calibrated to meet 1994 U.S. emissions regulations and had primary oil recommendations of API CG-4. The engines were installed in over-the-road trucks used in long haul, moderate to severe service. Under the operating conditions experienced during the trial, maximum engine builder oil drain interval recommendations would have been 15,000 miles. Two fleets using each type of engine were selected for the trial. The engines used were 14.6L, 435 hp and 10.3L,

The test fleets were selected based on number of factors, which included type of service, mileage accumulation rate, and appropriateness of maintenance program.

FIELD-TEST PROTOCOL

During the trial, oils were randomly assigned to test units in each fleet. Based on the number of trucks available at a fleet, anywhere from two to four of the test oils were assigned to the fleet (with a minimum of two units for each oil to allow for loss of units due to unforeseen circumstances – accidents, failure to keep records, sale of vehicle, etc). Within each fleet, the units were operated on each oil at specified oil drain intervals as indicated in Table 2. The trial duration was to be sufficient time for the test units to accumulate 500,000 miles of service. Oil filter condition was monitored via differential pressure monitors, and filter changes were made when needed based on pressure monitors or when the unit reached scheduled oil change mileage. Used oil samples were taken every 10,000 miles and oil changes which were analyzed to determine the condition of the oil. Used oil filters were also analyzed to determine the structural integrity of the filter housing and filter media.

Table 2: Tested Oil Drain Intervals by Fleet

Fleet	1	2	3	4
Engine	14.6L	14.6L	10.3L	10.3L
# Units	18	10	15	16
Oil Drain Targets, Milesx1,000				
Blue	25 & 40	25 & 40	25	25
Red	35 & 50	35 & 50	35 & 50	35 & 50
Silver	75 & 100	---	60	75
White	75 & 100	---	---	75

Table 1: Test Oil Typical Properties

	Blue	Red	Silver	White
SAE Viscosity Grade	15W-40	15W-40	5W-40	5W-40
Kinematic Viscosity @ 100°C (cSt)	15.0	15.7	15.0	15.2
Kinematic Viscosity @ 40°C (cSt)	115	117	85	91
Viscosity Index	135	142	186	177
HTHS Viscosity @ 150°C (cP)	4.0	4.3	3.9	3.9
CCS Viscosity @ -25°C (cP)	-	-	2400	2800
CCS Viscosity @ -15°C (cP)	3000	3100	-	-
MRV/Yield Stress @ -35°C (P/Pa)	-	-	180/<35	175/<35
MRV/Yield Stress @ -25°C (P/Pa)	200/<35	120/<35	-	-
TBN (D2896)	8	12	11	11
Sulfated Ash (%Mass)	0.83	1.41	1.2	1.2
Elementals (%Mass)				
Calcium	0.05	0.31	0.23	0.23
Magnesium	0.11	0.03	0.06	0.06
Zinc	0.12	0.12	0.13	0.13
Phosphorus	0.11	0.11	0.12	0.12

This data was analyzed to determine if any fuel consumption differences were present amongst the test oils.

To confirm overall acceptability of the extended drain intervals tested, several engines were inspected for cleanliness and wear after they had accumulated over 500,000 miles of service in the trial. This mileage is a representative point to look at the engines to determine if any excessive wear or deposit formation has occurred.

DISCUSSION OF RESULTS

USED OIL ANALYSIS – The primary mechanism used for ensuring that the test oils were performing satisfactorily at the drain intervals tested was analysis of used oil data. There are three primary areas of concern when looking at the used oil data from extended drain service. These are the overall condition of the oil, indicated by the bulk properties such as Total Base Number (TBN) and viscosity, wear protection as indicated by wear metals levels, and contamination as indicated by water, coolant, and soot levels. About 1,000 used oil samples were received from the test units and analyzed for the key parameters that indicate how the oil is performing. For each engine type, a summary of the average used oil data from each fleet and oil is included in Table 3. Details of several of the key used oil parameters are discussed in the following sections based on data from Fleet 4, which was the most severe test site. Results are plotted in Figures 1 through 4 employing a best-fit second order polynomial curve (linear fit if noted) through all of the used oil analysis data.

Overall Condition of Oil – The used oil samples taken throughout the drain intervals and at the oil changes indicated that all of the oils were in satisfactory condition after the tested service periods. As shown in Figure 1, the viscosity of all oils generally remained within the specification of the SAE 40 grade at their respective drain intervals. The Blue Oil was clearly beginning to

neering the end of its useful life. The Red Oil shows a linear trend, which approaches the upper limit of the viscosity grade at 50,000 miles; however, it never breaks as the Blue Oil does. The two synthetic oils, Silver and White, remain comfortably within the SAE 40 grade with no indication of an upturn in viscosity even after 75,000 miles in the engine. This shows the increased ability of these oils to maintain a satisfactory condition under greatly increased drain periods. This is likely due primarily to the better soot handling properties of the synthetic base oils as well as their increased oxidation stability.

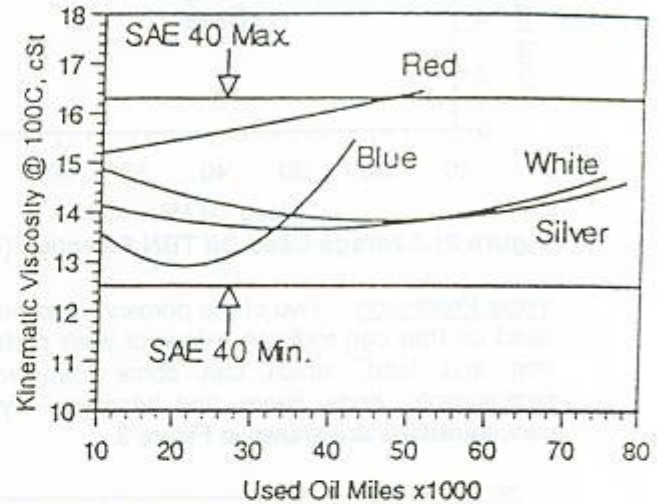


Figure 1: Average Used Oil Viscosity

The TBN, which gives an indication of the oil's alkalinity, is a function of the additive system utilized. Generally, as this decreases, the ability of the oil to continue to function properly with respect to neutralizing acidic contamination in the oil is reduced. Figure 2 shows the trends in TBN depletion for all oils in the trial. The Blue Oil has lower fresh oil TBN and depletes to a TBN of less than 5 at the end of a 40,000-mile drain interval. Red, Silver and White Oils all have higher starting TBN and all maintain a higher level of TBN at the end of their respective drain intervals. In many applications, as TBN falls below 4, as measured by

Table 3: Summary of Average Used Oil Data (at longest tested drain interval)

	14.6L Engines						10.3L Engines							
	Fleet 1				Fleet 2		Fleet 3			Fleet 4				
	Blue	Red	Silver	White	Blue	Red	Blue	Red	Silver	Blue	Red	Silver	White	
Actual ODI, miles	40K	50K	100K	100K	40K	50K	40K	50K	75K	40K	50K	75K	75K	
KV @ 100C, cSt	12.9	14.5	12.8	12.7	13.2	15.1	13.0	16.6	12.8	15.5	16.4	14.5	14.7	
TBN (D2896)	7.1	9.8	8.2	8.2	7.5	9.0	5.8	7.1	7.0	4.6	7.0	6.0	8.0	
Soot, % (FTIR)	0.4	0.4	0.4	0.5	0.6	0.6	1.3	1.1	1.8	2.6	2.5	1.9	2.5	
Wear Metals, ppm														
Aluminum	2	3	2	3	2	4	2	5	3	3	5	3	5	
Chromium	0.1	0.3	0.6	0.6	0.8	0.6	1	1	1	1	2	2	2	
Iron	17	19	60	37	40	42	65	61	127	104	102	177	187	
Lead	5	4	5	3	7	9	9	9	7	9	10	6	6	
Tin	2	1	2	2	4	2	4	2	2	4	3	3	2	

ASTM D2896, significant corrosive attack of bearings and other metallic surfaces in the engines can occur. This is evident in the trends observed in lead concentrations with these oils.

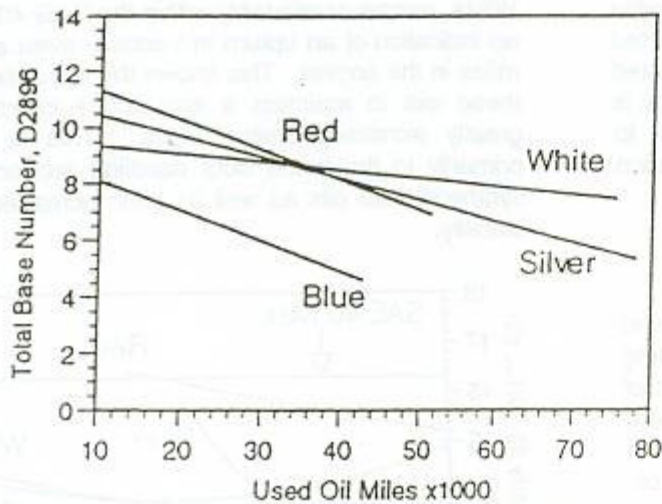


Figure 2: Average Used Oil TBN Retention (Linear)

Wear Protection – Two of the primary wear metals in the used oil that can indicate a lack of wear protection are iron and lead, which can come from valve train components, rings, liners, and bearings. Typical iron concentrations are shown in Figure 3.

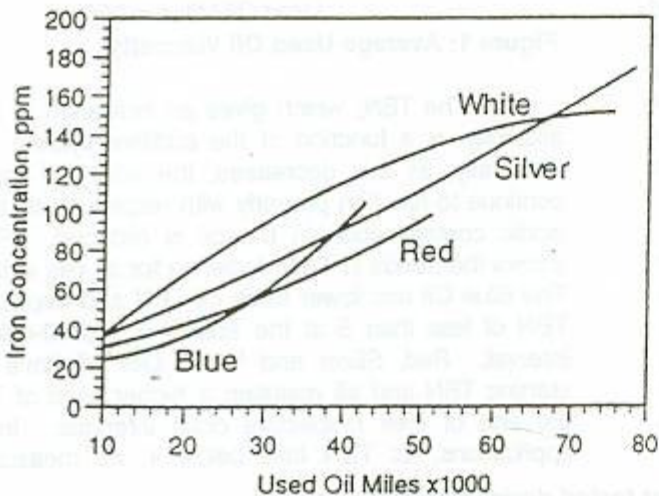


Figure 3: Average Used Oil Iron Concentration

The trends indicate that the Blue Oil begins to have an increased rate of iron wear after about 25,000 miles of service. The Red Oil also shows a directional increase in iron wear rate, which starts around 40,000 miles of service. The synthetic oils do not show any increase in the rate of iron wear throughout the entire drain interval, up to and including 75,000 miles of service. The lead wear rates, shown in Figure 4, show the same general trends as those seen for iron, although the increase in wear rate for the Blue and Red Oils are more dramatic. Both of these wear metals indicate that the various oils are capable of protecting the engine at different extended drain intervals. The increases seen in the Blue and Red Oil wear rates indicate that the limits of their

capabilities had been reached during the tested drain intervals, at about 25,000 and 40,000 miles respectively, when the rate of wear metals accumulation began to increase rapidly. The trends for the Silver and White Oils out to 75,000 miles indicate the strong performance of these oils at extended drains.

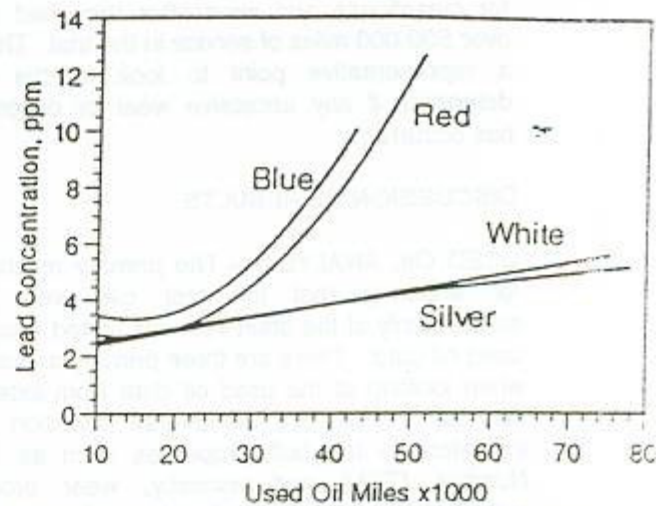


Figure 4: Average Used Oil Lead Concentration

Contamination – During the trial, the primary contaminant seen in the used oils was soot, which is a by-product of the diesel combustion process. Water, coolant, and silicon (dirt) contamination was minimal and was of no concern during the trial. Soot levels varied by fleet and engine type and were generally in the range of 0.5% to 2.5% at the end of the drain intervals. This amount of soot is not unexpected under the operating conditions experienced in the trial. As indicated by the viscosity data, the oils were generally capable of withstanding this level of soot without significant thickening.

ENGINE INSPECTION RESULTS – Although the used oil analysis is an important indicator of the ability of an oil to perform satisfactorily under extended drain conditions, for ultimate confirmation of acceptable engine durability, inspections are needed. As part of this field trial program, three engines were inspected after mileage accumulations of over 500,000 miles of extended drain service. The results of these inspections, conducted on Red and Silver Oil, confirm that there were no adverse effects on engine durability from the use of these oils at significantly extended drain intervals. The inspected engines were in excellent mechanical condition, similar to what would normally be seen after 500,000 miles with standard recommended oil and filter change intervals. We believe that these engines could have remained in extended drain service without needing a major overhaul until one million or more miles were accumulated. Summary piston deposit, engine cleanliness, and visual wear data from the engine inspections are shown in Table 4. Aspects of the inspected engines' conditions are discussed in more detail below by engine type.

operated on Red Oil at 50,000-mile drain intervals and Silver Oil at 75,000-mile drain intervals. Overall, both of these engines were in very good condition at the time of inspection. The unit that operated on Red Oil showed slightly higher levels of piston deposits than the one operated on Silver Oil (201 versus 170 unweighted demerits), although both are very good for the extended drain service at 500,000 miles of operation. Both engines had ~17% bore polish on average and no serious distress to the bearings inspected. The Red Oil unit, which was fully inspected in the field, had an average sludge rating of 9.5 (10.0 = clean), which is very clean. This unit had minimal visible wear in the valve train areas inspected. The unit operated on Silver Oil would be expected to have better overall engine cleanliness and lower amounts of wear, but these items were not assessed as only the power kits were made available for inspection.

Table 4: Summary of Engine Inspection Data

	14.6L Engines		10.3L Engine
	1	1	3
Fleet	Red	Silver	Red
Oil	Red	Silver	Red
Mileage	525,000	510,000	627,000
Target ODI, miles	50,000	75,000	50,000
<u>Average Piston Deposits*</u>			
TLHC, %	56.0	39.0	36.0
TGF, %	33.0	15.8	39.7
Int. GF, %	12.0	10.5	27.5
Demerits	201	170	196
<u>Sludge Merit (10.0 = Clean)</u>			
Oil Pan	9.5	Not Rated	9.2
Rocker Covers	9.4	Not Rated	8.8
Valve Deck	9.6	Not Rated	9.0
Pump Screen	9.8	Not Rated	9.8
<u>Average Visual Wear</u>			
Bore Polish, %	17.5	17.0	31.7
Cam Lobes	Minimal	Not Rated	Normal
Valve Bridges	Minimal	Not Rated	Normal
Rocker Arm Pads	---	---	Normal
Push Rods	---	---	Normal

- * TLHC = Top Land Heavy Carbon
- TGF = Top Groove Fill
- Int. GF = Intermediate (second) Groove Fill
- Demerits shown are the total unweighted demerits.

10.3L, 350 HP Engine Inspection – A 10.3L engine operated at Fleet 3 was inspected after more than 625,000 miles of operation on Red Oil at 50,000-mile drain intervals. Overall, this engine was in very good condition. Overall engine cleanliness was good with a sludge rating of 8.9. In comparison to the 14.6L engine Red Oil inspection, this poorer sludge rating is expected, as the 10.3L engine produced higher levels of soot in the oil and would therefore be expected to form directionally higher amounts of sludge in the engine. Overall unweighted piston deposits were 196, which is very

14.6L engine that ran on the same oil. There was a bit more bore polish in this engine as compared to the 14.6L engine, with an average polish of 32%, although the unit did not have any oil consumption problems related to this level of bore polish. There was no excessive wear or distress noted in the valve train areas of the engine.

OIL FILTER PERFORMANCE – Physical inspection of over 200 used filters showed that the filter media remained in excellent condition. These used filters showed a range in filter delta P from 10 to 20 kPa, relative to 3.7 kPa for typical new filters. Additionally, the recommended terminal delta P for such filters is 68.9 kPa. This clearly shows that the filters had residual life left, but since the particulate loading for filters is an exponential function, it is impossible to determine the precise amount of life remaining. Based upon these results, when the oil filters are changed at the same interval as the oil, the tested filter can be used for extended oil drain intervals up to 50,000 miles for on-highway use.

OIL CONSUMPTION – Oil consumption was also measured on all of the units on field test. The oil consumption in the test units was within the normal range for the engine types. The 10.3L engine does have lower average oil consumption than the 14.6L engines. The lower oil consumption of the 10.3L engines accounts for the additional wear metals and soot shown in the used oil analysis, as compared to the 14.6L engines.

FUEL CONSUMPTION – Fuel consumption data varies with each fleet, as expected, and shows a consistent advantage for the synthetics. Table 5 lists the average fuel consumption for mineral and synthetic oils in each fleet that had both types of oil on test.

Table 5: Average Fuel Consumption Data

Fleet	Mineral Oils miles/gallon	Synthetic Oils miles/gallon	% Improvement (for synthetics)
1	6.10	6.21	1.9
3	7.08	7.48	5.6
4	6.29	6.42	2.0

The data for the two mineral oils (Blue and Red) and the two synthetic oils (Silver and White) have been combined, as there would not be any expected differences in fuel economy between the two mineral oils or between the two synthetics. For each fleet, a single miles per gallon (mpg) number was calculated for each oil type for the one year period (only 9 months of data available on Fleet 4) that yielded the most data. This calculation was based on the total miles driven and fuel consumed from all trucks on each oil type that reported data in greater than 75% of the months evaluated.

These values were then used to calculate a percentage benefit for the synthetic oils as shown in Table 5. Overall, a statistically significant improvement in fuel consumption averaging 3.2% was provided by the synthetic oils in the test fleets.

CONCLUSIONS

It was documented that different levels of oil drain extension can be achieved when various performance level diesel engine oils are utilized. This variation is seen across the range of diesel engine oils tested, which all meet the minimum performance requirements of API CG-4. During the trial, all oils performed acceptably at the maximum oil drain intervals tested. However, based on detailed analysis of the trends in oil condition at the end of the drain intervals with some allowance for a safety margin, the following drain intervals are concluded to be acceptable under the test conditions:

- The fighting-grade mineral diesel oil was found to be acceptable for drain intervals of approximately 15,000 miles, which is consistent with the engine builder's recommendations for API CG-4 oils in these engines.
- The premium mineral diesel oil was found acceptable for use at drain intervals of approximately 25,000 to 30,000 miles depending on engine type, which is double the engine builder's standard recommendation.
- The premium, fully synthetic diesel oils were found to provide good engine protection with drain intervals as long as 45,000 to 60,000 miles depending on engine type, which is three to four times the engine builder's standard recommendation for this type of service.

In addition to the extended drain potential, the trial documented that on average a 3.2% reduction in fuel consumption was provided by the premium, fully synthetic diesel oils relative to the mineral oils tested.

The media of the oil filters which were tested during the trial remained in excellent condition at the oil changes and appear well suited for use at service intervals of up to 50,000 miles.

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