QUALITY MONITORING OF ENGINE OILS FOR EQUIPMENT ON EXTENDED DRAIN INTERVALS

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Word count: 3,514 words text + 9 tables/figures x 250 = 5,764 words

July 31, 2015
ABSTRACT
Preventive maintenance is a key component of effective equipment fleet management. Engine oil provides wear protection, thermal management, and corrosion inhibition functions that are critical to engine performance and longevity. Regardless of the oil type used, quality declines during use as a result of degradation and/or contamination. Oil must be changed regularly to counter degradation and contamination, and to maintain the quality necessary to protect the engine. The frequency at which oil should be changed depends on the rate at which it degrades and/or becomes contaminated. This paper presents preliminary results from an on-going research project to monitor oil quality for individual machines on an extended oil drain interval and to quantify the rates of oil degradation and/or contamination. Samples of fresh and used oil from two classes of on-road trucks were analyzed on-site to quantify physical and chemical properties. Conventional 15W-40 and synthetic 5W-40 oils were studied. The conventional oil was tested in 13 trucks with similar engines and no significant chemical or physical changes in the oil were found to an age of 6,500 miles. The synthetic oil was tested in 13 trucks with either a 6.4L or 6.7L engine, and the oil in each engine experienced different rates of chemical degradation marked by decreasing TBN. In the 6.4L engines, TBN decreased 50 percent faster than in the 6.7L engines. The preliminary results suggest that the existing drain interval of 5,000 miles can be extended for the class 0209 trucks and the 0210 trucks with 6.7L engines.

Keywords: Preventive maintenance, engine oil, drain interval, oil analysis
INTRODUCTION
Preventive maintenance (PM) is a key component of effectively managing an equipment fleet in a safe and functional manner. Regularly draining and replacing engine oil is a common PM action performed to prolong engine life. The North Carolina Department of Transportation (NCDOT) operates and maintains a fleet of on-road and off-road equipment that includes approximately 7,900 motor driven machines. Regular oil changes for these machines result in significant costs due to the required labor, replacement oil, and disposal of used oil, as well as downtime for the machine. These costs can be reduced if the oil drain interval can be extended while still providing oil quality sufficient to maintain adequate engine protection.

Oil drain intervals are usually scheduled based on machine use and/or calendar days. Under the current NCDOT PM program, oil changes are scheduled for every 5000 miles or 250 hours depending on the equipment type or annually, whichever comes first. The program does not include regular sampling and analysis, and oil quality is not explicitly considered when scheduling oil changes. This is largely due to the approximate two week time lag between oil sampling and receipt of the analysis results when analysis is performed by an independent laboratory.

OBJECTIVES
This paper describes and presents preliminary results from an on-going research project sponsored by NCDOT to evaluate the effects of extending oil drain intervals for machines. The objectives of the study are to:

1. Monitor oil quality for individual machines on an extended oil change schedule through on-site analysis
2. Quantify rates of oil degradation and/or contamination
3. Assess the adequacy of the existing PM schedule and provide recommendations regarding extension of the schedule

BACKGROUND
Engine oil serves many functions in an internal combustion engine, including lubrication (friction reduction), wear protection, thermal management, and corrosion inhibition (1). Additionally, oil aids in compression ring seal and helps keep engines clean by maintaining particulate matter in suspension (2). These functions are critical to the performance and longevity of the engine.

Oil is formulated blend of a base oil and additives designed to meet required performance criteria. Base oils are the primary component, comprising 75 to 99 percent by volume of the oil (1). Engine oil is termed either conventional or synthetic depending on the process by which the base oil is derived. Conventional oil is a petroleum based mineral oil derived from crude oil. Synthetic oil is from a polyalphaolefin (PAO) base oil, which is a synthesized hydrocarbon, and have higher viscosity indices, lower volatility, and premium cold flow characteristics (3). Additives are used to enhance oil performance and are commonly friction and wear modifiers, antioxidants or corrosion inhibitors, and detergents (4).

Regardless of whether conventional or synthetic oils are used, engine oil quality declines during use as a result of degradation and/or contamination. Degradation can be the result of changes in the oil chemistry or changes in viscosity. Chemical degradation is caused by chemical reaction of the base oil with oxygen, sulfur, and nitrogen to form compounds harmful to the engine and through depletion of additives through reactions with contaminants (5).
Viscosity degradation is a change in viscosity and can be either an increase or decrease in viscosity. An increase in viscosity is caused by intrusion of soot, or partially combusted fuel particles, into oil through blow-by (6). A decrease in viscosity can be the result of mechanical degradation (7) or caused by oil dilution resulting from leaking seals allowing fuel, water, and/or glycol to mix with the oil.

Contamination is the presence of impurities in the oil, which include wear metals, dirt, fuel, water, or glycol. Wear metals are shavings generated from friction between metal surfaces inside the engine. Common metals found in oil are aluminum, iron, copper, chromium, lead, and tin. Dirt, fuel, water, and glycol contamination result from defective gaskets/seals, blow-by, or condensation in the crankcase. Circulation of oil contaminated with wear metals or dirt can result in abrasive action as the oil is circulated throughout the engine. Contamination from water, fuel, and/or glycol reduces oil viscosity. Water in large quantities can cause the formation of acids leading to engine corrosion.

Oil must be changed regularly to counter degradation and contamination, and to maintain the quality necessary to provide engine protection. Oil drain intervals that are too short result in unnecessary PM costs, while intervals that are too long increase engine wear and the likelihood of engine damage. The frequency at which oil should be changed depends on the rate at which it degrades and/or becomes contaminated.

The ideal means of determining the optimum drain interval is through continuous monitoring of the physical and chemical conditions of the oil (8, 9). Continuous monitoring requires on-board sensors to indirectly infer oil quality, typically by direct measurement of oil conductivity (10). Outfitting a large fleet with on-board instrumentation and communication equipment can cost prohibitive. An alternative to continuous monitoring is a PM program that includes regular sampling and analysis based on direct measures of oil quality. Providing actionable information in a timely manner requires that analysis be performed on site, as opposed to being sent to an independent laboratory. On site sampling and analysis can be completed in 30 to 60 minutes per sample (11).

Measureable oil parameters that are representative of oil quality include viscosity, total acid number (TAN), total base number (TBN), soot contamination level, and wear metal contaminant levels (5, 12). Oil quality parameters are listed and described in Table 1. Viscosity is a measure of the resistance of the oil to flow, which affects to ability to lubricate contacting surfaces. It is dependent on temperature and is typically measured at 40°C and 100°C (13). TAN and TBN are both measures of the oil chemistry. TAN is an indicator of the amount of acidic components in the oil, typically resulting from combustion and oxidation (1). TBN is an indicator of the quantity of basic oil components, which enable the oil to neutralize acids formed.

### Table 1 Engine Oil Quality Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity (cSt)</td>
<td>A measure of the ability of the oil to flow at a given temperature</td>
</tr>
<tr>
<td>Soot (% wt)</td>
<td>Formed during combustion and enters the crankcase via blow-by; increases viscosity (6)</td>
</tr>
<tr>
<td>Water (% wt)</td>
<td>Typically the result of crankcase condensation; promotes the formulation of acids</td>
</tr>
<tr>
<td>Fuel (% wt)</td>
<td>Typically the result of leaking injectors or blow-by; lowers viscosity and promotes engine wear (14)</td>
</tr>
<tr>
<td>Glycol (% wt)</td>
<td>Antifreeze contamination through coolant leak; promotes engine wear</td>
</tr>
<tr>
<td>TBN (mg KOH/g)</td>
<td>A measure of the ability to neutralize acids</td>
</tr>
<tr>
<td>Oxidation (abs)</td>
<td>Promotes acidic reactions in the oil</td>
</tr>
</tbody>
</table>
Nitrination (abs) | Promotes acidic reactions in the oil
Wear metals (ppm) | The result of engine wear; can cause abrasive action in the engine

**SAMPLING AND ANALYSIS METHODS**

Two classes of on-road trucks and two classes of off-road tractors are included in the research project. Presented in this paper are the preliminary results for the on-road trucks, which are:

1. Class 0209 crew cab trucks with gross vehicle weight (GVW) between 20,000 and 35,000 lbs used for various operations
2. Class 0210 4X4 extended cab trucks with 9,900 GVW used for Incident Management Assistance Patrol (IMAP)

In each class, 13 trucks were selected for the study based on the proximity of their assigned location to the on-site oil analyzer. Attributes of the individual trucks are presented in Table 2.

Three samples of oil, each approximately 150 ml, is drawn from the trucks via the engine oil dipstick using a hand operated vacuum pump at 1000 to 1500 mile intervals.

Oil samples are transported via NCDOT courier to a central location for analysis using an OSA4 TruckCheck® benchtop analyzer. The OSA4 uses a dual atomic emission spectrometer, infrared spectrometer, and viscometer to measure contaminant levels and viscosity at 100°C. Analysis is performed accordance with ASTM D7417 and requires approximately 15 minutes per sample.

**TABLE 2 Attributes of Studied NCDOT Trucks**

<table>
<thead>
<tr>
<th>Truck</th>
<th>Year</th>
<th>Make</th>
<th>Model</th>
<th>Engine</th>
<th>Oil Sump Capacity (qt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0209-1</td>
<td>2000</td>
<td>International</td>
<td>4700</td>
<td>Navistar DT466 7.6L I6</td>
<td>30</td>
</tr>
<tr>
<td>0209-2</td>
<td>2000</td>
<td>International</td>
<td>4700</td>
<td>Navistar DT466 7.6L I6</td>
<td>30</td>
</tr>
<tr>
<td>0209-3</td>
<td>2003</td>
<td>International</td>
<td>7300</td>
<td>Navistar DT466 7.6L I6</td>
<td>30</td>
</tr>
<tr>
<td>0209-4</td>
<td>2003</td>
<td>International</td>
<td>7300</td>
<td>Navistar DT466 7.6L I6</td>
<td>30</td>
</tr>
<tr>
<td>0209-5</td>
<td>2004</td>
<td>International</td>
<td>7300</td>
<td>Navistar DT466 7.6L I6</td>
<td>30</td>
</tr>
<tr>
<td>0209-6</td>
<td>2004</td>
<td>International</td>
<td>7300</td>
<td>Navistar DT466 7.6L I6</td>
<td>30</td>
</tr>
<tr>
<td>0209-7</td>
<td>2005</td>
<td>International</td>
<td>7300SFA</td>
<td>Navistar DT466 7.6L I6</td>
<td>30</td>
</tr>
<tr>
<td>0209-8</td>
<td>2007</td>
<td>International</td>
<td>7300SFA</td>
<td>Navistar DT466 7.6L I6</td>
<td>30</td>
</tr>
<tr>
<td>0209-9</td>
<td>2013</td>
<td>International</td>
<td>7300SFA</td>
<td>Navistar MAXXFORCE 7.6L I6</td>
<td>32</td>
</tr>
<tr>
<td>0209-10</td>
<td>2004</td>
<td>International</td>
<td>7300</td>
<td>Navistar DT466 7.6L I6</td>
<td>30</td>
</tr>
<tr>
<td>0209-11</td>
<td>2004</td>
<td>International</td>
<td>7300</td>
<td>Navistar DT466 7.6L I6</td>
<td>30</td>
</tr>
<tr>
<td>0209-12</td>
<td>2005</td>
<td>International</td>
<td>7300SFA</td>
<td>Navistar DT466 7.6L I6</td>
<td>30</td>
</tr>
<tr>
<td>0209-13</td>
<td>2005</td>
<td>International</td>
<td>7300SFA</td>
<td>Navistar DT466 7.6L I6</td>
<td>30</td>
</tr>
<tr>
<td>0210-1</td>
<td>2008</td>
<td>Ford</td>
<td>F350</td>
<td>International (Powerstroke) 6.4L V8</td>
<td>15</td>
</tr>
<tr>
<td>0210-2</td>
<td>2008</td>
<td>Ford</td>
<td>F350</td>
<td>International (Powerstroke) 6.4L V8</td>
<td>15</td>
</tr>
<tr>
<td>0210-3</td>
<td>2008</td>
<td>Ford</td>
<td>F350</td>
<td>International (Powerstroke) 6.4L V8</td>
<td>15</td>
</tr>
<tr>
<td>0210-4</td>
<td>2008</td>
<td>Ford</td>
<td>F350</td>
<td>International (Powerstroke) 6.4L V8</td>
<td>15</td>
</tr>
<tr>
<td>0210-5</td>
<td>2008</td>
<td>Ford</td>
<td>F350</td>
<td>International (Powerstroke) 6.4L V8</td>
<td>15</td>
</tr>
<tr>
<td>0210-6</td>
<td>2008</td>
<td>Ford</td>
<td>F350</td>
<td>International (Powerstroke) 6.4L V8</td>
<td>15</td>
</tr>
<tr>
<td>0210-7</td>
<td>2010</td>
<td>Ford</td>
<td>F350</td>
<td>International (Powerstroke) 6.4L V8</td>
<td>15</td>
</tr>
</tbody>
</table>
RESULTS

Analysis results include measurements of physical and chemical properties of the oil. In addition to samples drawn from the trucks, samples of fresh oil were drawn from bulk containers and analyzed to provide baseline values.

Fresh Oil

The conventional mineral based Conoco HD Fleet Supreme® 15W-40 oil is used in the class 0209 trucks, while Shell Rotella® T6 synthetic 5W-40 oil is used in the class 0210 trucks. Typical properties published by the oil producers are presented in Table 3. It should be noted that these values are published as typical values and subject to variation.

<table>
<thead>
<tr>
<th>TABLE 3 Fresh Oil Properties (15, 16)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oil Type</strong></td>
</tr>
<tr>
<td>Brand</td>
</tr>
<tr>
<td>SAE Viscosity</td>
</tr>
<tr>
<td>Kinematic Viscosity @ 100ºC (cSt)</td>
</tr>
<tr>
<td>Total Base Number (mg KOH/g)</td>
</tr>
<tr>
<td>Sulfated Ash (% wt)</td>
</tr>
<tr>
<td>Density (kg/l)</td>
</tr>
</tbody>
</table>

TBN and viscosity results from analysis of 18 samples of fresh mineral oil were similar to the published values. Viscosity ranged from 13.95 to 15.92 cSt with an average value of 14.98 cSt, while TBN ranged from 9.1 to 10.2 with an average of 9.3 mg KOH/g.

A total of 30 samples of synthetic oil were analyzed due to a greater observed variability in viscosity measurements. Results indicate that the tested fresh oil had values for both viscosity and TBN lower than the published values. Viscosity ranged from 12.07 to 14.35 cSt with an average value of 12.84 cSt. This average viscosity complies with the SAE J300 minimum 12.5 cSt value for 40 weight oil, but 6 of the 30 analyses resulted in viscosity measurements less than the required minimum. TBN for the synthetic oil ranged from 9.4 to 10.6 with an average value of 9.7 mg KOH/g, which is 0.9 mg KOH/g lower than the published typical value.

Used Oil

Analyses of used engine oil revealed the conventional oil in class 0209 trucks performed better than the synthetic oil in the class 0210 trucks. Also, the synthetic oil performed better in trucks
with newer 6.7L engines than in trucks with the 6.4L engine. Better oil performance was defined as less or slower degradation, as very little contamination was found in either oil.

As noted previously, three samples were drawn at predetermined sampling intervals. The results presented are the average of the three samples.

Viscosity

Viscosity measurements of conventional oil in the class 0209 trucks show an initial decrease and then consistent values to approximately 6,500 miles. As shown in Figure 1, viscosity decreased by approximately 15 percent (from about 15 cSt to about 13 cSt) after approximately 1,000 miles. Nearly all measurements to an oil age of approximately 6,500 miles remained between 12 and 14 cSt. This initial decrease in viscosity appears to be the result of fuel dilution. Neither water nor glycol was detected in the oil, and the OSA4 cannot detect diesel fuel due to the molecular similarity between fuel and oil.

As shown in Figure 2, synthetic oil viscosity remained effectively unchanged in the class 0210 trucks with 6.7L engines to approximately 14,000 miles. However, trucks with the 6.4L engine showed a significant decrease in viscosity at early oil ages. Viscosity decreased approximately 30 percent (from 13 cSt to 9 cSt) in about the first 4,000 miles, then remained at about 9 cSt to approximately 8,000 miles. Like the conventional oil, this decrease in synthetic oil viscosity appears to be the result of fuel dilution. At 9 cSt, oil viscosity is significantly below the SAE specified minimum of 12.5 cSt for 40 weight oils tested at 100°C. However, elevated levels of wear metal concentrations were not found in the oil. This indicates that the oil continues to provide adequate lubrication.

FIGURE 1  Viscosity of conventional oil in class 0209 trucks.
Minimum acceptable TBN values reported in the literature vary from 1 to 4 mg KOH/g \((1, 3, 9, 17, 18)\), and a minimum of 4 mg KOH/g was applied in this research to ensure that the oil retained sufficient capacity to continue to neutralize acids. TBN measurements for class 0209 trucks showed very little decrease as the oil aged. There was a clear linear relationship between TBN and oil age for the class 0210 trucks. Linear regression was applied to quantify and assess the relationships for both classes of trucks.

TBN remained virtually unchanged at approximately 9 mg KOH/g to an oil age of approximately 6,500 miles for the class 0209 trucks, as shown in Figure 3. The rate of TBN decrease determined through regression analysis was 0.06 mg KOH/g per 1,000 miles. The p-value for the age coefficient was 0.082, indicating that it is not significant at the 95 percent confidence level \((\alpha = 0.05)\). From a practical perspective, the observed rate of TBN decrease in the class 0209 trucks is insignificant.

The TBN of the synthetic oil decreased linearly as the oil aged, and oils in the 6.4L engines had a faster rate of TBN decrease than those in the 6.7L engines. The measured TBN values for class 0210 trucks are shown in Figure 4. From regression analyses, the rate of decrease for the 6.4L engines was 0.59 mg KOH/g per 1,000 miles and the p-value was 2.7E-17. The rate of TBN decrease was 0.38 mg KOH/g per 1,000 miles and the p-value was 8.4E-15 for the 6.7L engines. Both p-values indicate that oil age is significant to TBN well beyond the 95 percent confidence level. From a practical perspective, the results indicate that oil in the 6.4L engines reach the minimum TBN threshold in approximately 8,000 miles and the in the 6.7L engines in approximately 12,000 miles.

FIGURE 2 Viscosity of synthetic oil in class 0210 trucks.
FIGURE 3  TBN of conventional oil in class 0209 trucks.

FIGURE 4  TBN of synthetic oil in class 0210 trucks.
Oxidation and Nitration

Oxidation and nitration reactions alter the chemical composition of the oil by depleting additives. These reactions promote the formation of acidic components and can result in a corresponding decrease in TBN. Minimal levels of oxidation and nitration were found in oils from the class 0209 trucks, which agrees with the near constant measured values of TBN. However, both oxidation and nitration were observed to linearly increase with oil age in the class 0210 trucks. These results are shown in Figures 5 and 6.

Regression analyses showed that the rate of oxidation of oils in the 6.4L engines was 3.5 times greater and the rate of nitration was approximately twice that of oils in the 6.7L engines. These differences agree with the observed difference in rate of TBN decrease.

FIGURE 5 Oxidation level of synthetic oil in class 0210 trucks.
CONCLUSIONS

The regular oil sampling and on site analysis performed as part of an on-going research project has provided important insight into the quality of both fresh and used engine oils. The program provides an effective means of monitoring the physical and chemical properties of oil, with results provided in a timely manner allowing for oil changes to be performed when dictated by the analysis results.

Based on the preliminary results presented for two equipment classes, it appears that the existing drain interval of 5,000 miles can be extended. The comprehensive oil analysis results should be considered in revising the drain intervals, rather than relying solely on a single measurement such as TBN.

The Conoco HD Fleet Supreme® 15W-40 conventional oil widely used across the fleet and in the studied class 0209 trucks has performed well to a tested age of 6,500 miles. The data suggests that engines in 0209 trucks may be capable of a 10,000 mile drain interval provided that fuel dilution of the oil remains at an acceptable level.

Measurements of the Rotella® T6 5W-40 synthetic oil used in the class 0210 trucks do cause some concern. The measured viscosity of the fresh oil was only slightly greater than the minimum required for 40 weight oil, and 20 percent of the measured values were less than the minimum. Additionally, a significant decrease in viscosity due to fuel dilution was measured in class 0210 trucks with a 6.4L engine.

A single drain interval should not be applied to the 6.4L and 6.7L engines in the class 0210 trucks. The interval for 6.4L engines could likely be extended to 6,000 miles. However, it is conservatively recommended that the existing 5,000 mile drain interval be retained for these trucks in light of the fuel dilution observed.

FIGURE 6 Nitration level of synthetic oil in class 0210 trucks.
The same Rotella® T6 oil performed differently in the 6.7L engines and the drain interval for these trucks can be extended. The oil performed very well to an age of approximately 14,000 miles and showed practically no change in viscosity and only minimal levels oxidation and nitrination. The data suggests that oil in these class 0210 trucks with 6.7L engines can be operated on 10,000 to 12,000 mile drain intervals.

The cause of the observed differences between oil in the 6.4L and 6.7L engines has not been fully determined. It is hypothesized that the differences may be related to the exhaust gas recirculation (EGR) processes in the engines, but this cannot be confirmed at this time.

ACKNOWLEDGEMENT

This research is sponsored by the North Carolina Department of Transportation (NCDOT) and the Federal Highway Administration (FHWA). The authors express gratitude to the NCDOT Fleet and Material Management Unit, NCDOT Research and Development Unit, project steering committee, and the NCDOT Division 10 equipment management personnel for their support in this work.

DISCLAIMER

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