RESEARCH & DEVELOPMENT

Preventive Maintenance Criteria Validation

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Preventive Maintenance Criteria Validation

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by

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16. Abstract

Preventive maintenance (PM) is a strategic component an effective fleet management program designed to ensure vehicles and equipment are fully functional and safe to operate. Regularly draining and replacing engine oil is a common PM action performed to maintain engine health and prolong engine life. The interval at which oil should be drained and changed depends on the rate at which it degrades and/or becomes contaminated. Intervals that are too short result in unnecessary PM costs and downtime, while intervals that are too long increase engine wear and the likelihood of engine damage. The purpose of this project was to further the previous NCDOT research regarding the rate at which engine oil degrades by expanding the equipment classes and geographic region studied. The Spectro Scientific MicroLab 30 on-site oil analyzer was used to analyze the physical and chemical properties of fresh and used oil samples of Xtreme synthetic blend 15W-40 oil and Rotella T6 5W-40 synthetic oil. Samples of used oil were collected and analyzed from 15 machines that consisted of trucks in classes 0205, 0210, and 0212; backhoe loaders in class 0314; and excavators in class 1854. Oil drain intervals for these machines were extended beyond the typical schedule and changed based on a comparison of analysis results with the established threshold values. Oil samples were collected at 3000, 6000, and then every 1000 miles for the trucks. The backhoe loaders and excavators were sampled every 100 hours. Analyses of the used oil sampled from the NCDOT equipment showed that the oils degraded chemically as the oil aged, and viscosity degradation and/or contamination was not observed. The results indicate that the oil drain intervals for the studied equipment can be conservatively extended. It was conservatively estimated that over $530,000, over 11,800 gallons of oil, and over 4,400 hours of downtime can be saved annually.

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EXECUTIVE SUMMARY

Preventive maintenance (PM) is a strategic component an effective fleet management program designed to ensure vehicles and equipment are fully functional and safe to operate. Regularly draining and replacing engine oil is a common PM action performed to maintain engine health and prolong engine life. The interval at which oil should be drained and changed depends on the rate at which it degrades and/or becomes contaminated. Intervals that are too short result in unnecessary PM costs and downtime, while intervals that are too long increase engine wear and the likelihood of engine damage.

The purpose of this project was to further the previous NCDOT research regarding the rate at which engine oil degrades by Hildreth and Tymvios (2016) by expanding the equipment classes and geographic region studied. The goals were to:

1. Evaluate engine oil quality throughout its service life to identify controlling factors and quantify degradation rates.
2. Compare the results to those from similar equipment classes to evaluate operational environment factors.
3. Compare existing results to those from additional equipment classes to recommend oil drain intervals.

The Spectro Scientific MicroLab 30 on-site oil analyzer was used to analyze the physical and chemical properties of fresh and used oil samples of Xtreme synthetic blend 15W-40 oil and Rotella T6 5W-40 synthetic oil. The MicroLab 30 system optical emission spectroscopy to measure metal levels, infrared spectroscopy to measure physical properties of the lubricant, and a dual temperature viscometer to measure viscosity at both 40ºC and 100ºC. Samples of fresh oil were collected from bulk tanks at the NCDOT equipment shop and analyzed to establish baseline properties.

A total of 281 samples of used oil were collected and analyzed from 15 machines that consisted of trucks in classes 0205, 0210, and 0212; backhoe loaders in class 0314; and excavators in class 1854. Oil drain intervals for these machines were extended beyond the typical schedule and changed based on a comparison of analysis results with the established threshold values. Oil samples were collected at 3000, 6000, and then every 1000 miles for the trucks. The backhoe loaders and excavators were sampled every 100 hours.

Analyses of the used oil sampled from the NCDOT equipment showed that the oils degraded chemically as the oil aged, and viscosity degradation and/or contamination was not observed. The results indicate that the oil drain intervals for the studied equipment can be conservatively extended.

The conclusions drawn from the results of this research are briefly summarized as:

1. The Microlab 30 on-site oil analyzer performed well and no significant issues were experienced. The repeatability of the results obtained was very good, with, substantial variability noted in additive level measurements.

2. The Xtreme synthetic blend 15W-40 oil and Rotella T6 5W-40 synthetic oil are both good quality oils and performed well in the tested machines. Analyses of samples of fresh oils showed adequate levels of chemical base reserve to neutralize acidic compounds and viscosity within the SAE standards for 40 weight oil.

3. The measured viscosity of the oils was consistent throughout its use and did not degrade.
4. TBN values were observed to decrease linearly as oil age increased, and the rate of decrease varied by equipment class. The predictive ability of models varied with the metric used to quantify oil age. Engine run time hours was the metric most predictive of TBN for the trucks, while gallons of fuel was most predictive for equipment. Miles driven was the metric least predictive of TBN for the trucks.
5. The tested machines were not subject to significant contamination of the oil by water, glycol, soot, dirt, or wear metals.
6. There is opportunity to extend oil drain intervals without significant danger of unacceptable oil quality.
7. The potential benefits to be realized from extending oil drain intervals for machines in the NCDOT fleet that are similar to those tested are substantial. It was conservatively estimated that over $530,000, over 11,800 gallons of oil, and over 4,400 hours of downtime can be saved annually.

Recommended drain intervals are predicated on use of the synthetic blend oil tested and are briefly summarized as:

1. Trucks with the Navistar DT466 engine in various classes – Consider extending the drain interval for these engines to 10,000 miles or 1,200 hours.
2. Trucks with the Ford 6.7L engine – Consider extending the oil drain interval to 15,000 miles or 600 hours.
3. Model GU713 Mack trucks – Consider defining the oil drain interval in terms of hours operated and extending interval to 750 hours. If the PM schedule is maintained in terms of miles drive, consider extending it to 10,000 miles.
4. Class 0314 JCB backhoe loaders with the JCB 444 engine – Consider extending the drain interval to 600 hours of operation or 24 months.
5. Class 1854 excavators with the Hyundai 4.2L engine – Consider extending the drain interval to 1,000 hours of operation or 24 months.

Machines on extended oil drain intervals should be operated at least once per month under load such that they come to normal operating temperature. Extending oil drain intervals may impact equipment warranties. It is recommended that any and all PM actions be performed to maintain a valid warranty.

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1 INTRODUCTION

Preventive maintenance (PM) is a strategic component an effective fleet management program designed to ensure vehicles and equipment are fully functional and safe to operate. PM plans include a variety of actions are typically scheduled at fixed and predetermined intervals set by equipment manufacturer's specifications or other external sources (Bernspang and Kali 2011). Regularly draining and replacing engine oil is a common PM action performed to maintain engine health and prolong engine life. Oil drains for machines in the North Carolina Department of Transportation (NCDOT) maintenance fleet are scheduled to be performed at intervals of 5,000 miles for vehicles, 200 hours for equipment, or annually if the miles/hours threshold is not met.

Engine oils are complex mixtures of base oils and additives designed reduce engine wear, help prevent harmful deposits, and lubricate moving parts (PennzOil 2014). Regardless of the oil formulation, oil quality degrades throughout it useful life as a result of degradation and/or contamination. Oil is drained and changed regularly to maintain quality and counter the effects of degradation and contamination.

The interval at which oil should be drained and changed depends on the rate at which it degrades and/or becomes contaminated. Intervals that are too short result in unnecessary PM costs and downtime, while intervals that are too long increase engine wear and the likelihood of engine damage.

Previous NCDOT research studied the rate at which engine oil degrades to an unacceptable quality (Hildreth and Tymvios 2016). The work focused on equipment in a limited number of classes and operated in the greater Charlotte region. The purpose of this project was to further the research by expanding the equipment classes and geographic region studied. The goals were to:

1. Evaluate engine oil quality throughout its service life to identify controlling factors and quantify degradation rates.
2. Compare the results to those from similar equipment classes to evaluate operational environment factors.
3. Compare existing results to those from additional equipment classes to recommend oil drain intervals.

2 BACKGROUND

The purpose of this section is to provide a foundational base of knowledge related to engine oils and the changes undergone as a result of engine operation. A comprehensive review is provided by Hildreth and Tymvios (2016).

Engine oil serves many functions within an internal combustion engine, including lubrication (friction reduction), wear protection, thermal management, and corrosion inhibition (Basu et al. 2000). Additionally, oil aids in compression ring seal and helps keep engines clean by maintaining particulate matter in suspension (Barnes et al. 2001). 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 (Basu et al. 2000). 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, a synthesized hydrocarbon, and have higher viscosity indices, lower volatility, and premium cold flow characteristics (Bergstra et al. 1998). Additives are used to enhance oil performance and are commonly friction and wear modifiers, antioxidants or corrosion inhibitors, and detergents (Caines and Haycock 1996).

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 (Jun et al. 2006). 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 (Troyer 1999). A decrease in viscosity can be the result of mechanical degradation (Herbeaux and VanArsdale 1993) 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 tool 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 (Agoston et al. 2005, Kollman et al. 1998). Continuous monitoring requires on-board sensors to indirectly infer oil quality, typically by direct measurement of oil conductivity (Wang 2001). 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 (EPA 1999).

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 (Jun et al. 2006, Jagannathan and Raju 2000). Oil quality parameters are listed and described in Table 2.1. 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 40ºC and 100ºC (Lynch 2007). 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 (Basu et al. 2000). TBN is an indicator of the quantity of basic oil components, which enable the oil to neutralize acids formed.

Table 2.1: Engine Oil Quality Parameters

Parameter	Description
Viscosity (cSt)	A measure of the ability of the oil to flow at a given temperature
Soot (% wt)	Formed during combustion and enters the crankcase via blow-by; increases viscosity (Troyer 1999)
Water (% wt)	Typically the result of crankcase condensation; promotes the formulation of acids
Fuel (% wt)	Typically the result of leaking injectors or blow-by; lowers viscosity and promotes engine wear (AMSOIL 2004)
Glycol (% wt)	Antifreeze contamination through coolant leak; promotes engine wear
TBN (mg KOH/g)	A measure of the ability to neutralize acids
Oxidation (abs)	Promotes acidic reactions in the oil
Nitration (abs)	Promotes acidic reactions in the oil
Wear metals (ppm)	The result of engine wear; can cause abrasive action in the engine

3 OIL ANALYSIS PROGRAM

The program established to analyze and monitor oil quality included selection of the oil analysis equipment and selection of NCDOT equipment for the study. The threshold values for oil quality parameters and oil sampling protocols established in the previous study were incorporated into the program.

3.1 Oil Analysis Equipment

The Spectro Scientific MicroLab 30 on-site oil analyzer, shown in Figure 3.1, was used to analyze physical and chemical oil parameters. The MicroLab 30 is a fully automated, bench-top analyzer designed for analysis of engine, transmission, gearbox, hydraulic, power steering, and transmission fluids in accordance with ASTM D7417. It uses optical emission spectroscopy to measure metal levels, infrared spectroscopy to measure physical properties of the lubricant, and a dual temperature viscometer to measure viscosity at both 40ºC and 100ºC.

Figure 3.1: Spectro Scientific MicroLab 30 On-Site Oil Analyzer

The time required for sample analysis varies based on the quality of the oil sampled, but was typically in the range of 10 to 15 minutes per sample. The system employs an automated self-cleaning process and requires periodic standardization. Considering these processes, approximately 3 samples can be analyzed in the period of an hour. Analysis results are compiled into a formatted report that can be printed for archiving and are also stored electronically on the internal computer hard drive.

3.2 Threshold Values

Threshold values for measured oil quality parameters, both physical properties and contamination levels, established as part of the previous research were used in this study to protect the engine and components of the tested NCDOT equipment. The threshold values shown in Table 3.1 were conservatively set and broadly applied to all tested vehicles and equipment.

Table 3.1: Threshold Values for Measured Oil Quality Parameters

Parameter	Description	Threshold
TBN (mg KOH/g)	A measure of the ability of the oil to neutralize acids. With ultralow sulphur diesel fuel, levels as low as 3 are acceptable. A threshold of 4 is better when biodiesel is used.	<4 mg KOH/g severe <3 mg KOH/g critical
Viscosity (cSt)	A measure of the ability of the oil to flow. Industry standards for viscosity are set by SAE J300.	12.5 to 16.3 cSt for 40 weight oil
Fuel (% by wt)	Fuel typically results from blow-by of incompletely combusted fuel or leading seals and/or injectors. Decreases viscosity and oil additives (Fitch and Troyer 2010).	>4%
Soot (% by wt)	An accumulation of combustion by-product. Promoted by light loads, low RPM, irregular timing, and long idling. Increases viscosity (Cummins 2007)	>3%
Water (% by wt)	Water typically results from crankcase condensation and is a by-product of combustion. Water typically evaporates during operation, but can promote oxidation and the formation of acids (Fitch and Troyer 2010).	>0.5%
Glycol (% by wt)	Coolant resulting from leaks. Promotes formation of acids and decreases viscosity (Cummins 2007, Fitch and Troyer 2010). Evidenced by sodium, potassium, and silicon in combination.	>0%
Silicon (ppm)	Typical sources are dirt, coolant (silicates), and sealant materials (silicone). Likely dirt if in combination with high aluminum levels. May promote abrasion and engine wear (Evans 2012).	>40 ppm >10 ppm if dirt
Iron (ppm)	A time dependent element from wear of shafts, piston rings, and gears. A good indicator of oil extended use and/or engine health.	>100 ppm severe >130 ppm critical
Copper (ppm)	Main source is oil passivation, may also result from wear of bearings, connecting rods, piston pins, or camshaft. With use of same type/brand of oil, copper levels should decrease over time.	>15 ppm
Aluminum (ppm)	Typical sources are dirt (4/1 silicon to aluminum ratio), pistons, and air-charge coolers. (Schumacher et al. 1991).	>15 ppm
Chromium (ppm)	Typical sources include chrome plated piston rings and valves. Can be triggered by dirt, coolant, water, and extreme fuel dilution. (Schumacher et al. 1991).	>10 ppm
Sodium (ppm)	Most common source is dirt, but also from coolant. Not an issue by itself, but is in combination with potassium.	>50 ppm with equal potassium
Potassium (ppm)	Most common source is coolant, also from fertilizer or soap. Not an issue by itself, but is in combination with sodium.	>50 ppm with equal sodium
Oxidation	Occurs as additives and the base oil degrade, accelerated by contamination or heat. Increases viscosity and decreases ability to protect against wear and corrosion	>20
Nitration	A by-product of combustion, consumes TBN and increases viscosity. Use of biodiesel may increase nitration.	>15

3.3 Baseline Analysis of Fresh Oil

Baseline values of TBN and viscosity were established by collecting and analyzing samples of fresh, or unused, oil. Samples of Rotella T6 synthetic 5W-40 and Xtreme synthetic blend 15W-40 used by the NCDOT were collected from bulk containers. For each of the tested oils, 24 samples of fresh oil samples were collected analyzed at multiple points in time from November 2016 to April 2017. The results were compared to the typical properties published by the manufacturers shown in Table 3.2.

Table 3.2: Published Typical Properties of Fresh Oil (Martin Lubricants 2014, Shell 2018)

Oil Type	Synthetic	Synthetic Blend
Brand	Shell Rotella® T6	Xtreme™
SAE Viscosity	5W-40	15W-40
Kinematic Viscosity @ 40ºC (cSt)	87	116.4
Kinematic Viscosity @ 100ºC (cSt)	14.2	15.8
Total Base Number (mg KOH/g)	10.6	10.1
Sulfated Ash (% wt)	1.0	1.0 max
Density (kg/l)	0.858	0.8745

3.4 Experimental PM Program

A total of 15 machines were selected for the experimental PM program from the equipment classes shown in Table 3.3. Oil drain intervals for these machines were extended beyond the typical schedule and changed based on a comparison of analysis results with the established threshold values.

Table 3.3: Summary of Equipment Classes in Experimental PM Program

Class	Description	Oil Used
0205	Truck, Dump 33000 GVW	Xtreme Synthetic Blend 15W-40 Shell Rotella T6 5W-40
0210	4X4 extended cab IMAP truck, 9,900 GVW	Xtreme Synthetic Blend 15W-40
0212	Truck, Dump 50000 GVW	Xtreme Synthetic Blend 15W-40
0314	Backhoe, Tractor Loader	Xtreme Synthetic Blend 15W-40
1854	Excavator, Track 12-18 Metric Ton	Xtreme Synthetic Blend 15W-40

Four class 0205 trucks with the Navistar DT466 engine were included to allow comparison of the results with the previously studied class 0209 trucks with the same engine. Two trucks each used the synthetic and synthetic blend oils. Two class 0210 trucks using the synthetic blend oil were added to the program midway through the study based on their heavy use and to allow comparison with previous results obtained for synthetic and conventional oils. Three machines from classes 0212, 0314, and 1854 were included to expand the classes and engines studied. The equipment in the experimental program are summarized in Table 3.4.

Table 3.4: Summary of NCDOT Equipment in the Experimental Program

Class	Year	Make	Model	Engine	Sump (qt)
0205	2008 – 09	International	7300SFA	Navistar DT466 7.6L I6	30
0210	2013	Ford	F350	Powerstroke 6.7L V8	13
0212	2012 – 14	Mack	GU713	MP7395C 11L I6	44
0314	2007 – 13	JCB	3C15	JCB 444 4.4L I4	16
1854	2008 – 12	Hyundai	R140LC7A R140LC9	D04FD-TAA 4.2L I4	24

Engine oil was drained and refilled in fall 2016 (Sept. to Nov.) to start the analysis program. Trucks in class 0210 were drained and refilled in October 2017. Oil samples were collected at 3000, 6000, and then every 1000 miles for the trucks. The backhoe loaders and excavators were sampled every 100 hours. At each sampling, three samples of approximately 150 ml were drawn while the engine was warm and idling via the engine oil dipstick using a hand operated vacuum pump. The results presented are the average measurements from the three samples.

The age of the oil at the time of sampling was measured relative to the its most recent drain in terms of miles driven, engine hours operated, and fuel dispensed to the machine. The machine ID, date, and odometer or hour meter reading were recorded for each sample. Engine run hours at the time of sampling was collected via the on-board diagnostic (OBD) connection for the class 0205, 0210, and 0212 trucks. Fuel measurement on the date of oil sampling was collected from records in SAP. Where a measurement was not available for the date of sampling, the measurement was estimated by interpolation between the records for adjacent dates.

4 OIL ANALYSIS RESULTS

The samples of fresh and used oil collected and analyzed using the Microlab 30 to measure physical and chemical parameters, as well as to assess the level of contamination.

4.1 Fresh Oil Analysis Results

A total of 48 fresh oil samples were tested to establish baseline quality, 24 samples each of Shell Rotella T6 5W-40 synthetic and Xtreme 15W-40 synthetic blend oil. Viscosity measurements were made on half of the samples. The results are summarized in Table 4.1, and a complete set of results are provided in Appendix B.

The average measured TBN for both oils was less than the typical values published by the oil manufacturers. The average measured TBN was 9.53 mg KOH/g for the synthetic oil, which was less than the typical value of 10.6 mg KOH/g. The average TBN of the synthetic blend was 8.61 mg KOH/g, which less than the published typical value of 10.1 mg KOH/g.

The average measured kinematic viscosity at both 40ºC and 100ºC for both oils was less than the typical values published by the oil manufacturers. The results of tests at 100ºC are important because the results represent oil performance at normal engine operating temperature. The average measured viscosity was 13.15 cSt for the synthetic oil, which was less than the typical value of 14.2 cSt. The average viscosity of the synthetic blend was 13.91 cSt, which less than the published typical value of 15.8 cSt. While both oils had slightly lower measured viscosity, the values indicate that the oils met the SAE viscosity grade requirements.

Only trace levels of metals were detected in the fresh oils, with the exception of vanadium. Vanadium is found in crude oils from the Caribbean area, Venezuela, and Mexico, but would not explain its presence in the synthetic oil. Another potential source is its use as a corrosion inhibitor and dispersant.

Most analysis results were consistent, as indicated by the small standard deviation relative to the average values. However, there was noticeable variability in the measured levels for additives. The source of this variability appears to be oil sample source, as a group of samples drawn from the same drum had similar results. While samples drawn at a different time and from a different drum, while consistent among the group, differed from other groups. This was most noticeable in the synthetic blend results.

Table 4.1: Fresh Oil Analysis Results

	Shell Rotella T6 5W-40		Xtreme Synthetic Blend, 15W-40	
Parameter	**Average**	**Std. Dev.**	**Average**	**Std. Dev.**
Oil Condition				
TBN (mg KOH/g)	9.53	0.07	8.61	0.39
Viscosity @ 100°C (cSt)	13.15	0.23	13.91	0.14
Viscosity @ 40°C (cSt)	80.90	1.29	100.17	2.03
Viscosity Index	165	2.11	141	2.90
Oxidation	1.3	0.41	0.0	0.00
Nitration	0.9	0.36	0.9	0.43
Contamination				
Fuel (% by wt)	0.0	0.00	0.0	0.84
Soot (% by wt)	0.2	0.02	0.1	0.03
Water (% by wt)	0.0	0.02	0.0	0.00
Glycol (% by wt)	0.06	0.02	0.0	0.00
Silicon (ppm)	0.00	0.00	0.61	0.74
Metals				
Aluminum (ppm)	0.00	0.00	0.02	0.04
Copper (ppm)	0.99	1.30	1.72	1.30
Iron (ppm)	0.16	0.54	0.04	0.07
Tin (ppm)	0.19	0.42	0.18	0.47
Lead (ppm)	0.00	0.00	0.00	0.00
Chromium (ppm)	0.00	0.00	0.45	0.63
Nickel (ppm)	0.02	0.08	0.02	0.04
Titanium (ppm)	0.00	0.00	0.00	0.00
Manganese (ppm)	0.76	0.49	1.24	0.30
Barium (ppm)	0.00	0.00	0.00	0.00
Vanadium (ppm)	18.12	4.57	14.81	5.60
Additives				
Sodium (ppm)	7.50	1.41	0.56	1.22
Potassium (ppm)	22.43	3.01	17.00	5.29
Boron (ppm)	60.97	2.67	344	367
Magnesium (ppm)	1330	120	671	429
Calcium (ppm)	1124	86	1619	383
Zinc (ppm)	1718	128	1968	799
Phosphorus (ppm)	1137	395	1181	449
Molybdenum (ppm)	47.23	11.05	57.04	14.00

4.2 Experimental Program Results

The 15 machines in the experimental program were monitored from September 2016 to August 2018. A total of 299 samples were collected and analyzed from the machines, based on use of the machines. A summary of the analyses by equipment class is provided in Table 4.2.

Table 4.2: Summary of Oil Analyses by Equipment Class

Class	No. of Machines Sampled	No. of Samples Analyzed
0205	4	21
0210	2	48
0212	3	126
0314	3	47
1854	3	57
Total	**15**	**299**

The results obtained from the Microlab 30 analyzer were assessed and verified by collecting duplicate samples from three class 0212 trucks when the oil reached the end of a cycle and was changed. One set of samples were sent to an independent Caterpillar oil analysis lab for testing and the remaining set analyzed on-site using the Microlab 30. The results are provided in Tables 4.3 through 4.5.

Table 4.3: Summary of Verification Analysis Results for Truck 1460-0131-0212

Equipment ID 1490-0131-0212 **Sample Date** 3-Oct-17 **Miles on Sample** 14,460

Sample ID	TBN	V100	H2O	Sul	Ox	Nit	Soot	Fe	Al	Cu	Cr	Pb	Sn	Ni	Ba	Si	Na	K	Mo	Ca	Mg	Zn	P
Caterpillar Analysis Results																							
D180-47310-0818	1.5	11.4	N	28	28	11	17	15	4	8	0	7	7	3	0	5	6	3	62	1040	816	1004	980
D180-47310-0819	1.5	11.4	N	34	35	13	6	13	5	8	0	9	3	3	0	5	5	3	62	1003	770	977	953
D180-47307-0520	4.5	11.7	N	22	19	9	2	13	5	8	0	5	8	3	0	5	5	3	61	1009	801	930	885
D180-47306-0928	4.0	11.6	P	33	36	13	3	12	5	8	0	6	7	3	0	5	4	3	60	991	801	932	863
Average	**2.9**	**11.5**		**29**	**30**	**12**	**7**	**13**	**5**	**8**	**0**	**7**	**6**	**3**	**0**	**5**	**5**	**3**	**61**	**1011**	**797**	**961**	**920**
Range	**3**	**0.3**		**12**	**17**	**4**	**15**	**3**	**1**	**0**	**0**	**4**	**5**	**0**	**0**	**0**	**2**	**0**	**2**	**49**	**46**	**74**	**117**
Microlab 30 Analysis Results																							
1222	3.5	12.0	0.10	0	14.8	18.8	0.4	5.7	3.0	12.7	0.0	2.7	0.0	1.3	0	0.6	10.0	22.6	52.7	1616	763	1379	471
1223	3.6	12.0	0.10	0	15.1	17.8	0.4	6.3	3.8	11.6	0.0	3.9	2.5	1.4	0	1.3	8.5	22.0	49.3	1999	829	1748	594
1224	3.4	12.0	0.10	0	15.0	18.5	0.4	4.7	3.3	22.6	0.0	3.1	0.0	0.7	0	1.7	9.0	15.1	50.8	1623	156	1537	553
Average	**3.5**	**12.0**	**0.10**	**0**	**15.0**	**18.4**	**0.4**	**5.6**	**3.4**	**15.6**	**0.0**	**3.2**	**0.8**	**1.1**	**0**	**1.2**	**9.2**	**19.9**	**50.9**	**1746**	**582**	**1555**	**539**
Range	**0.2**	**0.0**	**0**	**0**	**0.3**	**1.0**	**0**	**1.6**	**0.8**	**11.0**	**0.0**	**1.2**	**2.5**	**0.7**	**0**	**1.1**	**1.5**	**7.5**	**3.4**	**383**	**673**	**369**	**123**

Table 4.4: Summary of Verification Analysis Results for Truck 1460-0202-0212

Equipment ID 1490-0202-0212 **Sample Date** 23-Aug-17 **Miles on Sample** 12,988

Sample ID	TBN	V100	H2O	Sul	Ox	Nit	Soot	Fe	Al	Cu	Cr	Pb	Sn	Ni	Ba	Si	Na	K	Mo	Ca	Mg	Zn	P
Caterpillar Analysis Results																							
D180-47275-1101	2.5	12.5	N	33	33	14	6	19	4	20	0	4	4	3	0	5	7	5	61	1069	789	1103	959
D180-47269-0539		13.5	N	32	33	14	8	19	5	21	0	3	8	3	0	5	8	5	60	1038	841	1057	941
D180-47269-0538		13.3	N	32	33	14	6	19	5	21	0	2	4	3	0	5	7	6	61	1045	825	1064	953
D180-47269-0526		12.8	N	32	33	14	6	19	5	21	0	4	7	3	0	5	6	6	58	1001	768	1032	935
Average	**2.5**	**13.0**		**32**	**33**	**14**	**6.5**	**19**	**5**	**20.8**	**0**	**3**	**6**	**3**	**0**	**5**	**7**	**6**	**60**	**1038**	**806**	**1064**	**947**
Range		**1**		**1**	**0**	**0**	**2**	**0**	**1**	**1**	**0**	**2**	**4**	**0**	**0**	**0**	**2**	**1**	**3**	**68**	**73**	**71**	**24**
Microlab 30 Analysis Results																							
1201	3.3	12.4	0.27	0	12.8	20.1	0.5	12.7	1.0	30.5	0.4	0.3	2.2	1.6	0	0.0	9.4	10.0	56.4	1288	746	1589	558
1202	3.1	12.4	0.17	0	15.2	17.3	0.5	12.4	1.9	28.0	0.5	0.0	0.0	1.8	0	0.0	9.2	11.1	58.0	1483	705	1563	543
1203	3.0	12.4	0.07	0	15.2	17.4	0.5	11.8	1.9	30.4	0.0	0.2	1.5	1.0	0	0.2	11.1	13.8	59.4	1471	701	1491	509
Average	**3.1**	**12.4**	**0.17**	**0**	**14.4**	**18.3**	**0.5**	**12.3**	**1.6**	**29.7**	**0.3**	**0.2**	**1.2**	**1.4**	**0**	**0.1**	**9.9**	**11.6**	**57.9**	**1414**	**717**	**1548**	**537**
Range	**0.3**	**0.1**	**0.2**	**0**	**2.4**	**2.8**	**0**	**0.9**	**1.0**	**2.5**	**0.4**	**0.3**	**2.2**	**0.8**	**0**	**0.2**	**1.9**	**3.8**	**3.0**	**195**	**45**	**98**	**49**

Table 4.5: Summary of Verification Analysis Results for Truck 1460-0264-0212

Equipment ID 1490-0264-0212 **Sample Date** 3-Oct-17 **Miles on Sample** 8,998

Sample ID	TBN	V100	H2O	Sul	Ox	Nit	Soot	Fe	Al	Cu	Cr	Pb	Sn	Ni	Ba	Si	Na	K	Mo	Ca	Mg	Zn	P
Caterpillar Analysis Results																							
D180-47310-0608	2.5	13.1	P	28	27	13	1	12	4	20	0	0	4	1	0	4	5	5	58	960	772	936	943
D180-47307-0611	2.0	12.8	P	30	26	13	3	13	4	22	0	0	6	0	0	4	6	7	62	1064	875	1004	1004
D180-47306-0901	1.5	13.1	P	30	26	13	3	12	4	22	0	2	4	0	0	4	4	6	61	1040	859	930	930
D180-47306-0816	2.0	12.4	P	30	26	13	3	13	4	22	0	2	3	0	0	4	5	6	64	1027	819	941	941
Average	**2.0**	**12.9**		**30**	**26**	**13**	**2.5**	**13**	**4**	**21.5**	**0**	**1**	**4**	**0**	**0**	**4**	**5**	**6**	**61**	**1023**	**831**	**953**	**955**
Range	**1**	**0.7**		**2**	**1**	**0**	**2**	**1**	**0**	**2**	**0**	**2**	**3**	**1**	**0**	**0**	**2**	**2**	**6**	**104**	**103**	**74**	**74**
Microlab 30 Analysis Results																							
1219	3.1	12.6	0.10	0	12.7	16.3	0.4	6.6	0.0	1.4	0.6	0.0	0.0	0.0	0	1.9	0.0	4.6	14.0	943	107	772	363
1220	3.0	12.5	0.10	0	12.7	16.6	0.4	3.2	2.0	27.7	0.0	0.0	0.0	0.0	0	2.3	4.7	18.8	47.2	1375	141	1358	435
1221	3.1	12.6	0.10	0	12.9	16.3	0.4	5.0	2.2	22.1	0.0	0.0	0.0	0.0	0	0.0	10.2	25.3	53.3	1691	837	1449	478
Average	**3.1**	**12.6**	**0.10**	**0**	**12.8**	**16.4**	**0.4**	**4.9**	**1.4**	**17.1**	**0.2**	**0.0**	**0.0**	**0.0**	**0**	**1.4**	**4.9**	**16.2**	**38.2**	**1336**	**362**	**1193**	**425**
Range	**0.1**	**0.1**	**0**	**0**	**0.2**	**0.3**	**0**	**3.4**	**2.2**	**26.3**	**0.6**	**0.0**	**0.0**	**0.0**	**0**	**2.3**	**10.2**	**20.7**	**39.3**	**748**	**730**	**676**	**114**

4.3 Equipment Class 0205

The class 0205 trucks were driven very little during the study period, and only one truck was sampled multiple times. Truck 1094-7007-0205 was driven to 6,400 miles and synthetic blend oil samples were collected and analyzed at four points in time.

Results of TBN measurements with respect to oil age in terms of miles driven, engine run time, and fuel consumed are shown in Figure 4.1. Notwithstanding the limited data, there was a clear linearly decreasing relationship between TBN and oil age, in all three units of measurement. Regression analysis was applied to quantify the relationships, and the results are summarized in Table 4.6. All three relationships were statistically significant at the 95 percent confidence level.

Table 4.6: Summary of TBN Degradation in Class 0205 Trucks

Oil Age Unit	TBN Degradation Rate	p-value	R^2
Miles Driven	0.51 mg KOH/g per 1,000 miles	0.031	0.938
Hours Operated	0.42 mg KOH/g per 100 hours	0.029	0.943
Gallons Consumed	0.29 mg KOH/g per 100 gallons	0.031	0.868

Viscosity of the synthetic blend oil was consistent throughout the operation of the truck and measured to be at or slightly less than the SAE specified minimum of 12.5 cSt for grade 40 oil. The results are shown in Figure 4.2.

The analysis results did not indicate that there was, or was likely to be any, cause for concern for oil quality due to contamination by metals or other fluids.

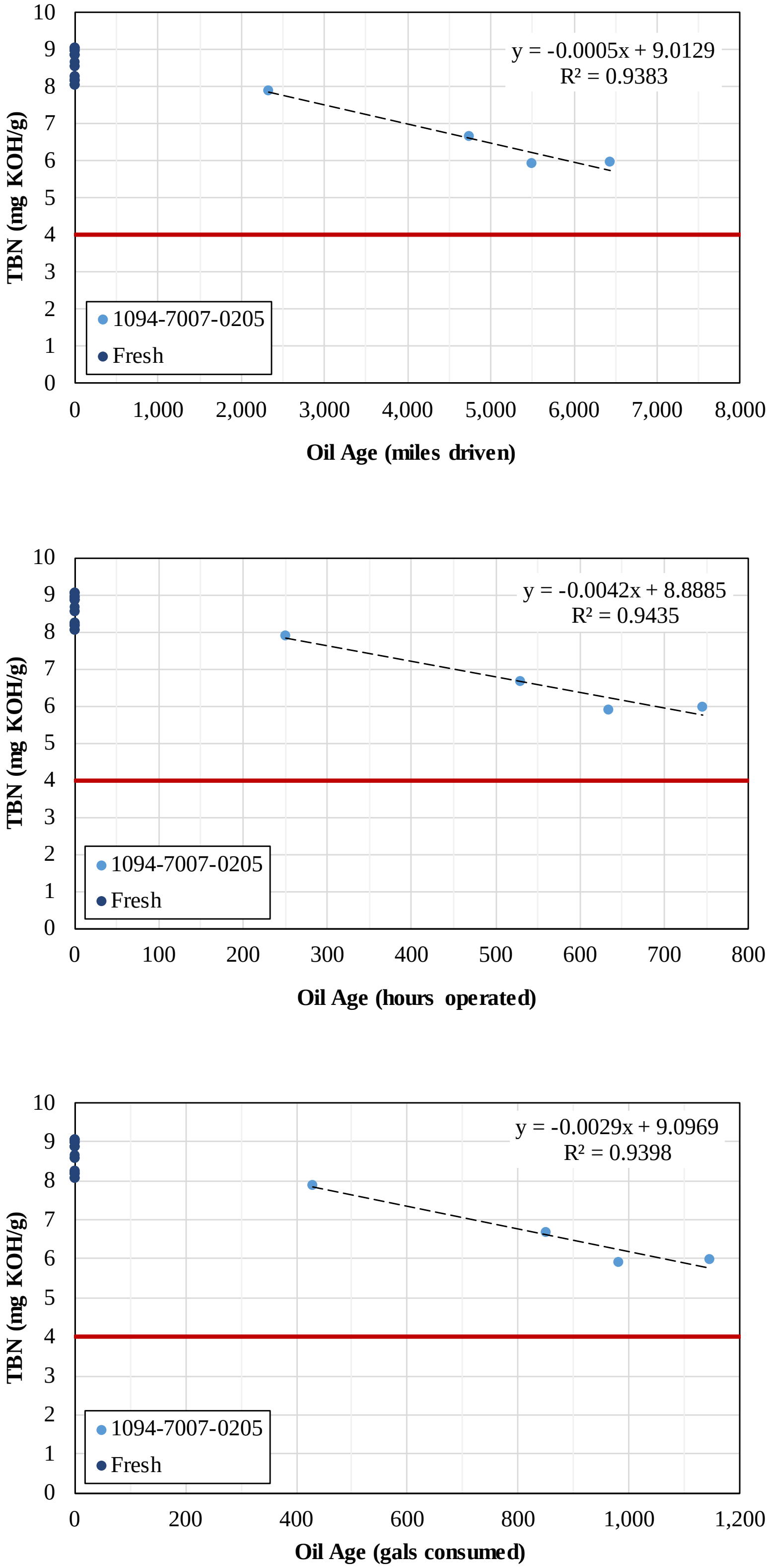


Figure 4.1: TBN of Synthetic Blend Oil in Class 0205 Trucks

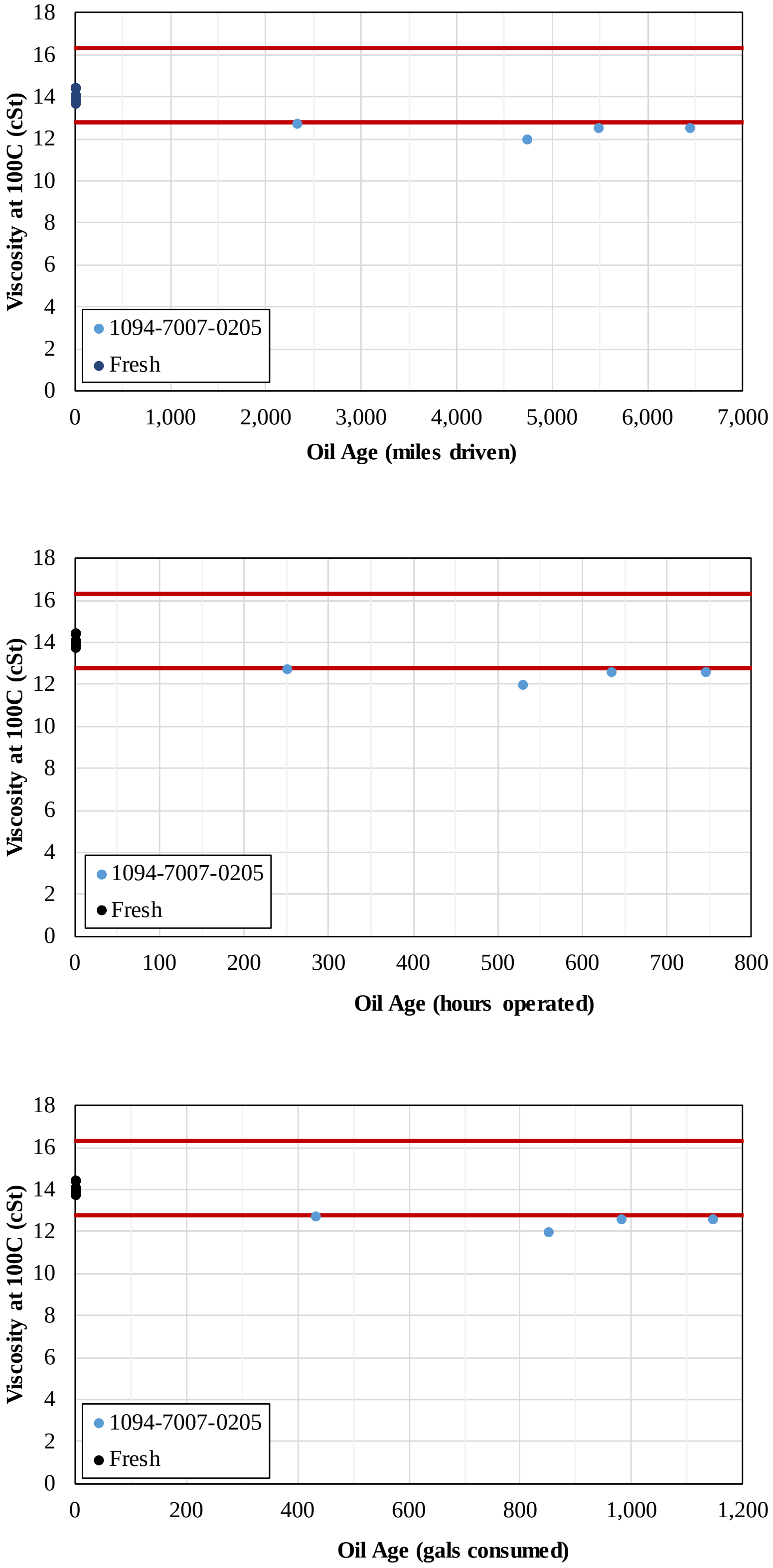


Figure 4.2: Viscosity at 100ºC of Synthetic Blend Oil in Class 0205 Trucks

4.4 Equipment Class 0210

A total of 48 samples of synthetic blend oil were analyzed from two class 0210 trucks, with oil extending in age to approximately 11,000 miles in one truck and 15,000 miles in the other. Neither truck was operated through a complete oil cycle where an oil change was warranted based on the analysis results.

TBN measurements exhibited very strong linearly decreasing relationships with oil age, as shown in Figure 4.3. All three relationships between oil age and TBN were statistically significant at the 95 percent confidence level and are summarized in Table 4.7.

Table 4.7: Summary of TBN Degradation in Class 0210 Trucks

Oil Age Unit	TBN Degradation Rate	p-value	R^2
Miles Driven	0.18 mg KOH/g per 1,000 miles	0.000	0.779
Hours Operated	0.59 mg KOH/g per 100 hours	0.000	0.901
Gallons Consumed	0.24 mg KOH/g per 100 gallons	0.000	0.853

Viscosity of the synthetic blend oil was consistent throughout the operation of the trucks and measured to be at or slightly less than the SAE specified minimum of 12.5 cSt for grade 40 oil. The results are shown in Figure 4.4.

Iron and aluminum were produced in the class 0210 truck engines as the oil aged, with both trucks producing at similar rates. As shown in Figure 4.5 and 4.6, the levels did not rise to levels causing concern. While aluminum levels did exceed the 15 ppm threshold, the corresponding silicon levels that would indicate dirt contamination were not present and aluminum by itself is a soft metal and not a great concern. If iron production were to continue at the observed rate, it would likely near the 100 ppm threshold and become a concern at about the same time TBN would reach the minimum threshold.

The analysis results did not indicate that other wear metals were being produced in any significant quantity or that there was contamination of the oil.

Oil oxidation levels remained well below the threshold value of 20, while nitration levels increased to approximately 10 in the oldest oil samples. This is nearing the threshold value of 15 as shown in Figure 4.7.

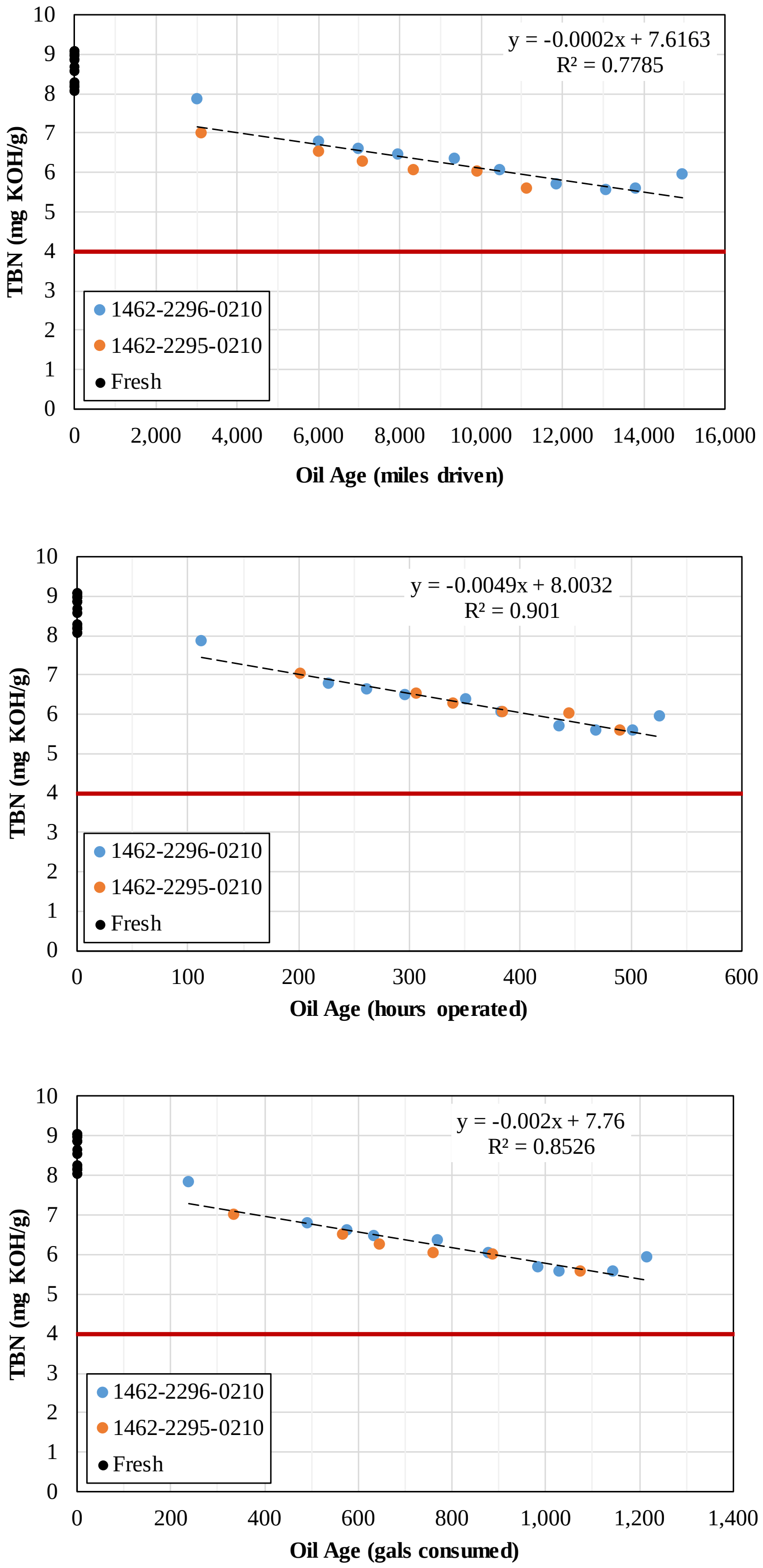


Figure 4.3: TBN of Synthetic Blend Oil in Class 0210 Trucks

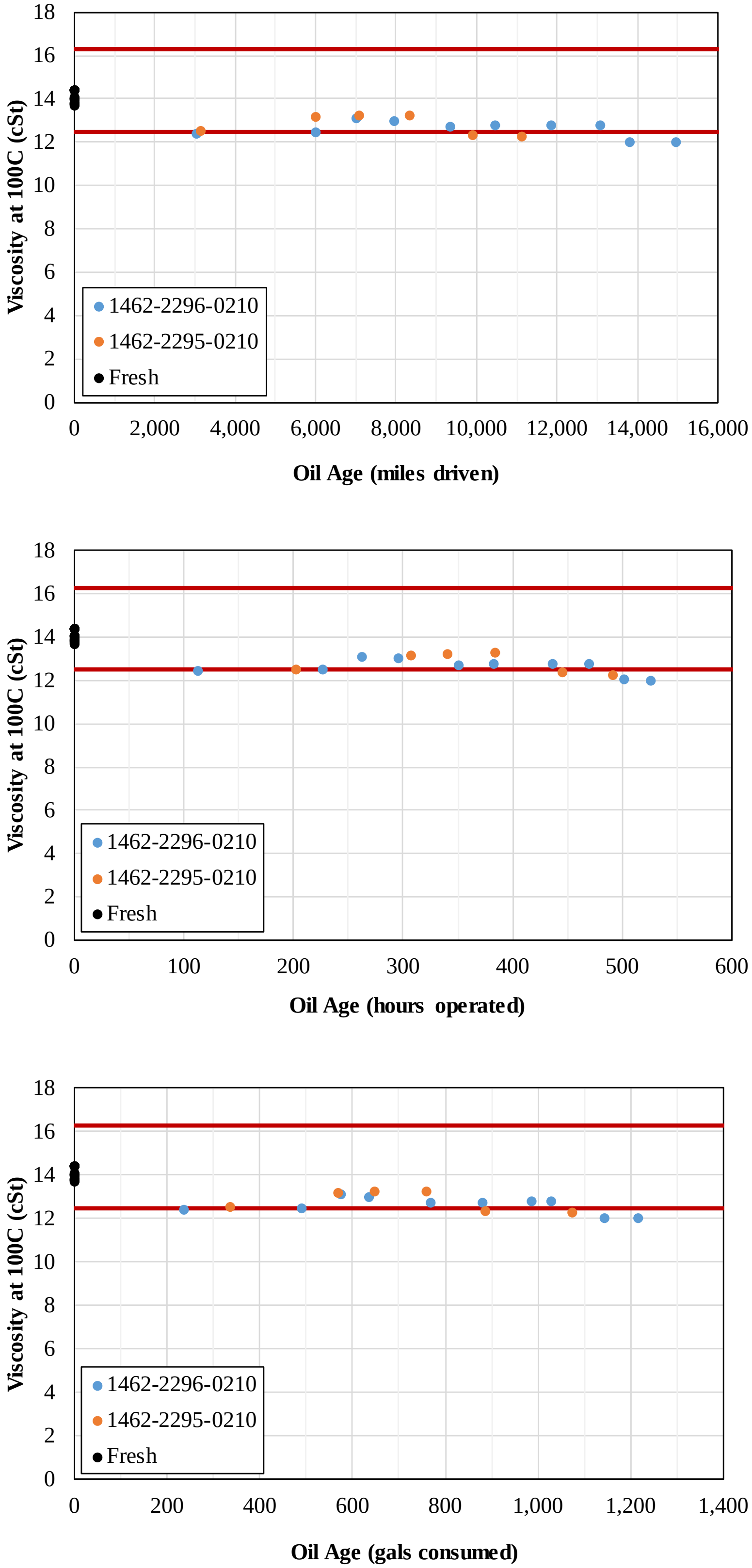


Figure 4.4: Viscosity at 100ºC of Synthetic Blend Oil in Class 0210 Trucks

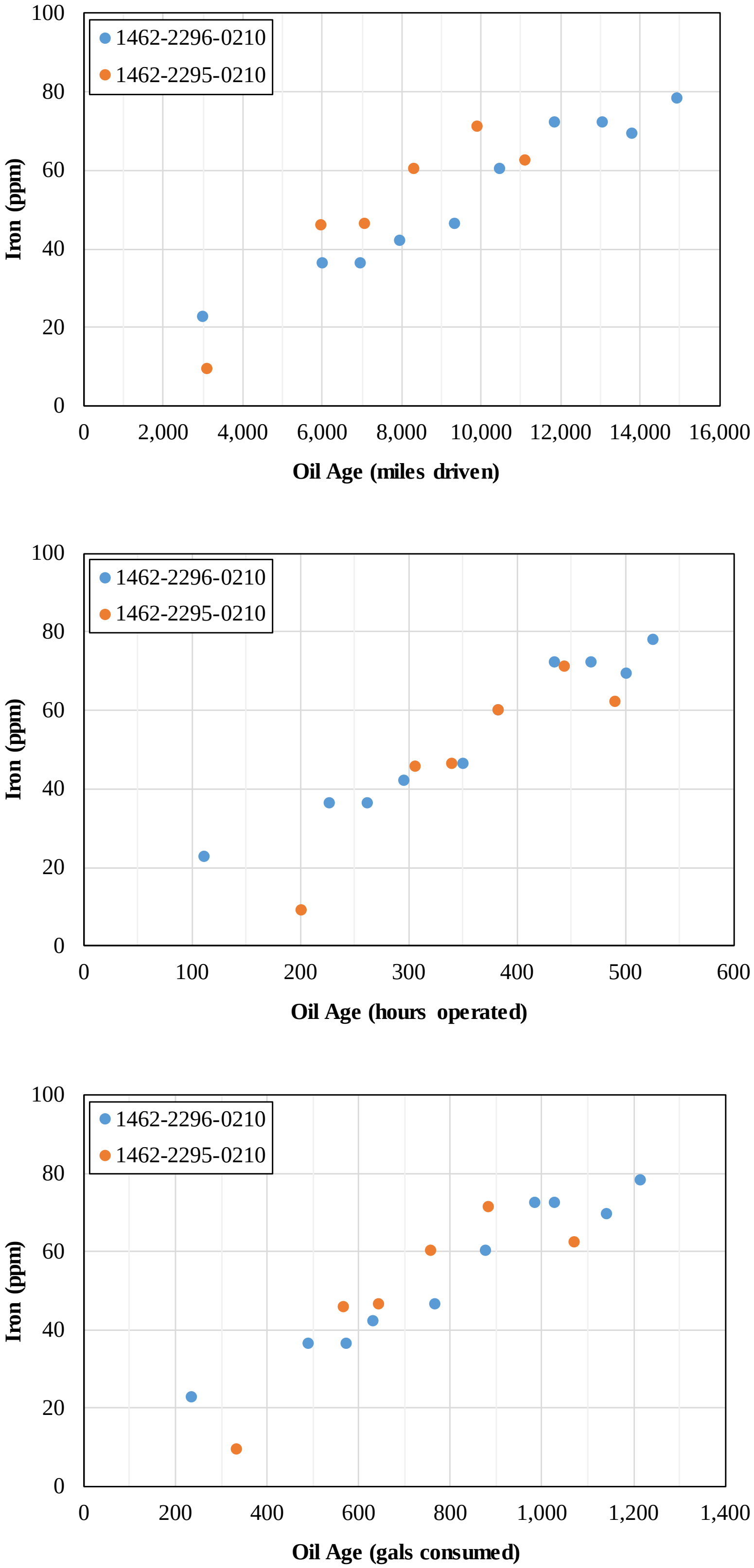


Figure 4.5: Iron Levels in Synthetic Blend Oil in Class 0210 Trucks

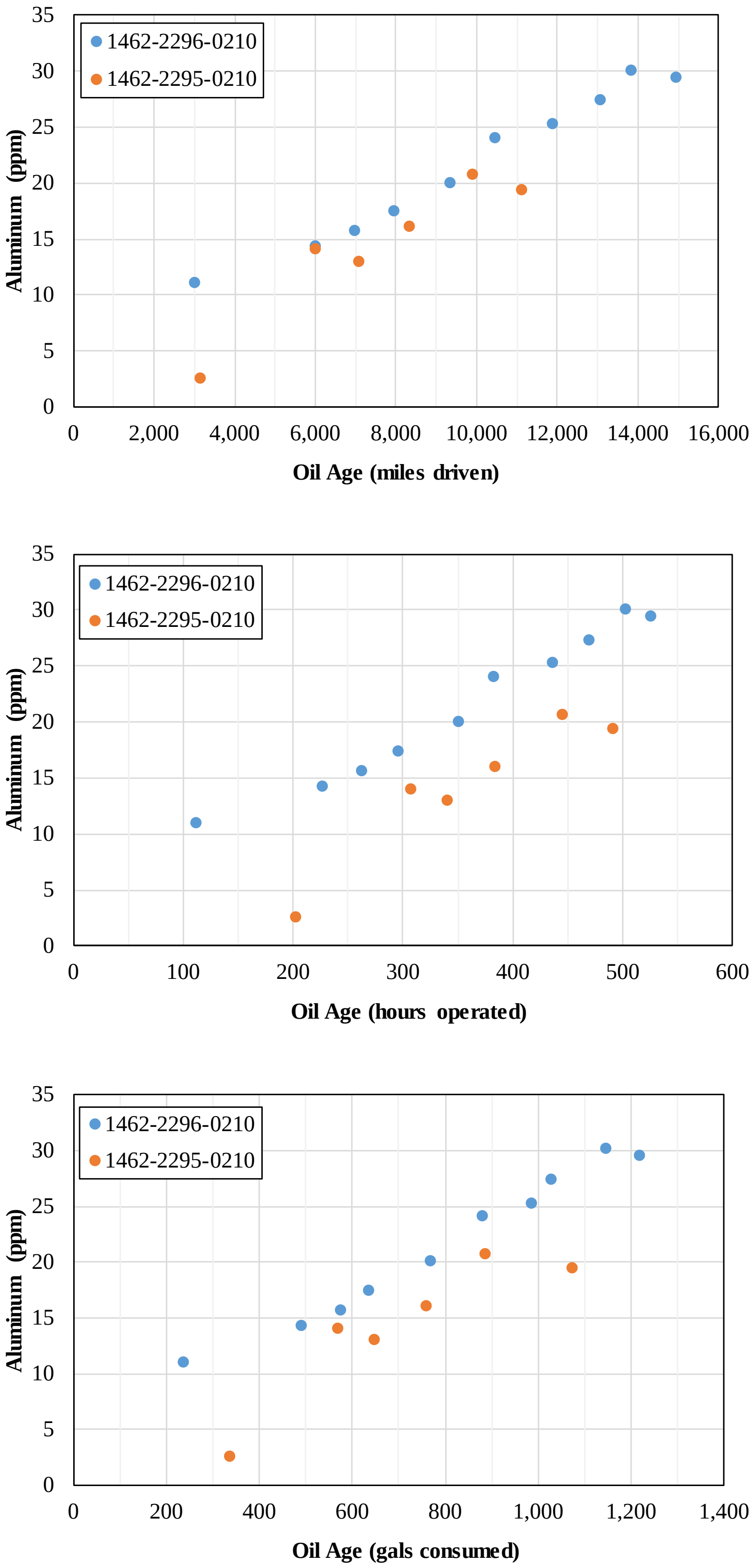


Figure 4.6: Aluminum Levels in Synthetic Blend Oil in Class 0210 Trucks

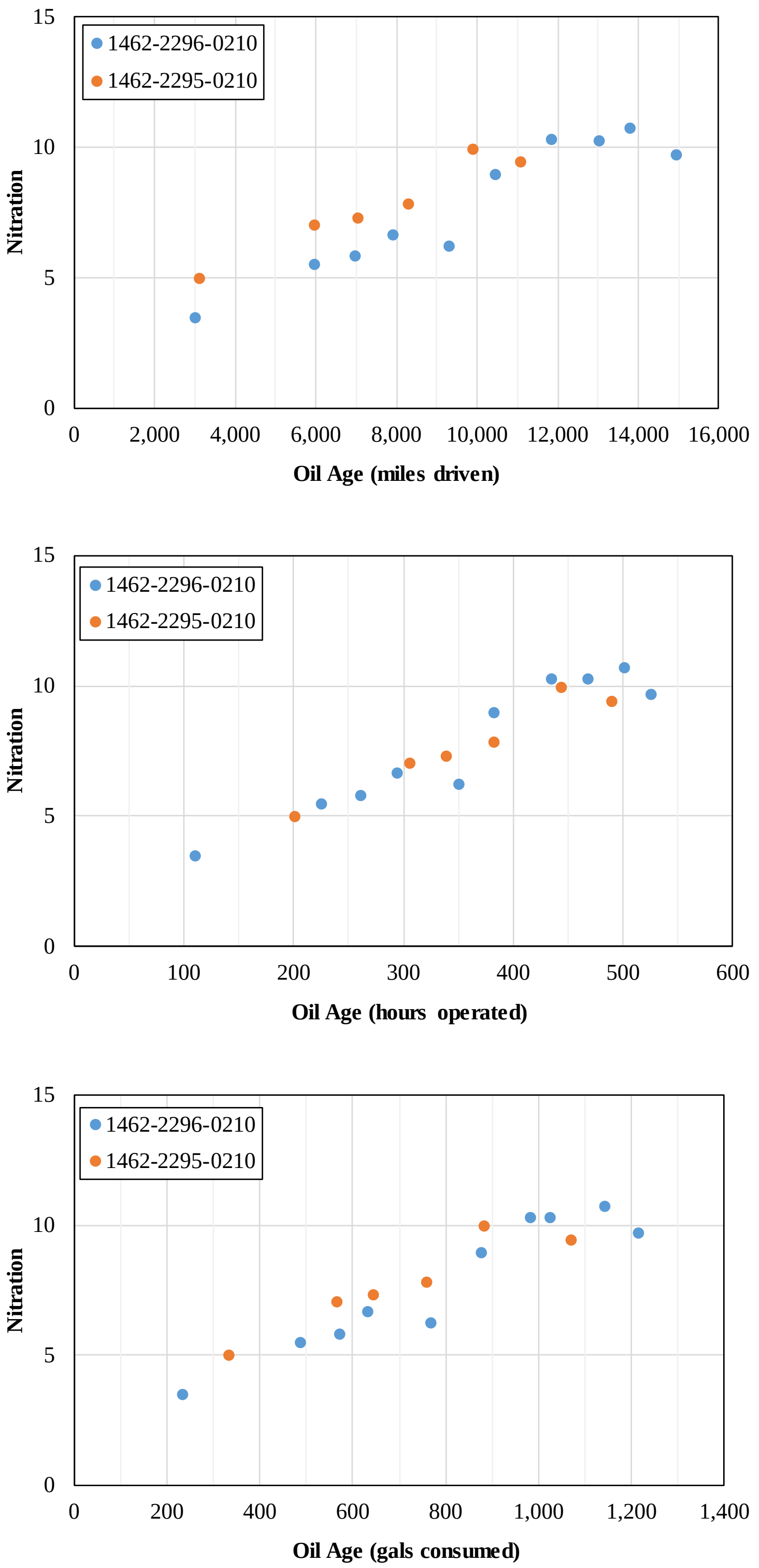


Figure 4.7: Nitration of Synthetic Blend Oil in Class 0210 Trucks

4.5 Equipment Class 0212

A total of 126 samples of synthetic blend oil were analyzed from three class 0212 trucks. The three trucks were all operated through one complete oil cycle where the oil was changed based on the analysis results. One truck was operated through two complete oil cycles. The cycles varied in length from 9,000 miles to 14,400 miles.

TBN measurements exhibited linearly decreasing relationships with oil age, as shown in Figure 4.8. All three relationships between oil age and TBN were statistically significant at the 95 percent confidence level and are summarized in Table 4.8.

Table 4.8: Summary of TBN Degradation in Class 0212 Trucks

Oil Age Unit	TBN Degradation Rate	p-value	R^2
Miles Driven	0.40 mg KOH/g per 1,000 miles	0.000	0.673
Hours Operated	0.76 mg KOH/g per 100 hours	0.000	0.952
Gallons Consumed	0.25 mg KOH/g per 100 gallons	0.000	0.878

Viscosity of the synthetic blend oil was fairly consistent throughout the operation of the trucks, although more variable than observed in other equipment classes. Approximately 40 percent of measurements were less than the SAE specified minimum of 12.5 cSt for grade 40 oil, and some measurements were less than 11 cSt. The results are shown in Figure 4.9.

Significant levels of iron and aluminum were not produced by the class 0212 truck engines. As shown in Figures 4.10 and 4.11, the levels were well less than the threshold values. Copper was measured in some samples at levels exceeding the threshold in one oil cycle for trucks 1490-0202-0212 and 1490-0264-0212. The levels varied and did not exhibit a relationship with oil age. There was no evidence of oil contamination by other fluids or other wear metals.

Oil oxidation levels remained below the threshold value of 20, while nitration levels increased to levels above the threshold value near the end of the oil cycle, as shown in Figure 4.12.

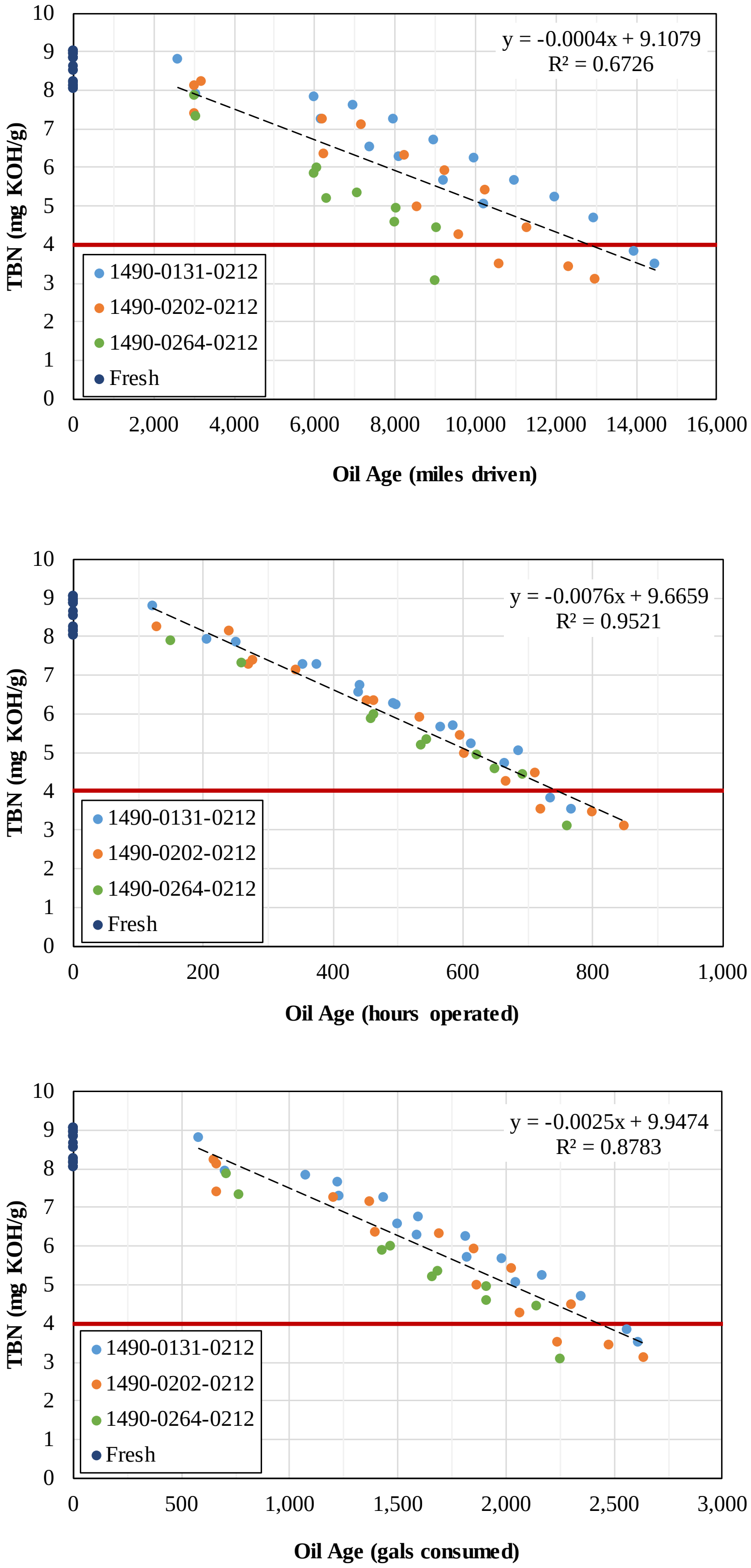


Figure 4.8: TBN of Synthetic Blend Oil in Class 0212 Trucks

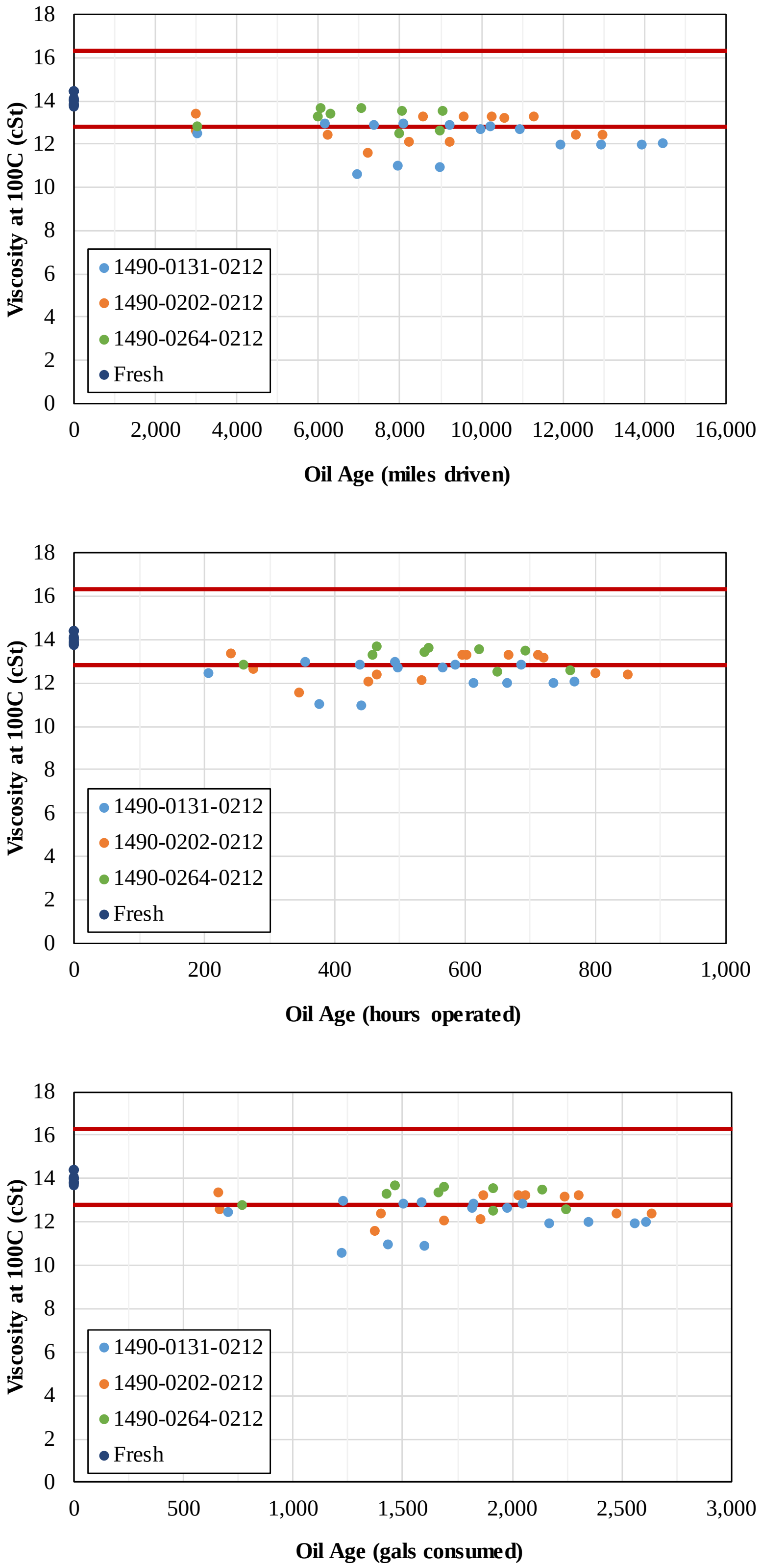


Figure 4.9: Viscosity at 100°C of Synthetic Blend Oil in Class 0212 Trucks

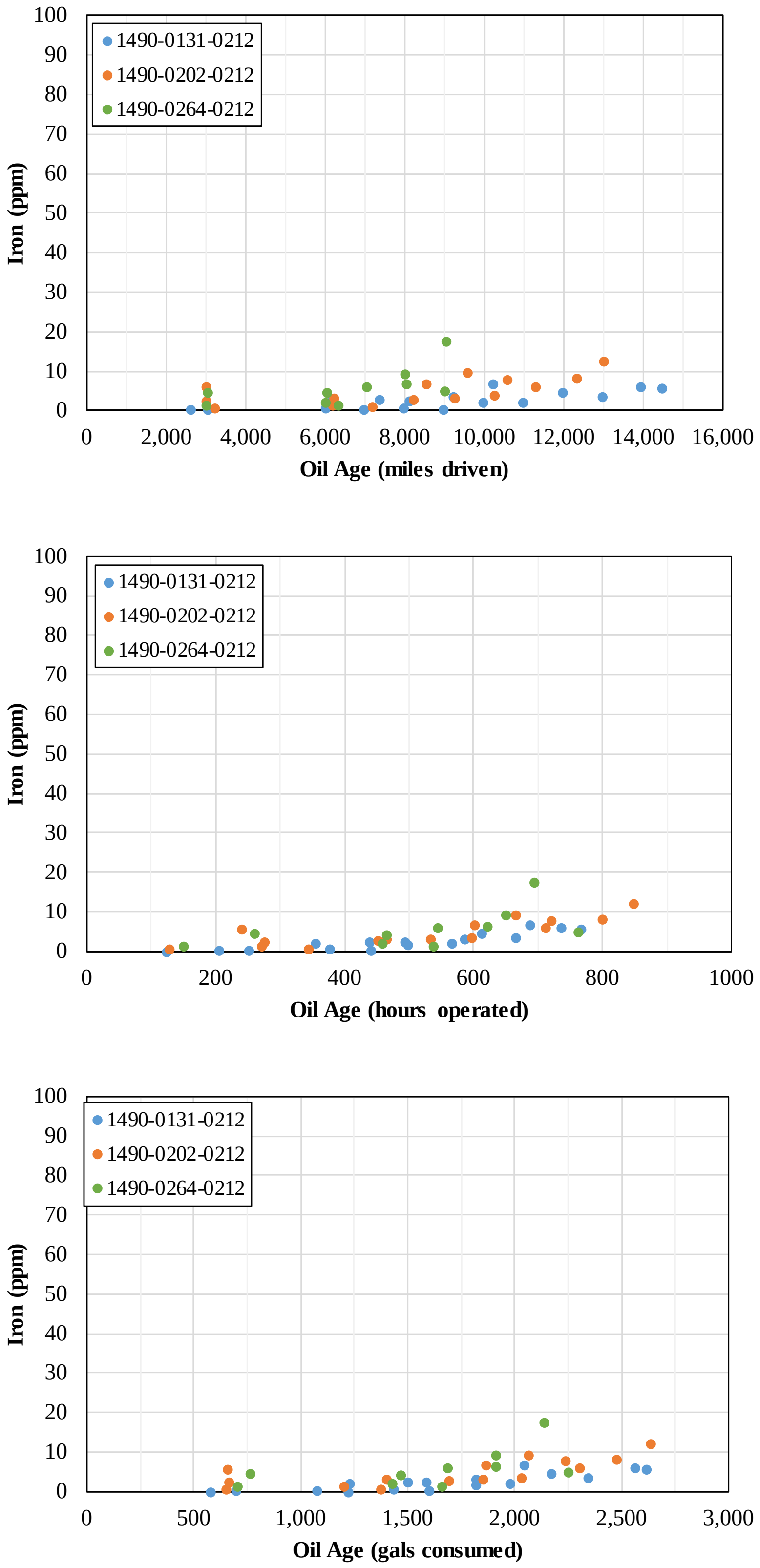


Figure 4.10: Iron Levels in Synthetic Blend Oil in Class 0212 Trucks

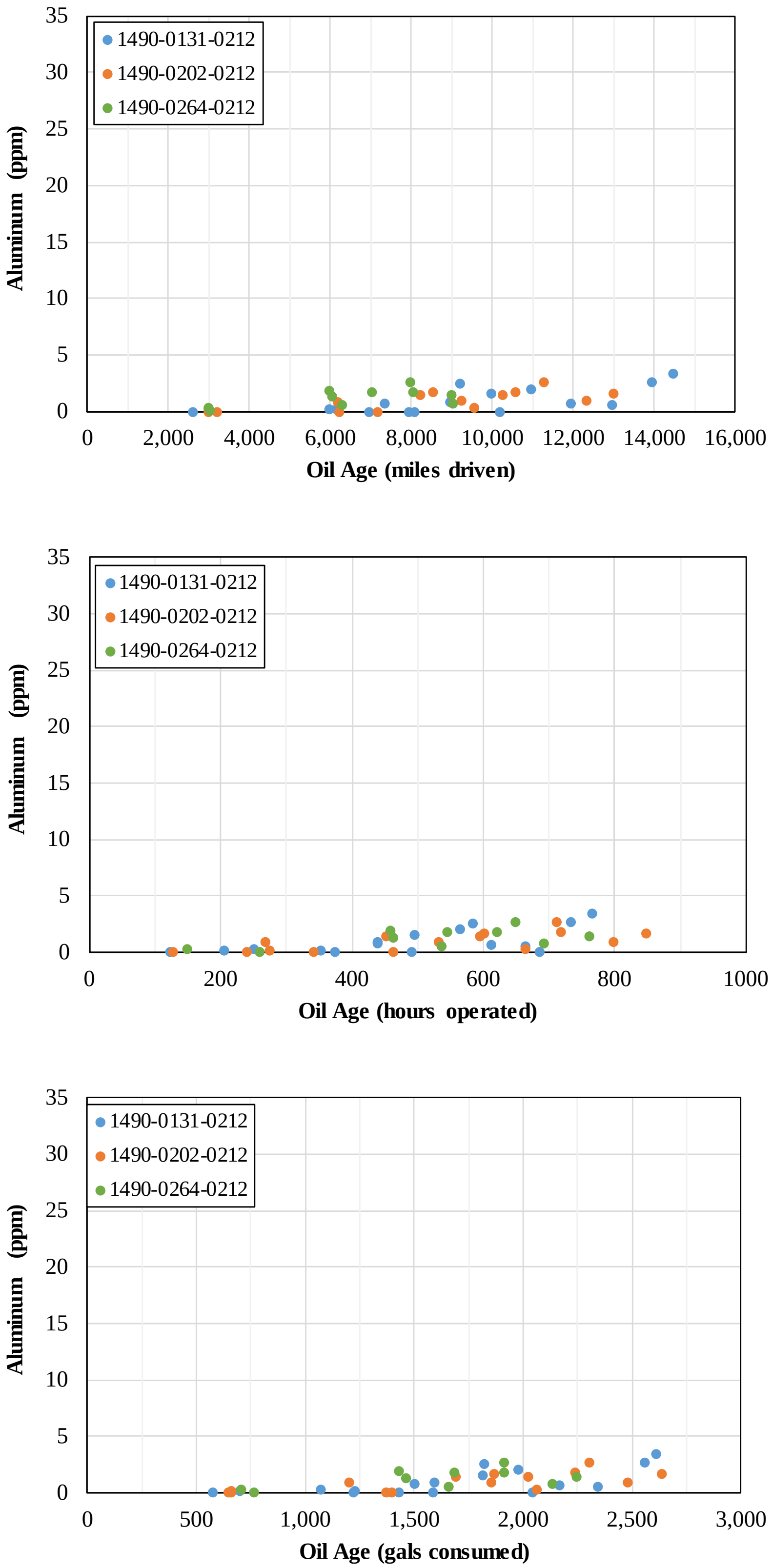


Figure 4.11: Aluminum Levels in Synthetic Blend Oil in Class 0212 Trucks

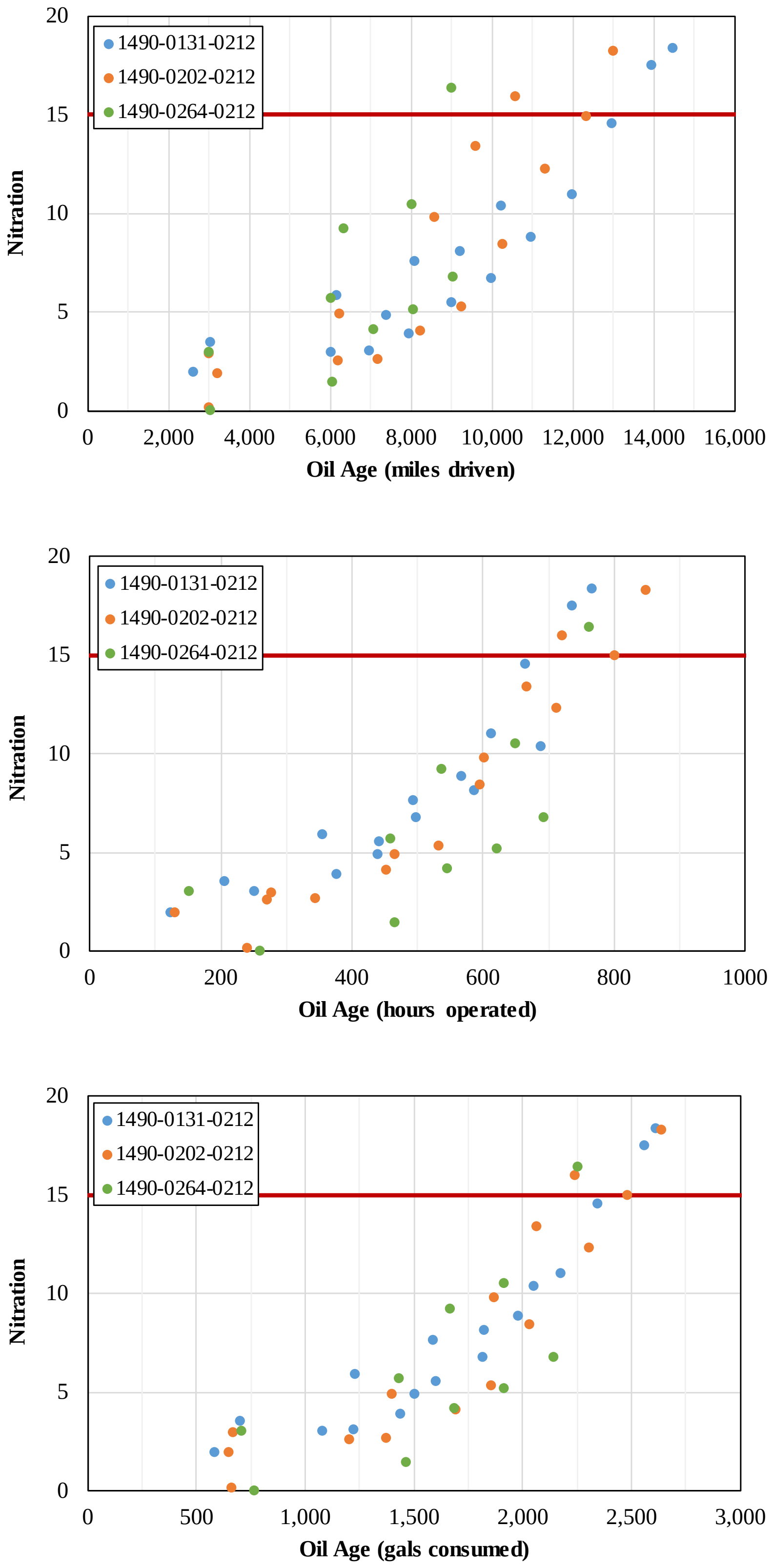


Figure 4.12: Nitration of Synthetic Blend Oil in Class 0212 Trucks

4.6 Equipment Class 0314

A total of 47 samples of synthetic blend oil were analyzed from three class 0314 backhoe loaders, with oil extending in age to approximately 500 hours in two machines and 300 hours in another. The third machine saw the oil changed at approximately 100 hours due to high silicon measurements, at approximately 200 hours mistakenly when it should have continued on an extended interval, and then operated to approximately 300 hours.

TBN measurements exhibited linearly decreasing relationships with oil age, as shown in Figure 4.13. The relationships between oil age, in terms of both hours operated and gallons of fuel consumed, and TBN were statistically significant at the 95 percent confidence level and are summarized in Table 4.9.

Table 4.9: Summary of TBN Degradation in Class 0314 Backhoe Loaders

Oil Age Unit	TBN Degradation Rate	p-value	R^2
Hours Operated	0.36 mg KOH/g per 100 hours	0.009	0.416
Gallons Consumed	0.24 mg KOH/g per 100 gallons	0.000	0.632

Viscosity of the synthetic blend oil was fairly consistent throughout the operation of the machines and was within the SAE specified limits for grade 40 oil. The results are shown in Figure 4.14.

The measured iron and aluminum levels were significantly less than the threshold values, as shown in Figure 4.15 and 4.16. With the exception of silicon measured at 47 ppm in backhoe loader 1803-0375-0314 at 100 hours when the oil was drained and changed, there were no indications of oil contamination.

Very low levels of oxidation and nitration were observed. Oxidation was measured at or very near 0.0 in all samples and nitration levels did not exceed 2.4.

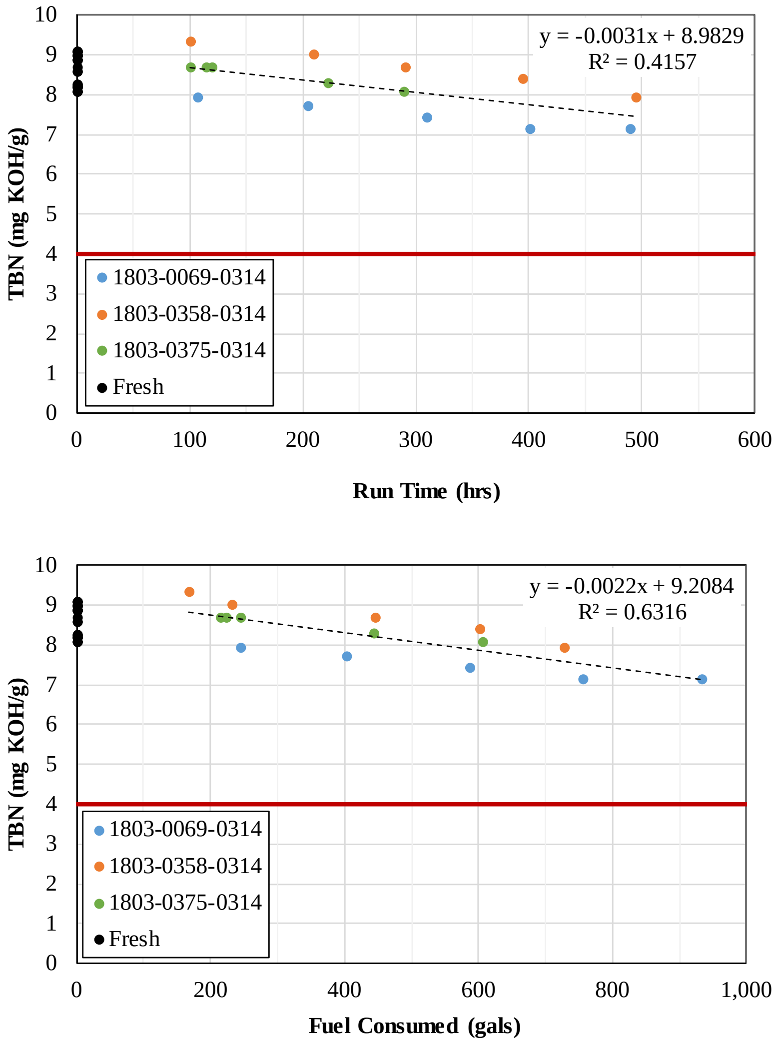


Figure 4.13: TBN of Synthetic Blend Oil in Class 0314 Backhoe Loaders

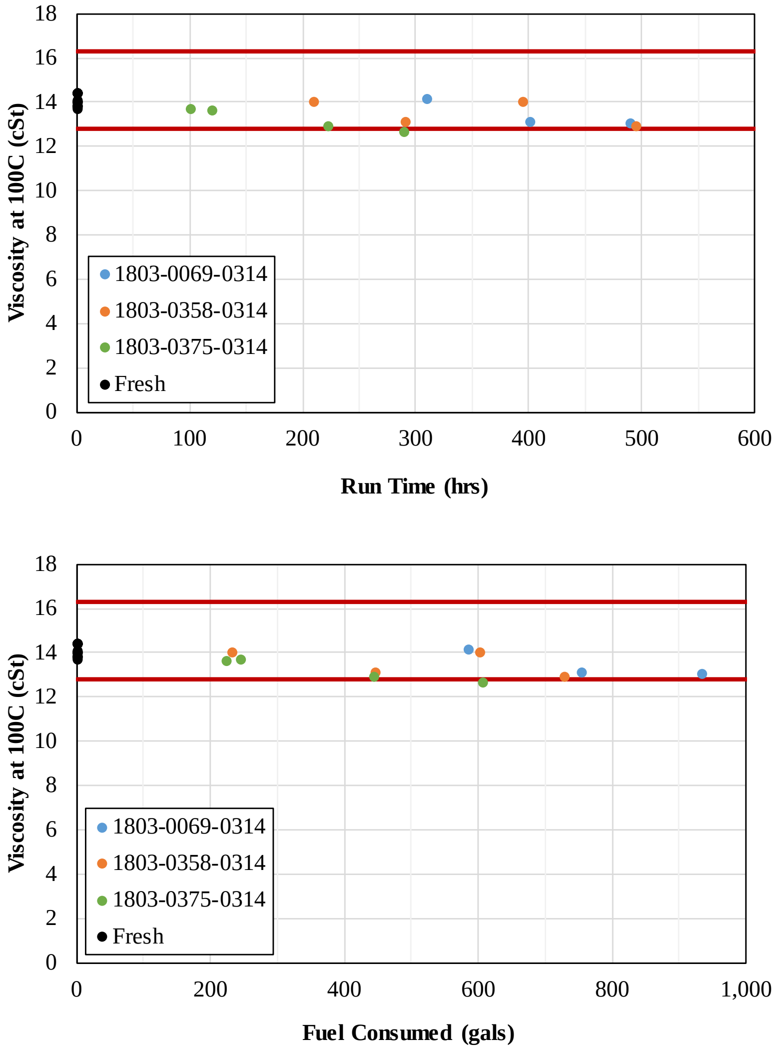
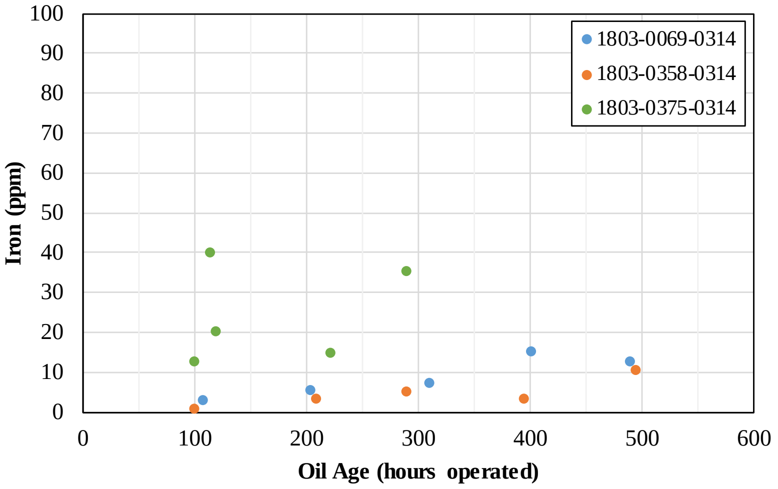


Figure 4.14: Viscosity at 100ºC of Synthetic Blend Oil in Class 0314 Backhoe Loaders



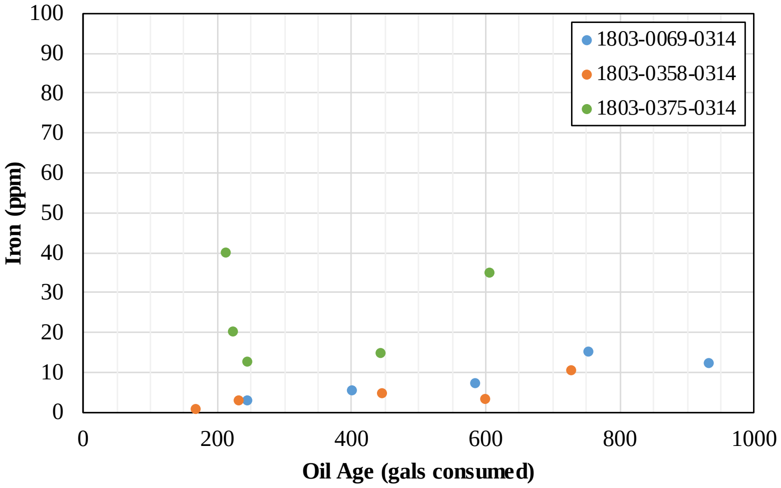


Figure 4.15: Iron Levels in Synthetic Blend Oil in Class 0314 Backhoe Loaders

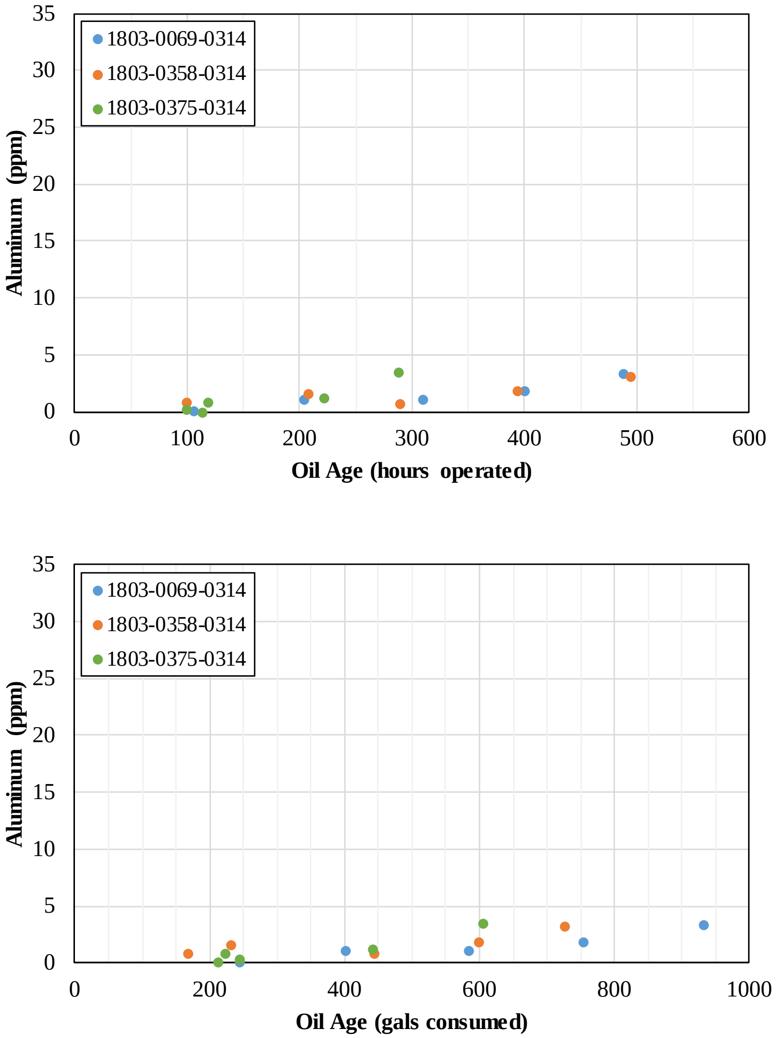


Figure 4.16: Aluminum Levels in Synthetic Blend Oil in Class 0314 Backhoe Loaders

4.7 Equipment Class 1854

A total of 57 samples of synthetic blend oil were analyzed from three class 1854 excavators, with oil extending in age to approximately 1,000 hours in one machine and 400 and 500 hours in the others. None of the machines were operated through a complete oil cycle where an oil change was warranted based on the analysis results.

TBN measurements exhibited strong linearly decreasing relationships with oil age, as shown in Figure 4.17. The relationships between oil age, in terms of both hours operated and gallons of fuel consumed, and TBN were statistically significant at the 95 percent confidence level and are summarized in Table 4.10.

Table 4.10: Summary of TBN Degradation in Class 1854 Excavators

Oil Age Unit	TBN Degradation Rate	p-value	R^2
Hours Operated	0.19 mg KOH/g per 100 hours	0.000	0.785
Gallons Consumed	0.09 mg KOH/g per 100 gallons	0.000	0.789

Viscosity of the synthetic blend oil was fairly consistent throughout the operation of the machines and was generally within the SAE specified limits for grade 40 oil. Only one result was less than the SAE minimum of 12.5 cSt, although approximately 25 percent of the measurements were very close. The results are shown in Figure 4.18.

The measured iron and aluminum levels were significantly less than the threshold values, as shown in Figure 4.19 and 4.20. There were no indications of oil contamination.

Very low levels of oxidation and nitration were observed. The highest levels of oxidation and nitration measured were 2.2 and 3.5, respectively.

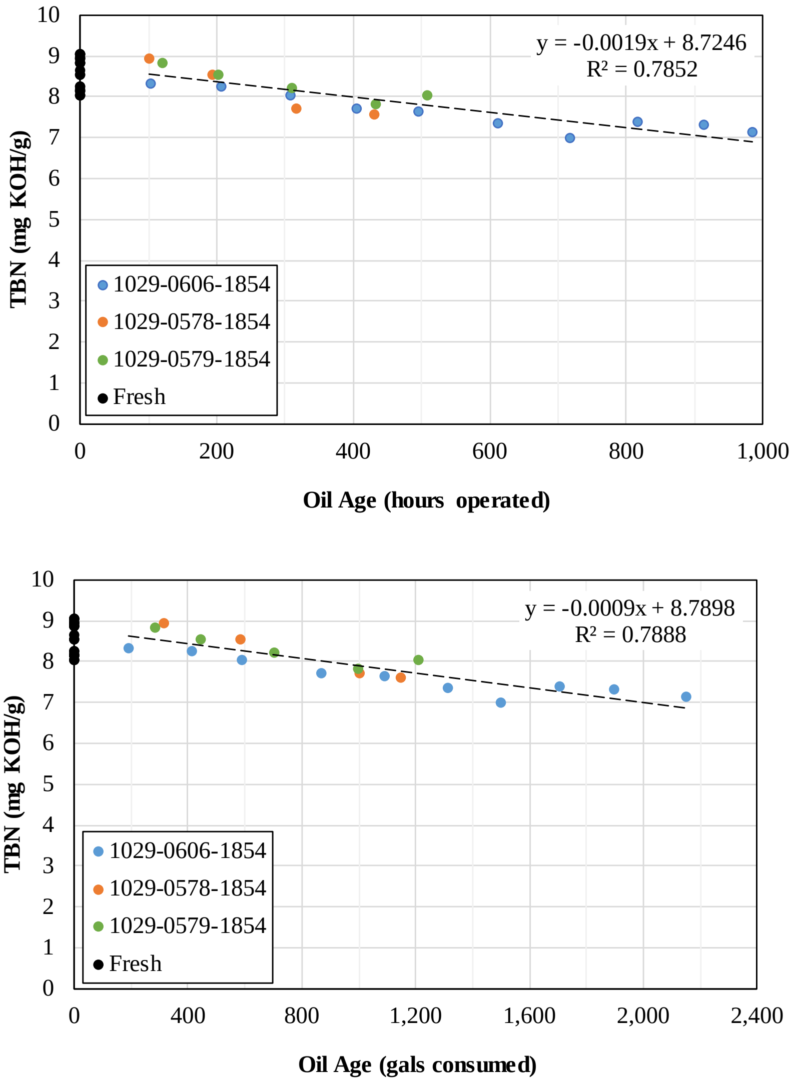


Figure 4.17: TBN of Synthetic Blend Oil in Class 1854 Excavators

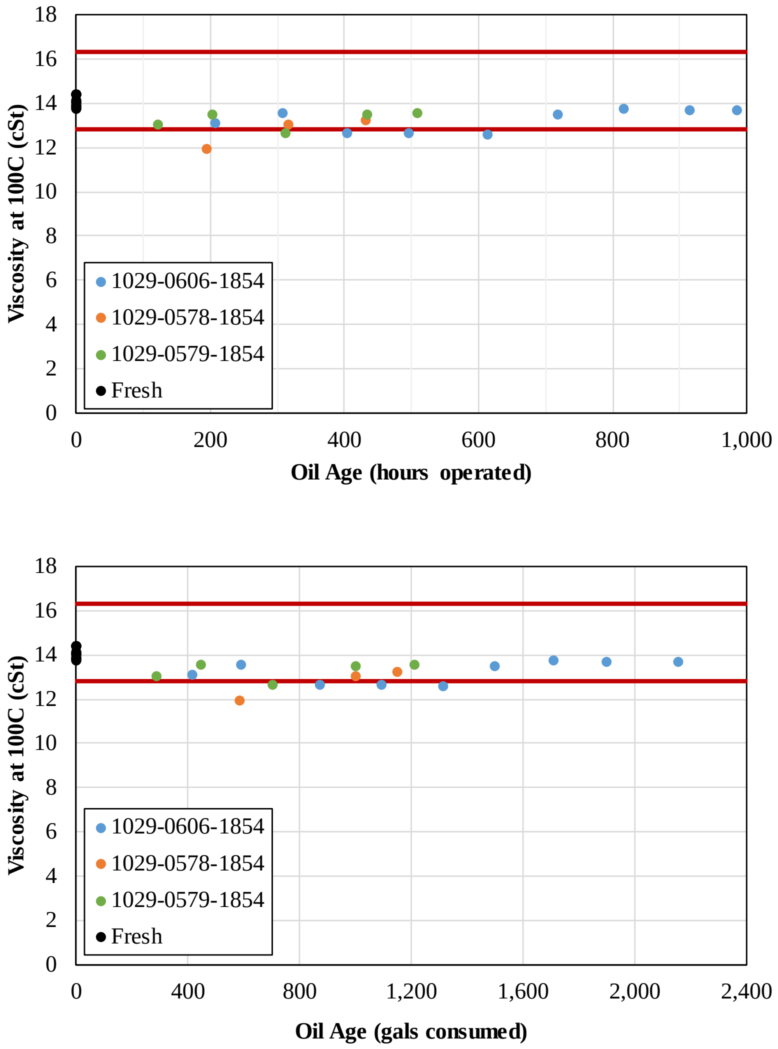


Figure 4.18: Viscosity at 100°C of Synthetic Blend Oil in Class 1854 Excavators

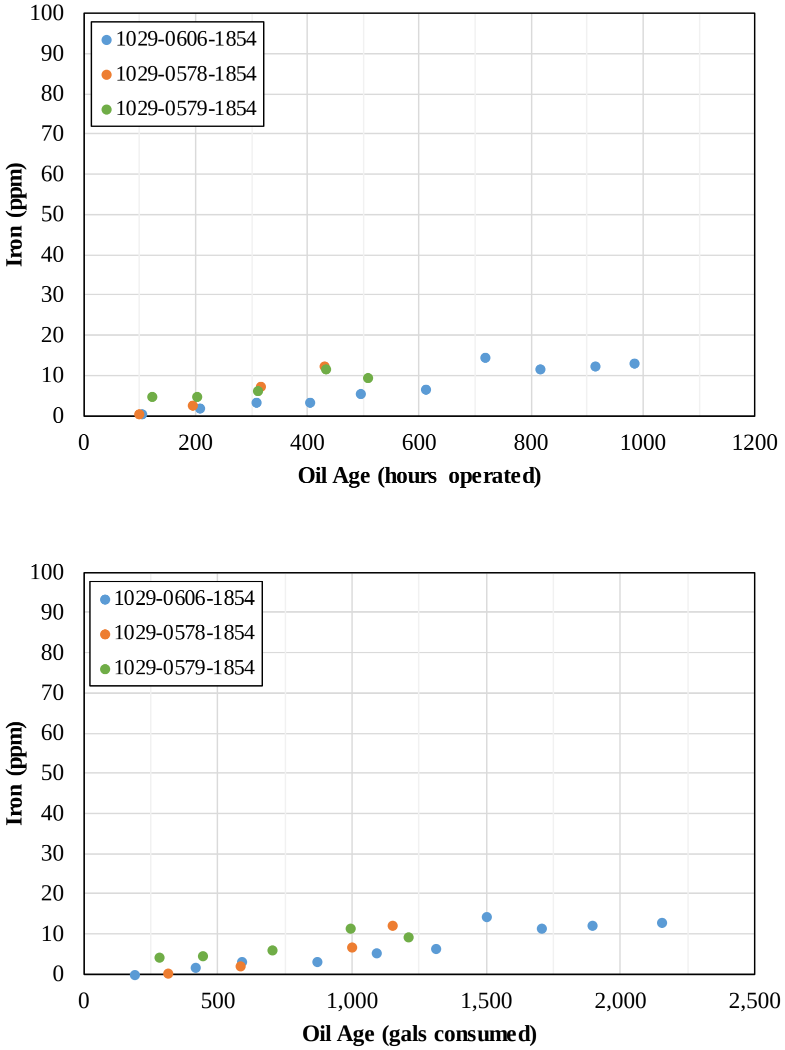


Figure 4.19: Iron Levels in Synthetic Blend Oil in Class 1854 Excavators

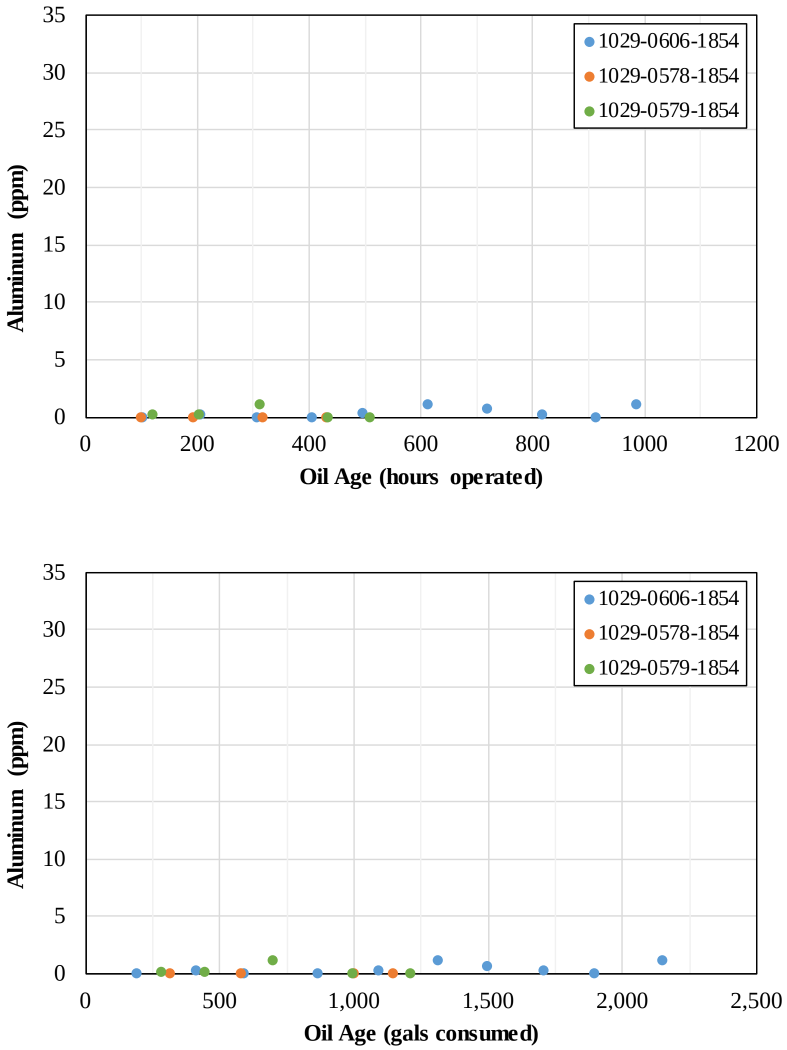


Figure 4.20: Aluminum Levels in Synthetic Blend Oil in Class 1854 Excavators

5 DISCUSSION OF EXPERIMENTAL RESULTS

The results of the experimental oil analyses indicated that the current PM program maintains the engine oil at a high level of quality and provides a high level of protection to the engines. The results obtained from the Microlab 30 oil analyzer were reliable and repeatable. The results indicated that an opportunity exists to extend the oil drain intervals for some equipment and realize economic and environmental savings.

5.1 Fresh Oil

Based on the analyses of fresh oil, the Xtreme synthetic blend 15W-40 oil is good quality. The average measured TBN was approximately 1.5 mg KOH/g lower than the published value, which results in less chemical base reserve available to neutralize acidic compounds that may form over the life of the oil. However, the results did indicate an adequate level of base reserve. The viscosity measured at 100ºC was approximately 1.9 cSt lower than the published value, but well within the SAE specifications.

Analyses of the synthetic Rotella T6 oil showed that the oil is good quality. Additionally, the average TBN and viscosity results agreed with those from the previous study. The measured TBN was approximately 1 mg KOH/g lower than the published value, and is an adequate level of base reserve. The viscosity measured at 100ºC was approximately 1 cSt lower than the published value, but well within the SAE specifications. None of the samples tested had a viscosity lower than the SAE minimum.

5.2 Verification of On-Site Analysis Results

In general, the results from the Microlab 30 agree with those obtained from the independent laboratory. While there are some discrepancies between the results, it appears that the Microlab 30 results are sufficiently reliable. It also appears that the results from the Microlab 30 are at least equal and several instances better in terms of repeatability, with the exception of additive levels (calcium, magnesium, zinc, and phosphorous).

The Microlab 30 generally produced higher readings for:

- TBN – Although on average only 0.5 to 1.0 mg KOH/g higher than the lab results, this is of interest because TBN was the primary parameter driving oil changes.
- Nitration – The results were similar, but the on-site results were approximately 4 points higher.
- Potassium – On-site results were higher, but the difference is negligible at the low levels measured.
- Calcium – Large variability observed in on-site results throughout the study.
- Zinc – Large variability observed in on-site results throughout the study.

The Microlab 30 generally produced lower readings for:

- Oxidation – On-site results were approximately half of levels reported by the lab.
- Iron – Results from both sources were tightly grouped. Difference is negligible at the low levels measured.
- Phosphorus – Large variability observed in on-site results throughout the study.
- Soot- Results are reported in different units. Lab results in number of particles > 10 μm and Microlab 30 in percent by weight.

5.3 Used Oil

Analyses of oil used in the NCDOT equipment showed that:

1. TBN was the oil quality parameter that most prominently and consistently changed with oil age. Across all equipment classes and oil age metrics, TBN decreased linearly with increasing oil age. The rate of decrease varied between equipment classes, and between machines in the same class when oil age was measured in miles driven.
2. The most common wear metals of iron and aluminum were only produced at any significant level and consistency in engines of the class 0210 trucks.
3. Viscosity did not change with oil age and was consistently measured within the SAE specified limits for 40 weight oil, or slightly less than the minimum.
4. Contamination of the oil by water, coolant, dirt, or wear metals was not observed at any significant or consistent levels.
5. Miles driven was the least effective measure of oil age when predicting TBN. Engine run time hours was the most predictive metric for the trucks. Gallons of fuel consumed was slightly better than hours operated for predicting TBN the excavators and substantially better for the backhoe loaders.

It appears based on the results of the analyses that the oil drain intervals for most of the studied equipment can be conservatively extended. However, some important limitations should be applied when considering extension of drain intervals.

5.3.1 Equipment Class 0205

The data available was limited to a single truck and an oil age of approximately 6,400 miles. The results obtained should be verified through additional testing. The TBN in the truck studied did decrease in a very linear and predictable manner. At 5,000 miles, TBN was measured at approximately 6.5 mg KOH/g. The engine in these trucks is the Navistar DT466 that was in the class 0209 trucks studied previously, although the synthetic blend oil was used by the trucks in this study. It was recommended in the study that drain intervals for these engines could be extended, with appropriate verification testing, to 10,000 miles. The limited data collected in this study supports a drain interval of 10,000 to 11,000 miles, or approximately 1,200 hours. Additional analyses should be performed in conjunction with drain interval extension to confirm adequate oil quality.

5.3.2 Equipment Class 0210

The relationship between TBN and oil age was very strong and the rate of decrease was very consistent in the studied class 0210 trucks. The relationship between TBN and hours operated was much stronger than with miles driven. TBN decreased slowly with oil age and was measured at approximately 6.0 mg KOH/g at an age of 15,000 miles (or 525 hours). The drain interval for these engines can likely be extended to at least 15,000 miles or 600 hours. At 600 hours, TBN is expected to be greater than 4 mg KOH/g, but the levels of iron and aluminum are expected to be nearing threshold levels.

5.3.3 Equipment Class 0212

The relationship between TBN and oil age was very strong and the rate of decrease was very consistent with oil age measured in hours operated. There was substantial variability in the TBN results with oil age measured in miles driven due to the inability of the metric to reflect engine idle operation. The drain interval for these engines can likely be extended to 750 hours. In terms of miles driven, the interval is conservatively recommended to be 10,000 miles to in consideration of engine idling.

5.3.4 Equipment Class 0314

The slow rate of TBN decrease and consistent viscosity measurements indicates that the oil drain interval for class 0314 backhoe loaders can be increased to 600 hours or 24 months, whichever comes first. Based on TBN alone, the drain interval could be substantially greater. TBN was measured to be greater than 7 mg KOH/g at an oil age of approximately 500 hours in two machines. Backhoe loaders in the fleet average slightly more than 300 hours of operation per year, and 600 hours is roughly equivalent to 2 years of use. There is no strong indication that the oil cannot last beyond 2 years. Oil has been in the engine of one of the studied backhoe loaders for 20 months and in another for 22 months. The analyses results for these oils indicate no question or concern for quality.

5.3.5 Equipment Class 1854

The very slow rate of TBN decrease, consistent viscosity measurements, and low levels of wear metals indicates that the oil drain interval for class 1854 excavators can be increased to at least 1,000 hours or 24 months, whichever comes first. TBN was measured to be greater than 7 mg KOH/g at an oil age of approximately 1,000 hours. Excavators in this class average slightly less than 550 hours per year of use. There is no strong indication that the oil cannot last beyond 2 years. Oil has been in the three studied excavators for over 20 months without any question or concern for quality.

5.4 Comparison of Results by Oil Type

The inclusion of the Navistar DT466 and Ford 6.7L V8 engines in both this and the previous study allows the performance of oils of different types in the same engines to be compared. HD Fleet Supreme conventional oil from the Navistar engine in the class 0209 trucks was analyzed as part of the previous study, and Xtreme synthetic blend oil was analyzed from the Navistar engine in the class 0205 trucks in this study.

TBN of conventional oil in the class 0209 trucks was observed in the previous study to not change as the oil aged to 8,000 miles. This lack of change was unique to the class 0209 trucks and TBN decreased linearly in all other equipment classes tested. The synthetic blend oil in the class 0205 trucks exhibited the typical linear decrease, although the amount of data is limited. Viscosity was measured in both the conventional and the synthetic blend oils to be near the 12.5 cSt minimum for 40 weight oil, and did not change as the oil aged. TBN and viscosity test results for oils in the Navistar DT466 engine are shown in Figures 5.1 and 5.2, respectively.

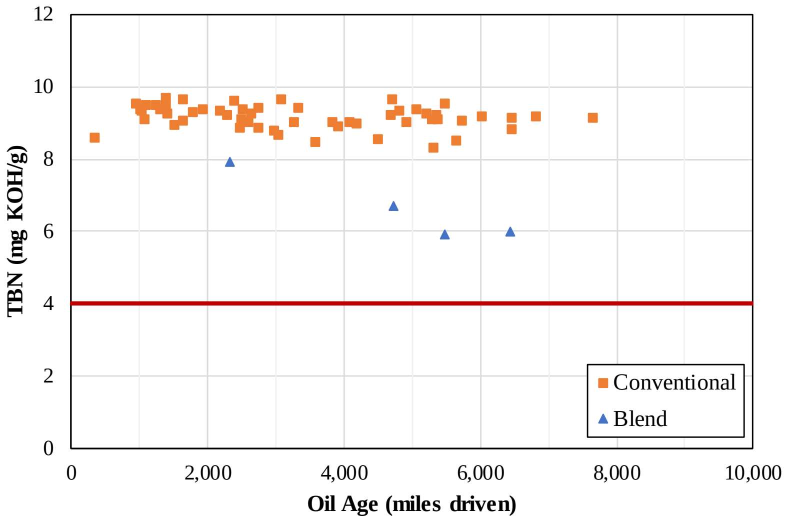


Figure 5.1: TBN of Conventional and Synthetic Blend Oils in DT466 Engines

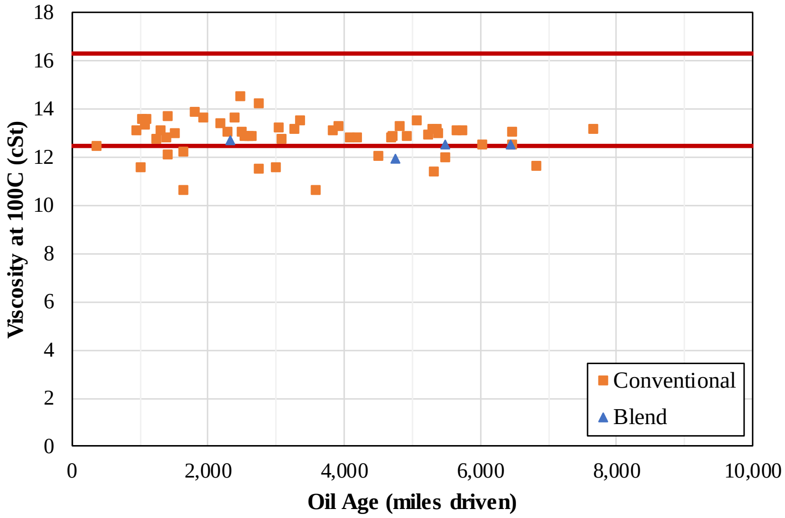


Figure 5.2: Viscosity of Conventional and Synthetic Blend Oils in DT466 Engines

HD Fleet Supreme conventional oil and Rotella T6 synthetic oil were analyzed from Ford 6.7L engines in class 0210 trucks in the previous study, and Xtreme synthetic blend oil from the class 0210 trucks in this study. Where available, engine hours and fuel data was collected from SAP for trucks from the previous study and used as a measure of oil age. However, data was not available for all trucks and was particularly limited in terms of hours operated.

TBN was similar in magnitude for all oils and exhibited a linear decrease with age. As shown in Figure 5.3, none of the oils consistently maintained a higher TBN than the others throughout its use. While the volume of measurements for conventional oil is limited, its performance is almost identical to the synthetic oil. The TBN for fresh samples of both are approximately 9.5 mg KPH/g and TBN decreased at a rate of approximately 0.4 mg KOH/g per 1,000 miles driven. Both reached a TNB of approximately 4 mg KOH/g at an age of 14,000 miles.

Fresh samples of the synthetic blend oil had a TBN of approximately 8.6 mg KOH/g and TBN decreased at approximately 0.2 mg KOH/g per 1,000 miles. This rate of decease is half of that measured for the synthetic and conventional oils, and results in a TBN of approximately 5.5 mg KOH/g at an age of 14,000 miles. At this slower rate of TBN decrease, the minimum of 4 mg KOH/g would not be reached until an age of approximately 18,000 miles.

While the synthetic blend oil tested would provide for a longer drain interval based on TBN alone, it was observed that the engines using the blend oil produced iron and aluminum in greater concentrations and at a higher rate, as shown in Figures 5.4 and 5.5. Engines using the synthetic oil produced iron at a rate that was twice that of engines using conventional oil and approximately 1.5 times that engines using synthetic oil. At the observed rate of 5.7 ppm per 1,000 miles driven, the 100 ppm limit for iron would be reached at approximately 17,500 miles. Aluminum was produced at a rate of 2.1 ppm per 1,000 miles driven, which was approximately 2.5 times greater than conventional oil and 4 times greater than synthetic oil.

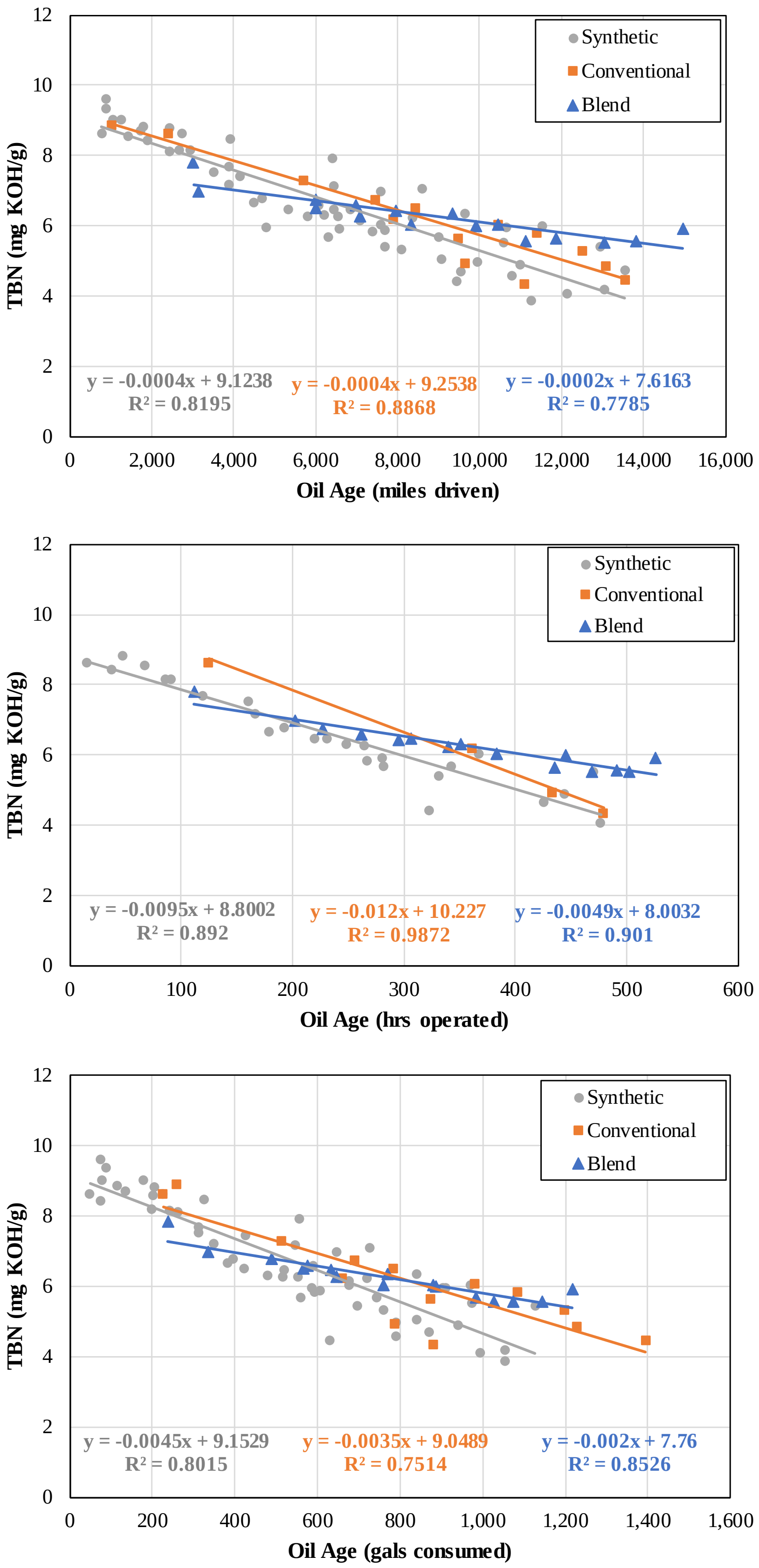


Figure 5.3: TBN of Synthetic, Blend, and Conventional Oils in Ford 6.7L Engines

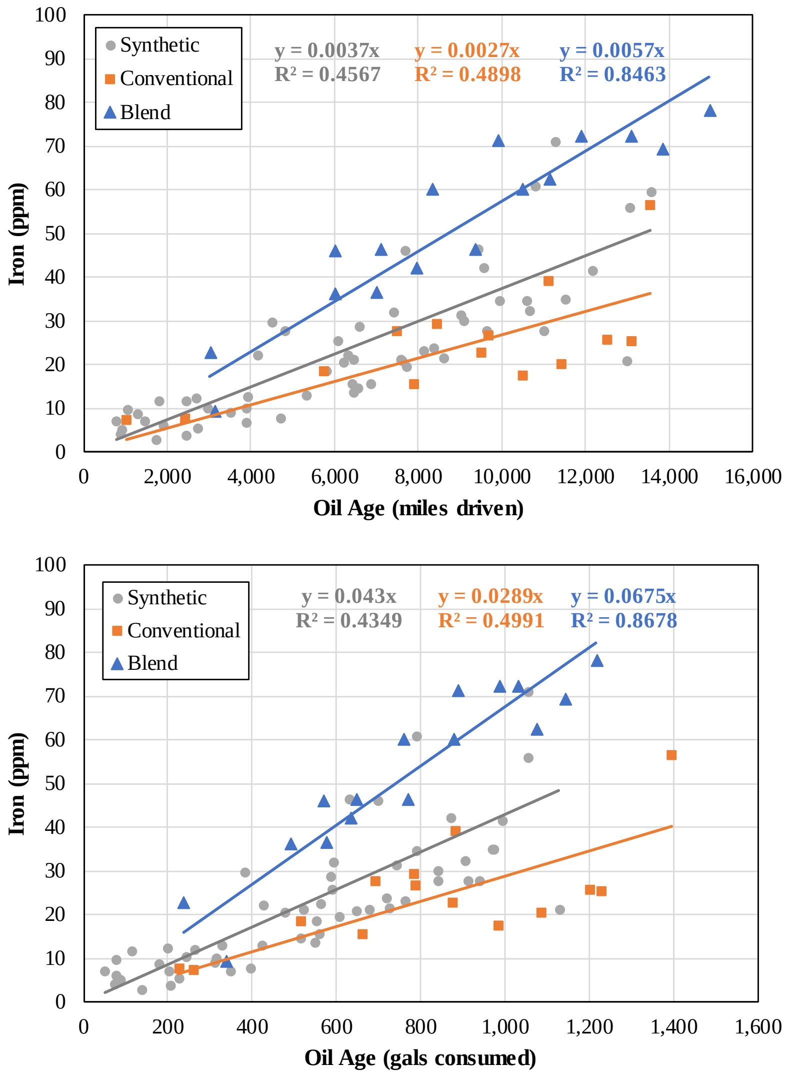


Figure 5.4: Iron Levels in Synthetic, Blend, and Conventional Oils in Ford 6.7L Engines

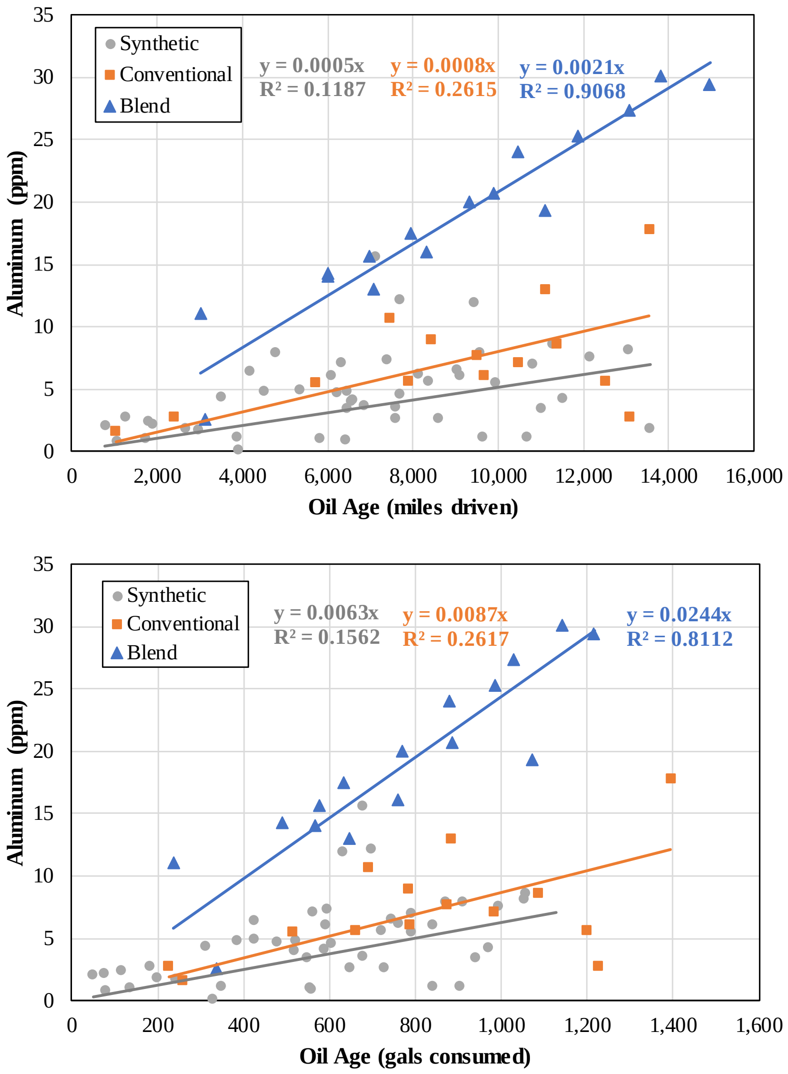


Figure 5.5: Aluminum Levels in Synthetic, Blend, and Conventional Oils in Ford 6.7L Engines

5.5 Comparison of TBN Decrease by Equipment Class

The average rate of TBN decrease was determined through linear regression for the equipment classes in this study, as well as for those in the previous study where the engine hours and fuel use data was available in SAP. The average rates are summarized in Table 5.1. The rates were almost entirely specific to the equipment class and type of oil used. In the previous study, a difference was also noted between engine types in the class 0210 trucks.

There was a similar rate of approximately 0.25 mg KOH/g per 100 gallons of fuel consumed for the synthetic blend oil in the trucks and backhoe loaders. TBN of the synthetic blend oil tended to decrease at a slower rate than the conventional and synthetic oils from the previous study.

Table 5.1: Summary of Average TBN Decrease Rates

Class	Oil	mg KOH/g per 100 hours of operation	mg KOH/g per 100 gals of fuel	mg KOH/g per 1,000 miles driven
0205	Synthetic Blend	0.42*	0.29*	0.51*
0210 6.7L Engine	Synthetic Blend	0.49	0.20	0.15
0212	Synthetic Blend	0.76	0.25	0.40
0314	Synthetic Blend	0.31	0.22	N/A
1854	Synthetic Blend	0.19	0.09	N/A
From previous project				
0209	Conventional	N/A	N/A	0
0210				
6.4L Engine	Synthetic	0.86	0.45	0.50
6.7L Engine	Synthetic	0.95	0.44	0.39
6.7L Engine	Conventional	1.20*	0.35	0.35
0303 & 0311	Conventional	0.41	0.12	N/A

* based on a small sample size

5.6 Impact of Extended Oil Drain Intervals

Extending oil drain intervals would decrease the number of oil changes required and result in positive economic and environmental impacts. To estimate the magnitude of impacts, a list of equipment matching those studied was extracted from SAP. The current meter reading for the matching equipment was extracted from SAP and used to calculate the average miles or hours the machine was operated each year. This information is summarized in Table 5.2.

Table 5.2: Summary of NCDOT Equipment by Engine

Engine	Sump (qt)	Class	No. of Machines	Avg. Annual Use
Navistar DT466 7.6L I6	30	0205	405	8,184 miles
		0206	203	5,000 miles
		0209	92	10,255 miles
		0218	3	7,192 miles
Powerstroke 6.7L V8	13	0202	3	11,834 miles
		0203	117	12,225 miles
		0204	6	13,528 miles
		0206	10	11,849 miles
		0207	2	5,060 miles
		0210	88	29,552 miles
		0211	1	19,541 miles
		0220	20	17,858 miles
		0224	67	14,535 miles
		0233	199	16,309 miles
		0234	2	19,665miles
MP7395C 11L I6	44	0212	251	12,035 miles
		0232	36	12,763 miles
		0230	3	5,399 miles
JCB 444 4.4L I4	16	0314	373	323 hours
D04FD-TAA 4.2L I4	24	1854	15	547 hours

The potential economic and environmental savings resulting from extending oil drains to the recommended intervals for studied engines is significant. To estimate the potential savings, classes with less than 10 machines were neglected due to the impracticality of implementing alternative drain intervals for a small number of machines in a class. The combined estimated savings, as shown in Table 5.3, is over $530,000 and 11,800 gallons of oil annually. Additionally, machine downtime savings exceeds 4,400 hours based on a conservative estimate of two hours per oil change.

Table 5.3: Estimated Savings from Extended Oil Drain Intervals

					Estimated Annual Savings			
Engine	**Sump (qt)**	**Cost per Oil Change**	**Class**	**No. of Machines**	**Oil Changes per Machine**	**Cost**	**Oil (gals)**	**Downtime (hrs)**
Navistar DT466 7.6L I6	30	$ 250	0205	405	1 oil change/year	$ 101,250	3,038	810
		$ 250	0206	203	None	$ 0	0	0
		$ 250	0209	92	1 oil change/year	$ 23,000	690	184
Powerstroke 6.7L V8	13	$ 170	0203	117	1 oil change/year	$ 19,890	380	234
		$ 170	0206	10	1 oil change/year	$ 1,700	33	20
		$ 170	0210	88	4 oil changes/year	$ 59,840	1,144	704
		$ 170	0220	20	2 oil changes/year	$ 6,800	130	80
		$ 170	0224	67	2 oil changes/year	$ 22,780	436	268
		$ 170	0233	199	2 oil changes/year	$ 67,660	1,294	796
MP7395C 11L I6	44	$ 400	0212	251	1 oil change/year	$ 100,400	2,761	502
		$ 400	0232	36	1 oil change/year	$ 14,400	396	72
JCB 444 4.4L I4	16	$ 300	0314	373	1 oil change/year	$ 111,900	1,492	746
D04FD-TAA 4.2L I4	24	$ 250	1854	15	1 oil change/year	$ 3,750	90	30
Total						**$ 533,370**	**11,882**	**4,446**

6 ESTIMATE OF RESEARCH BENEFIT-COST RATIO

The ratio of potential benefits to costs of implementing the results of this research project were estimated based on the model developed by Nicholas et al. (2017) and is calculated by:

$$BC = \frac{K * (HB + SB)}{RC + IC}$$

Where:

BC = Benefit-cost ratio for research and implementation efforts
K = Impact constant
HB = Value of annualized "hard" benefits
SB = Value of annualized "soft" benefits
RC = Cost of the research project
IC = Cost of research implementation

The impact constant (K) is calculated as:

$$K=1 + IF$$

Where:

IF = Impact factor based on qualitative benefits of the research

The impact factor (IF) is the weighted sum of qualitative impact factors and is calculated as:

$$IF = 0.19(K_i) + 0.18(IR_i) + 0.17(E_i) + 0.15(GS_i) + 0.16(V_i) + 0.15(PC_i)$$

Where:

K_i = Level of knowledge gained
IR_i = Implementation of research products
E_i = Experienced gained between NCDOT and the researcher
GSi = Student participation and exposure
V_i = Positive visibility of NCDOT
PC_i = Publications of research results

IF was calculated to be 1.56 for this project based on the following qualitative impact factors:

K_i = 1; the project resulted in new knowledge
IR_i = 0.33; the results have not been fully implemented
E_i = 0.33; NCDOT personnel gained experience by working with the researchers
GSi = 0.67; two graduate research assistants worked on the project
V_i = 0.33; limited communication to stakeholders regarding the project
PC_i = 0.67; results have been disseminated at three conferences across the country

The annualized value of the "hard" benefits (*HB*) is the estimated costs savings of \$533,370. The annualized value of the "soft" benefits (*SB*) was estimated based on the reduced exposure to injury by NCDOT shop personnel due to the decreased number of oil changes. The injury incident rate for repair and maintenance personnel is 2.6 incidents per 100 full-time workers, which equates to 2.6 incidents per 200,000 hours worked (Bureau of Labor Statistics, 2016). Implementation is estimated to reduce the time required for oil drains by 4,446 hours annually, which equates to the elimination of 0.057 incidents annually. This is equivalent to $1,850 in savings annually, based on an average injury incident cost of $32,000 (National Safety Council, 2018).

The cost of this two year research project was $198,670 and required purchase of the Microlab 30 at a cost of $80,000. Therefore, *RC* is $99,335 and *IC* is $40,000.

Based on the estimated benefits and costs, *BC* is calculated as:

$$BC = \frac{1.56 * (533{,}370 + 1{,}850)}{(99{,}335 + 40{,}000)} = 6.0$$

7 SUMMARY AND CONCLUSIONS

Extended oil drain intervals were implemented for machines in five NCDOT equipment classes as part of an experimental PM designed to monitor the quality of engine oil and assess degradation rates. Samples of fresh synthetic and synthetic blend oils were collected and analyzed to establish a baseline of oil quality. Used oil samples were periodically collected from the machines as the oil aged, and oil age was monitored in terms of miles driven, hours operated, and gallons of fuel consumed. The Microlab 30 on-site oil analyzer was used to measure metal levels with optical emission spectroscopy, physical properties with infrared spectroscopy, and viscosity with a dual temperature viscometer. The analysis results obtained through on-site analysis were verified through comparison with results for duplicate samples analyzed by an independent laboratory. The experimental results provided a basis for understanding and quantifying changes with age in oil quality in terms of chemical degradation, viscosity degradation, and contamination. The observed degradation rates were also compared with similar results obtained from the previous study by Hildreth and Tymvios (2016). The following conclusions were drawn from this research:

1. The existing PM program with oil changes scheduled at intervals of 5,000 miles for vehicles, 200 hours for equipment, or annually if the miles/hours threshold is not met serves the NCDOT machines well and provides adequate protection against failure. Oil at these ages had measured TBN values well above the 4 mg KOH/g minimum threshold, viscosity within the SAE standards, and no substantial evidence of contamination.
2. The Microlab 30 on-site oil analyzer performed well. Over 300 samples were analyzed for this study with no significant issues experienced. The Microlab 30 is effectively an updated version of the OSA4 TruckCheck used previously and did not return negative values for very low metal concentrations as the OSA4 did. The repeatability of the results obtained was very good. However, substantial variability was noted in the additive levels measured. The results from the Microlab 30 are sufficiently reliable based on the general agreement with results obtained from the independent laboratory.
3. The Xtreme synthetic blend 15W-40 oil and Rotella T6 5W-40 synthetic oil are both good quality oils and performed well in the tested machines. Analyses of samples of fresh oils showed adequate levels of chemical base reserve to neutralize acidic compounds and viscosity within the SAE standards for 40 weight oil. Both oils had TBN and viscosity measurements lower than the typical values published by the manufacturer, but both were acceptable.
4. The measured viscosity of the oils was consistent throughout its use and did not degrade. Viscosity was generally measured to be near or slightly below the SAE minimum of 12.5 cSt. Viscosity less than the minimum was most prevalent in the class 0212 trucks where approximately 40 percent of measurements were below the minimum.
5. The oils chemically degraded with age. TBN values were observed to decrease linearly as oil age increased, and the rate of decrease varied by equipment class. The predictive ability of models varied with the metric used to quantify oil age. Engine run time hours was the metric most predictive of TBN for the trucks, while gallons of fuel was most predictive for equipment. Miles driven was the metric least predictive of TBN for the trucks.

6. The tested machines were not subject to significant contamination of the oil by water, glycol, soot, dirt, or wear metals. Trace amounts of water, glycol, soot, or silicon were only occasionally detected in the sampled oil.
7. There is opportunity to extend oil drain intervals beyond the existing 5,000 miles or 200 hours program without significant danger of unacceptable oil quality. Oil analyzed at the 5,000 miles or 200 hours age were not contaminated, had TBN values indicating sufficient chemical base reserve, and viscosity was measured within the SAE standards.
8. The potential benefits to be realized from extending oil drain intervals for machines in the NCDOT fleet that are similar to those tested are substantial. It was conservatively estimated that over $530,000, over 11,800 gallons of oil, and over 4,400 hours of downtime can be saved annually.

8 RECOMMENDATIONS

The primary recommendation resulting from this research extended oil drain intervals should be considered for machines in the tested equipment classes with the same engine type and size included in the experimental program. Based on the oil analyses performed, specific recommendations are as follows:

6. Trucks with the Navistar DT466 engine in various classes – Consider extending the drain interval for these engines to 10,000 miles or 1,200 hours. Additional testing is required to confirm the results obtained and that this recommended drain interval is appropriate.
7. Trucks with the Ford 6.7L engine – Consider using the synthetic blend oil in these engines as it performed better than the previously tested synthetic and conventional oils. Also consider extending the oil drain interval to 15,000 miles or 600 hours.
8. Model GU713 Mack trucks – Consider defining the oil drain interval in terms of hours operated and extending interval to 750 hours. If the PM schedule is maintained in terms of miles drive, consider extending it to 10,000 miles.
9. Class 0314 JCB backhoe loaders with the JCB 444 engine – Consider extending the drain interval to 600 hours of operation or 24 months.
10. Class 1854 excavators with the Hyundai 4.2L engine – Consider extending the drain interval to 1,000 hours of operation or 24 months.

The above recommended drain intervals are all predicated on use of the synthetic blend oil tested in this study. For all machines on extended oil drain intervals, oil analysis should be performed at least at the time of oil change to confirm that the oil quality has been maintained and is sufficient to provide protection to the engine. Additionally, it is recommended that machines on extended oil drain intervals be operated at least once per month to prevent dry starts and to deter rust accumulation in the engine. Machines should be operated under load a sufficient period of time that they come to normal operating temperature to burn off any accumulated moisture.

Extending oil drain intervals may impact equipment warranties. It is recommended that any and all PM actions be performed to maintain a valid warranty.

The annual savings resulting from extending the oil drain intervals for the engines tested was estimated to be over $530,000, over 11,800 gallons of oil, and over 4,400 hours of downtime. It is recommended that similar research be conducted on machines in additional equipment classes to investigate further potential savings within the NCDOT fleet.

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APPENDIX A – EQUIPMENT LIST

Table A1: NCDOT Equipment in the Experimental Program

Class	Equipment ID	Inventory No.	Year	Make	Model	Engine	Sump Capacity (qt)	Meter at Start		
								Miles	Hours	Fuel
0205	30155246	1094-7007-0205	2008	International	7300SFA	Navistar DT466 7.6L I6	30	54,717	2,570	8,490.0
	30166500	1094-7054-0205	2009	International	7300SFA	Navistar DT466 7.6L I6	30	73,362	4,066	59,446.5
	30166501	1094-7055-0205	2009	International	7300SFA	Navistar DT466 7.6L I6	30	103,366	20,451	16,502.4
	30166502	1094-7056-0205	2009	International	7300SFA	Navistar DT466 7.6L I6	30	82,612	4,261	13,792.9
0210	30265513	1462-2295-0210	2013	Ford	F350	Powerstroke 6.7L V8	13	135,006	5,225	11,251.2
	30265514	1462-2296-0210	2013	Ford	F350	Powerstroke 6.7L V8	13	110,473	3,536	8,713.0
0212	30230524	1490-0131-0212	2012	Mack	GU713	MP7395C 11L I6	44	75,842	2,480	13,566.2
	30245526	1490-0202-0212	2013	Mack	GU713	MP7395C 11L I6	44	64,358	3,478	12,978.2
	30265566	1490-0264-0212	2014	Mack	GU713	MP7395C 11L I6	44	39,635	2,444	8,419.6
0314	30152039	1803-0069-0314	2007	JCB	3C15	JCB 444 4.4L I4	16		3,452	6,663.8
	30244591	1803-0358-0314	2012	JCB	3C15	JCB 444 4.4L I4	16		2,080	3,813.4
	30262000	1803-0375-0314	2013	JCB	3C15	JCB 444 4.4L I4	16		1,618	3,768.8
1854	30168002	1029-0578-1854	2008	Hyundai	R140LC7A	D04FD-TAA 4.2L I4	24		3,536	10,534.6
	30168500	1029-0579-1854	2008	Hyundai	R140LC7A	D04FD-TAA 4.2L I4	24		3,469	8,814.2
	30240506	1029-0606-1854	2012	Hyundai	R140LC9	D04FD-TAA 4.2L I4	24		2,516	5,664.2

APPENDIX B – BASELINE ANALYSIS RESULTS OF FRESH OIL

Table B1: Xtreme Synthetic Blend 15W-40 Fresh Oil Physical Parameters

Sample ID	TBN (mg KOH/g)	Viscosity @ 100C (cSt)	Viscosity @ 40C (cSt)	Viscosity Index	Ox	Nit	Sulf	Water (% by wt)	Glycol (% by wt)	Fuel (% by wt)	Soot (% by wt)
26	8.20				0.0	1.5	0.0	0.0	0.0	1.8	0.0
27	8.26				0.0	0.8	0.0	0.0	0.0	0.4	0.1
28	8.06				0.0	1.1	0.0	0.0	0.0	0.0	0.1
29	8.66				0.0	1.0	0.0	0.0	0.0	0.6	0.1
30	8.56				0.0	0.9	0.0	0.0	0.0	0.2	0.1
31	8.56				0.0	0.9	0.0	0.0	0.0	0.2	0.1
1049	8.26				0.0	0.3	0.0	0.0	0.0	0.0	0.1
1050	8.16				0.0	0.1	0.0	0.0	0.0	0.0	0.1
1051	8.06				0.0	0.4	0.0	0.0	0.0	0.0	0.1
1052	8.16				0.0	0.2	0.0	0.0	0.0	0.0	0.1
1053	8.06				0.0	0.8	0.0	0.0	0.0	0.0	0.1
1054	8.16				0.0	0.7	0.0	0.0	0.0	0.0	0.1
1097	9.00	14.1	101.8	141	0.0	1.9	0.0	0.0	0.0	2.8	0.0
1098	8.96	14.0	98.9	144	0.0	1.5	0.0	0.0	0.0	2.0	0.1
1099	9.06	14.1	102.3	141	0.0	1.0	0.0	0.0	0.0	1.4	0.1
1100	8.96	14.0	102.3	139	0.0	1.1	0.0	0.0	0.0	1.5	0.1
1101	9.06	14.1	100.6	142	0.0	0.7	0.0	0.0	0.0	1.4	0.1
1102	9.06	14.1	101.1	142	0.0	0.8	0.0	0.0	0.0	1.5	0.1
1109	8.86	13.7	100.6	136	0.0	1.1	0.0	0.0	0.0	0.0	0.1
1110	8.86	13.9	101.4	139	0.0	1.4	0.0	0.0	0.0	0.0	0.1
1111	8.86	13.8	99.4	141	0.0	1.3	0.0	0.0	0.0	0.0	0.1
1112	8.96	13.8	100.1	139	0.0	1.1	0.0	0.0	0.0	0.0	0.1
1113	9.06	13.8	95.2	147	0.0	1.0	0.0	0.0	0.0	0.0	0.1
1114	8.86	13.9	98.2	144	0.0	1.1	0.0	0.0	0.0	0.0	0.1
Average	**8.61**	**13.9**	**100.2**	**141**	**0.0**	**0.9**	**0.0**	**0.0**	**0.0**	**0.6**	**0.1**
Median	**8.76**	**13.9**	**100.6**	**141**	**0.0**	**1.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**
Min	**8.06**	**13.7**	**95.2**	**136**	**0.0**	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Max	**9.06**	**14.1**	**102.3**	**147**	**0.0**	**1.9**	**0.0**	**0.0**	**0.0**	**2.8**	**0.1**

Table B2: Xtreme Synthetic Blend 15W-40 Fresh Oil Metals

Sample ID	Fe (ppm)	Al (ppm)	Cr (ppm)	Cu (ppm)	Pb (ppm)	Sn (ppm)	Ni (ppm)	Ti (ppm)	Mn (ppm)	Si (ppm)	Ba (ppm)	V (ppm)
26	0.24	0.00	1.52	2.43	0.00	0.00	0.05	0.00	1.72	2.47	0.00	10.21
27	0.00	0.00	1.94	1.21	0.00	0.00	0.00	0.00	0.95	1.79	0.00	11.87
28	0.00	0.01	1.97	0.96	0.00	0.00	0.00	0.00	1.07	1.06	0.00	13.55
29	0.00	0.00	0.98	1.12	0.00	0.00	0.00	0.00	1.63	0.97	0.00	16.31
30	0.00	0.16	0.95	1.00	0.00	0.00	0.05	0.00	1.13	1.98	0.00	17.81
31	0.00	0.15	1.00	0.03	0.00	0.00	0.00	0.00	0.78	0.73	0.00	16.35
1049	0.05	0.00	0.18	0.78	0.00	0.00	0.00	0.00	1.21	0.90	0.00	14.87
1050	0.04	0.00	0.32	0.07	0.00	0.00	0.14	0.00	1.91	0.82	0.00	13.43
1051	0.11	0.00	0.16	1.64	0.00	0.00	0.00	0.00	1.88	0.80	0.00	15.61
1052	0.00	0.06	0.33	1.69	0.00	0.00	0.00	0.00	1.16	1.31	0.00	17.21
1053	0.00	0.00	0.08	2.43	0.00	0.00	0.00	0.00	0.99	1.23	0.00	16.01
1054	0.00	0.00	0.09	0.81	0.00	0.00	0.15	0.00	1.54	0.60	0.00	18.41
1097	0.19	0.00	0.13	4.07	0.00	0.00	0.00	0.00	1.41	0.00	0.00	20.76
1098	0.00	0.00	0.00	3.26	0.00	0.00	0.00	0.00	1.20	0.00	0.00	18.98
1099	0.00	0.00	0.00	1.94	0.00	0.00	0.00	0.00	1.31	0.00	0.00	16.89
1100	0.00	0.00	0.00	1.20	0.00	0.00	0.00	0.00	0.86	0.00	0.00	18.63
1101	0.17	0.00	0.81	0.00	0.00	0.30	0.06	0.00	1.21	0.00	0.00	8.21
1102	0.15	0.00	0.00	0.00	0.00	0.74	0.00	0.00	1.23	0.00	0.00	17.73
1109	0.00	0.00	0.00	2.04	0.00	0.00	0.00	0.00	0.85	0.00	0.00	17.21
1110	0.06	0.00	0.38	1.90	0.00	0.81	0.00	0.00	1.24	0.00	0.00	16.46
1111	0.00	0.00	0.00	5.04	0.00	0.00	0.00	0.00	1.13	0.00	0.00	23.83
1112	0.00	0.00	0.00	3.31	0.00	0.48	0.00	0.00	1.23	0.00	0.00	0.00
1113	0.00	0.00	0.00	1.83	0.00	2.11	0.00	0.00	1.05	0.00	0.00	15.15
1114	0.01	0.00	0.00	2.59	0.00	0.00	0.00	0.00	1.20	0.00	0.00	0.00
Average	**0.04**	**0.02**	**0.45**	**1.72**	**0.00**	**0.18**	**0.02**	**0.00**	**1.24**	**0.61**	**0.00**	**14.81**
Median	**0.00**	**0.00**	**0.14**	**1.67**	**0.00**	**0.00**	**0.00**	**0.00**	**1.21**	**0.30**	**0.00**	**16.33**
Min	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.78**	**0.00**	**0.00**	**0.00**
Max	**0.24**	**0.16**	**1.97**	**5.04**	**0.00**	**2.11**	**0.15**	**0.00**	**1.91**	**2.47**	**0.00**	**23.83**

Table B3: Xtreme Synthetic Blend 15W-40 Additives

Sample ID	Mo (ppm)	B (ppm)	Mg (ppm)	Ca (ppm)	Z (ppm)	Na (ppm)	K (ppm)	P (ppm)
26	58.89	800.00	402	1899	1404	0.00	7.31	1388
27	56.83	800.00	386	1983	1410	0.00	10.68	1362
28	59.24	800.00	374	1872	1410	0.00	12.18	1269
29	55.89	242.15	673	1984	1496	0.00	25.61	1350
30	49.09	224.22	644	1875	1460	0.00	24.56	1478
31	48.35	215.86	617	1817	1444	0.00	24.31	1289
1049	66.08	800.00	141	1923	1526	0.10	19.85	1469
1050	63.11	800.00	138	1981	1603	0.00	17.20	1496
1051	70.28	800.00	141	2004	1561	0.00	18.49	1447
1052	77.55	800.00	141	2020	1542	0.00	17.85	1466
1053	76.33	800.00	142	1945	1539	0.21	16.80	1515
1054	70.59	800.00	138	1982	1564	0.00	13.72	1406
1097	71.10	38.95	1188	1568	1885	4.64	16.35	522
1098	71.18	37.34	1233	1692	1801	3.17	18.32	489
1099	61.69	38.03	1101	1529	1744	2.78	17.22	488
1100	59.44	34.88	1098	1561	1795	0.17	16.80	498
1101	11.39	7.21	132	689	760	0.00	2.18	182
1102	47.58	33.66	1028	1457	1694	1.31	16.26	452
1109	41.77	32.57	1006	1111	3106	0.00	17.38	1348
1110	45.88	26.51	1051	1182	3273	0.29	17.76	1449
1111	54.06	36.40	1121	1231	3563	0.00	14.37	1596
1112	52.13	31.59	1071	1170	3219	0.00	21.85	1528
1113	48.02	25.81	1039	1126	3037	0.71	19.79	1309
1114	52.54	25.49	1093	1245	3399	0.00	21.17	1552
Average	**57.04**	**343.78**	**671**	**1619**	**1968**	**0.56**	**17.00**	**1181**
Median	**57.86**	**127.40**	**658**	**1755**	**1583**	**0.00**	**17.30**	**1375**
Min	**11.39**	**7.21**	**132**	**689**	**760**	**0.00**	**2.18**	**182**
Max	**77.55**	**800.00**	**1233**	**2020**	**3563**	**4.64**	**25.61**	**1596**

Table B4: Rotella T6 5W-40 Fresh Oil Physical Parameters

Sample ID	TBN (mg KOH/g)	Viscosity @ 100C (cSt)	Viscosity @ 40C (cSt)	Viscosity Index	Ox	Nit	Sulf	Water (% by wt)	Glycol (% by wt)	Fuel (% by wt)	Soot (% by wt)
1032	9.52				1.4	1.1	0.0	0.0	0.1	0.0	0.2
1033	9.62				1.3	0.8	0.0	0.0	0.1	0.0	0.2
1034	9.52				1.3	1.0	0.0	0.0	0.1	0.0	0.2
1035	9.52				1.4	0.9	0.0	0.0	0.1	0.0	0.2
1036	9.62				1.3	0.8	0.0	0.0	0.1	0.0	0.2
1037	9.62				1.2	0.7	0.0	0.0	0.1	0.0	0.2
1071	9.52				1.1	1.1	0.0	0.0	0.1	0.0	0.2
1072	9.52				1.0	1.1	0.0	0.0	0.1	0.0	0.2
1073	9.52				1.0	1.1	0.0	0.0	0.1	0.0	0.2
1074	9.62				1.1	0.9	0.0	0.0	0.1	0.0	0.2
1075	9.62				1.1	0.9	0.0	0.0	0.1	0.0	0.2
1076	9.62				1.0	0.9	0.0	0.0	0.1	0.0	0.2
1091	9.46	13.00	80.55	161	0.4	1.8	0.0	0.1	0.0	0.0	0.1
1092	9.52	13.05	81.28	163	0.7	1.4	0.0	0.0	0.0	0.0	0.2
1093	9.52	12.90	79.32	164	1.0	1.1	0.0	0.0	0.1	0.0	0.2
1094	9.52	12.90	79.57	162	1.1	1.2	0.0	0.0	0.1	0.0	0.2
1095	9.42	13.00	79.81	164	0.9	1.2	0.0	0.0	0.1	0.0	0.2
1096	9.62	12.85	79.32	164	1.0	0.8	0.0	0.0	0.1	0.0	0.2
1118	9.42	13.47	82.30	168	1.9	0.5	0.0	0.0	0.1	0.0	0.2
1119	9.52	13.31	80.76	167	1.8	0.4	0.0	0.0	0.1	0.0	0.2
1120	9.42	13.21	81.27	165	1.9	0.5	0.0	0.0	0.1	0.0	0.2
1121	9.52	13.41	83.33	164	1.9	0.4	0.0	0.0	0.1	0.0	0.2
1122	9.62	13.31	81.01	167	1.9	0.1	0.0	0.0	0.1	0.0	0.2
1123	9.42	13.41	82.30	166	1.8	0.8	0.0	0.0	0.1	0.0	0.2
Average	**9.53**	**13.15**	**80.90**	**165**	**1.3**	**0.9**	**0.0**	**0.0**	**0.1**	**0.0**	**0.2**
Median	**9.52**	**13.13**	**80.88**	**164**	**1.2**	**0.9**	**0.0**	**0.0**	**0.1**	**0.0**	**0.2**
Min	**9.42**	**12.85**	**79.32**	**161**	**0.4**	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**
Max	**9.62**	**13.47**	**83.33**	**168**	**1.9**	**1.8**	**0.0**	**0.1**	**0.1**	**0.0**	**0.2**

Table B5: Rotella T6 5W-40 Fresh Oil Metals

Sample ID	Fe (ppm)	Al (ppm)	Cr (ppm)	Cu (ppm)	Pb (ppm)	Sn (ppm)	Ni (ppm)	Ti (ppm)	Mn (ppm)	Si (ppm)	Ba (ppm)	V (ppm)
1032	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.28
1033	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	17.58
1034	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	18.74
1035	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.56	0.00	0.00	21.49
1036	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.59	0.00	0.00	20.95
1037	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.00	0.00	22.07
1071	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.47	0.00	0.00	16.06
1072	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.00	0.00	14.07
1073	0.00	0.00	0.00	0.66	0.00	0.60	0.00	0.00	0.40	0.00	0.00	16.86
1074	0.06	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.78	0.00	0.00	18.93
1075	0.10	0.00	0.00	3.11	0.00	0.98	0.26	0.00	0.69	0.00	0.00	19.00
1076	0.03	0.00	0.00	1.63	0.00	0.00	0.32	0.00	0.76	0.00	0.00	20.41
1091	2.62	0.00	0.00	2.86	0.00	1.73	0.00	0.00	0.86	0.00	0.00	20.97
1092	0.72	0.00	0.00	1.95	0.00	0.76	0.00	0.00	1.15	0.00	0.00	20.74
1093	0.00	0.00	0.00	1.54	0.00	0.00	0.00	0.00	1.00	0.00	0.00	17.78
1094	0.18	0.00	0.00	3.08	0.00	0.00	0.00	0.00	1.80	0.00	0.00	0.00
1095	0.00	0.00	0.00	2.27	0.00	0.00	0.00	0.00	0.86	0.00	0.00	20.58
1096	0.22	0.00	0.00	4.11	0.00	0.00	0.00	0.00	1.25	0.00	0.00	20.47
1118	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.46	0.00	0.00	19.71
1119	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.00	0.00	16.98
1120	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.99	0.00	0.00	17.70
1121	0.00	0.00	0.00	0.65	0.00	0.00	0.00	0.00	1.15	0.00	0.00	14.73
1122	0.00	0.00	0.00	0.04	0.00	0.16	0.00	0.00	1.81	0.00	0.00	17.05
1123	0.00	0.00	0.00	1.77	0.00	0.24	0.00	0.00	1.28	0.00	0.00	24.68
Average	**0.16**	**0.00**	**0.00**	**0.99**	**0.00**	**0.19**	**0.02**	**0.00**	**0.76**	**0.00**	**0.00**	**18.12**
Median	**0.00**	**0.00**	**0.00**	**0.05**	**0.00**	**0.00**	**0.00**	**0.00**	**0.73**	**0.00**	**0.00**	**18.84**
Min	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Max	**2.62**	**0.00**	**0.00**	**4.11**	**0.00**	**1.73**	**0.32**	**0.00**	**1.81**	**0.00**	**0.00**	**24.68**

Table B6: Rotella T6 5W-40 Fresh Oil Additives

Sample ID	Mo (ppm)	B (ppm)	Mg (ppm)	Ca (ppm)	Z (ppm)	Na (ppm)	K (ppm)	P (ppm)
1032	31.50	55.32	1232	1027	1484	7.03	20.94	1342
1033	34.05	60.80	1316	1126	1592	4.70	22.29	1414
1034	34.63	58.69	1262	1025	1500	7.59	22.34	1348
1035	41.88	63.80	1438	1195	1632	7.45	25.27	1496
1036	41.30	63.69	1388	1186	1598	7.71	25.51	1497
1037	42.07	63.68	1386	1185	1611	8.53	23.20	1546
1071	43.58	55.33	1237	1217	1701	6.03	23.78	1176
1072	46.66	60.31	1307	1179	1712	7.45	24.25	1132
1073	51.86	61.84	1311	1205	1754	7.42	24.22	1145
1074	51.32	61.86	1295	1226	1864	7.91	22.81	1247
1075	58.39	62.64	1287	1163	1743	5.60	24.67	1271
1076	58.77	63.36	1374	1306	1805	6.17	25.03	1258
1091	60.11	58.26	1486	1059	1944	5.35	19.70	502
1092	59.24	61.04	1465	1089	1852	7.45	21.06	527
1093	58.16	60.32	1431	1061	1713	9.50	19.75	441
1094	62.19	62.20	1530	1195	1952	8.48	21.42	524
1095	59.37	62.38	1453	1159	1801	7.03	21.21	473
1096	69.23	63.76	1563	1173	1860	8.00	24.52	525
1118	34.08	56.49	1166	1002	1585	5.12	23.96	1292
1119	35.73	58.70	1157	1009	1583	9.06	27.26	1251
1120	37.16	59.60	1180	1047	1731	8.88	25.41	1367
1121	38.40	63.16	1180	995	1669	9.56	15.66	1445
1122	40.32	62.07	1241	1086	1775	9.17	15.44	1537
1123	43.48	64.05	1227	1071	1774	8.82	18.60	1542
Average	**47.23**	**60.97**	**1330**	**1124**	**1718**	**7.50**	**22.43**	**1137**
Median	**43.53**	**61.85**	**1309**	**1143**	**1722**	**7.52**	**23.00**	**1265**
Min	**31.50**	**55.32**	**1157**	**995**	**1484**	**4.70**	**15.44**	**441**
Max	**69.23**	**64.05**	**1563**	**1306**	**1952**	**9.56**	**27.26**	**1546**