ENGINE OIL ANALYSIS ON THE NORTH CAROLINA DEPARTMENT OF TRANSPORTATION FLEET

by

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CODY WARREN BEAL. Engine oil analysis on the North Carolina Department of Transportation Fleet. (Under the direction of DR. JOHN HILDRETH)

Preventative maintenance is a key component in maintaining fleet quality. Engine oil provides thermal management, wear protection, and corrosion resistance functions that optimize engine performance and life. Engine oil quality degrades through the result of chemical change and contaminants. The rate at which the oil degrades determines the frequency at which the engine oil should be changed. Engine oil is changed to combat contaminants and oil degradation, and to maintain a quality necessary to protect the engine

This thesis presents the results on an extended oil drain interval program on selected equipment, done to quantify engine oil degradation and contamination. Conventional mineral oil (Conoco HD Fleet Supreme® 15W-40) and synthetic oil (Rotella® T6 5W-40) were studied. The results show that the existing interval of 5,000 miles can be extended. The synthetic oil was tested on class 0210 trucks (6.4L and 6.7L engines). There is a significant difference in oil performance and chemical degradation between the 6.4L and 6.7L engines. The 6.4L engine oil had an approximate life of 8,000 miles, whereas the 6.7L engine oil had an approximate life of 12,500 miles. Class 0209 trucks operated using conventional mineral oil and had no significant chemical or physical changes up to approximately 6,500 miles. It was found that degradation rates for class 0303 and class 0311 tractors engine oil, both physical and chemically, occurred at the same rate. The intervals for class 0303 tractors were able to be extended out to approximately 250 hours and for class 0311 tractors were extended out to approximately 450 hours. Both classes of oil quality still measured well above the threshold limits.

ACKNOWLEDGEMENTS

"Trust in the Lord with all your heart, and lean not on your own understanding; in all your ways acknowledge Him, and He shall direct your paths." Proverbs 3:5-6

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Lubricating oil is the life blood of an engine with the engine oil performing critical functions, such as wear protection, thermal management, and corrosion inhibition necessary to maintain performance and maximize useful service life. Mineral and synthetic are the two basic oil types offered today for use in vehicles and heavy equipment. Regardless of the type of engine oil used, engine oil quality decreases throughout its useful life. The American Petroleum Institute (API) sets the standards for parameters on engine oil contaminants and bulk properties, providing stringent requirements insuring that the engine oil meets qualifications to minimize wear and contamination in engine oil. Heavy equipment operates under different conditions that affect oil performance, such as heat, cold, extended idle time, airborne contaminants and larger engine loads. Excessive internal heat can cause faster breakdown of oil, causing sludge deposits and altering the bulk properties of the oil as well as creating a greater demand in the cooling system. This increases the chance of coolant contamination of the engine oil. Cold weather or extended idle times can limit the ability of the engine oil to lubricate at start up, allowing unwanted moisture and unburned fuel to enter into the oil resulting in fuel dilution and inadequate lubrication (FMC 2010).

Since oil is such a vital aspect to the quality of an engine, it is repetitively drained and replaced at predetermined and fixed intervals as part of a preventative maintenance program to counter degradation and contamination of the engine oil. These regular fixed intervals result in increased labor, maintenance cost, and downtime for equipment. The cost to provide oil replacement and the reduced production that results due to equipment down time drives the need to determine if engine oil drain intervals can be extended.

The economy resulting from extended drain intervals must be balanced with the increased risk of potential engine damage resulting from poor oil performance. There is a need to examine and understand oil performance in terms of the rate of degradation and contamination of engine oil over its period of use. Measured oil quality must be compared to carefully establish threshold values for selected performance metrics to estimate appropriate drain intervals.

This research is significant because of the very large fleets that are maintained and used on a daily basis. North Carolina Department of Transportation (NCDOT) operates and maintains a fleet of off-road and on-road equipment that includes approximately 7,900 motor driven machines. Six to seven percent of the annual operating budget for the NCDOT is spent on engine oil and preventative maintenance labor for on-road and off-road equipment. NCDOT's current preventative maintenance program does not include regular engine oil sampling and analysis, and the oil quality is not considered when scheduling engine oil changes, which can result in unnecessary expenditures associated with engine oil changes.

CHAPTER 2: LITERATURE REVIEW

Fleet and equipment services impact the cost and delivery of almost every project. A quality preventative maintenance (PM) plan ensures the quality of the fleet and equipment services. A scheduled preventative maintenance plan is a systematic method of proactive inspections of equipment, including services and repairs, before a failure can happen. Preventative maintenance plans produce a decrease in reactive maintenance plans, which are a request for repair that are written after the operator has completed the job. Preventative maintenance plans also lead to a decrease in repair cost, because if a preventative maintenance plan is in place for equipment, the repair cost is usually minimal (Milwaukee 2008). This periodic servicing of equipment is important to maintaining a reliable high quality fleet, ensuring the equipment has minimum downtime (Milwaukee 2008). Preventative maintenance plans are commonly predetermined base preventative maintenance plans, which utilize parameters that are measured at a predetermined interval to maintain performance based off the manufacture’s specifications or other external sources (Bernspang and Kali 2011). Fleet managers often customize their own personal preventative maintenance intervals based on past performance of similar equipment, with similar demands such as extreme temperature changes and working conditions.

Preventative maintenance schedules can consist of many different intervals, with each maintenance interval reflecting on different aspects of that certain piece of equipment. Keller (2014), identifies that a predetermined preventative maintenance interval is broken down into the four sections which are shown below:

- PM A – "Safety Inspection", generally consist of inspecting components such as brakes, lights, tires, and fluids, including but not limited to, engine oil, hydraulic fluid, antifreeze and transmission fluid. Normal inspection intervals are 1,500 to 2,500 miles for light vehicles and 5,000 to 10,000 miles for heavy vehicles (Keller 2014).
- PM B – Includes PM A plus recommendation to the air filter, engine oil and oil filter replacement. Typical service intervals are 3,000 to 5,000 miles for light vehicles and 5,000 to 10,000 miles for heavy vehicles (Keller 2014).
- PM C – PM C is commonly an annual inspection. This includes PM A and PM B and also includes front end alignment, scheduled component replacement and annual department of transportation inspection (Keller 2014).
- PM D – Includes PM A-C, and usually consist of scheduled rebuild or replacement of major equipment component (engine, transmission, etc.). PM D can included special maintenance to equipment such as winterization or summarization (Keller 2014).

A primary component of a preventative maintenance plan includes engine oil. Engine oil performs critical functions that are necessary to maintain performance and maximize useful service life (FMC 2010). With equipment operating in different environments, engine oil replacement intervals become important in maintaining quality equipment. Optimization of oil change intervals can be an effective way to save money and the environment. Not only can the number of oil changes be decreased and thereby reducing the amount of engine oil used, but the wear of the engine and its components, and the downtime of equipment can be decreased as well. Extending oil drain intervals without a carefully planned program is gambling with the life of the engine, therefore carefully planned programs need to be implemented (MacAllister, 2014).

Engine oils are complex mixtures of base oils and additives designed to perform a variety of tasks: reducing engine wear, helping to prevent deposits that form from internal engine components and, separating and lubricating moving parts (PennzOil 2014). Engine oil is a formulated blend of base oils and additives that are designed to meet required performance criteria. Engine oil's primary component is base oils, which are 75 to 99 percent by volume of oil (Basu, et al. 2000). Engine oil is termed either mineral or synthetic oil depending on the process by which the base oil is derived. Mineral oil is a petroleum base oil derived from crude oil. Synthetic oil is from a polyalphaolefin (PAO) base oil, which is a synthesized hydrocarbon. Synthetic oils have high viscosity indices and superior cold flow characteristics (Bergstra, et al. 1998). To enhance engine oil performance additives are used, these additives are commonly friction and wear modifiers, antioxidants and corrosion inhibitors, and detergents (Caines and Haycock 1996). Another function of engine oil is to act as a cleaning agent in the engine by flushing contaminants from critical components. Engine oil cleans and disperses sludge and oxidation that can buildup on piston rings and seals (Cummins 2007).

Engine oil degradation can come from either chemical changes in the oil chemistry or changes in viscosity. Chemical degradation comes from chemical reactions of the base oils with oxygen and nitrogen that form compounds through depletion of additives from reactions with contaminants (Jun, et al. 2006). Viscosity degradation can either be an increase or decrease in viscosity. Decreased viscosity can result from mechanical degradation, where as an increase in viscosity can be the result from intrusion of soot into the oil from blow-by (Troyer 1999).

Contamination in engine oil is the occurrence of impurities in the oil. Contamination results from wear metals, dirt (silicon), fuel, water or glycol. Wear metals are generated from internal engine components; friction between metal surfaces produces metal shavings inside of the engine. Common metals that make up engine components are iron, copper, aluminum, lead, tin, and chromium. Contamination within the engine can result from dirt, fuel, glycol, and water. These contaminants can have an abrasive action within the engine components when the oil is circulated in the engine. These contaminants combined with wear metals can alter the oil's viscosity and cause the formation of acids which can lead to internal engine corrosion.

Engine oil is a critical component to the life of an engine. Engine oil intervals can be observed using many different techniques. The parameters shown below are typically measured and analyzed as a method to determine the oil intervals for equipment (Milwaukee 2008):

- Time – This is a frequently used system for on-road equipment, where the equipment is serviced by hours and can be serviced daily, monthly, quarterly, semi-annually or annually (Milwaukee 2008). Time is used as an indicator for service intervals, if equipment travel distance is unknown.
- Mileage – A common method for on-road equipment used for service intervals, scheduled services are check after traveling a predetermined distance. Predetermined mileage service intervals are most effective when equipment is

used for the same work, or for vehicles that have high mileage applications (Milwaukee 2008).

- Hours – A method for off-road equipment, where predetermined service intervals are based off hours of use is for vehicles/equipment that have high hourly rates, without having a demand for high mileage use. Engine hours often indicate trends in wear, and is often used for PM intervals (Milwaukee 2008).
- Fuel Consumption – Fuel consumption is a method for off-road equipment. This method realistically reflects engine wear, especially when combined with recorded travel distance and operating hours. Fuel consumption allows a fleet manger to determine how hard the equipment is being used (Milwaukee 2008).

Engine oil must be changed regularly to combat contamination and degradation and, to provide engine protection. Over the years, the rule of thumb was to change a vehicle's engine oil every 3,000 miles (DMV 2014). Diesel vehicles recommended oil change interval is approximately 5,000 miles. Whereas for heavy equipment oil change is recommended either at 250 hours (Caterpillar 1998) or at 5000 miles (NCDOT 2014). The current NCDOT program does not include regular oil sampling and analyzing. Continuous sampling and analyzing is critical in determining optimal drain intervals, considering drain intervals can vary with different pieces of equipment that are powered by diesel engine.

With the advancement of computerized analysis equipment, engine oil analysis can be economically valuable, but it is not often done. When these equipment are used to examine engine oil intervals, utilizing criteria such as, new oil sample analysis and regular interval analysis. The new oil sample represents a baseline of the oil and its characteristics. Continuous interval sampling produces a trend that reflects the degradation of the engine oil. If continuous interval sampling is not completed, the results may be misleading and hard to interpret. Trends in wear metals also are not a full representation of the oil sample, but rather the condition of the engine, therefore baseline and regular drain intervals are needed (Anonymous 2009).

Bulk properties, wear protection and contamination are the main focus to keeping quality equipment with adequate engine oil service life. These aspects of oil provide key information on engine quality and efficiency. Knowing these specific properties of engine oil, drain intervals can be altered to achieve maximum efficiency.

2.1 Bulk Properties

Engine oil has bulk properties that are formulated with a variety of additives to enhance the lubricity and to reduce the tendency for sludge and deposit formations (Tribology 2004). To access the amount of additives remaining in a used oil sample, the total base number and viscosity are checked. A reduction of the total base number allows the user to know the additives are being depleted and the oil is becoming acidic. Whereas the measure of degrading viscosity allows the user to know when the oil has reached its useful life when it changes SAE grades (Tribology 2004).

2.1.1 Total Base Number

Total Base Number (TBN) is an important property of engine oil that quantifies alkalinity of an oil. Engine oils have high alkalinity levels that can neutralize the acids that are generated by combustion of an engine or blow-by. Blow-by occurs when there are gaps between the piston rings and engine cylinders, allowing fuel to fall into the crankcase where the engine oil is. When the alkalinity of the oil is depleted, the oil can become very acidic and corrode engine parts (Fitch and Troyer 2010). The depletion of the alkalinity of the oil is caused by a physical lubricant change (Mobil 2009). Engine oils that are designed for extended operations to perform in severe conditions are produced with higher alkalinity levels. High alkalinities allow the engine oil to avoid corrosion in oil-wetted parts of the engine.

2.1.2 Viscosity

Viscosity is defined as resistance to flow. Viscosity change can result in either physical change or contamination by other fluids (Mobil 2009). Increase of viscosity can result in loss of wear protection which comes from primarily high-temperatures and high-load service. Decrease in viscosity can cause corrosion or sludge in the engine, this is primarily caused from winter conditions or repeated short-trips. The most common viscosity test is at 100°C and is recorded in centistokes (cSt).

2.2 Wear Protection

Wear metal analysis can indicate which engine components are wearing at an excessive rate to alert when the wearing is becoming significant. Wear metals are represented in parts per million (ppm). The most common elements found in an engine are iron, aluminum, chromium, lead and copper (Tribology 2004). Wear metals vary with the engine type and oil product. They are also dependent on engine speed and air charging. Wear metals should be evaluated for trends such as increasing, decreasing and sudden and gradual change (Stauffer, F.).

- Iron

  Increasing levels of iron may indicate wear from shafts, piston rings and gears. This could also come from the break-in of the engine. Increase of iron could also come from rust particles in the cooling system, causing them to leak into the engine (Stauffer, F.).

- Aluminum

Aluminum increases can vary from many different components. The main sources that cause an aluminum increase are scorning or burning of the aluminum pistons, aluminum bearing wear, or dirt contamination to aluminum parts causing abrasion (Stauffer, F.).

- Chromium

Chromium can increase when water is present, even if there is a cooling leak in the engine. Chrome plated pistons rings or valves can cause an increase in the particle count. This increase can also be caused by engine wear or scoring and scuffing of the piston rings (Stauffer, F.).

- Copper

Increase of copper can come from bearing wear, which may be in conjunction with the main bearing and connecting rods, pistons pins, and camshaft. The presence of glycol, attacks the copper components causing them to break down (Stauffer, F.).

2.3 Contamination

When engine oil is contaminated it can cause damage in various different ways to engine parts. Contamination, by definition, is anything that is foreign to the original oil chemistry. Engine oil can be contaminated by various ways; it can be generated within the motor or enter through the air filter. Contamination of the engine oil, robs the life and quality of the oil, leading to failure (Fitch and Troyer 2010). When engine oil becomes contaminated, the oil must be changed because it can no longer adequately perform its intended function within the engine. Oil contamination can also result from normal engine operation. The load factor, fuel used and environmental conditions all have a direct effect on the rate of oil contamination (Cummins 2007).

2.3.1 Fuel Dilution

Fuel dilution comes primarily from blow-by which occurs in the engine's crankcase. Extended oil drain intervals, improper operation or engine malfunction can cause fuel dilution. Fuel dilution can affect the properties of oil in many different ways. It can cause premature oxidation, which affects the stable hydrocarbons of the oil. Premature oxidation can lead to sludge, increased viscosity or acid increase in the engine. If blow-by occurs and fuel is present in the oil, oil viscosity rises due to the increasing amount of heavy molecules in the oil. Whereas if raw fuel is being leaked into the oil the viscosity decreases. If fuel dilution is 10 percent in any engines oil, it will cause a 10 percent loss in any additives to the oil, and a reduction in viscosity by more than 36 percent (Fitch and Troyer 2010). There are two primary tests that can obtain information to quantify fuel dilution. The first test is flash point testing. If the flash point has a reduction of 20-30° C this means that the oil sample has critical fuel dilution. The second test is with an FTIR Spectroscopy, this uses infrared spectra that can find the presence of fuel in lubricants (Fitch and Troyer 2010).

2.3.2 Water Contamination

Water contamination is one of the most destructive contaminants that can cause engine oil to fail, resulting in engine component failure. Oil will dissolve a small amount of water depending on the types of additives to the oil. When water reacts with additives, it can form precipitants and create aggressive chemical by-products, by a process called hydrolysis. Water also increases the rate of oxidation. Oxidation produces chemically unstable compounds from the stable oil hydrocarbons. Oxidation causes corrosive acids, resins and sludge; these can accumulate in piping, coolers, filters, valves and oil reservoirs.

Since water acts as a catalyst to promote oxidation when in contact with common engine metals (iron, copper and lead), it can lead to pitting on the surfaces of the metals. Gradual loss of oxidation stability over an extended drain interval is normal, but it should not be allowed to progress too far (Fitch and Troyer 2010). When water accumulates in reservoirs and sumps, microorganisms and bacterial growth can occur (AMSOIL 2010). These organisms feed off the oil additives and can grow into thick biomasses and lead to corrosion, clogged filters, and surface deposits. Water contamination weakens the load-bearing strength of the oil; leading to premature wear of bearings, gears, and pistons. (Fitch and Troyer 2010). Finding the source of water contamination is difficult because water enters from cooling system leaks, lower operating temperatures, outside water contamination, poor crankcase ventilation and frequent shutdowns (Stauffer, F.). Two ways to analyze water contamination is the Karl Fisher Test (ASTM D1744) and by distillation (ASTM D95) (Kaleli 1998). The Karl Fischer test relies on chemical reactions and electric current to measure the amount of water in an oil sample (AMSOIL 2010).

2.3.3 Silicon

Silicon can accumulate from dust, dirt or silicon-based gaskets (Evans 2012). Elevated silicon levels usually come from dirt contamination caused by faulty intake filtration (Cummins 2007). It can also result from low oil levels, contamination from engine work and leaks in piping (Stauffer, F). Silicon particles are non-metal but have abrasive behavior to the engine components (SynMAX). Dirt or dust is not made up of purely silicon dioxide, but of many other compounds. Another compound that is commonly found in dirt is aluminum trioxide. If dirt is identified in an oil analysis reading then an increase in the aluminum particle count should be expected. Since dirt is abrasive an increase of general wear should be seen in the analysis; along with an increase of iron, chromium, lead and copper. If silicon increases but aluminum does not increase, then dirt is not the source of silicon (Evans 2012).

2.3.4 Soot

Fuel soot is formed of carbon and is typically found in diesel engine oil. The fuel soot level will indicate the engine's combustion efficiency (Tribology 2004). Soot is a solid contamination which can be both suspended and non-suspended in the oil. When the soot levels are too high, this can cause the oil's viscosity to increase or prematurely breakdown and promote engine wear. This breakdown and increase in viscosity can also lead to clogged pipe lines and filters (Stauffer, F). Soot contamination is caused by irregular injection timing, blow-by or burning fuel that is mixed with oil on the cylinder liner (Cummins 2007). When the additives are depleted the soot particles attach to each other to make larger particles. This can influence valve and injection wear to occur at an accelerated rate. When these rates are increased this can lead to elevated levels of iron in the metal count (Cummins 2007). Soot percentage can be measured using a Fourier Transform Infrared (FTIR) Spectroscopy, optical soot meters or viscosity test. The FTIR Spectroscopy test uses infrared energy because soot absorbs it. (Fitch and Troyer 2010).

2.3.5 Glycol

Glycol, also known as ethylene or propylene glycol, is a combination of antifreeze and water that can enter into the engine system (AMSOIL 2010). It can cause engine seizures, engine failure and oil starvation if not detected at an early stage. Glycol can enter through the coolant system due to cracks in the engine head and liner or failures in O-rings and gaskets. This can occur while the engine is running or when the engine is cooling after shutdown (Stauffer, F). Elevated levels of glycol are not always detected because it can react with certain additives and boil off at operating temperatures. Deteriorated glycol, which forms at normal engine operating temperatures reacts with bearing and bushing materials to form elevated levels of lead in the oil (Cummins 2007). Glycol can rapidly attack copper, which can be found in bearings and cause early bearing failure. Glycol also causes increased viscosity, forms gels and emulsions, increases in oxidation and forms “oil balls” that are hard and abrasive (Fitch and Troyer 2010). Two tests that can be used to determine if glycol is present in an oil sample is the elemental spectroscopy test, viscosity test and an onsite test using the Schiff’s Reagent Method (ASTM D2982) (Fitch and Troyer 2010).

2.4 Previous Research

Although there is a common understanding on when engine oil needs to be changed on predetermined intervals and common threshold variables, there has been minimal research in evaluating extended drain intervals. Kaleli implemented a new test to evaluated specific properties of oil, such as oxidation stability, changes in viscosity and wear characteristics (Kaleli 1998). It is advantageous to know how the characteristics of the engine oil and how the engine components are changing without having to dismantle the engine. This allows a user to determine the chemical and physical changes of engine oil to predict engine wear. Kaleli (1998) determined that iron levels correlated with engine oil deterioration. In these tests, an engine operated with engine oil samples being taken at every 2000 kilometers (1242.74 miles). Viscosity, flashpoint, total base number and iron levels where recorded and graphed. Figures 1 through 3 show the iron levels, total base number and viscosity compared to trip length in an extended oil drain intervals of a gasoline engine.

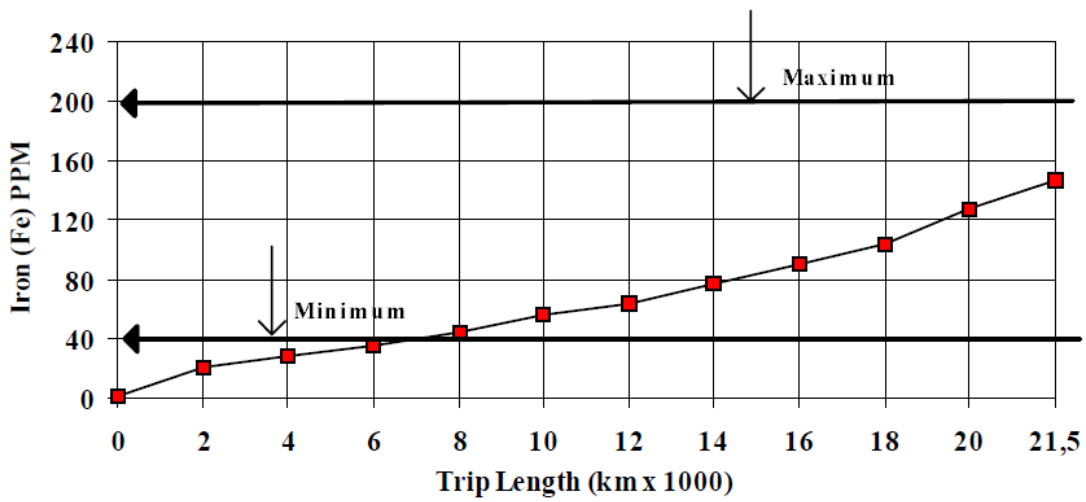

FIGURE 1 : Iron level wear and trip length in a gasoline engine (Kaleli 1998)

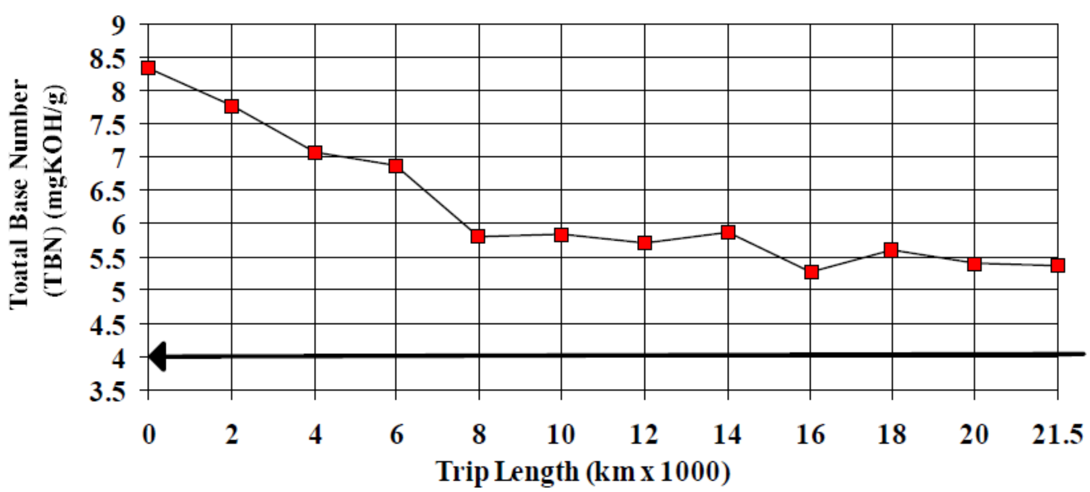

FIGURE 2 : Total base number and trip length in a gasoline engine (Kaleli 1998)

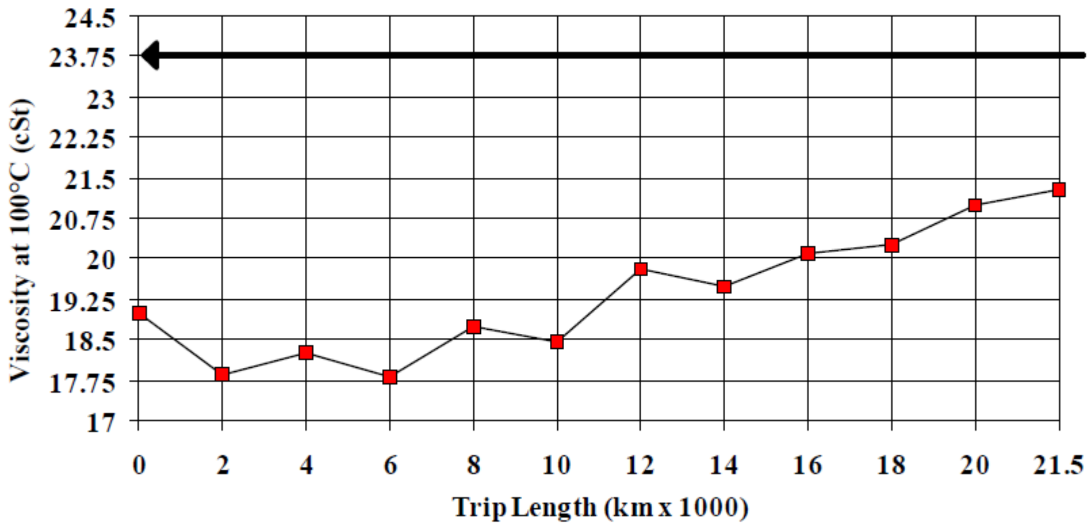

FIGURE 3 : Viscosity (100°C) and trip length in a gasoline engine (Kaleli 1998)

It was found that optimal extended oil drain period could be extended to 11,000 kilometers (6835.08 miles), overall decreasing the amount of engine oil changes. It was determined that when the oil drain interval was increased the oil cost decreased, but the overhaul cost per km increased (Kaleli 1998).

In September of 1979, R.M Hosie and D.A Lawrence published Field Experience of Extended Oil Drain Intervals in off-Highway Diesel Engines. This was an investigation into extending engine oil drain intervals in a fleet of large off-highway vehicles engaged in open-cast mining operations (Hosie and Lawrence 1979). In 1977, it became apparent that the politico-economic factors of central Africa would limit the supply of lubricants, therefore extended drain intervals were tested. The test consisted of using 12 100-ton haul trucks, 6 with engines that had more than 3000 hours and 6 fitted with newly-rebuilt engines. These trucks ran for 1500 hours without an oil change, five times the original equipment manufacturers service recommendation, with engine oil samples taken every 80 hours while idling (Hosie and Lawrence 1979). The oil analysis data consisted of the qualitative assessment of alkalinity (total base number), contaminations and viscosity, by oil-spot test and fuel dilution. Wear metals (iron, chromium, copper, and lead) and air-borne contaminants (silicon) where tested using spectrophotometry (Hosie and Lawrence 1979). Figure 4 and figure 5 represent the quantitative data of the 12 tested trucks variability with respect to hours of use:

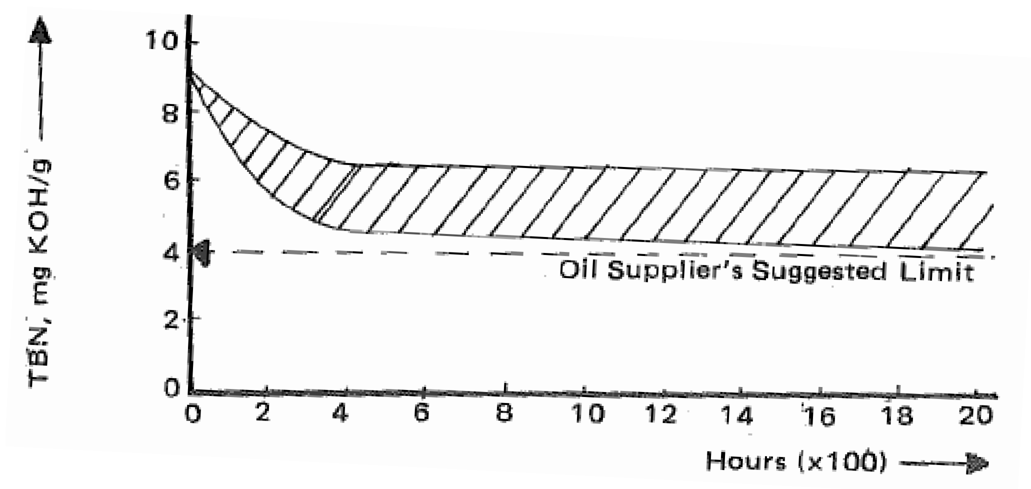

FIGURE 4 : Total base number with respect to hours operated
(Hosie and Lawrence 1979)

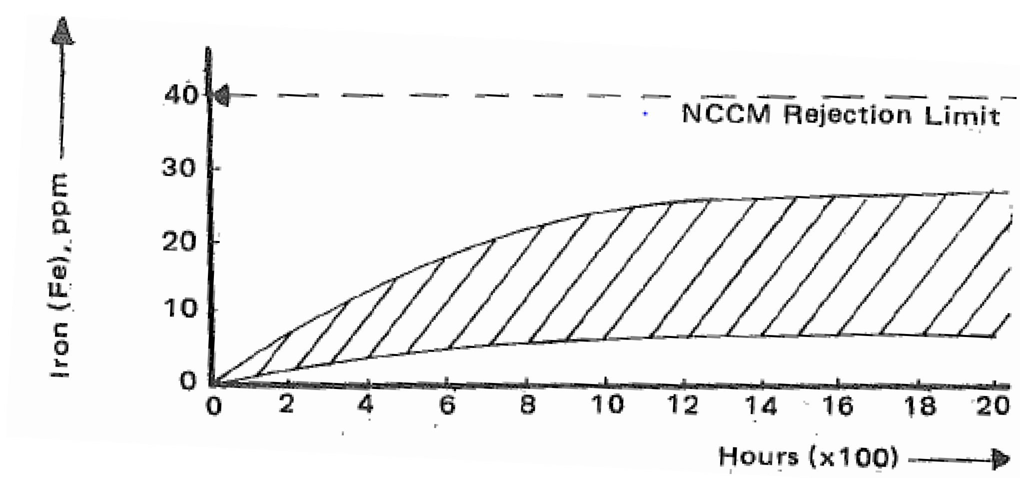

FIGURE 5 : Iron (ppm) with respect to hours operated (Hosie and Lawrence 1979)

Performance of diesel engines is limited to their economic life, which the lubricating engine oil is expected to control. In the investigation, it is shown that lubricating engine oils can give indefinite oil drain intervals for that particular diesel engine. In conclusion, there was no discernable differences in engine performance between the trucks on normal drain intervals and trucks with extended intervals (Hosie and Lawrence 1979). R.M. Hoise and D.A. Lawrence concluded that the severe contamination was caused by fuel dilution, coolant and abrasion, which are largely controlled by engine maintenance. The practice of unlimited oil drain may be applied as a standard in similar engines. This reduction of engine oil changes could potentially reduce the annual oil consumption by 50 percent as well as a reduction in the cost associated with the disposal of waste oil. Other potential savings were found in maintenance cost and equipment downtime with the extended oil drain intervals (Hosie and Lawrence 1979).

Mobil Technology Company, conducted an extended oil drain performance capabilities test on diesel engine oils. Four different engine oils were tested in a fleet of 59 trucks over a period of two to three years. Four test oils where used in the evaluations and consisted of standard reference oil (blue), premium mineral diesel engine oil (red), synthetic diesel engine oil (silver) and premium synthetic diesel engine oil (white). All test oils met the requirements of that latest API heavy-duty diesel engine category CG-4, including the premium and synthetic oils, which exceeded the requirements (Jetter, et al. 1998). The fleet of 59 trucks was tested in four locations of the U.S and Canada, with two different engine types being used. All test trucks where calibrated to meet the 1994 U.S. emissions regulations and were used in long haul, moderate to severe service. During the trial, two to four different oils were randomly selected and assigned to each fleet. Standard oil was tested to 40,000 miles, premium diesel engine oil was tested to 50,000 miles and the synthetic and premium synthetic diesel engine oils were tested to 100,000 miles. The test trucks had sample intervals at every 10, 000 miles of use. Oil analysis was completed at the intervals to determine the condition of the oil, as well as the used oil filters to analyze the structural integrity of the filter housing and filter media (Jetter, et al. 1998). Total base number and viscosity, along with wear protection as indicated by wear metals and contaminations such as water, coolant and soot levels were analyzed. Figures 6 through 8 present the trends found by the Mobil Technology Company.

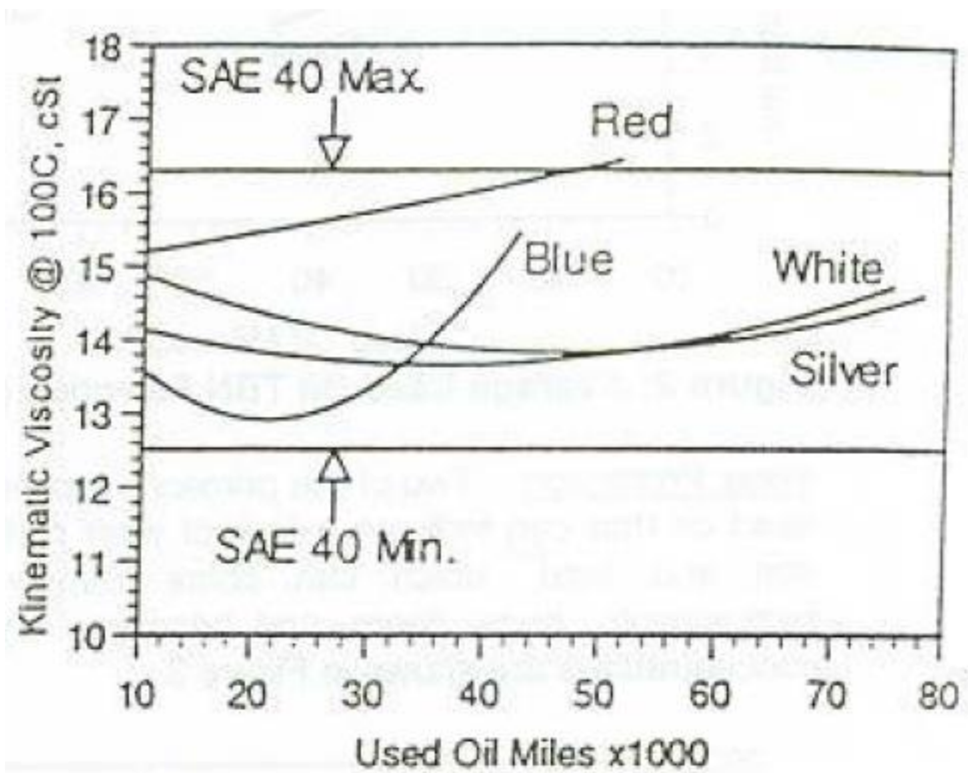

FIGURE 6 : Average viscosity with respect to miles on oil (Jetter, et al. 1998)

Viscosity of all engine oils, except red stayed within the range of SAE 40 grade oil criteria. While the blue oil was getting near the end of its use life, the red oil shows a linear trend and approaches the upper limit of its viscosity grade at 50,000 miles. Both synthetic oils, silver and white, remained within the limits of SAE 40 grade oil to 75,000 miles, primarily due to the properties of synthetic base oils ability to handle soot and increase oxidation stability (Jetter, et al. 1998). Kinematic viscosity tests of all oils shows that these oils can maintain satisfactory conditions under extended drain intervals.

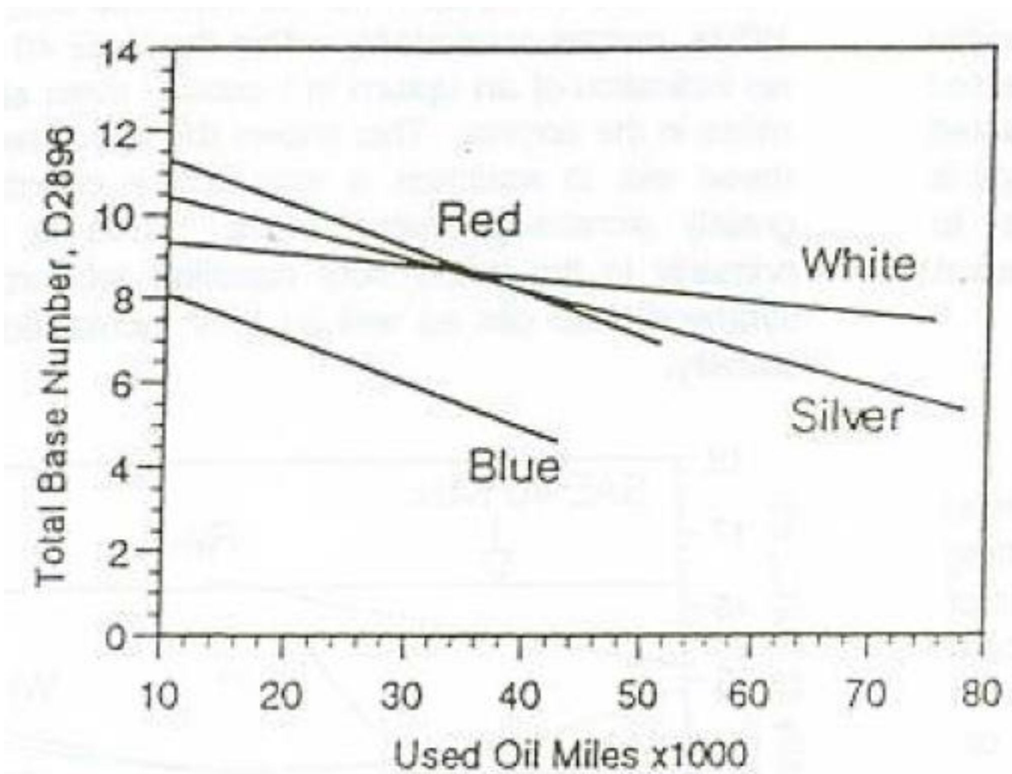

FIGURE 7 : Average total base number with respect to miles on oil
(Jetter, et al. 1998)

The total base number (TBN), which is a function of additive system and indicate alkalinity levels in engine oil never met the minimum recommendation of 4. The blue oil had a lower fresh and used TBN and depleted to less than 5 after 40,000 miles. Whereas the red, white and silver oils all had higher fresh and used TBN, staying well above the parameter at the end of their respected drain interval (Jetter, et al. 1998).

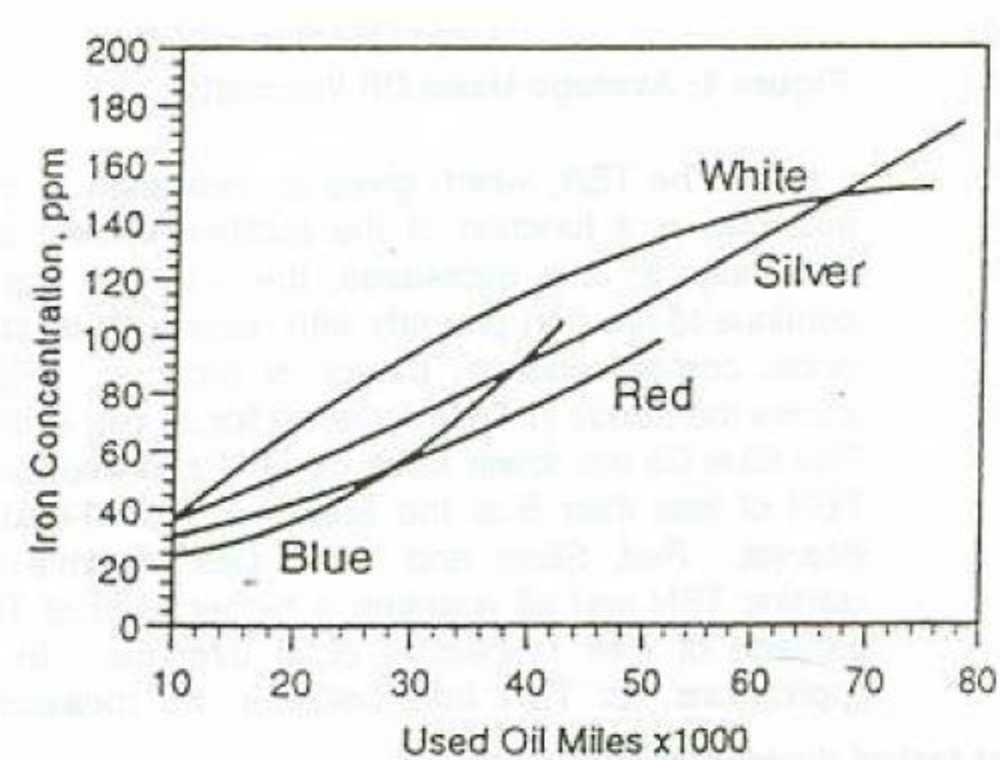

FIGURE 8 : Average iron concentration with respect to miles on oil (Jetter, et al. 1998)

Two of the primary wear metals in engine oil that can indicate a lack of wear protection are iron and lead. The trends from Figure 8 indicate that the blue oil has a loss of wear protection at 25,000 miles, due to the trend line starting to have an exponential increase. The red oils, have a loss of wear protection around 40,000 miles, whereas the synthetic oils (white and silver) do not show an exponential increase in the loss of wear protection throughout the 75,000 miles of service (Jetter, et al. 1998).

In conclusion to the extended drain intervals research, it was shown that the standard oil (blue) could have acceptable drain intervals of 15,000 miles, the premium mineral engine oil had acceptable drain intervals of 25,000 to 30,000 miles. However, the premium, fully synthetic oils could be extended to 45,000 to 60,000 miles depending on engine type and use. In addition to the extended drain intervals data, it was found that the extended drain intervals documented a 3.2 percent reduction in fuel consumption, which was provided by the premium, fully synthetic oils (Jetter, et al. 1998).

In, 2014 the Texas Department of Transportation (TxDOT) conducted extended oil drain interval testing in regards to the parameters of running time, idling time, engine temperature, and engine load. TxDOT used a Caflor IOSiX Data Logger, which was capable of logging the parameters listed above and had appropriate connectors for the selected on-road dump truck. TxDOT applied there extended oil program and data logging on 16 Sterling Dump trucks that had an MBE-4000 motor. Two different types of oil (Natures Choice Oil and Goldenwest Oil). The oil was analyzed for the following parameters: viscosity, oxidation, nitration, total acid number, total base number, wear metals, soot, and fuel dilution. The following figures show the data from the TxDOT research for extending oil drain intervals using Natures Choice Oil (Kader et al 2014).

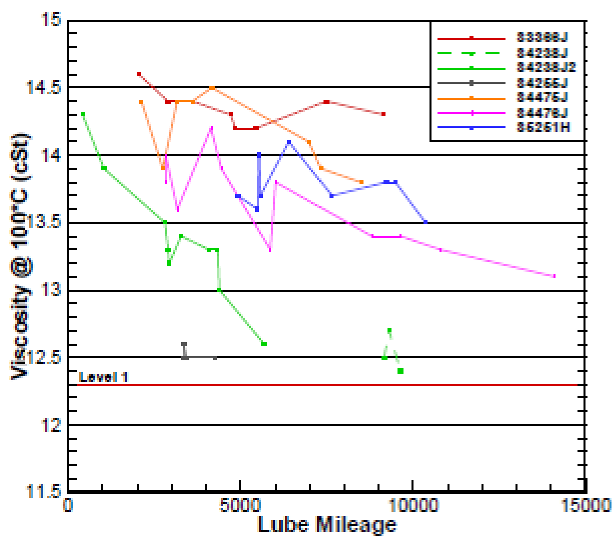

FIGURE 9 : Viscosity degradation in Nature's Choice oil (Kadar, et al. 2014)

From figure 9 above, it is noted that none of the tested vehicles reached level 1 severity. From the data that is represented, the test vehicles viscosity was extended up to or passed 10,000 miles (Kader et al 2014).

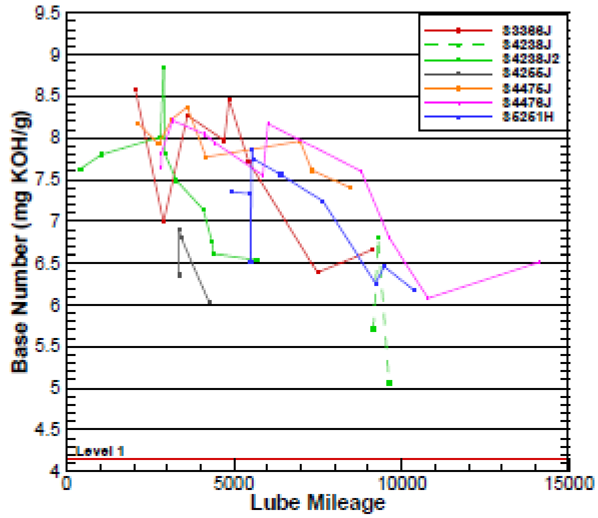

FIGURE 10 : Total base number vs. lube mileage in Nature's Choice oil
(Kadar, et al. 2014)

Total base number has a negative trend, as represented in Figure 10 above. This trend shows that the additives in the oil are working to control the acidic components in the oil. It is noted that none of the test vehicles reached level 1 severity, with the test vehicles oil being extended past 10,000 miles (Kader et al 2014).

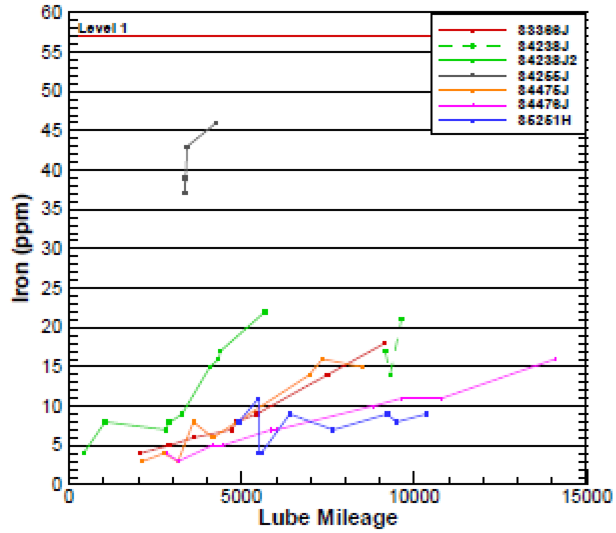

FIGURE 11 : Lube mileage in Nature's Choice oil (Kadar, et al. 2014)

It is expected for oil to accumulate iron over its extended life. Figure 11 above shows that none of the test vehicles reached level 1 severity when extended up-to or past 10,000 miles (Kader et al 2014).

TxDOT found that the low levels of oil degradation observed is attributed to the low-load and high levels of idling in the observed trucks. These findings indicate that there was low oil degradation throughout the extended oil drain interval analysis, with test vehicles being extended beyond 10,000 miles (Kader et al 2014).

Knowing the useful life of an engine oil is critical in any application of the engines oil efficiency. The Remaining Useful Life Evaluation Routine (RULER) is a technique used to find the remaining useful life (RUL) of an engine, or other piece of equipment's operating time available, from the time the lubricant is sampled until large changes occur within the oil (Jefferies and Ameye 1997).

The Remaining Useful Life technique is done to evaluate the oils viscosity, total acidic number, and total base number to ensure that is not past its RUL; using antioxidant capacity of the lubricant allows the engine oil to eliminate the need for schedule oils changes and potentially providing cheaper maintenance cost. RULER is completed by voltammetric techniques using a glassy carbon working electrode, platinum wire reference electrode, and a platinum wire auxiliary electrode. The electrode is inserted into the diluted oil sample, voltage is added, and as the voltage increases the antioxidant additives become chemically excited, causing a current flow that peaks at the oxidation potentials of the antioxidant (Jefferies and Ameye 1997). These peaks and areas when charted, can then be compared to a new oil sample to observe and track changes, which identify abnormal operating conditions. There are three types of common additives in oil to control the degradation of oxidation.

- Radical Scavengers
- Hydroperoxide Decomposers
- Synergistic Mixtures

RULER can be used to determine the effective antioxidant concentration when compared to the original new oil sample. With a plot of additive depletion versus oil age, it can be used to determine the used engine oil condition. RULER is not a standalone test, but does add valuable information about oil properties through extended use. This test should be used with conjunction of other engine oil analytical methods. This technique gives a linear calibration graph and has a precision of 2.5 percent relative standard deviation (RSD) for the additives used in diesel engine oils (Jefferies and Ameye 1997).

2.5 Threshold Limits

Measurable oil parameters that represent oil quality included viscosity and total base number, whereas contaminations and wear metals represent the quality of the engine. Viscosity is dependent on temperature and is typically measured at 40°C and 100°C. Total base number is a measure of the oil's chemistry and is an indication of how the engine oil is able to neutralize acids. Contaminations such as fuel, glycol, dirt, and fuel along with wear metals directly affect the engine oil quality, but also represent the internal components and quality of the engine itself. Table 1 below represents the parameters used to define oil quality along with a description and the threshold limit exhibited with the parameters.

TABLE 1 : Engine oil threshold limits

Parameter	**Description**	**Threshold**
TBN (mg KOH/g)	Measure of the ability to nuetralize acids	≤ 4 (severe) ≤ 3 (critical)
Viscosity (cSt)	Measure of the ability of the oil to flow at a given temperature	12.5 cSt - 16.3 cSt (40 weight)
Fuel (% wt)	Typically result from blow-by resulting in premature oxidation, changes in viscosity, and decrease additive influence (Fitch and Troyer 2010)	≥ 4 % (critical)
Soot (% wt)	Formed from combustion, irregular timing or blow-by: increases viscosity (Cummins 2007)	≥ 3 % (critical)
Water (% wt)	Typically result from crankcase condensation, promotes oxidation and acidic reactions (Fitch and Troyer 2010)	≥ .5 % (critical)
Glycol (% wt)	Antifreeze contamination through coolant leak; acidic reactions, increase viscosity and promotes engine wear (Cummings 2007, Fitch and Troyer 2010)	Any trace is deemed critcal
Silicon (ppm)	Typically the result from dust or dirt, abrasive behavior and promotes engine wear (Evans 2012)	> 40 (critical)
Iron (ppm)	Wear from shafts, piston rings, and gears; promotes engine wear (Volvo 2012)	> 100 (severe) > 130 (critical)
Copper (ppm)	Main bearing and connecting rods, piston pins, and camshaft: promotes engine wear (Volvo 2012)	> 15 (severe) > 30 (critical)
Aluminum (ppm)	Scoring or burning of aluminum pistons, bearing wear; promotes engine wear (Volvo 2012, Schumacher and Frisby 1991)	> 10 (severe) > 15 (critical)
Chromium (ppm)	Chrome plated piston rings or valves in combination with water; promotes engine wear (Volvo 2014, Schumacher and Frisby 1991)	> 5 (severe) > 10 (critical)

CHAPTER 3: PURPOSE AND SCOPE

The purpose of this research was to quantitatively understand the degradation of engine oil over its life cycle. Knowing the degradation of the engine oil allows the user to alter and potentially improve the existing predetermined preventative maintenance schedule. Defining degradation limits of the oil characteristics allows engine oil to be used to its maximum life potential. The objectives of this research are:

1) Identify key oil performance parameters and establish threshold values for engine oil.

2) Establish an experimental preventative maintenance program for regularly collecting and analyzing engine oil.

3) Establish a baseline of oil performance through analysis of equipment on an existing, fixed drain interval.

4) Quantify the oil performance through analysis of equipment on an extend drain schedule.

5) Compare fixed drain interval with extended drain intervals to their corresponding threshold values.

6) Draw conclusions and provide recommendations regarding extended oil drain intervals for NCDOT equipment classes 0209, 0210, 0303, and 0311.

The scope of this research was to establish an experimental PM program. This program included threshold limits for engine oil contaminates, wear metals, and bulk properties to ensure that engine oil provided sufficient lubrication. This PM program was completed by regularly analyzing engine oil samples. An extended drain interval program was established for continuous analyses of engine oil. The data was then plotted and the oil degradation was rates were analyzed.

Machines studied were selected by the North Carolina Department of Transportation (NCDOT). Used engine oil samples were collected by NCDOT personnel and previous data (oil intervals, type of oil, equipment condition) were given by Division 10 (Anson, Cabarrus, Mecklenburg, Stanly and Union County). The four classes of equipment tested were:

- 0209 – Crew Cab Trucks (International 7300 SFA)
- 0210 – Crew Cab and Extended Cab Trucks (Ford 6.4L & 6.7L)
- 0303 – 4X4 Tractor (John Deere 4.5L & New Holland 6.7L)
- 0311 – 4X4 Tractor (John Deere 4.5L & John Deere 6.8L)

Used engine oil samples were analyzed using the OSA4 TruckCheck®. These used oil samples were compared against established threshold limits for three properties of the oil: contamination, wear protection and bulk properties.

CHAPTER 4: METHODOLOGY

4.1 Maintaining Engine Oil Quality by Setting Oil Parameters

Oil threshold limits were set to ensure that the oil properties are sufficient enough to provide adequate lubrication and protection to the engine. Threshold values were established based on published methods and results from related research. API and ASTM Standards also contributed to determining threshold values for engine oil degradation. The following oil properties had designated threshold values:

- Bulk Properties (Total Base Number, Viscosity)
- Contamination (Fuel, Soot, Water, Glycol, Silicon)
- Wear Metals (Iron, Copper, Aluminum, Chromium)

These engine oil properties ensure that the oil does not cause accelerated failure within the engine. It is important to make sure that the fixed drain interval of the current NCDOT PM plan could be extended. These oil parameter values were key to extending the current NCDOT PM program.

4.1.1 Equipment Selection

Two classes of on-road diesel trucks and two classes of off-road diesel tractors were included in the research project. There were 13 individual machines from each class selected for this study. Below is a description of the classes related to the research:

1. Class 0209 diesel crew cab trucks (International 7300 SFA) with a gross vehicle weight (GVW) between 20,000 and 35,000 lbs used for various operations.
2. Class 0210 4X4 extended cab and crew cab diesel trucks (Ford 6.4L & 6.7L) with 9,900 GVW used for Incidental Management Assistant Patrol (IMAP).
3. Class 0303 4X4 diesel tractors (John Deere 4.5L & New Holland 6.7L) used for various mowing operations.
4. Class 0311 4X4 diesel tractors (John Deere 6.8L) used for slope mowing.

Class 0210 machines use Rotella® T6 synthetic 5W-40 and Conoco HD Fleet Supreme® 15W-40 conventional mineral oil is used in class 0209, 0303, and 0311 machines.

4.2 Engine Oil Analysis

Continuous engine oil sampling is needed to quantify engine oil degradation. This allows for tracking engine oil degradation and ensuring the engine oil provides sufficient protection to the engine and its components (Agoston et al. 2005 & Kollman et al. 1998). A continuous monitoring program includes regular sampling based on direct measures of oil quality.

4.2.1 Analyzer Selection

Used engine oil samples were analyzed using the OSA4 TruckCheck®. The OSA4 uses dual atomic emission spectrometer, infrared spectrometer, and a viscometer to measure contamination levels and viscosity at 40°C and 100°C. Figure 12 represents a sample report generated by the OSA4 TruckCheck® for a typical oil analysis. Three samples of oil, each approximately 150 ml, was drawn from the equipment through the dip stick using a hand operated vacuum pump. Analyses were performed in accordance with ASTM D7417 and requires approximately 15 minutes to complete

NC DOT DIV10 A	Vehicle ID: 462-2302	Component ID: 462-2302	OSA4 TRUCKCHECK® OnSite Oil Analyzer
Phone:	Vehicle Make: FORD	Component Make: FORD	NC DOT
Email:	Vehicle Model: F-350 C/C	Component Model: F-350 C/C	4809 BERYL ROAD
Fax: ___-___-____	Vehicle Year : 2013	Component Year: NA	RALEIGH NORTH CAROLINA
	FleetID : 0209	Component Type : DIESEL ENGINE	___-___-____
	Component Description:	Sump Capacity: 13 Quarts	

Sample ID	Date Taken	Miles on Component	Miles on Oil	Oil Weight	Oil Brand	Oil Type	Oil Changed	Date Analyzed	User Sample ID
734	9/28/2015	75205	10998	5W40	SHELL	ROTELLA T6	No	9/28/2015	3
Comments	VISCOSITY LOWER THAN TYPICAL FOR THE GIVEN OIL TYPE. MODERATE DEGREE OF OXIDATION INDICATED. SUSPECT HIGH OPERATING TEMPERATURE AND/OR OVER EXTENDED DRAIN INTERVAL. OIL DRAIN AND REFILL MAY BE NECESSARY. CONSULT SERVICE PROVIDER FOR FURTHER RECOMMENDATIONS. TO CONFIRM, RESAMPLE AT 5,000 MILES - 8,000 KM - OR 100 HOURS.								
733	9/28/2015	75205	10998	5W40	SHELL	ROTELLA T6	No	9/28/2015	2
Comments	LOW VISCOSITY INDICATES POSSIBLE PRESENCE OF FUEL DILUTION, VISCOSITY SHEARING OR INCORRECT OIL IN SUMP. CHECK FOR INCREASED OIL LEVEL ON DIPSTICK CHECK FOR LOW OIL PRESSURE. CORRECT OIL WEIGHT MUST BE ENTERED FOR PROPER FUEL DILUTION DETECTION.Fleet CHECK FUEL INJECTOR SYSTEM. CHECK FOR POWER LOSS, BLOW-BY, SMOKING, OIL CONSUMPTION, ETC. OIL DRAIN AND REFILL MAY BE NECESSARY. CONSULT SERVICE PROVIDER FOR FURTHER RECOMMENDATIONS. TO CONFIRM, RESAMPLE AT 5,000 MILES - 8,000 KM - OR 100 HOURS.								
732	9/28/2015	75205	10998	5W40	SHELL	ROTELLA T6	No	9/28/2015	1
Comments	VISCOSITY LOWER THAN TYPICAL FOR THE GIVEN OIL TYPE. MODERATE DEGREE OF OXIDATION INDICATED. SUSPECT HIGH OPERATING TEMPERATURE AND/OR OVER EXTENDED DRAIN INTERVAL. OIL DRAIN AND REFILL MAY BE NECESSARY. CONSULT SERVICE PROVIDER FOR FURTHER RECOMMENDATIONS. TO CONFIRM, RESAMPLE AT 5,000 MILES - 8,000 KM - OR 100 HOURS.								

	Wear Metals(ppm)							Contaminant Metals (ppm)			Multi-Source Metals (ppm)					Additives (ppm)				
Sample ID	Iron	Chromium	Aluminum	Copper	Lead	Tin	Vanadium	Silicon	Sodium	Potassium	Titanium	Molybdenum	Nickel	Manganese	Boron	Magnesium	Calcium	Barium	Phosphorus	Zinc
734	27	<2	4	7	<2	<2	17	4	11	19	0	34	0	0	5	177	1940	0	401	1944
733	27	<2	2	8	<2	<2	25	5	5	13	0	30	0	2	3	209	2415	0	497	2442
732	29	<2	4	7	<2	<2	15	4	11	17	0	34	0	0	5	191	2444	0	525	2185

	Contaminants				Physical Properties								
Sample ID	Fuel	Soot	Water	Glycol	Nitration	TBN	Oxidation	V40C	V100C	VIndex	V40C Limit	V100C Limit	Visc Mode
734	-	0.9	<0.1	-	11.2	4.6	14.6	74	11.7	153	78.7 - 96.1	12.5 - 16.3	M
733	-	0.7	0.1	-	9.5	5.2	10.5	30	5.9	145	78.7 - 96.1	12.5 - 16.3	M
732	-	0.9	<0.1	-	11.3	4.8	14.3	74	12.3	165	78.7 - 96.1	12.5 - 16.3	M

ABNORMAL SEVERE D = DETECTED - = NOT DETECTED X = NOT TESTED / NOT APPLICABLE NA = NOT AVAILABLE C = CALCULATED M = MEASURED

FIGURE 12 : Example of OSA4 TruckCheck® analysis result

4.3 Experimental PM Procedure for Collecting and Analyzing Engine Oil

A continuous oil analysis program was needed to maintain quality throughout the research. Engine oil data was continuously recorded guaranteeing that the used oil did not extend past its useful life, which could cause harm to the engine and its components. When trying to extend the engine oil life through extended drain intervals, it is optimal that the criteria meets the Original Engine Manufacturers (OEM) guidelines when trying to set parameters and obtain baseline data. This is done to maintain an efficient engine, without pushing the engine oil past its expected life. NCDOT's current predetermined preventative maintenance plan, allows for equipment drain intervals every 5,000 miles or 200 hours.

4.3.1 Analysis Intervals

It is important that the engine oil be regularly tested throughout the use of its life in the equipment, this is done to obtain engine oil degradation trends. Oil from classes 0209 and 0210 was sampled every 1000 to 1500 miles, and from classes 0303 and 0311 was sampled every 50 hours. This frequent schedule provided the data required to develop sufficient trends of oil degradation.

4.4 Establish Baseline Oil Performance

Before engine oil samples were collected from the equipment and analyzed, fresh oil samples were analyzed to establish baseline oil performance. Thirty samples of Rotella® T6 synthetic 5W-40 and eighteen samples of Conoco HD Fleet Supreme® 15W-40 were analyzed and plotted on their respected graphs. Extra samples for the synthetic oil were analyzed due to variation in the results.

Using the current NCDOT preventative maintenance plan, engine oil was analyzed and plotted for degradation trends for 10 machines in classes 0209, 0303, and 0311. This data represents the baseline values for the engine oil degradation. This data was used to determine how the oil performed on the current predetermined preventative maintenance plan.

4.5 Quantify Oil Performance from Extended Drain Intervals

Quantifying oil performance from the extended drain intervals enables the user to be able to predict the useful life through the oil properties and the rate of degradation. Not all machines have the same rate of oil degradation and it is crucial to determine the rate of oil degradation after it is extended past the current preventative maintenance plan.

4.5.1 Engine Oil Extended Intervals

Three machines from classes 0209, 0303, 0311 and all 13 trucks from class 0210 were on an extended drain interval schedule after the baseline data was obtained. These equipment were regularly tested after they had surpassed the regular preventative maintenance schedule and the oil was pushed towards the end of its useful life. Classes 0209 and 0210 had samples collected every 500 to 1,000 miles after 5,000 miles, depending on the oil degradation rate. Equipment in classes 0303 and 0311 were still sampled every 50 hours after 200 hours.

Through these intervals, engine oil degradation trends were observed for each property of the engine oil. Throughout the research, degradation trends were observed and used to determine if and when extended oil drain intervals can be applied. With the use of oil degradation trends help identify the point that oil drain intervals can be extended to, it can be ensured that no damage will occur to the equipment and its functions. All oil threshold values are set to ensure that the oil does not pass its useful life.

4.6 Compare Existing Drain Intervals to Extended Intervals and Threshold Values

The comparison of the existing drain intervals to extended drain intervals was done to see if the rate of oil degradation is increased after it surpassed the current preventative maintenance plan provided by the NCDOT. If extended drain intervals increased the rate of oil degradation after it surpassed the current preventative maintenance plan, then the use of extended drain intervals would be meaningless.

4.6.1 Degradation Trends

The data was collected from the computer of the OSA4 TruckCheck®. The data given from the print-out did not give an exact number or percentage for the engine oil analysis. The data was obtained by going into the computer through the C-drive, accessing the OSA 3 file, and then finding the SampleRes.txt file. This file gave the engine oil analysis exact results. This file was then imported into Microsoft Excel® for future analyses.

Through this research, trends of the oil degradation over time were observed and plotted. Since engine oil degrades over time, plotting the data allows the user to use statistical analysis and determine a line of best fit or degradation equations for each property of oil based on hours worked or miles. Regression techniques were used to define the linear relationship between oil quality and oil age. The significance of the regression coefficients were assessed at the 95% confidence level. Confidence intervals were conducted at 95% to ensure that the lower limit was used for the drain interval recommendation.

CHAPTER 5: RESULTS

A total of 716 engine oil analyses were performed from 44 machines. Table 2 presents each class breakdown. An overview of each class with the make, model, and engine type is shown in Table 3.

TABLE 2 : Summary of analysis performed

Equipment Class	No. of Machines	No. of Machines Analyzed	No. of Analyses
0209	13	11	122
0210	13	12	243
0303	13	8	138
0311	13	13	213
Total		**44**	**716**

TABLE 3 : Overview of equipment parameters

Class	Year	Make	Model	Engine	Oil Sump Capacity (qt)
0209	2000-2005	International	4700 & 7300	7.6L	30-32
0210	2008-2013	Ford	F350	6.4 & 6.7L	13-15
0303	2006-2014	New Holland & John Deere	TS125A 6420 & 6150M	4.5L 6.7L	16 22
0311	2000-2014	John Deere	7600 & 7410	4.5L & 6.8L	16-24

5.1 Fresh Oil

Analyses were performed on 18 fresh conventional mineral oil samples and 30 fresh synthetic oil samples. The averaged measured total base number (TBN) and viscosity values for the mineral oil samples were similar to the published values of SAE 15W-40 engine oil. However, there was a larger variation of the averaged measured results for the synthetic oil as shown in Table 4. The mineral oil TBN ranged from 9.1 to 10.2 mg KOH/g with an average of 9.33 mg KOH/g and the viscosity ranged from 13.95 to 15.92 cSt with an average of 14.99 cSt. The TBN of the 30 synthetic oil samples ranged from 9.42 to 10.6 cSt with an average of 9.66 cSt. The viscosity of the synthetic oil ranged from 12.07 to 14.35 mg KOH/g with an average of 12.84 mg KOH/g. This actual measured average is 1.36 cSt below the published average for the Shell Rotella® T6. Six of 30 (20 percent) synthetic oil samples had a viscosity below the minimum limit for a SAE 40 weight oil as shown in Figure 13.

TABLE 4 : Published specifications vs. analysis results for fresh oil

Oil Type	**Mineral**		**Synthetic**	
Brand	Conoco HD Fleet Supreme®		Shell Rotella® T6	
SAE Viscosity	15W-40		5W-40	
	Published	**Measured**	**Published**	**Measured**
Kinematic Viscosity @ 100°C (cSt)	15.2	14.99	14.2	12.84
Total Base Number (mg KOH/g)	9.5	9.33	10.6	9.66
Sulfated Ash (% wt)	1.18		1.0	
Density (kg/l)	0.878		0.858	

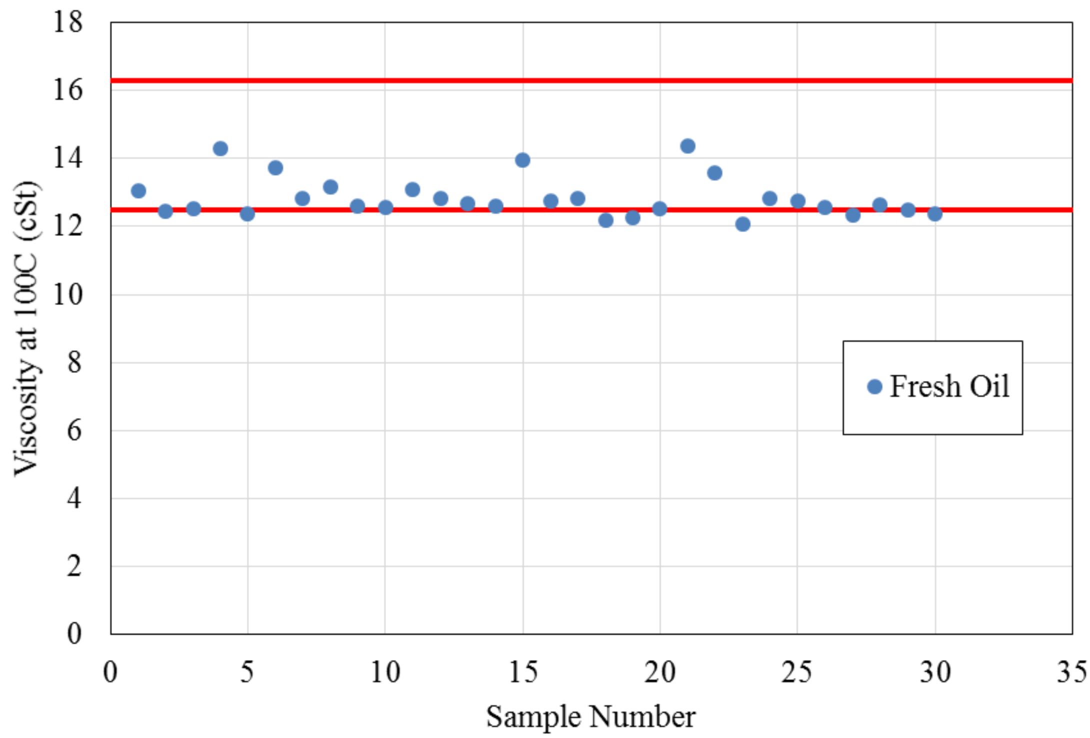

FIGURE 13 : Fresh synthetic oil viscosity

5.2 Class 0209 Trucks

A total of 122 samples were analyzed from 11 trucks. Oil age ranged from approximately 1,000 to 6,500 miles. No truck from class 0209 reached the minimum total base number or the upper or lower limits of viscosity to deem the engine oil insufficient.

5.2.1 Total Base Number

As the mileage increased in class 0209, there was a minor decrease in TBN as represented in Figure 14. ConocoPhillips 15W-40 oil had a fresh oil TBN value of approximately 9.25 mg KOH/g. Engine oil samples with approximately 5,000 to 6,500 miles had an approximate minimum TBN of 9 mg KOH/g. This TBN value is well above the minimum threshold value of 4 mg KOH/g.

In the linear relationship between TBN and oil age, the age coefficient was found to be -6.122E-05. The observed t-statistic for the coefficient was -1.785 with a corresponding p-value of 0.081. This implies that the slope is not statistically different from zero and there is a not relationship between TBN and age for class 0209. Confidence intervals at 95% were developed as well to establish the lower and upper limits of the estimated TBN values.

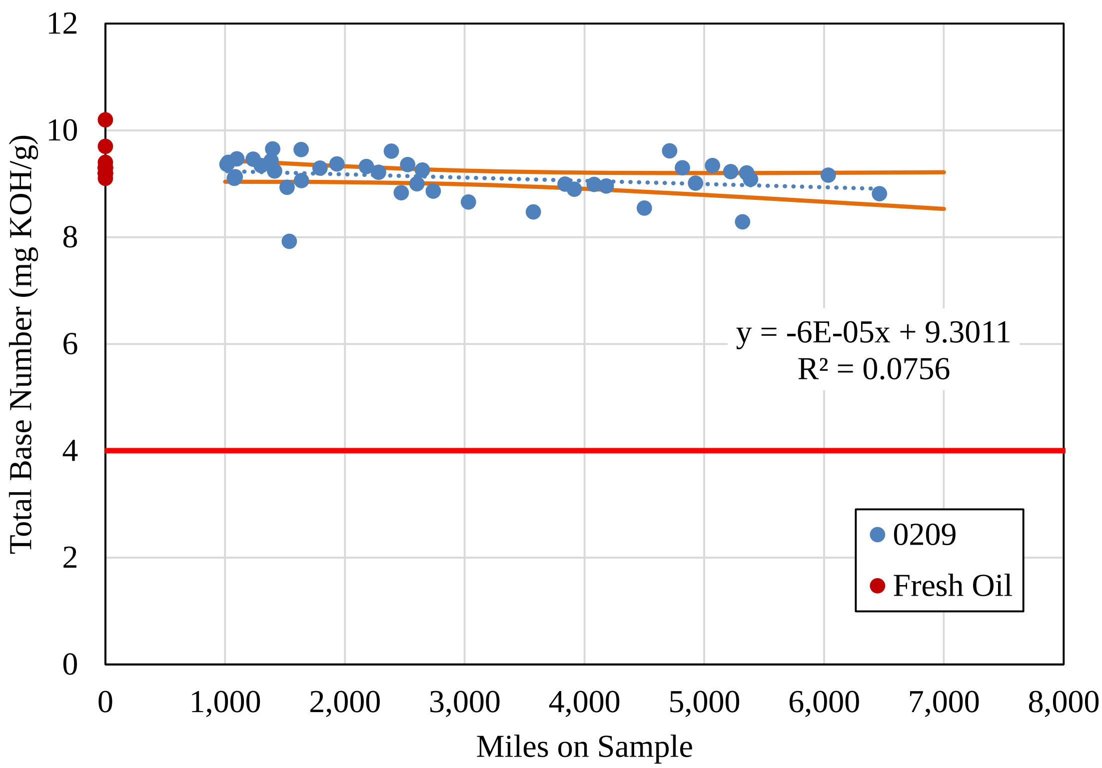

FIGURE 14 : Total base number for class 0209 trucks

5.2.2 Viscosity

Equipment in class 0209 had a viscosity decrease within the first 1,000 miles, but then remained near the lower limits of an SAE 40 weight oil with minimum change as the oil aged. This decrease could be the result from possible fuel dilution. The viscosity limits for an SAE 40 weight oil is 12.5 to 16.3 cSt. As shown in Figure 15, there were a few instances where the viscosity ranged from approximately 10.5 to the lower viscosity limit of 12.5 cSt. These measurements below the minimum viscosity limit for an SAE 40 weight oil were from two trucks (215-6374 & 215-6377). These trucks consistently had lower viscosity measurements and slightly increased near the lower viscosity limit as the age of the oil increased.

In the linear relationship between viscosity and oil age, the age coefficient was found to be -3.339E-05. The observed t-statistic for the coefficient was -0.446 with a corresponding p-value of 0.658. This implies that the slope is not statistically different from zero and there is no relationship between viscosity and age for class 0209.

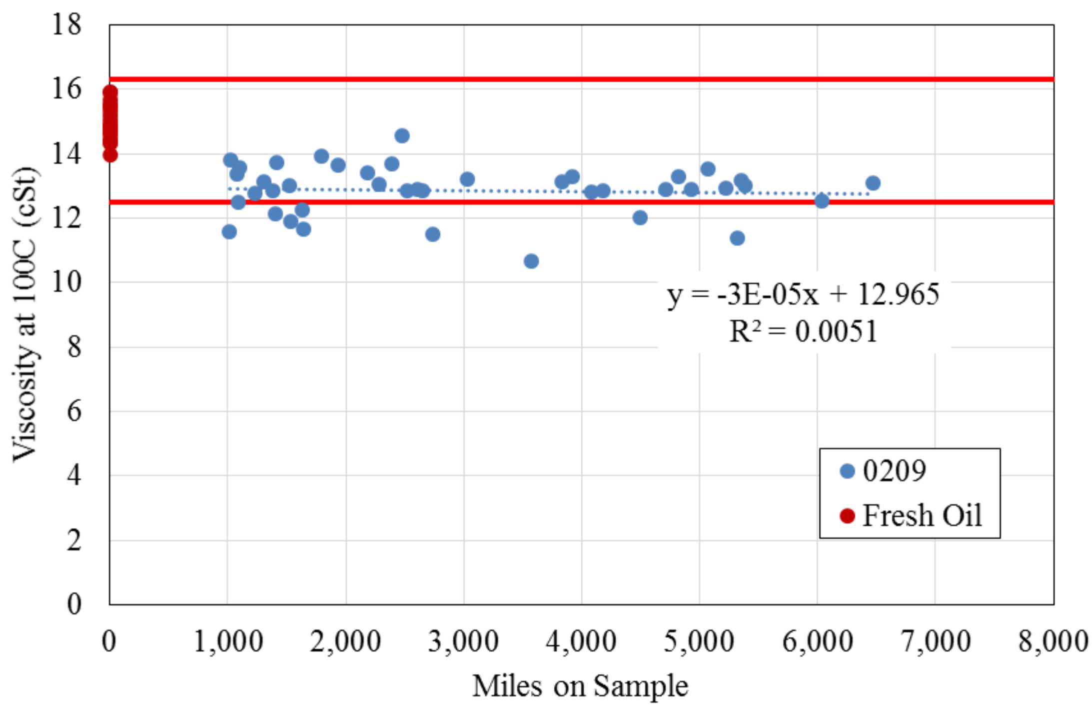

FIGURE 15 : Viscosity for class 0209 trucks

5.2.3 Wear Metals

Engine oil analyses did not indicate any significant levels of iron, copper, aluminum, or chromium as represented in Figure 16. No trucks reached the threshold value for iron or chromium concentration within the engine oil. Truck 215-6260 had one measurement of high copper of 32.07 ppm at 1,414 miles, but was then subsequently measured at 2.75 ppm at 3,032. This high copper reading could be the result from a faulty test, the reduced copper levels could be the result from the acidic compounds within the oil deteriorating the copper or deposits of copper in the engine. Truck 215-6883 had consistently high aluminum concentrations within its engine oil. Levels ranged from 28.39 ppm at 1,636 miles to 96.68 ppm at 4,712 miles. The oil in the truck was then changed and subsequently measured at 53.51 ppm 1,383 miles later. This analysis shows there may be an internal engine component failure causing high aluminum readings. No other truck had significantly high aluminum readings with all remaining below 10 ppm.

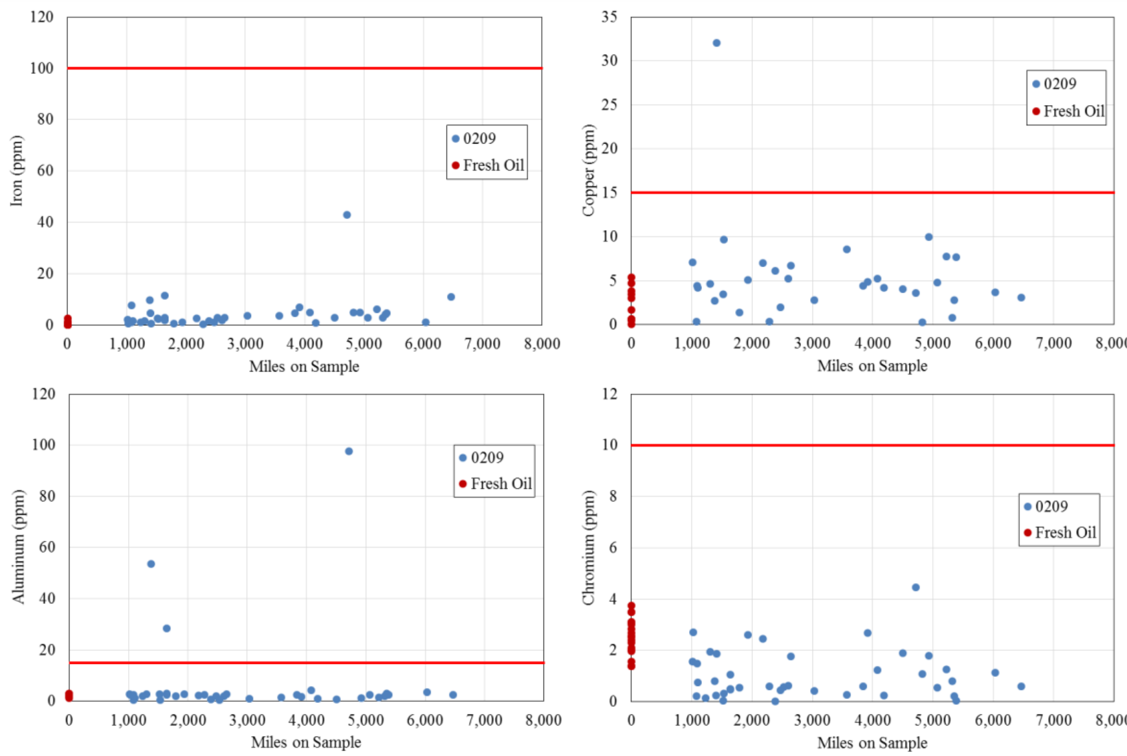

FIGURE 16 : Wear metal concentration for class 0209 trucks

5.3 Class 0303 Tractors

A total of 138 samples were analyzed from 8 tractors. Oil age ranging from approximately 50 to 250 hours of use. No tractor from class 0303 ever reached the minimum total base number or the upper or lower limits of viscosity to deem the engine oil insufficient.

5.3.1 Total Base Number

There was a strong relationship between TBN and hours of use as shown in Figure 17. Samples started out with an initial TBN of 9.25 mg KOH/g with a decline to approximately 9 mg KOH/g at 50 hours of use. Eventually reaching approximately 200 to 250 hours with a TBN of 8 to 8.5 mg KOH/g which is well above the threshold value.

In the linear relationship between TBN and oil age, the age coefficient was found to be -4.899E-03. The observed t-statistic for the coefficient was -8.099 with a corresponding p-value of 2.904E-10. This implies that the slope is statistically different from zero and there is a relationship between TBN and age for class 0303. Confidence intervals at 95% were developed as well to establish the lower and upper limits of the estimated TBN values.

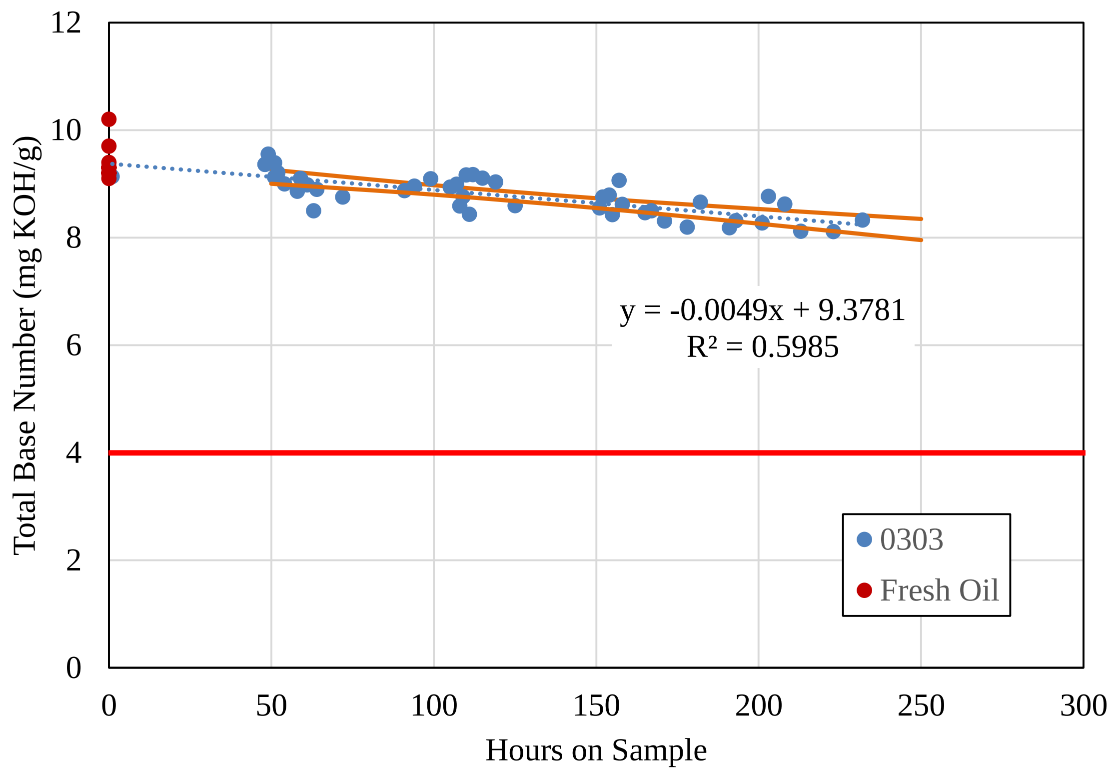

FIGURE 17 : Total base number for class 0303 tractors

5.3.2 Viscosity

Analyses indicated that there was no relationship between viscosity and hours of use for class 0303 tractors as shown in Figure 18. Viscosity remains consistent between the upper and lower viscosity limits through the hours of use to approximately 250 hours.

In the linear relationship between viscosity and oil age, the age coefficient was found to be 3.051E-04. The observed t-statistic for the coefficient was 0.266 with a corresponding p-value of 0.792. This implies that the slope is not statistically different from zero and there is no relationship between viscosity and age for class 0303.

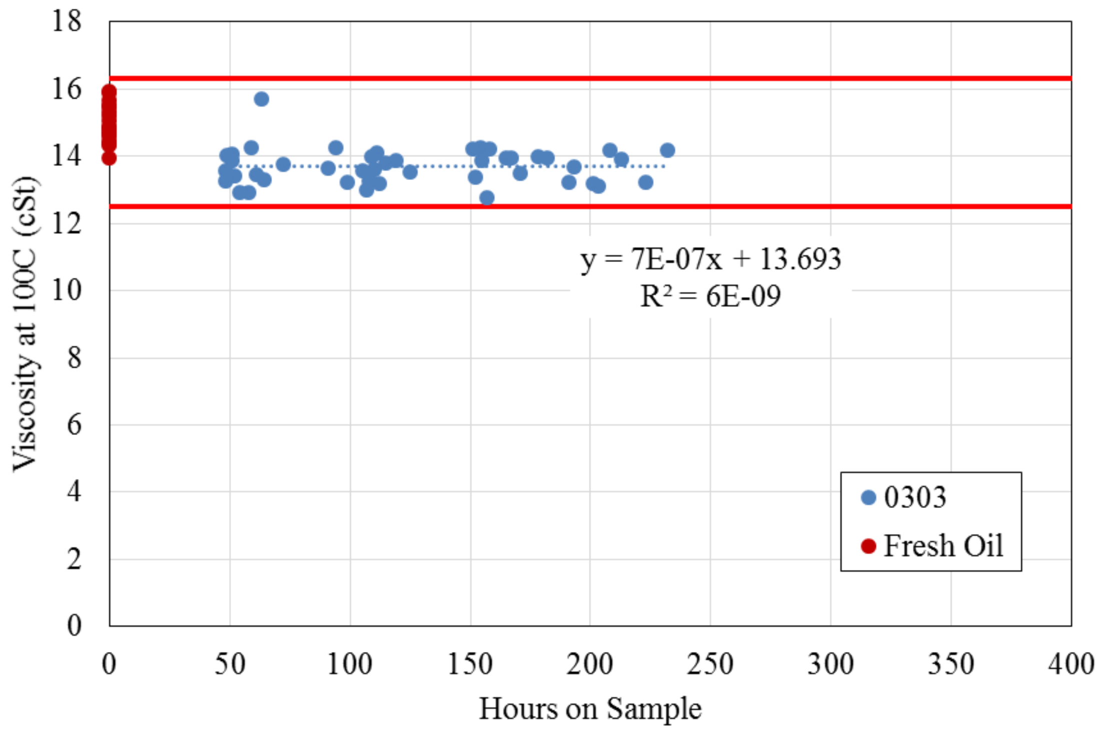

FIGURE 18 : Viscosity for class 0303 tractors

5.3.3 Wear Metals

Wear metal concentrations remain well below threshold values, with the exception of copper as shown in Figure 19. Copper concentration exceeded threshold limits in new tractors, which had a starting odometer of less than 6 hours. This indicates that if the engine and its components have no internal problems, then wear metal concentrations will not play a factor in extending engine oil drain intervals up to approximately 250 hours.

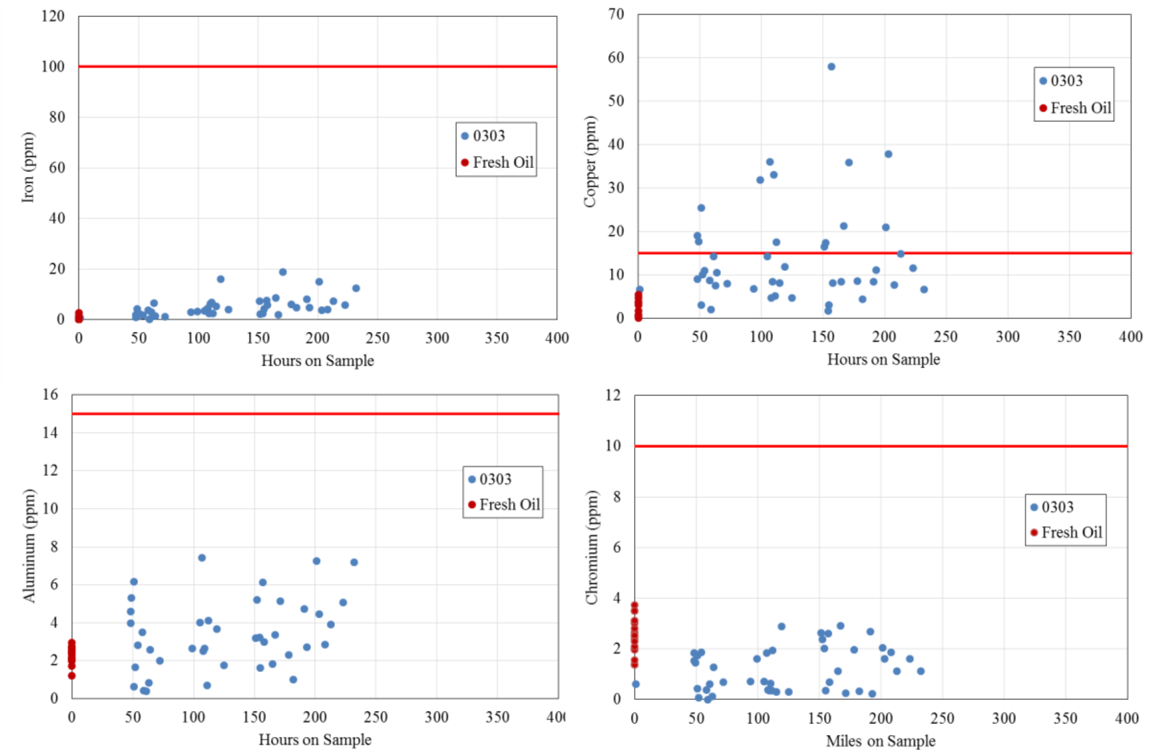

FIGURE 19 : Wear metal concentrations for class 0303 tractors

5.4 Class 0311 Tractors

A total of 213 samples were analyzed from 13 tractors. Oil age ranging from approximately 50 to 450 hours of use. No tractor from class 0311 ever reached the minimum total base number or the upper or lower limits of viscosity to deem the engine oil insufficient.

5.4.1 Total Base Number

Results indicate there is a strong relationship between TBN and hours of oil, as shown in Figure 20. Samples started out with an initial TBN of 9.25 mg KOH/g then declined to approximately 9 mg KOH/g at 50 hours of use. Eventually the engine oil was extended approximately 400 to 450 hours with a TBN of 7.5 to 7 mg KOH/g which is well above the threshold value.

In the linear relationship between TBN and oil age, the age coefficient was found to be -5.03E-03. The observed t-statistic for the coefficient was -9.982 with a corresponding p-value of 5.019E-15. This means that the slope is statistically different from zero and there is a relationship between TBN and age for class 0311. Confidence intervals at 95% were developed as well to establish the lower and upper limits of the estimated TBN values.

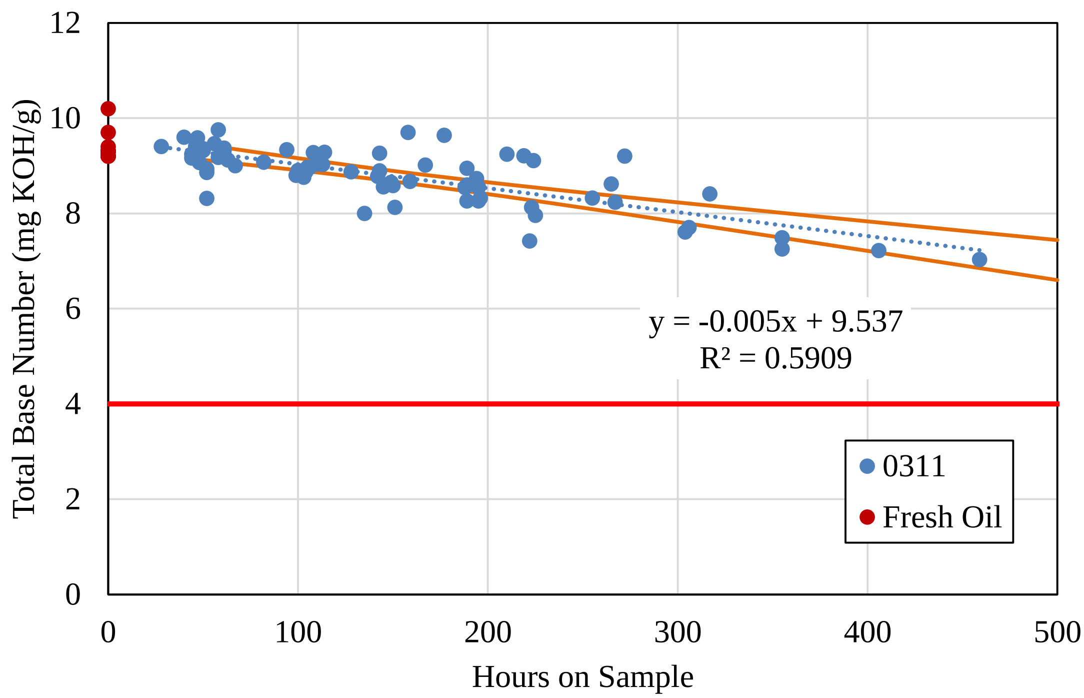

FIGURE 20 : Total base number for class 0311 tractors

5.4.2 Viscosity

Analysis indicate that there is a relationship between viscosity and hours of use for class 0311 tractors as shown in Figure 21. There is a possible decrease in the viscosity at 50 hours of use, then the viscosity remains consistent between the upper and lower viscosity limits through the hours of use up to approximately 250 hours. When increasing the hours on the engine oil to 450 hours there is a possible increase of viscosity, this increase does not extend past the upper limit of the viscosity threshold.

In the linear relationship between viscosity and oil age, the age coefficient was found to be 2.037E-03. The observed t-statistic for the coefficient was 3.528 with a corresponding p-value of 7.499E-04. This mean that the slope is statistically different from zero and there is a relationship between viscosity and age for class 0311.

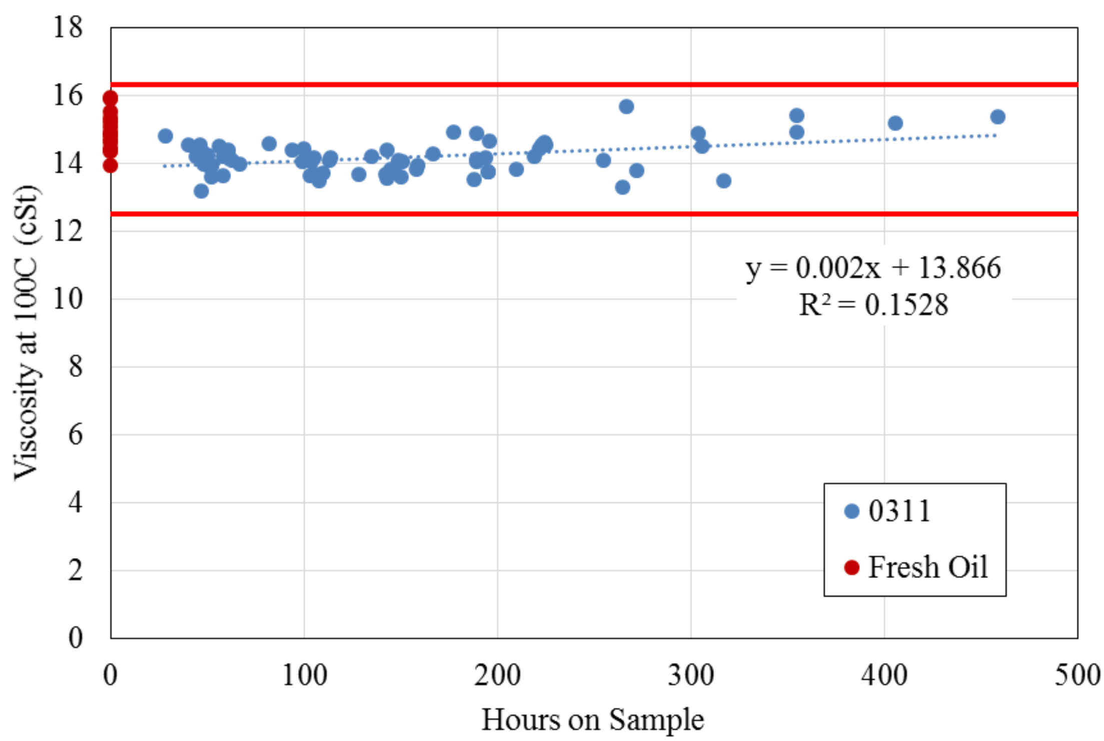

FIGURE 21 : Viscosity for class 0311 tractors

5.4.3 Wear Metals

Wear metal concentrations remained well below threshold values, with the exception of copper as shown in Figure 22. These high copper concentrations had approximately 50 hours on the engine oil. These analyses decrease down below the threshold value at the subsequent analysis occurring at approximately 100 hours. With the final results being an average of 3 samples, some of the copper concentration are skewed due to a high concentration count on one of the three samples of the engine oil. The remaining wear metals do not reach their threshold limits and will not limit the hours on the oil for extending oil drain intervals.

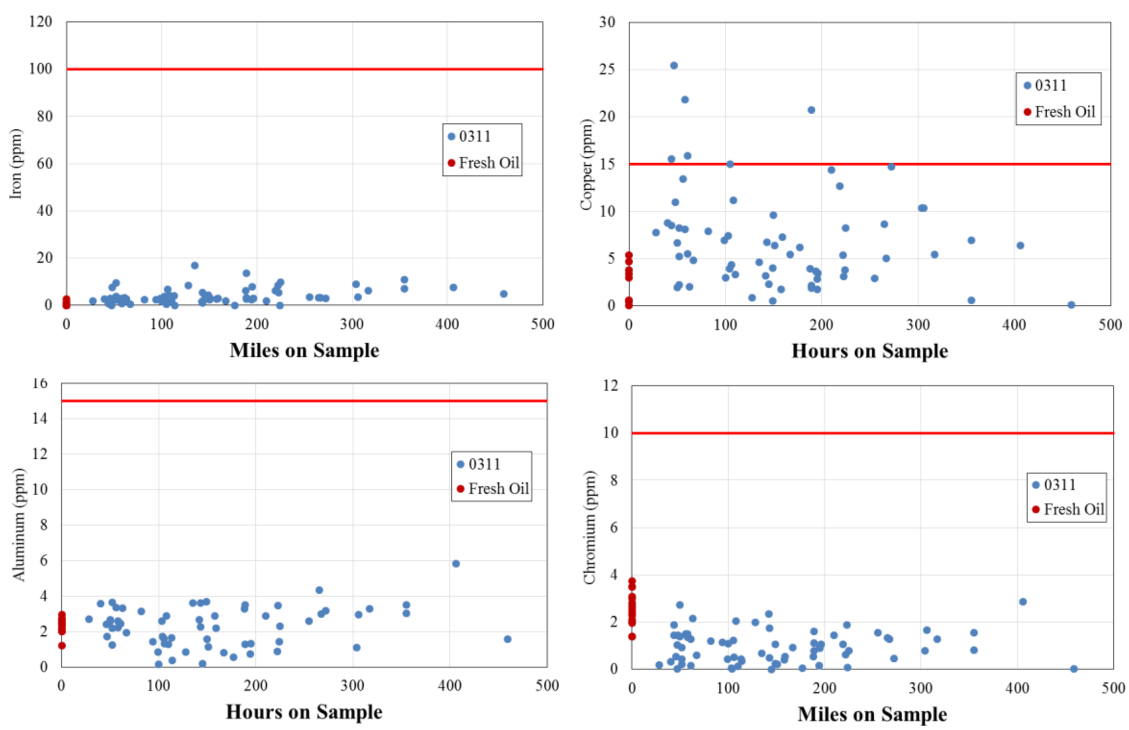

FIGURE 22 : Wear metal concentrations for class 0311 tractors

5.5 Class 0210 Trucks

A total of 243 samples were taken and analyzed from 12 trucks with approximately 800 to 13,500 miles. Multiple trucks from Class 0210 reached oil degradation threshold limits.

5.5.1 Total Base Number

The TBN of the synthetic oil reveled that there was a linear degradation rate. Oil in the 6.4L engine is shown to have a faster degradation rate than the oil in the 6.7L Engine. The 6.4L engine oil had a degradation rate of approximately 0.590 mg KOH/g per 1,000 miles. This engine dropped from the initial 10 mg KOH/mg to approximately 4 mg KOH/g at approximately 8,000 miles. In the linear relationship between TBN and oil age, the age coefficient was found to be 5.975E-04. Figure 23 presents TBN degradation for the 6.4L engines along with the 95% confidence interval. The observed t-statistic for the coefficient was -12.284 with a corresponding p-value of 3.009E-14. This means that the slope is statistically different from zero and there is a relationship between TBN and age for class 0210. Confidence intervals at 95% were developed as well to establish the lower and upper limits of the estimated TBN values.

The 6.7L engine had an oil degradation rate of approximately 0.383 mg KOH/g per 1,000 miles. Allowing the engine oil to be extended to approximately 12,500 miles. In the linear relationship between TBN and oil age, the age coefficient was found to be of -3.845E-04. Figure 24 presents TBN degradation for the 6.7L engines along with the 95% confidence interval. The observed t-statistic for the coefficient was -13.907 with a corresponding p-value of 2.561E-17. This means that the slope is statistically different from zero and there is a relationship between TBN and age for class 0210. Confidence intervals at 95% were developed as well to establish the lower and upper limits of the estimated TBN values.

One 6.4L truck reached the TBN threshold at approximately 8,000 miles. Whereas three 6.7L trucks were extended to the threshold limit, with one truck being extended to the threshold value twice. Table 5 below shows the 6.4L and 6.7L engines maximum extended interval for each truck, along with a projected limit for trucks that have not reached the threshold.

TABLE 5 : Projected mileage for TBN limit

Equipment ID	Engine	Oil Changed	Last Analysis	Projected to Reach TBN Limit
30185500	6.4L	TBN of 3.7 at 8,059 miles	TBN of 5.76 at 6,245 miles	9,700 Miles
30245515	6.7L	-------	TBN of 4.75 at 13,555 miles	15,800 Miles
30261557	6.7L	TBN of 4.19 at 13,061 miles	TBN of 4.10 at 12,146 miles	TBN Reached
30261558	6.7L	TBN of 3.88 at 11,264 miles	TBN of 5.94 at 6,595 miles	10,055 Miles

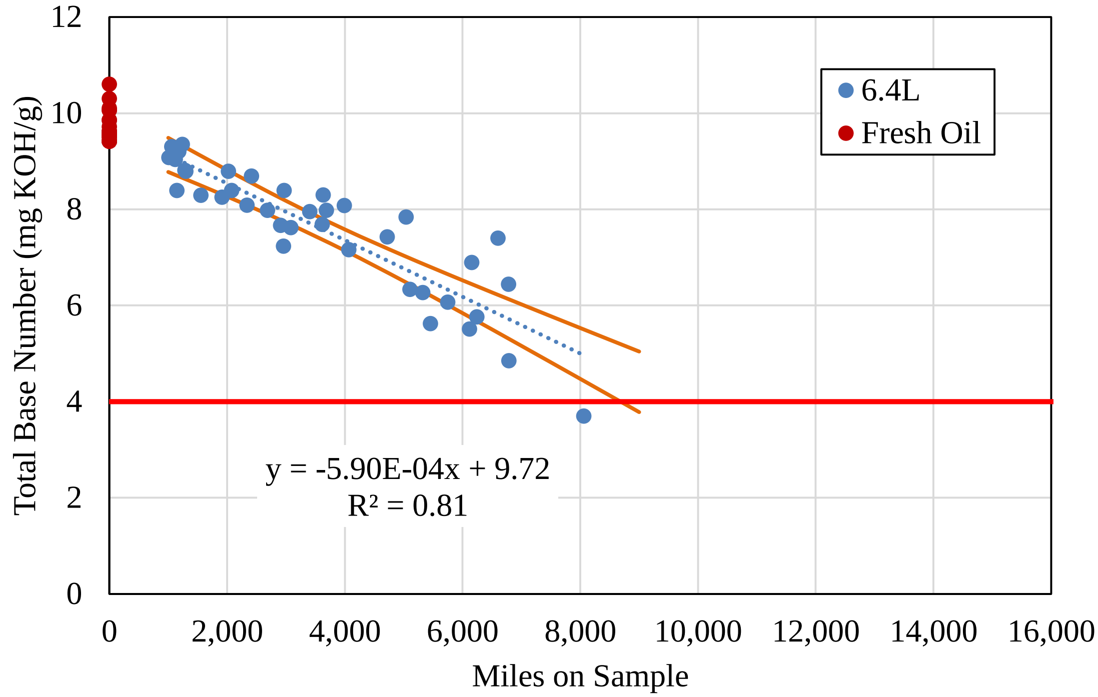

FIGURE 23 : Total base number for class 0210 trucks with 6.4L engine

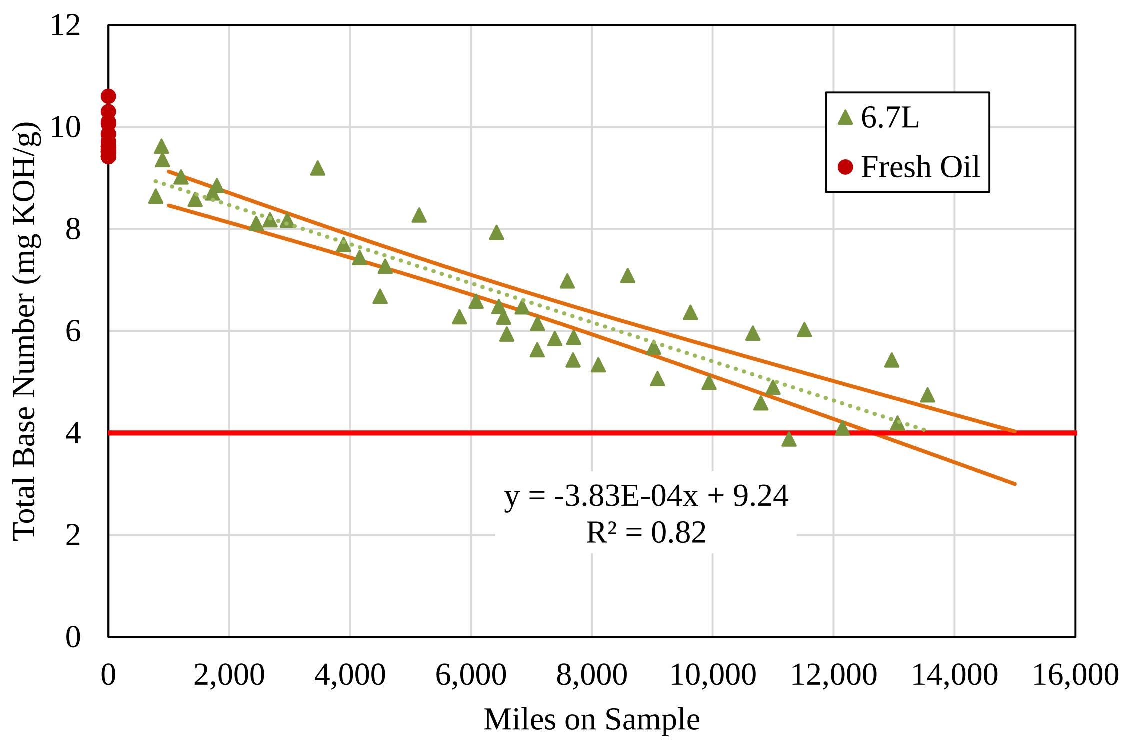

FIGURE 24 : Total base number for class 0210 trucks with 6.7L engine

Table 6 presents when the 6.4L and 6.7L engine oil will reach the TBN limit. This table represents the class as whole. It also shows how the TBN slope for the 6.4L is significantly higher, approximately double the 6.7L engine.

TABLE 6 : Class 0210 6.4L and 6.7L TBN projection comparison

Class	**Engine**	**TBN Reduction (mg KOH/g per 1,000 miles)**	**Projected to Reach TBN Limit**
0210	6.4L	0.590	9,400 Miles
0210	6.7L	0.383	13,800 Miles

5.5.2 Viscosity

Synthetic engine oil remained at the lower limits for the 6.7L engines throughout its useful life, however the 6.4L engines had an instant drop within the first 3,000 miles of use as shown in Figure 25. The 6.7L stayed around minimum threshold value of 12.5 cSt out to approximately 13,500 miles. For the 6.4L engines the viscosity decreased to approximately 8 to 11 cSt between 1,000 to 4,000 miles. After 4,000 miles the viscosity in the 6.4L engines stayed between 8 to 10 cSt up to approximately 8,000 miles. This decrease in viscosity was seen in all trucks with a 6.4L engine. In the linear relationship between viscosity and oil age for the 6.7L engines, the age coefficient was found to be -4.579E-05. The observed t-statistic for the coefficient was -3.971 with a corresponding p-value of 2.740E-04. This means that the slope is possibly statistically different from zero and there is a relationship between viscosity and age for class 0210 trucks with a 6.7L engine.

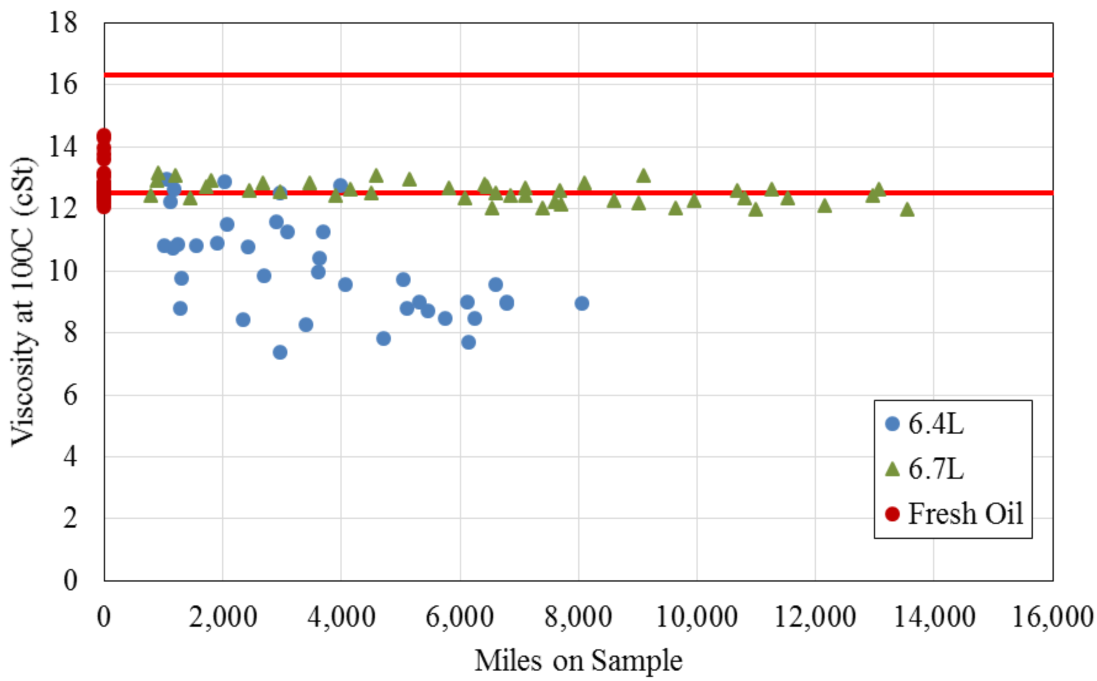

FIGURE 25 : Viscosity for class 0210 trucks

5.5.3 Wear Metals

Wear metal concentration analyses for Class 0210 is shown in Figure 26. This indicates that the 6.4L engines do have increased rates for iron, aluminum and chromium, but these increased rates do not cause concern because they are still below the threshold limits. Three trucks with 6.4L engine and one truck with a 6.7L engine had iron concentration analysis that extended above the threshold limit. 462-1271, 462-1199 and 462-0871 operated using the 6.4L engine. Their iron concentrations double when exceeding approximately 6,000 miles. These three machines also had high aluminum concentrations at approximately 6,000 miles. Whenever these concentration levels reached the maximum threshold value the engine oil was changed. After 462-1271 had two drain intervals due to high iron and aluminum concentrations at approximately 6,000 miles, it was brought into the shop and it was determine that the engine had internal engine malfunctions. This could indicate that trucks 462-1199 and 462-0871 could have the same engine malfunction as 462-1271 considering all three trucks have 6.4L engines. Truck 462-1523 has a 6.7L engine with increased iron and copper concentration at approximately 7,000 miles. These concentrations double after exceeding 7,000 miles. The engine oil in truck 462-1523 was changed when the threshold limit was reached, but this could also indicate that this truck may have internal engine problems. High copper concentrations were only observed in one of the 6.7L engines (462-2302). This truck had one analysis (1 of 3) with high copper concentrations which skewed the average indicating a higher value than what it actually is. The oil from truck 462-2302 had high copper concentration near the end of the useful life of the oil approximately at 12,500 miles, but the copper concentration dropped back down to the threshold limit of 15 ppm at 13,500 miles.

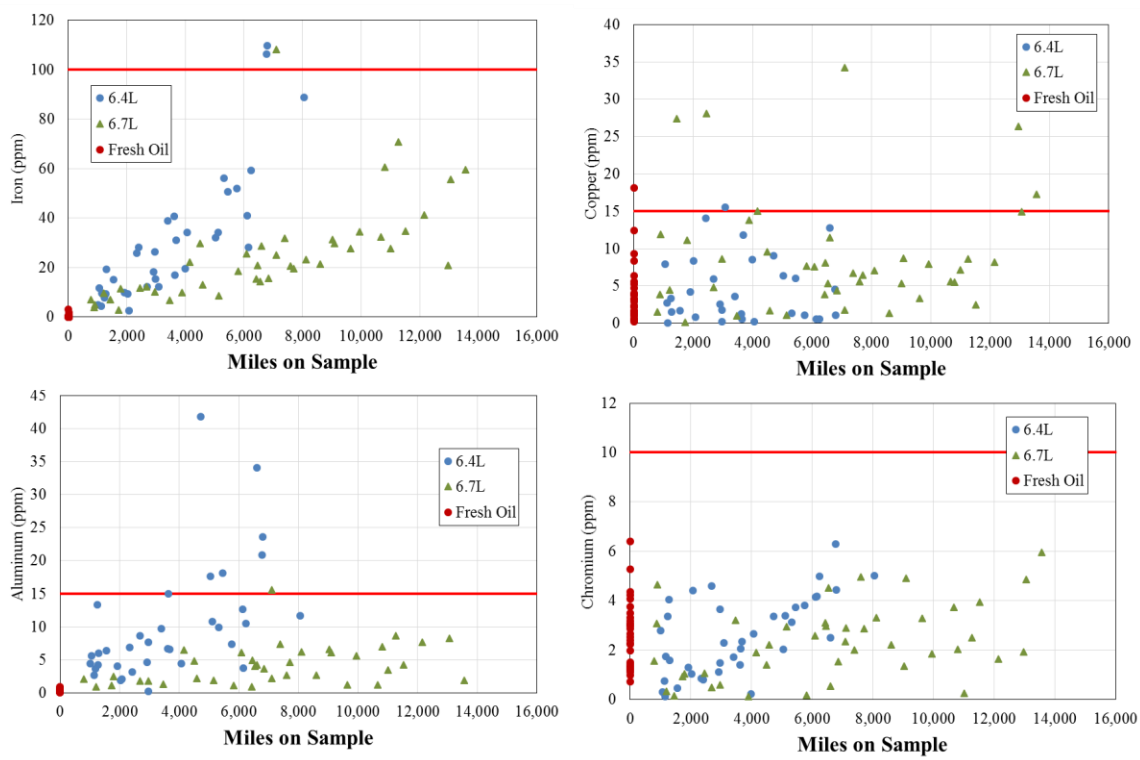

FIGURE 26 : Wear metals concentration for class 0210 trucks

5.6 Impact of Extended Drain Intervals on Oil Performance

One concern for extending engine oil drain intervals is to determine if oil degradation occurs at a faster rate after multiple extended drain intervals. Figure 27 shows three IMAP trucks (462-1270, 462-2302 & 462-2303) that were extended to the engine oils useful life twice. These figures compare TBN and iron concentration to miles of use. 462-1270 had a slight decrease in oil degradation on its second extended oil interval, but remained at the same rate of iron concentration. Trucks 462-2302 and 462-2303 had the same rate of oil degradation for TBN in the first and second extended oil interval. Iron concentration for these trucks seem to have decreased on the second extended oil interval. This indicates that extended oil intervals have the same degradation rates as the recommended intervals.

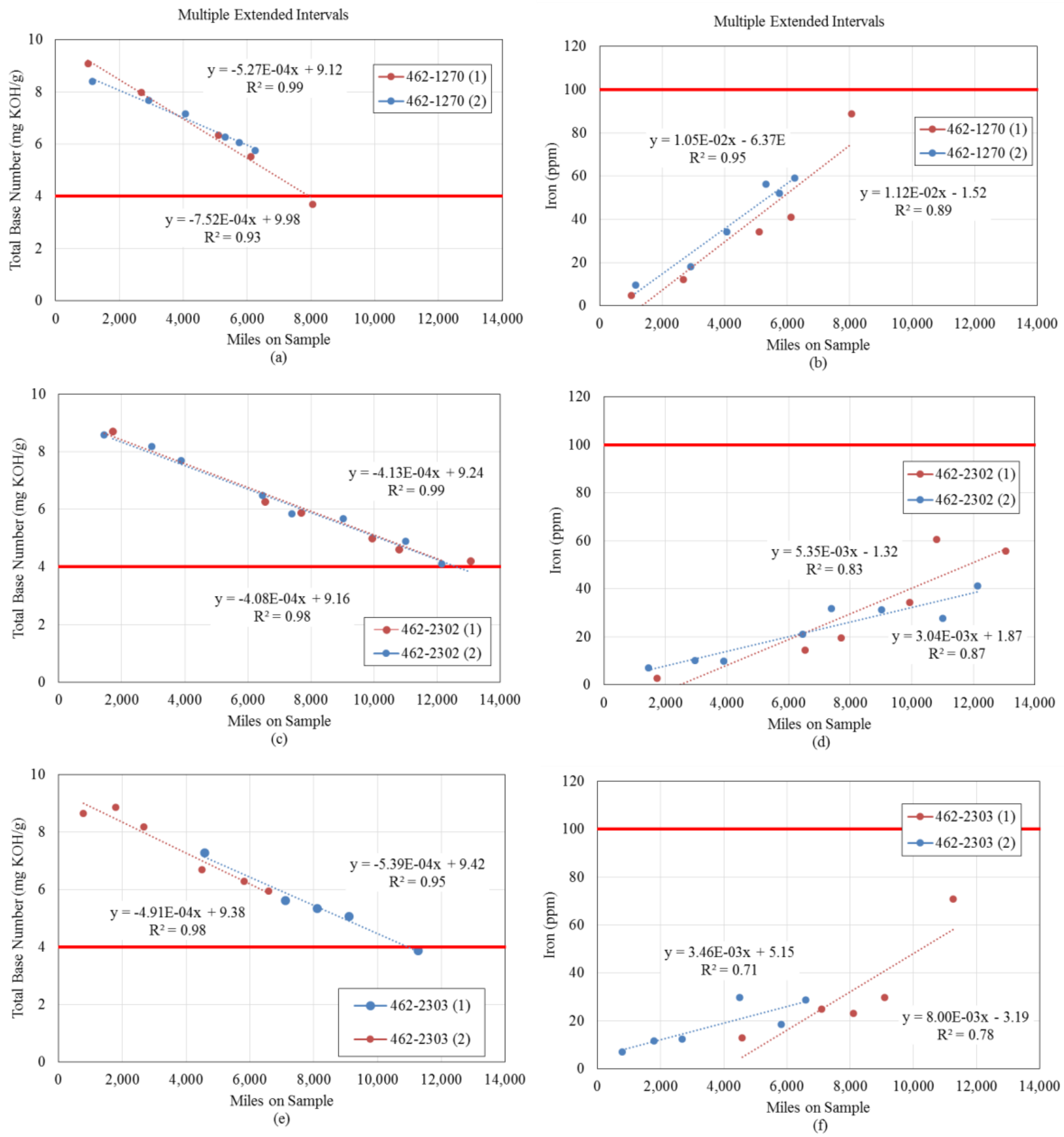

FIGURE 27 : Multiple extended oil drain intervals for class 0210 trucks

5.7 Extended Oil Drain Intervals Compared to the Age of the Class 0210 Truck

Another comparison for extending engine oil drain intervals was invesitaged to see if the age of the truck influenced the rate of oil degradation. Figure 28 represents TBN of the extended drain intervals for 6.7L engines compared to the odometer reading. The odometer readings from these trucks varied from approximately 35,0000 to 95,000 miles. Iron concentration was also investigated as the age of the trucks increased as shown in Figure 29. Iron concentraion rate remained consistant throughout the age of the truck. Figure 30 respresents the rate of oil degradation compared to the odometer reading. The rates of degrdation remain constant, ranging from approximately .0004 to .00055 mg KOH/g per mile.

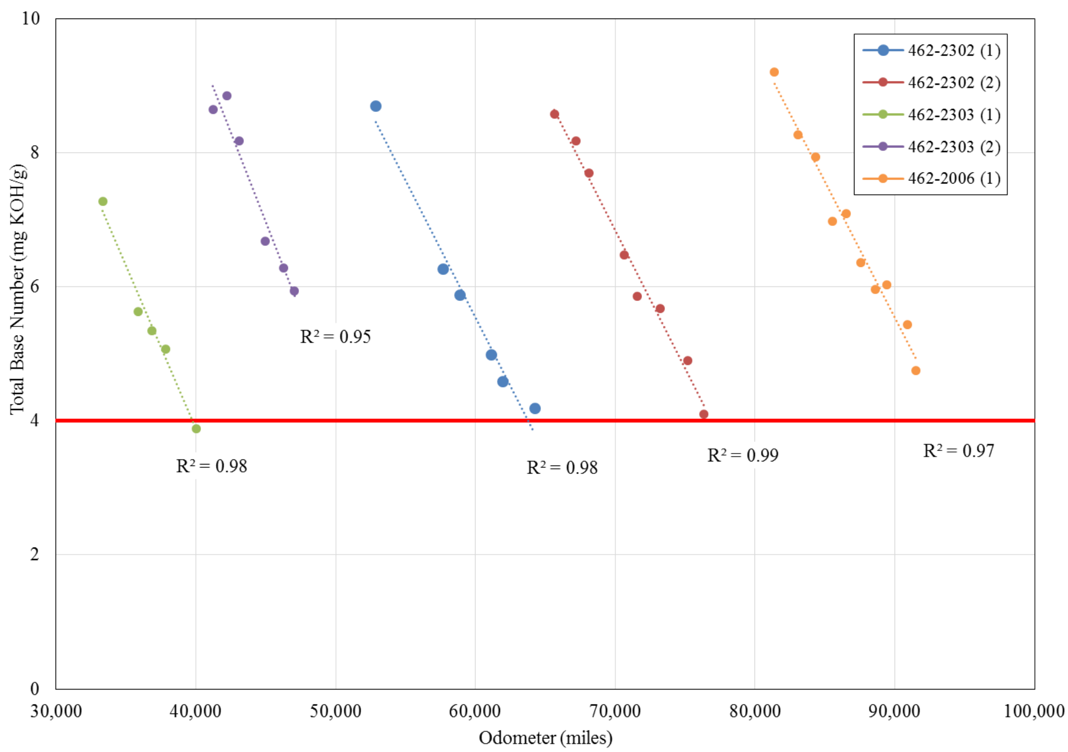

FIGURE 28 : Extended drain intervals (TBN) compared to the age of class 0210 trucks

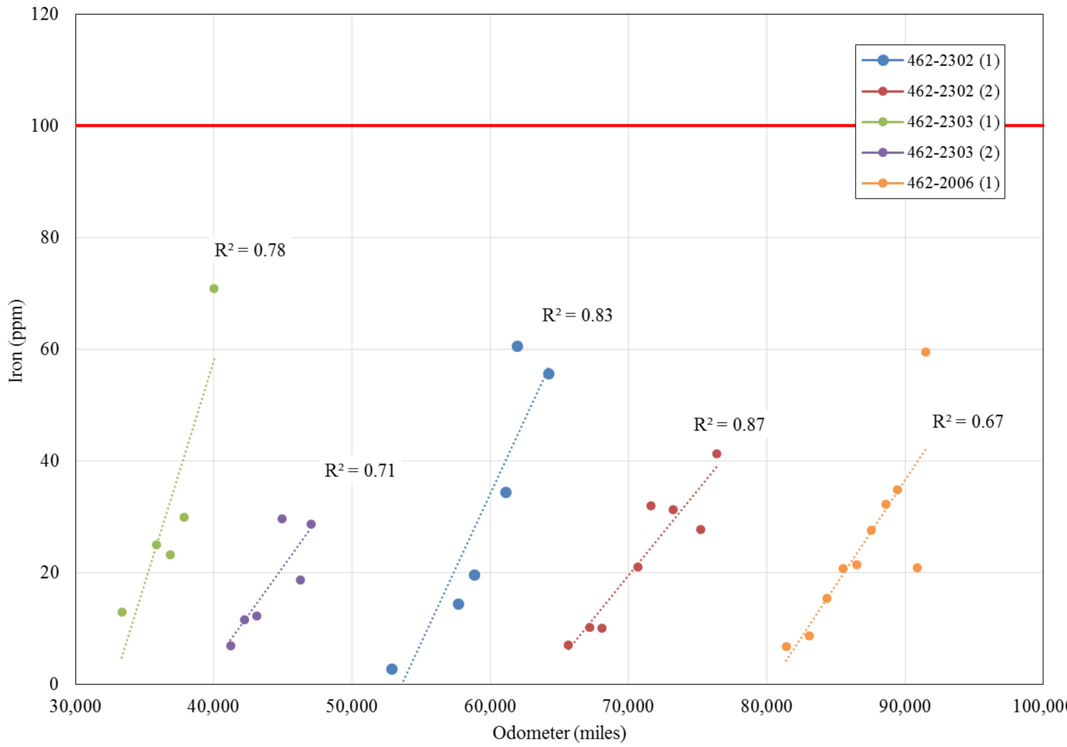

FIGURE 29 : Measured iron in class 0210 trucks on extended program

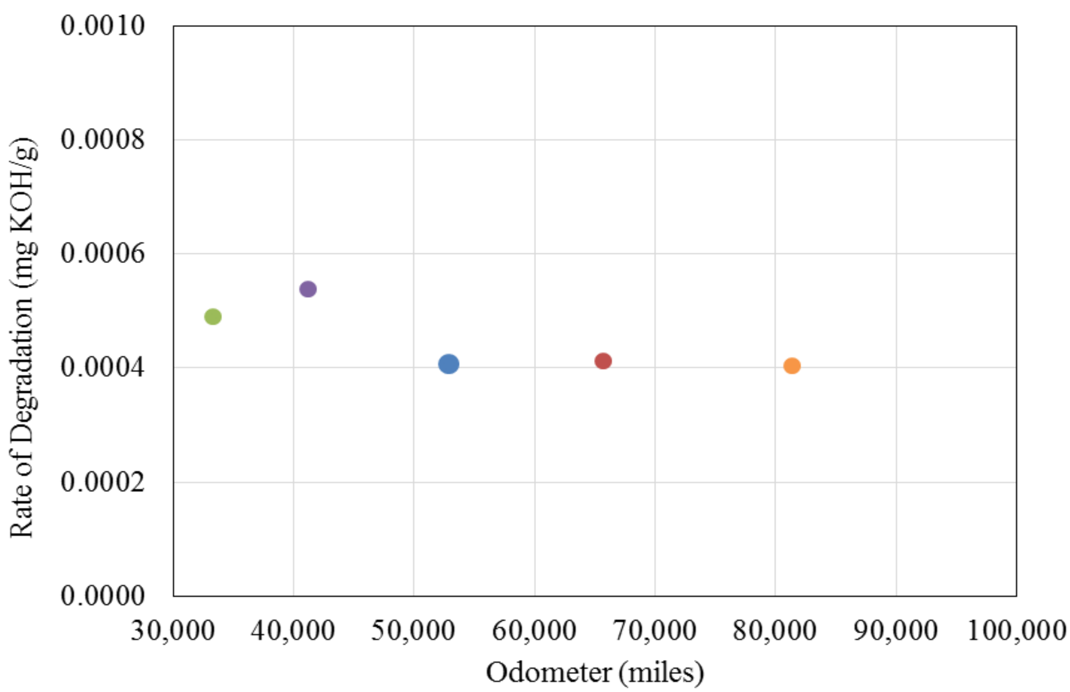

FIGURE 30 : Rate of degradation for class 0210 trucks

5.8 Class 0303 and Class 0311 Tractors Combined Data

Figure 31 presents the TBN data for class 0303 and class 0311 tractors. Class 0303 tractors are 6.7L New Holland's and 4.5L John Deere's. Class 0311 tractors are 4.5L and 6.8L John Deere tractors. Both classes started at the 9.33 TBN measured average and then that value was reduced down to approximately 8 to 9.5 mg KOH/g at 100 hours and 7 to 8.5 mg KOH/g at 225 hours. From the data obtained the TBN in both classes had approximately the same oil degradation rate. Figure 32 presents the Viscosity data for class 0303 and class 0311 tractors. Both classes of tractors have a consistent viscosity throughout the useful life of the engine oil. Both classes started out at the initial 14.99 cSt measured average and remained between the 12.5 to 16.3 cSt criteria for a 40-weight engine oil. Even though these classes are different tractor types and with different engine sizes, it can be concluded that oil degradation happens at the same rate.

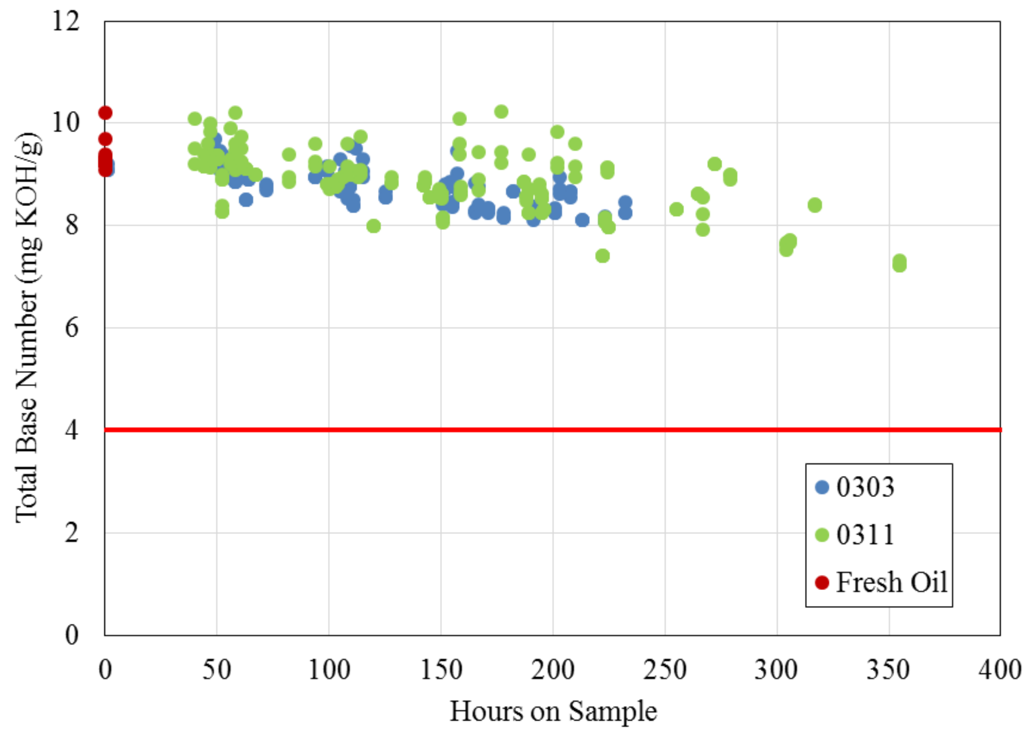

FIGURE 31 : Class 0303 and class 0311 tractors combined TBN data

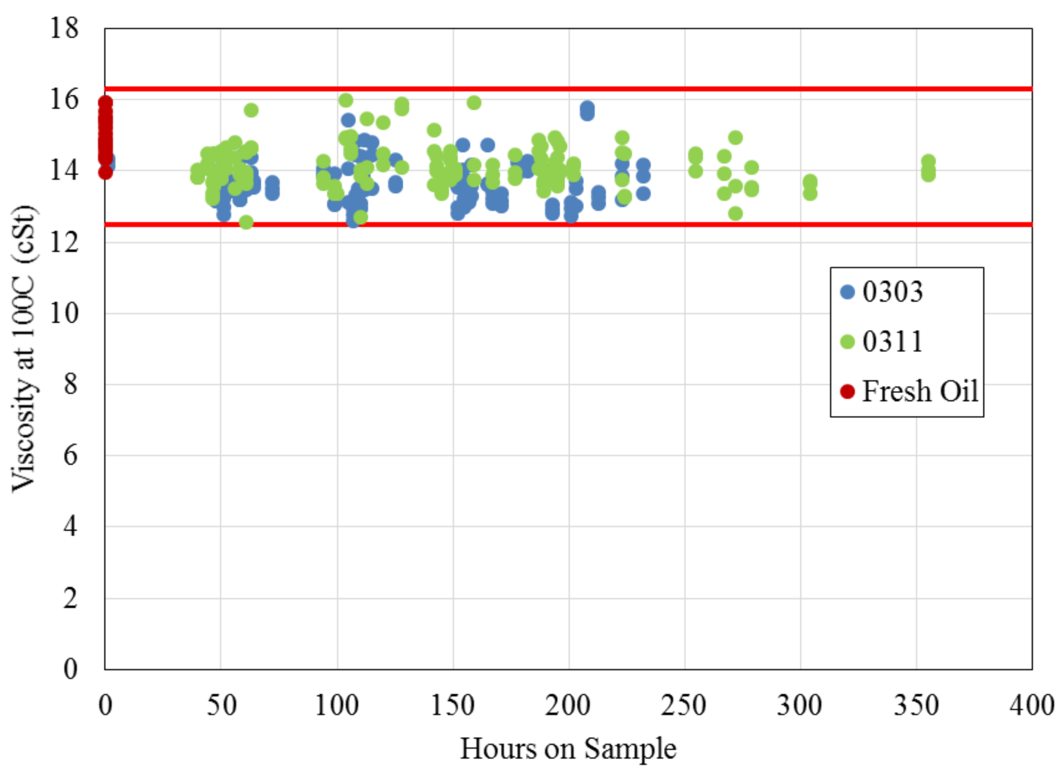

FIGURE 32 : Class 0303 and class 0311 tractors combined viscosity data

5.9 New Tractor Analysis Class 0303

Four tractors in class 0303 had significantly high copper concentrations. These tractors are 838-0311, 838-0312, 838-0313 and 838-0314. These tractors had a beginniing odometer reading of 4 to 6 hours. These new tractors had high copper concentrations due to the new engine break-in period. The orginal equipment manufactor (OEM) recommends that there first engine oil be replaced at 100 hours. Figure 33 shows these four tractors have higher copper concentrations within this break-in period of the engine. It also shows that the second interval drain may also need to be changed within th 100 hour engine oil interval. On the second oil interval, three tractors from class 0303 did not reach the copper threshold but are near the threshold throughout the engine oil's useful life. One tractor (838-0311), however, does reach the recommended threshold copper concentraion limit.

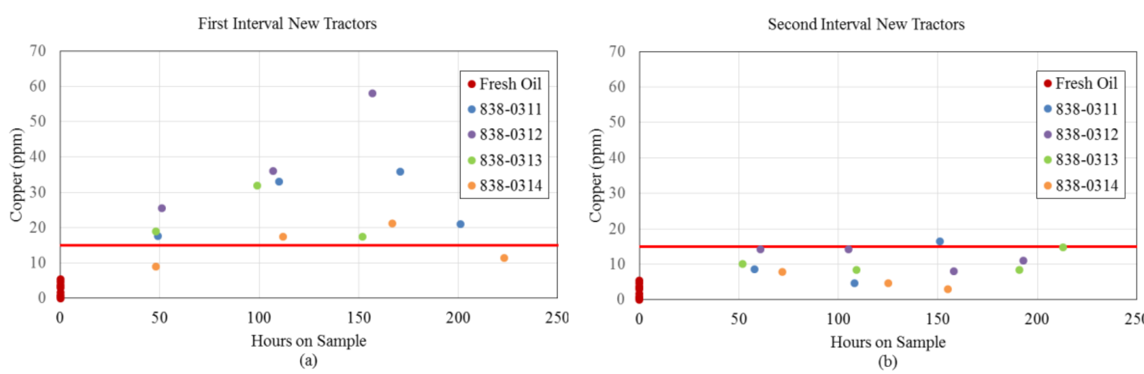

FIGURE 33 : Class 0303 new tractor engine oil analysis

5.10 Oil Drain Intervals (TBN) Compared to the Age of the Class 0311 Tractor

It is also equally important to compare the age of the tractor to the oil degradation rate as shown in Figure 34. The age of these tractors ranged from approximately 3,900 to 7,250 hours. The age of the tractor does not influenced the oil degradation rate as shown in Figure 35. Oil degradation rates were approximately .00055 to .0075 mg KOH/g per hour of use. This indicates that the age of the machine does influence or increase rate of oil degradation.

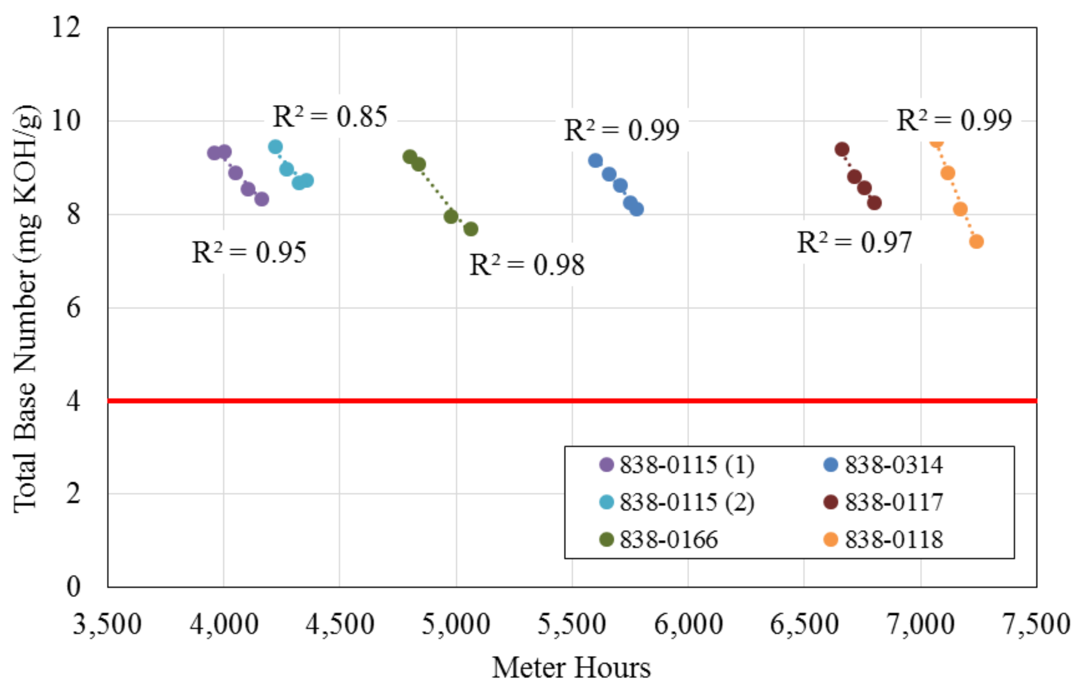

FIGURE 34 : Drain interval (TBN) compared to the age of class 0311 tractors

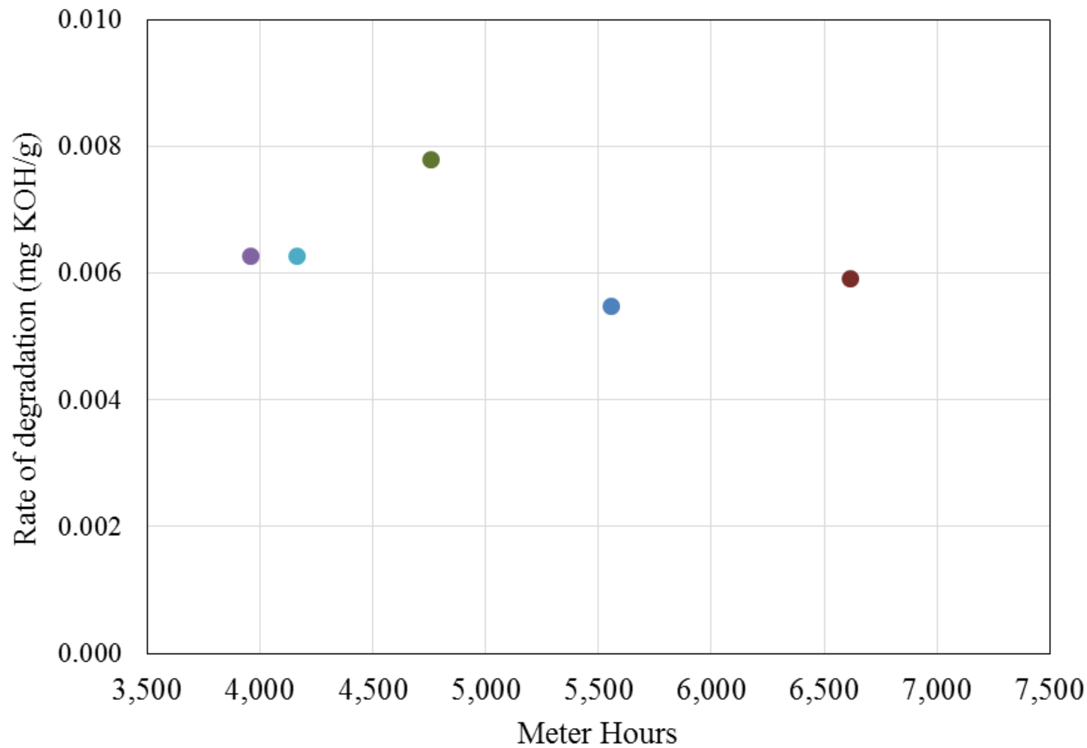

FIGURE 35 : Rate of degradation for class 0311 tractors

CHAPTER 6: DISCUSSION

Observing engine oil through continuous analysis provides insight for understanding changes in oil quality and extended engine oil intervals. To understand engine oil degradation, threshold limits on the oil properties need to be set to ensure oil quality that provides proper and sufficient lubrication.

Fresh oil analysis from the oil received by the NCDOT shows significant results regarding the Rotella® T6 synthetic 5W-40 oil. This synthetic oil used by the NCDOT under-performed compared to the published values for TBN and viscosity. Fresh oil TBN had a measured average of 9.66 mg KOH/g, which is 0.94 mg KOH/g less than the published value of 10.6 mg KOH/g. The measured average viscosity was 12.84 cSt, which is 1.36 cSt less than the published value of 14.2 cSt. The Conoco HD Fleet Supreme® 15W-40 conventional mineral oil had minimal variation between average measured values and published values.

TBN was found to be the best way to understand and measure engine oil quality. The mineral oil in class 0209 had a slight degradation rate, and the engine oil life was extended to approximately 6,500 miles with a TBN of 8.25 mg KOH/g which is well above the threshold value. Classes 0303 and 0311, which also used mineral oil, had a slight degradation rate and the engine oil life was extended to approximately 225 hours for class 0303 and 450 hours for class 0311 without reaching the threshold limit. Class 0210 engines operated using synthetic engine oil. This class had multiple trucks that reached the threshold limit for TBN. This class also had two different types of engines (6.4L and 6.7L). The 6.4L engine had a faster degradation rate than the 6.7L. The 6.4L can have an extended oil drain interval of approximately 8,000 miles whereas the 6.7L can be extended to approximately 12,000 miles. Linear regression analysis showed that there is a strong relationship between TBN to either hours or miles of use and that this slope is a good and consistent measure of oil quality.

Viscosity in the mineral oil also performed well in classes 0209, 0303 and 0311. Viscosity remained between the upper and lower limits through the useful life of the engine oil for these classes. Class 0209 and 0303 had no statistical relationship between viscosity and hours or miles of use. Class 0311 had a strong relationship between viscosity and hours of use, with a p-value of 7.499E-04. Class 0311 had an increase of viscosity after 250 hours of use. Even though there is a relationship that shows that the slope of degradation is not zero between viscosity and hours of use for class 0311, viscosity is still not a strong representation of oil degradation. Rather, viscosity is a representation of oil quality. The synthetic oil performed well for 6.7L engines in class 0210 and remained near the lower limits throughout its useful life. The 6.4L lacked viscosity performance. There was an instant drop of viscosity within the first 3,000 miles of use to approximately 8-10 cSt, which is well below the limits of a 40 weight oil. This drop in viscosity is from fuel dilution leaking into the crankcase. Overall, viscosity is a not a good measure of oil degradation. Viscosity in all machines except for the trucks with the 6.4L engines remain at a minimal slope throughout its useful life.

Wear metals are not an indicator of oil degradation but can be used to suggest internal engine malfunctions and indicate oil quality. Wear metals do not reach the threshold limits unless there is an internal engine malfunction or the machine is new. The engine of new machines go through a break-in period where high metal concentrations were observed.

New engine observation was conducted on class 0311. This class has four new tractors with an odometer reading from 4 to 6 hours. It was found that the engine oil in these four tractors had high copper concentrations within the first 100 hours of use. It was also found that the second engine interval had copper concentrations near the threshold limit as well.

Multiple extended engine oil intervals were performed on class 0210. It was found that the TBN rate of degradation was not increased as the engine oil interval increase. This is significant, because if the oil degradation rate increased as multiple extended drain intervals were conducted then the machines would not be able to be extended.

The age of the machine was also observed to see if the age of the machine influenced the TBN degradation rate. Class 0210 with the 6.7L engines and class 0303 tractors were analyzed. Class 0210 indicated that the degradation rate remain relatively consistent even as the odometer reading on the trucks increased. These trucks ranged from approximately 30,000 to 90,000 miles. Class 0303 also had the same degradation rate throughout its useful life. This class had tractors that ranged from approximately 3,400 to 7,200 hours.

Classes 0303 and 0311 tractors operated using different engine types. It was concluded that the TBN rate of degradation for these classes performed the same. The viscosity of these classes performed the same as well. Classes 0303 and 0311 can be operated on the same extended preventative maintenance plan.

Overall the mineral oil outperformed the synthetic oil. This can be observed by looking at the oil degradation trends for the TBN. Classes that operated using the conventional mineral did not reach the threshold limit for TBN and had a minimal slope of degradation. Whereas class 0210 that operated using synthetic reached the threshold value multiple times. TBN is the best way to observed engine oil degradation for all four classes. Viscosity and wear metals do not indicate oil degradation, but rather the overall quality of the engine oil. Wear metals presence in the oil is a factor of internal engine malfunctions. Multiple extended engine oil did not affect the rate of oil degradation. The rate of oil degradation is not influenced by the age of the machine as well.

Being able to extend the drain interval allows for less oil usage and maintenance cost. This will have a decrease in the life-cycle cost of equipment. Being able to interpret the engine oil analysis also allows for the user to understand how internal functions may be malfunctioning. Extending engine oil without being able to understand the results could result in excessive drain intervals that could have a detrimental effect on the engine and its components.

CHAPTER 7: CONCLUSION AND RECOMENDATIONS

In this research, oil degradation was observed and trends were developed from continuous oil analyses of the NCDOT fleet. Bulk properties, contaminants, and wear metal threshold limits were used to justify oil quality, ensuring the oil provides proper lubrication. The following conclusions were drawn from this research:

1) TBN presents better trends of oil degradation and shows the overall quality of the oil. This can be concluded by looking at the linear regression analysis. TBN data had strong relationship between the hours or miles of use. TBN degradation was observed in all classes, but had significantly higher degradation rate in class 0210. It is not practical to use TBN degradation rates to extend oil drain intervals in classes 0209, 0303, and 0311 due to minimal degradation. These classes can have extended engine oil drain interval that is double the current engine oil drain interval without reaching the threshold value for TBN. Viscosity does not indicate oil degradation but overall oil quality. There is a possible relationship between viscosity and hours or miles of use, but it should not be a consideration in extending oil intervals. Wear metals are not a measure of oil quality but rather a measurement of the quality of the engine.
2) Looking at each type of oil with respect to the equipment it is used in, the mineral oil outperformed the synthetic oil. The mineral oil had minimal

reduction in TBN and remained within the upper and lower viscosity limits with exception of a few machines due to internal engine malfunction or a corrupt analysis. This difference in performance can be observed by comparing class 0210 trucks to class 0209 trucks, and classes 0303 and 0311 trucks. Class 0210 operating with the synthetic oil had a higher degradation rate compared to class 0209. Class 0209 oil degradation rate was approximately zero. The mineral oil observed as a group had a slower measured degradation rate.

3) Class 0209 trucks oil degradation did not reach the threshold values at approximately 6,500 miles. This can be observed from Figure 15 and Figure 16. The engine oil for this class had minor oil degradation throughout its useful life.

4) The data also shows that class 0303 and class 0311 tractors approximately have the same oil degradation trends throughout the useful life of the oil as shown in Figure 31 and Figure 32. Oil samples did not reach threshold limits for TBN or viscosity at approximately 225 hours for class 0303 and approximately 450 hours for class 0311. The age of the machine does not influence the oil degradation rate as shown in Figure 34.

5) The four new tractors in class 0303 did have high copper concentrations at approximately 100 hours as shown in Figure 33. This is a result of the break-in period of the new engine. Engine oil with high copper concentrations can have a detrimental effect to the engine and its components.

6) From class 0210 trucks, the 6.4L and 6.7L oil degradation rates are sufficiently different. The 6.4L engine has a higher oxidation and nitration rate which ultimately allows the engine oil to degrade faster than the 6.7L. From the analysis, multiple extended oil drain intervals do not influence the rate of oil degradation for TBN and viscosity as shown in Figure 28. Also for class 0210 trucks the age of the truck does not influence the oil degradation rate. Trucks with approximately 35,000 to 95,000 miles had approximately the same oil degradation trends.

The following recommendations are made based on the results and conclusions of this research:

1. TBN degradation rates should be use to extend oil drain intervals for class 0210. Classes 0209, 0303, and 0311 TBN degradation rates are minimal and do not influence engine oil quality as much as class 0210.
2. Oil drain intervals for class 0209 trucks can likely be extended to 8,000 miles without significantly increasing the potential for damage to the engine.
3. Oil drain intervals for class 0303 and 0311 tractors can be on the same preventative maintenance plan, due to the similar oil degradation rates for TBN. These classes can be extended to 500 hours without significantly increasing the potential for damage to the engine.
4. The first engine oil drain interval for new tractors in class 0303 and class 0311 should be at approximately 100 hours. This is due to the first engine

oil drain interval containing high copper concentrations within the first 100 hours of use.

5. Oil drain intervals for class 0210 trucks with the 6.4L engine can likely be extended to 6,000 miles without significantly increasing the potential for damage to the engine. 6,000 miles was selected instead of the lower 95% confidence interval of approximately 8,000 miles due to the presence of fuel dilution in the engine oil.
6. Oil drain intervals for class 0210 trucks with the 6.7L engine can likely be extended to 12,000 miles with 95% confidence that extended drain interval is not significantly increasing the potential for damage to the engine.

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