ANALYSIS OF ENGINE OIL QUALITY DEGRADATION BASED ON FLEET OIL SAMPLING

by

Bhavana Dalia

A thesis submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Master of Science in
Construction and Facilities Management

Charlotte

2015

Approved by:

____
Dr. John Hildreth

____
Dr. Nicholas Tymvios

____
Dr. Don Chen

ABSTRACT

BHAVANA DALIA. Analysis of engine oil quality degradation based on fleet oil sampling (Under the direction of DR. JOHN HILDRETH).

Engine oil functions as the lifeblood of engine providing lubrication, and protecting the engine against failure and corrosion (Barnes et al. 2001; Basu et al. 2000). Engine oil samples are analyzed to determine the condition of oil and supervise the health of machines. Oil degradation is assessed by analyzing oil quality against the serviceability of oil. The current study was focused on determining whether the engine oil sampled periodically and infrequently by NCDOT for the purpose of monitoring the health of individual machines could be used to evaluate the rate of oil degradation. Therefore, the oil quality measures were obtained and regressed against each calculated oil age parameter to evaluate the relationship for the selected equipment classes. The analysis results indicated that a significant relationship between oil quality and oil age was not observed from the data collected and analyzed. The research was challenged by insufficient analyses data as the equipment classes for analysis were selected based on the number of oil analyses results and the classification of equipment. The equipment classification was limited to the availability of preventive maintenance records and the determination of oil age parameters. The study concludes that engine oil sampled periodically and infrequently for the purpose of monitoring the health of individual machines do not serve the purpose to determine the rate of oil degradation for the given classes of machines.

ACKNOWLEDGMENTS

I would like to thank and express my gratitude to my academic advisor Dr. John Hildreth for the current research idea, support and encouragement, continuous improvements to this document, advices and mainly for having faith in me. This thesis would not be complete without his corrections, support and knowledge. I am delighted to have an opportunity of working under his guidance. He has thoroughly worked with me with patience and always encouraged my thoughts. I would like to thank the members of my thesis committee, Dr. Nicholas Tymvios and Dr. Don Chen for providing their support in the committee and great comments to improve this thesis. I would like to thank them for their ideas and questions which helped me understand my thesis in a better way. This research would not be accomplished by the analysis of the data. I would like to thank NCDOT for providing the data which was utilized in conducting the research. I am always indebted to my family especially my parents to believe in me, to encourage me and support me in all the good and bad times

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Background

The Fleet Material and Management Unit (FMMU) operated by NCDOT conducts systematic preventive maintenance program on a substantial amount of equipment in the fleet. The fleet consists of approximately 16,000 machines valued at $650 million and consists of a variety of equipment including both on-road and off-road equipment. Preventive maintenance (PM) is essential to keep the fleet functioning in a safe and efficient manner and helps to avoid potential problems through the service period of equipment. The adopted PM procedures include changing oil, replacing air and oil filters, and checking the condition of vehicle and its parts. Preventive maintenance services are scheduled to be performed every 5,000 miles or 200 hours on all the equipment type, regardless to the usage of vehicle or manufacturer's recommendation.

Engine oil should be replaced as it approaches the degradation stage. Engine oil degradation process begins with the depletion of additives accompanied by oxidation of base components (Singh and Swaroop 1997). Engine oil further gets contaminated by fuel, water, ethylene glycol, soot, and other wear metals (Guan et al. 2011). Engine oil replacement is a crucial preventive maintenance task, primarily because the service life of the machine is dependent on the quality of the oil and, secondly due to the extensive cost involved in performing oil changes to the large number of equipment in the fleet. The process of understanding the rate of oil degradation can be explained by collecting and analyzing oil samples from the machine.

NCDOT conducts periodic and infrequent oil sampling on machines to monitor the health and check for potential problems of individual machines in the fleet. Engine oil samples collected from machines are analyzed for understanding the condition of oil as well as monitoring the machine condition (Fitch 2013). In an oil analysis, bulk oil properties, contamination and debris levels of the oil sample are measured. The benefits of oil analysis include optimum equipment life, increase in serviceability of oil, decrease in preventive maintenance costs for equipment, increased awareness towards safety and environment (Oil analysis 2009). Figure 1 gives an overview of the benefits of oil analysis.

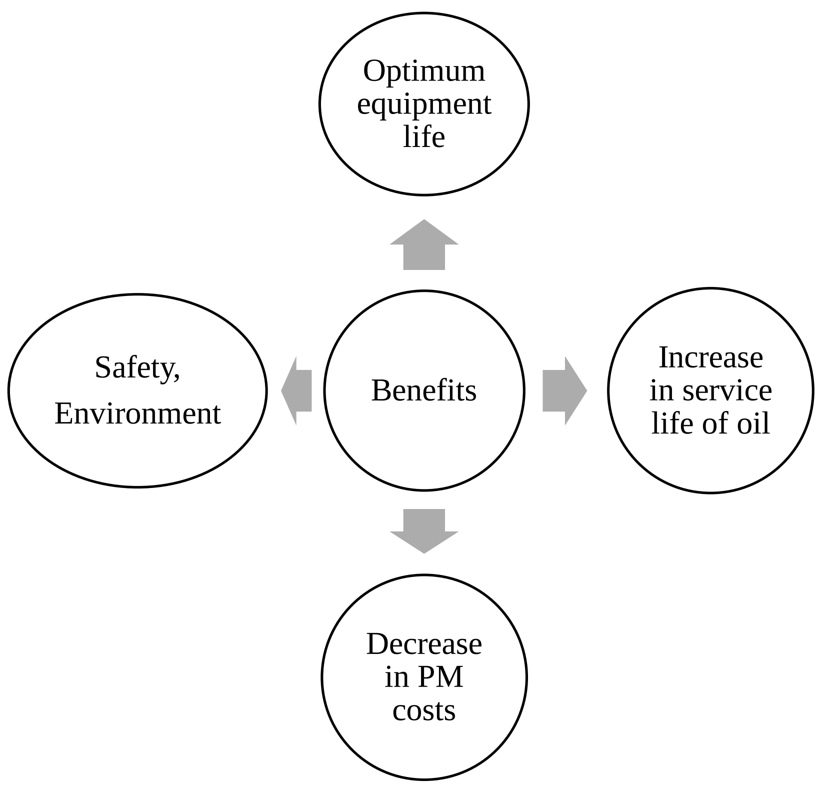

Figure 1: Benefits of oil analysis (Oil Analysis 2009)

1.2 Problem Statement

Oil quality can be measured in terms of physical and chemical properties, as well as contamination levels. Traditionally, the rate of oil degradation for a machine is determined by regular and periodic oil sampling of machine. Moreover, the condition of oil and health of individual machines in the fleet has been supervised individually with the help of laboratory oil analyses. Oil analyses results obtained either regularly or periodically measures similar properties of oil in the analysis. However, the difference in the experiment occurs in terms of the number of machines and duration in which the number of oil analysis results are obtained. Regular and consistent oil sampling can be practically conducted on particular machines, whereas periodic and infrequent oil sampling are feasibly conducted on a number of machines in the fleet.

Clearly, the condition of oil and the health of the machine is supervised with the help of laboratory oil analyses. Despite knowing the condition of oil in the machine, there is a limited understanding of the rate of degradation of oil of all of the machines. It would be highly beneficial to determine whether the oil sampling results conducted for the purpose of monitoring the health of individual machines yields the rate of oil degradation which would be traditionally be obtained by regular and consistent oil sampling of a single machine. The research aims at finding out whether the oil analysis sampling of a number of machines obtained would yield the rate of oil degradation as conventionally obtained by regular and consistent oil sampling of particular machines. The rate of oil degradation obtained would serve to determine an optimum oil change interval which would help to reduce the enormous cost incurred due to conducting regular preventive maintenance and wastage of engine oil.

1.2.1 Research Questions

The following research is designed and organized for the purpose of answering the following questions:

1) Whether the chosen oil age parameters, gallons of fuel consumed and miles travelled by an equipment could be utilized to evaluate oil quality.
2) Whether the analysis results of engine oil sampled periodically and infrequently for the purpose of monitoring the health of individual machines would yield similar rate of oil degradation as traditionally obtained by regular and consistent oil sampling of particular machines.

1.3 Scope and Limitations

1.3.1 Scope

The goal of the current research was to determine whether the oil analyses conducted periodically and infrequently by NCDOT for the purpose of managing the health of individual machines could be utilized to evaluate the rate of oil degradation. Hence, the scope of the current research includes determining the oil quality parameters and oil age parameters utilizing oil analysis sampling reports and NCDOT equipment database for the machines in NCDOT fleet.

1.3.2 Limitation: Available Oil Analyses Reports

This research was limited to existing oil analysis reports from the NCDOT fleet. The results of 495 analyses of oil sampled conducted on 10 equipment classes are available. Table 1 lists the available individual class numbers and the description of the class type.

Table 1: Class number and the description of the class

Class	Description of the class
0205	TRUCK, DUMP 33000 GVW
0206	TRUCK, MISC 32000 GVW
0209	TRUCK, MAP 5000/7000 GVW , EXT.CAB
0212	TRUCK, DUMP TANDEM 50000 GVW
0217	TRUCK, TRACTOR TANDEM 50000 GVW
0218	TRUCK, 37000 GVW
0219	TRUCK, C&C TILT CAB 31000 GVW
0227	TRUCK, TRACTOR TANDEM 75000 GVW
0230	TRUCK, C&C TANDEM 50000 GVW
0232	TRUCK,DUMP,4 AXLE 5000 GVW

1.3.3 Limitation: Measurable Oil Quality and Oil Age Parameters

Gallons of fuel consumed and miles driven by the equipment were the chosen oil age parameters for the current machines. Hence, fuel meter readings and odometer readings were limited to the ones that were available in the maintenance records of the NCDOT equipment database. The available analysis reports include various oil quality properties classified as bulk oil properties, contamination and wear metals shown in Table 2. However, the chosen oil quality measures were viscosity and TBN because these properties indicate the quality of oil due to the changes in the physical and chemical composition of oil. Contamination and wear metals enter the engine oil as the engine is utilized during the service period of machine.

Table 2: Measurable properties in engine oil analysis

Bulk oil properties	Contamination	Wear metals
Viscosity (cSt)	Water (% by wt)	Magnesium (ppm)
Total base number (mgKOH/g)	Soot/Solids (% by wt)	Calcium (ppm)
Oxidation (abs)	Fuel Dilution (% by wt)	Iron (ppm)
Nitration (abs)	Glycol (% by wt)	Lead (ppm)
	Sodium (ppm)	Copper (ppm)
	Potassium (ppm)	Chromium (ppm)
	Silicon (ppm)	

1.4 Objectives of the Current Research

The research was designed to accomplish after establishing a literature review, compiling oil analyses reports and equipment information, selection of equipment classes for study, analysis of oil quality and oil age and interpretation of results.

Objective 1: Literature Review

A thorough literature review was carried out to understand the background of engine oil in terms of types and formulation, the role of engine oil for an engine, measurable properties of engine oil quality, the process of engine oil degradation, optimum change interval for oil, and understanding the advantages and effects of extending the drain intervals on oil.

Objective 2: Compile Oil Analyses Reports and Equipment Information

Oil analyses sample reports were provided by NCDOT for 202 machines and contained information about equipment number, measurable engine oil properties such as bulk oil properties, contamination and wear metals. The data extracted about oil properties was integrated with the available physical description of each machine from the NCDOT equipment database system and was carefully compiled in a single spreadsheet.

Objective 3: Selection of Study Classes

Oil analyses reports were analyzed from every class to check if every class had sufficient number of oil analysis reports and number of machines for the analysis. Later, maintenance records were reviewed to determine the engine oil age parameters in terms of gallons of fuel consumed and miles travelled by the equipment for the selected classes. Later, the equipment from each class were classified further based on availability of preventive maintenance records and determination of oil age parameters. The equipment class which had adequate number of equipment after classification were selected based on for the analysis. The distribution of oil age (miles) in the form of histogram were obtained for each of the selected classes.

Objective 4: Analysis of Oil Quality and Oil Age

Regression analyses was conducted to perform longitudinal analyses of typical oil quality measures (viscosity and TBN) with respect to chosen oil age parameters, gallons of fuel consumed and miles travelled for the selected classes of machines. Regression results and graphs were analyzed and interpreted to evaluate the relationship between oil quality parameters and oil age parameters.

Objective 5: Interpretation of Results

The final objective was to answer the research question for which the current study was designed to accomplish. The relationship between oil quality and oil age was evaluated, the results were interpreting and conclusions drawn. It was also concluded whether the rate of oil degradation could be determined for individual classes of machines by conducting regression analysis of oil quality properties with respect to oil age parameters.

1.5 Organization of Thesis

The entire thesis contains six chapters with Appendixes A and B. Chapter one includes the introductory background to the purpose of research conducted, problem statement, scope and limitations and provides the objectives of the research conducted.

Chapter two includes the literature review about understanding the importance of engine oil, engine oil degradation, optimum oil change interval and the benefits of extending oil drain intervals.

Chapter three describes the methodology that was useful in conducting the research. The process of data collection and data analysis was explained in this chapter.

Chapter four includes the results of the analysis of the data conducted. The results were interpreted and discussed in this chapter. Chapter five gives a brief conclusion to the research conducted. Chapter six discusses the recommendations that could possibly be inferred from the analysis of the data conducted. Figure 2 helps in understanding the organization of the thesis. Figure 2 gives a pictorial representation of the organization of various chapters of thesis

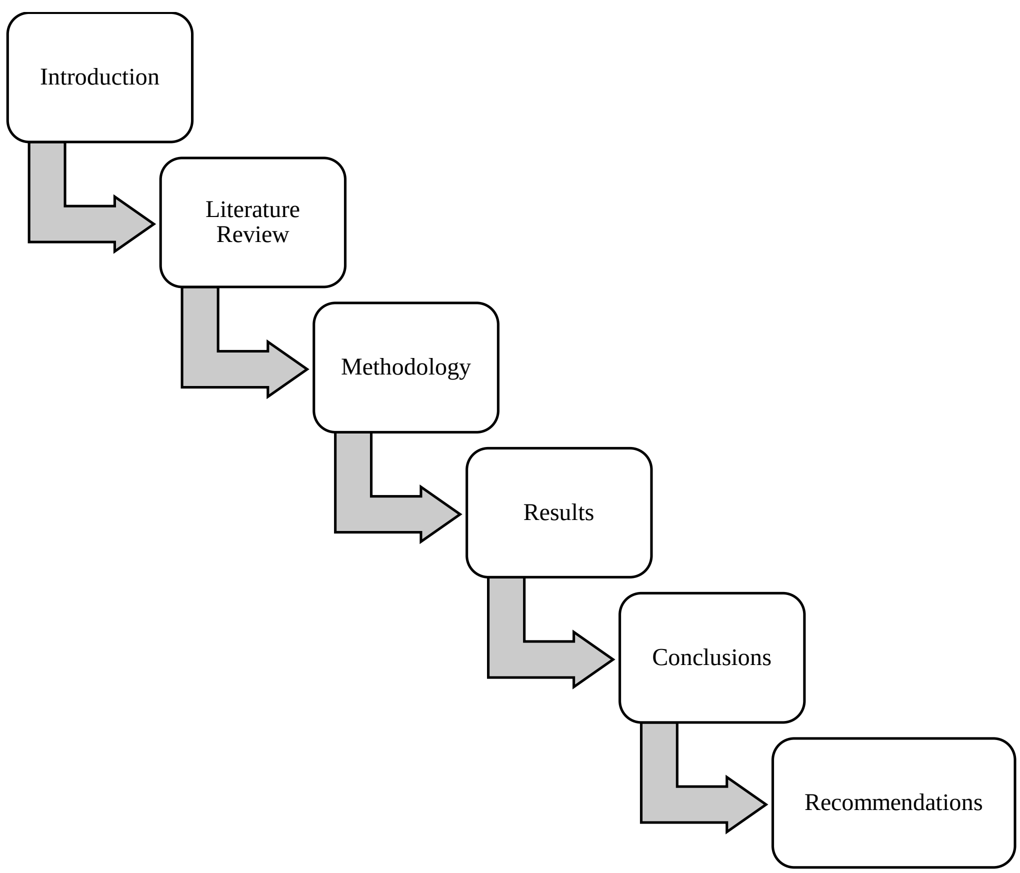

Figure 2: Organization of thesis

CHAPTER 2: LITERATURE REVIEW

The literature review begins by providing background information about engine oil regarding the importance, formulation and describes the qualitative properties of engine oil. Later, the literature review explores studies related to the life of engine oil, the process and effects of engine oil degradation. In the final phase, the literature review highlights the importance and advantages of optimum change interval for oil and extended oil drain intervals.

The maintenance and durability of an engine is important for any engine powered automobile. The durability of an engine primarily depends on oil quality, frequency of oil changes, filter quality and other factors such as engine design, operating conditions and climate (Youngk 2000). Engine oil is very important for supporting and improving the service life of an engine and maintenance costs can be significantly improved by understanding the dynamic changes in bulk oil properties and chemical composition of engine oil. Thus, an understanding of engine oil performance is important for ensuring engine health.

2.1 Background of Engine Oil

The background information about engine oil gives an overview about the types of engine oil, the formulation for engine oil to effectively function for an engine and the various functions of oil in an engine. This serves to develop foundational knowledge about engine oil and to understand its chemical and physical properties.

2.1.1 Types and Formulation of Engine Oil

There are two types of engine oil: conventional and synthetic, which differ by the base oil used in their function. Conventional oil is produced from a mineral base that is derived from fractional distillation of crude oil. Synthetic oil is formulated from base oil derived from polyolefin. The advantages of synthetic oil over mineral base oil includes purity, improved viscosity, and enhanced performance at higher temperatures (Totten et al. 2003).

Automobile engines have undergone several modifications over the recent decades that allow them to operate at high speeds, loads, and temperatures (Mujahid and Dickert 2012). Thus, base oil is enhanced with certain additives to meet the requirements in lubricating modern engines (Rudnick 2003; Rudnick 2009). These specific additives are blended with base oil on a volumetric basis where the percentage is in between 1% to 25%. Additives are a pack of concentrated solutions in engine oil and their concentration is between 10% and 100% (Basu et al. 2000). Common additives include detergents, viscosity index improvers, friction and wear modifier, pour point depressants, anti-oxidants, corrosion and rust inhibitors, and anti-foam agents (Caines and Haycock 1996).

2.1.2 Significance of Engine Oil for an Engine

Engine oil has various functions as the lifeblood of an engine. The primary function of engine oil is to provide necessary lubrication between moving parts of an engine to prevent wear (Barnes et al. 2001). It also functions to prevent engine failure against overheating by aiding in cooling engine parts such as crankshaft, bearings and piston (Jun et al. 2006). It protects the engine through anti-corrosion, sealing compression rings, cleaning engine parts, anti-foaming properties and suspending matter (Basu et al. 2000; Barnes et al. 2001).

2.2 Engine Oil Quality

The quality of engine oil is one of the primary factors while considering the effective functioning of an engine. The parameters that determine the quality of engine oil are bulk oil properties and contamination levels. Bulk oil properties include viscosity, total acid number (TAN), and total base number (TBN) whereas contaminants in engine oil are water, fuel, soot, solids, glycol and various other wear metals. These parameters present in the engine oil in acceptable limits indicate good quality engine oil. Also, it is important to note that when the values of these parameters in engine oil do not meet the acceptance criteria, it determines the onset of engine oil degradation.

2.2.1 Bulk Oil Properties

Viscosity is a measure of resistance to flow at certain temperatures (Oil analysis 2004). The given temperatures at which the viscosity of oil is measured are 40ºC and 100ºC (Lynch 2008). The importance of viscosity is its ability to detect causes of degradation of engine oil through oxidation, contamination and fuel dilution (Mujahid and Dickert 2012). Viscosity is dependent on time and temperature. The value of kinematic viscosity of an engine oil decays logarithmically with time (Herbeaux and Arsdale 1993). The relationship of viscosity with temperature for different grades of oil is described in Figure 3.

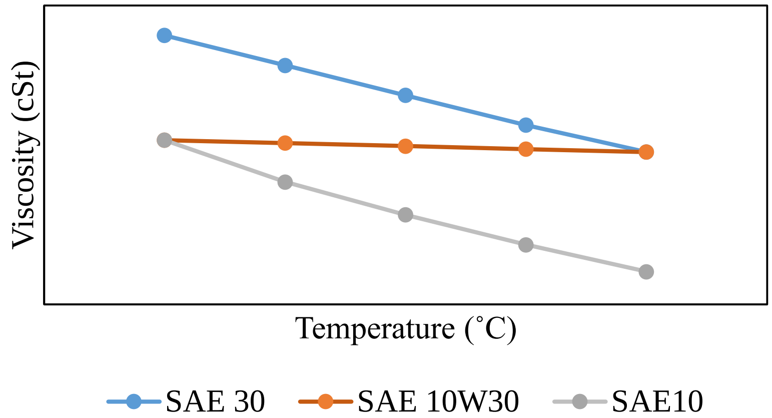

Figure 3: Relationship between kinematic viscosity and temperature (Oil analysis 2004)

Viscosity is a critical parameter as either an increase or decrease in viscosity can affect the performance of oil (Kader 2014). Higher viscosity can cause engine overheating, hinders oil flow, and promotes by-pass of the oil filter (Kader 2014). Decrease in viscosity levels in oil may result in poor lubrication, promote wear and overheating (Agoston et al. 2005). Hence, it is very important to maintain permissible limits of viscosity in oil. Viscosity is measured in centistokes (cSt). The SAE J300 specification for 5W-40 engine oil requires viscosity to be between 12.5 and 16.3 cSt when tested at 100ºC.

TAN and TBN are properties of the oil that indicate the oxidative properties of oil and end of service life of an oil. TAN increases with increase in the age of the oil (Moon et al. 2006). As the service life of engine oil increases, the components of oil are oxidized by reacting with oxygen, nitrogen and sulphur resulting in accumulation of several acidic compounds (Guan et al. 2011). The formation of acidic compounds leads to increase in contamination and oxidation levels of oil. The amount of acidic compounds present in the oil along with the compounds formed due to combustion and oxidation of oil is called total acid number (Basu et al. 2000). To prevent contamination due to acidic compounds, engine oil contains permissible amounts of basic reserves, typically in the form of detergents (Fitch 2012). The function of these basic reserves (additives) is to neutralize the effect of acidic compounds (Basu et al. 2000). The depletion of additives and increase in oxidation levels lead to decrease in the value of TBN. The acceptable value of TAN ranges from 4 to 7 mg KOH/g (Basu et al. 2000). A decrease in TBN by 50% and 75% are regarded as cautionary and critical limits of oil respectively (Angeles 2003). A value of TBN below 4 mg KOH/g indicates the depletion of additives and the need for engine oil replacement (Oil analysis 2004).

2.2.2 Contamination

Water enters the oil primarily through condensation in the crankcase (Jun et al. 2006) and causes oxidation of base oil and formulation of acidic compounds. Thus, contamination due to water may lead to corrosion of pistons, rings, and the liner (Gulf coast filters 2005). The status of engine oil for the concentrations of water in between the ranges 100-300ppm, 300-800ppm, and greater than 800ppm are classified as alert, critical and highly dangerous levels respectively (Angeles 2003).

Contamination due to fuel is caused primarily by repeatedly starting an engine before driving and secondly due to excessive idling of engine (AMSOIL 2004). Major fuel dilution problems are also caused by leaking, fuel system and injectors, as well as inefficient combustion. Fuel dilution results in lower oil viscosity which inhibits proper lubrication (Oil analysis 2004). It is measured in percentage by weight and maintenance action is required if the fuel dilution levels are in the range of 2.5 % to 5 % (AMSOIL, 2004).

Glycol or anti-freeze, is a contaminant in engine oil that lowers viscosity and reacts with water to cause oxidation and leads to corrosion (Fitch 2012). Glycol concentrations as low as few hundred parts per million can cause harmful changes to engine oil (Wang and Lee 1997).

Fuel soot is one of the products formed during the combustion process and enters the crankcase with combustion gas blow-by (Trujillo 2004). Excessive amount of soot may lead to increase in viscosity, carbon deposits, clogged filters and detrimental deposits (Oil analysis 2004). It is measured in percentage by weight and maintenance action is required when fuel soot levels reach 2% to 5% (Angeles 2003).

Wear Metals:

The analysis of wear metals can indicate the specific engine component wearing out and can also indicate if the wear rate is significant (Oil analysis 2004). The analysis could be useful to carry out engine maintenance ranging from minor repairs to major engine repairs (Oil analysis 2004). Iron (Fe), chromium (Cr), aluminum (Al), copper (Cu), lead (Pb), tin (Sn), nickel (Ni) and silver (Ag) are the common metals present that indicate the wear rate of an engine. Table 3 presents moderate and critical values of most common metals.

Table 3: Moderate and critical contamination levels of wear metals (Angeles 2003)

Metal Traces	Moderate contamination	Critical contamination
Iron	100ppm	200ppm
Chromium	10ppm	30ppm
Copper	10ppm	50ppm
Lead	40ppm	100ppm
Aluminum	10ppm	30ppm

The presence of silicon, sodium, or boron in engine oil indicates contamination from dirt or antifreeze (Hilligoss 2012). The threshold values of silicon in engine oil are approximately 10ppm to 30ppm and an increase silicon levels can indicate excessive dirt in engine oil (Angeles 2003). Calcium, phosphorous, and zinc indicate lubrication characteristics (Hilligoss 2012).

2.3 Engine Oil Degradation

Fitch (2014) stated that the life of engine oil is mainly dependent on three parameters 1) engine design, age and conditions 2) driving patterns and conditions and 3) oil properties. Various engine operations can lead to degradation and contamination of engine oil (Ramani et al. 2014). Fitch (2014) also described that the fuel efficiency of an engine strongly relates to the life of engine oil and contaminants in oil can cause a decrease in fuel efficiency. Extreme driving patterns and conditions can result in internal degradation and accumulation of contaminants.

Engine oil degradation is caused by the following chemical deteriorations. The primary degradation is caused due to oxidation of base oil compounds through reaction with oxygen, nitrogen and sulphur, resulting in formation of acidic compounds in crankcase (Jun et al 2006). Engine oil also degrades due to the depletion of additives and accumulation of contaminants such as water, fuel, glycol, soot/solids and wear metals (Guan et al. 2011).

Engine oil degradation can significantly affect the engine performance in terms of reducing the service life, increasing wear rates and also increasing the scope of major engine failure (Agoston et al. 2005; Ramani et al. 2014). To avoid unexpected problems due to engine failure, engine oil replacement should occur before oil loses its quality. Field tests and on-board monitoring devices are two techniques that monitor engine oil condition. During field testing, oil is sampled periodically at defined intervals and the various properties of oil are measured and analyzed to assess oil quality. Various kinds of sensors like electrochemical sensors, chemical sensors, and solid-state micro sensors have been developed to measure engine oil degradation (Mujahid and Dickert 2012). The concept of developing and installing sensors in engine was to measure the permittivity or conductivity of the oil and correlate them to engine oil qualitative properties (Agoston et al. 2005).

Herbeaux and VanArsdale (1993) measured the mechanical degradation of engine oil based on permanent viscosity loss and shear stability index. The kinematic viscosity data was collected by conducting field tests and engine tests on five different oils of same formulation, but with different viscosity index improvers. They found that kinematic viscosity of engine oil decreases logarithmically with time and the kinematic viscosity of degraded oil does not approach an asymptotic value, but reaches a minimum value due to mechanical degradation and oxidation of engine oil.

Kollmann et al. (1998) observed that accumulation of contaminants in engine oil and deterioration of the oil occur at similar rates. This was the foundation to develop on-board oil conductivity measurements. On similar lines, Wang (2000) predicted the stages of engine oil degradation by installing and measuring the outputs of an on-board sensor. He concluded that there are three stages of engine oil degradation: 1) consumption of additives 2) oxidation of oil leading to a rapid increase in TAN and 3) rapid increase in viscosity. The initial decrease in sensor outputs due to the consumption and transformation of additives determines the first stage of oil degradation. Rapid oxidation and accumulation of acidic compounds resulted in rapid increase in the value of TAN that can be detected by the increase in sensor outputs. The third and final stage of degradation was marked by a rapid increase in viscosity. Figure 4 gives a brief overview of the process of engine oil degradation.

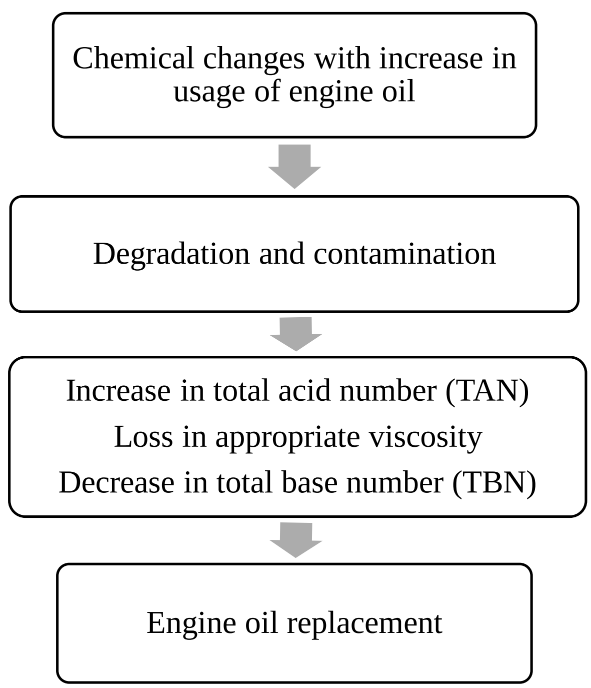

Figure 4: Process of engine oil degradation

2.4 Engine Oil Replacement

Engine oil replacement is the procedure of removing used oil along with its contaminants and additives and replacing it with fresh oil (Youngk 2000). The term oil change is synonymous to oil drain, oil replacement, oil fill and maintenance and it is regarded as one of the basic preventive maintenance procedures for any automobile engine (Youngk 2000). There is a need for determining an optimum oil change interval as an excessive duration between oil changes can lead to excessive wear and damage to the engine. Conversely, frequent oil changes in short durations can increase the maintenance cost of equipment and cause wastage of natural resources (Basu et al. 2000). Youngk (2000) stated that changing engine oil at proper mileage can improve the life of the engine, as well as help in reducing the nationwide waste and recycled oil by 325 million gallons.

The following are the conditions that determine the appropriate oil change interval (Fitch 2012):

1) Engine oil degrades to its maximum limit
2) Internal corrosion caused due to decrease in the value of TBN
3) Accumulation of soot and sludge that settle on internal engine components

2.5 Extended Oil Drain Intervals For Engine Oil

Engine oil is an important component of engine that requires frequent servicing (Bergstra et al. 1998). Normally, manufacturers recommend change intervals based on the climate and type of driving (Wang 2000; Youngk 2000). An interest in the concept of extended drain intervals emerged due to improvements in oil quality and desire to control maintenance costs.

Hosie and Lawrence (1979) conducted field tests to measure the effect of extended oil drain intervals in different highway diesel engines using heavy diesel engine oil. They studied 12 100-ton haul trucks operated for 1500 hours without oil changes which is approximately five times the manufacturer recommended interval. They found that the engine failure does not occur gradually, but rapidly when heavy duty oils are extended over drain intervals. They recommended proper selection of crankcase oil and concluded that unless the oil is severely contaminated by fuel, coolant, abrasion and hydraulic, the practice of unlimited oil drain may be applied without deterioration of engine whose excess hours lasts to an average of 10,000 hours. The noted advantages of extended oil drain intervals include reduction of oil waste and annual engine costs by 50% through decreased maintenance costs and equipment downtime.

Bergstra et al. (1998) developed and tested a new synthetic engine oil to measure the effect of extending drain intervals up to 25,000 miles or three years. Engine tests derived from American Petroleum Institute (API) and Association des Constructeurs Europeans d'Automobile (ACEA) standards, along with non-standard tests such as extended length engine tests, vehicle fuel economy retention tests, high mileage chassis rolls tests and extended oil drain tests under a number of driving tests were conducted on the engine oil. They stated that oil consumption, detergency, reserve, resistance to oil thickening, impact of oil thickening on cold starts, and fuel economy are factors to be considered when evaluating the impacts of extended service intervals. The test results prove that oil formulation can be improved to provide excellent durability, engine wear protection and cleanliness under severe extended oil drain intervals.

Jetter et al. (1998) conducted a study to examine the extended oil drain performance for different type of diesel engine oils. Four test oils identified as blue, red, silver and white oil were developed for this experiment conforming to API CG-4 requirements. Blue oil was a standard oil which does not provide alkalinity reserve beyond the requirements of API CG-4. Red oil was a premium conventional oil that provided reserved alkalinity and exceptional piston deposit exceeding the requirements of API CG-4. Silver oil was a premium, fully synthetic oil which provided excellent alkalinity reserve for excessive wear protection. White oil was also a premium, fully synthetic diesel oil which not only met API CG-4 requirements, but also 1998 U.S. emission requirements. Oils were randomly assigned and tested in 59 heavy duty diesel engines. Test was conducted on a trial distance at approximately 500,000 miles of service. The oil samples were tested every 10,000 miles to determine the condition of the oil.

The viscosity of red oil steadily increased to an upper limit of 16.3 cSt at 50,000 miles, whereas white and silver oil remained within the acceptable limits to 75,000 miles of driving. The viscosity of blue oil dropped at 20,000 miles but it remained in the acceptable limits throughout the study. Hence, it could be proved that oil can maintain satisactory conditions under increased durations. Figure 5 shows the viscosity values for different grades of oil.

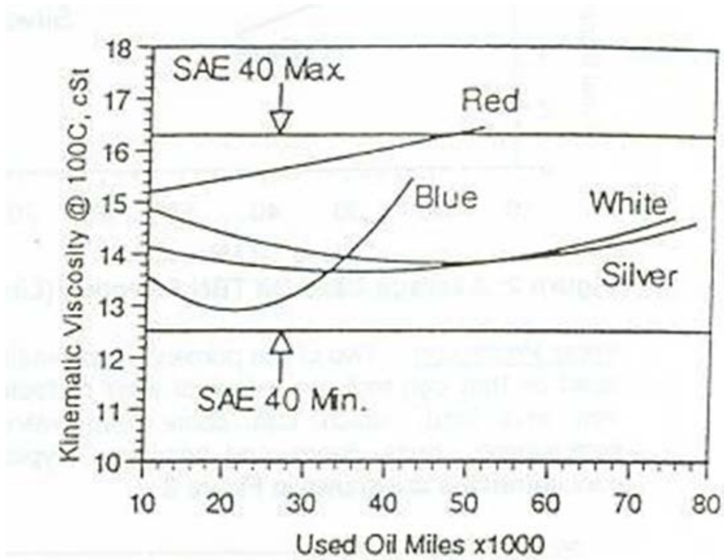

Figure 5: Kinematic viscosity values with increase in usage of oil (miles)

Conventional base oils such as red and blue oils show a sharp decline in the value of TBN compared to synthetic oils such as white and silver oils. It can be seen that the trend lines of red and blue oils have approximately similar slope. The value of total base number of blue oil was less than 5 after 50,000 miles of driving. Whereas, the total base number of red, silver and white oils have greater value because of the increased alkaline reserves at the end of their respective drain intervals. The slope for red and blue oils are equal and declines faster than synthetic oils. This is interesting because red is supposed to have an alkalinity reserve which is expected to slow the rate of TBN decrease. The linear trend in the values of TBN for different oils can be described in Figure 6.

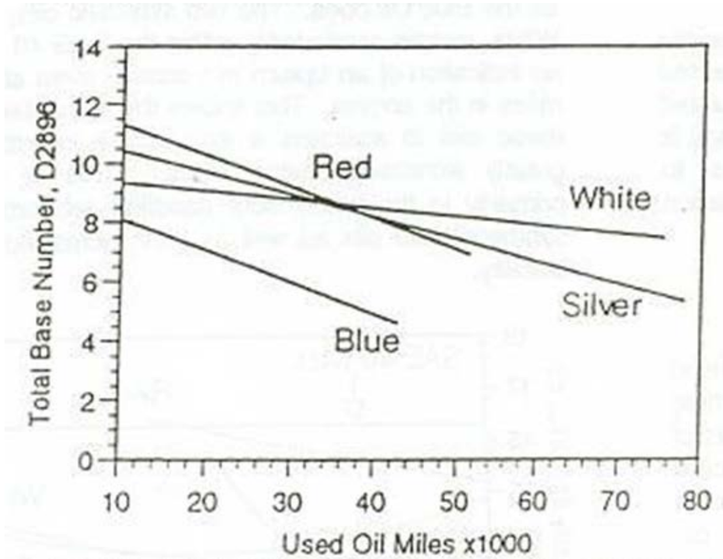

Figure 6: Total base number values with increase in usage of oil (miles)

The authors concluded that drain intervals necessary to maintain acceptable oil quality vary based on the type of oil used. An interval of 15,000 miles was found for standard conventional oil which was also the interval recommended by the equipment manufacturer. The premium conventional oil could be extended to approximately 30,000 miles, while the premium synthetic oils could be even further extended to 45,000 to 60,000 drain intervals.

2.6 Summary

Engine oil is the lifeblood of an engine and conducts various functions for the effective functioning of an engine. Engine oil differs in the kind of manufacture of base oil and is classified as conventional mineral oil and synthetic oil. The base oil is fused with certain additives to meet the requirements of lubricating modern engines. Bulk oil properties and contamination are the parameters that determine the quality of an engine oil. Engine oil loses its quality with increase in service life in various stages of its degradation. In the first stage, the additives get consumed followed by second stage in which oxidation of oil leads to a rapid increase in the value of TAN. In the final stage, the viscosity of oil increases. Oil quality should be regularly monitored to determine the optimum change interval. However, the concept of extended drain intervals was desired to decrease maintenance costs and wastage of engine oil. Some researchers have determined the advantages and effects of extended drain intervals of oil. Engine oil has to be regularly monitored to determine its quality to determine the extension of drain interval. The interval primarily depends on two factors, the engine oil and the type of machine. The current research study measures the effect of type of machine on engine oil degradation. Gallons of fuel consumed and miles travelled by an equipment were the oil age parameters that will be used to measure the effect of machine type on engine oil degradation. The current study would also determine whether oil quality could be explained by the oil age parameters in terms of gallons of fuel consumed and miles travelled by the equipment.

CHAPTER 3: RESEARCH DESIGN AND METHODOLOGY

The fundamental objective of the research was to determine whether the analysis results of engine oil sampled periodically and infrequently for the purpose of managing the health of individual machines can be used to estimate the rate of oil degradation. The objective was accomplished through regression analysis of oil quality measures with respect to oil age parameters. Viscosity and TBN were chosen as the oil quality parameters, whereas the oil age parameters were gallons of fuel consumed and miles travelled by the equipment. The parameters were obtained by extracting data from NCDOT oil analyses results, NCDOT equipment database, and reviewing the maintenance records of machines.

The methodology for conducting the research was divided in three stages. The first stage was collecting and compiling the data from oil sampling tests, equipment information and engine oil age parameters. NCDOT had conducted 495 oil sampling tests on 10 classes of machines that contained information about bulk oil properties and contamination. The oil quality measures were determined through the bulk oil properties. The NCDOT equipment database was utilized to extract data regarding the physical description of the equipment including equipment type, manufacturer, model and engine parameters. Oil age parameters were determined by reviewing the maintenance records of the machines from the NCDOT equipment database system.

After collecting and compiling the data, the second stage was selecting study classes for conducting the study. The selection criteria were developed and every class was examined to determine whether the requirements were being met. Further, the distribution of oil ages in each of the selected classes was determined using the oil age parameters. The final stage in the methodology was analyzing and interpreting the data by conducting regression analysis for selected class of machines on independent variables (oil age parameters) verses dependent variables (oil quality measures). Regression analysis results and graphs obtained were utilized in evaluating the relationship between oil quality and oil age for the selected class of equipment.

3.1 Collection and Compilation of Data

The oil analysis reports indicated the test results on engine oil samples, the dates on which the oil was sampled, and identification number for each machine. Identification number of the machine and oil analyses sample date served as fundamental keys in obtaining data regarding physical description of equipment, oil age parameters and oil quality measures, respectively, from the NCDOT equipment database system. Thus, collection and compiling of data was executed by obtaining data from oil analyses reports and by extracting equipment properties as well as reviewing the maintenance records of machines on NCDOT equipment database system.

3.1.1 Oil Analysis Reports

During the oil analysis of machines, the properties of engine oil measured were bulk oil properties and contamination levels. Table 4 lists all the bulk oil properties and contamination levels in each oil sampling test conducted on the equipment.

Table 4: Parameters measured in engine oil analysis of equipment

Bulk oil properties	**Contamination levels**	
Viscosity @100˚C	Iron (Fe)	Silicon(Si)
TBN	Chromium (Cr)	Boron(B)
	Lead (Pb)	Sodium(Na)
	Copper(Cu)	Magnesium(Mg)
	Tin(Sn)	Calcium(Ca)
	Aluminum(Al)	Phosphorous(P)
	Vanadium(V)	Zinc(Zn)
	Potassium(K)	Water (%)
	Nickel (Ni)	Soot/Solids

Machine ID	Sample ID	Date	Viscosity@100C	TBN	FE	CR	PB	CU	SN	AL	NI	SI	B	NA	MG	CA	P	ZN	V	K	Water	Soot/Solids
			(cSt)	(mgKOH/g)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(%)	
2156344	R07C014461	2/28/2007	12.3	11.4	81	2	3	10	0	10	2	0	7	6	15	3147	1199	1315	0	5	0.05	0.5
	R07E018294	5/8/2007	10.31	7.3	98	3	3	16	0	12	1	10	7	7	16	3578	1133	1258	0	6	0.05	0.5
	R07J016097	9/19/2007	12.57	7.4	27	1	1	3	1	4	0	0	1	2	1076	994	1220	1498	1	3	0.05	0.4
2156328	R07D000324	3/26/2007	12.89	9.3	26	1	2	3	0	5	1	11	2	2	250	1915	1000	1207	0	0	0.05	0.2
	R07J016105	9/20/2007	12.99	7.4	21	1	1	3	1	4	0	1	7	2	829	1150	1229	1497	0	1	0.05	0.2
2156147	R07D017075	4/13/2007	12.88	10.3	11	1	2	3	0	2	1	9	0	4	6	2178	671	733	0	0	0.05	0.1
	R07J016107	9/18/2007	12.72	9	42	2	3	7	0	5	0	1	1	3	14	3519	1341	1644	1	3	0.05	0.3
644884	R07A015521	12/21/2006	12.84	11	8	1	2	1	0	3	0	5	1	8	7	3092	442	1356	0	0	0.05	0.5

Figure 7: Excerpt of oil analysis results

Figure 7 is an excerpt of the compiled test results extracted from the reports along with machine identification number, name of the experiment and the date on which the oil sample test was conducted.

After compiling the oil analysis reports, the class type of each machine was identified by utilizing the machine identification number in the NCDOT equipment database system. Summarizing the oil analyses reports, it was concluded that 495 oil analysis tests were conducted on 202 machines that were further categorized into 10 equipment classes. Table 5 gives a summary of the type of class, description of the class, number of equipment in each class, and the number of oil analyses tests conducted.

Table 5: Summary of the number of engine oil analyses

Class	Description of the class	Number of machines	Number of oil analyses tests conducted
0205	TRUCK, DUMP 33000 GVW	58	129
0206	TRUCK, MISC 32000 GVW	15	34
0209	TRUCK, CREW CAB 32000 GVW	21	37
0212	TRUCK, DUMP TANDEM 50000 GVW	84	235
0217	TRUCK, TRACTOR TANDEM 50000 GVW	7	19
0218	TRUCK, 37000 GVW	1	3
0219	TRUCK, C&C TILT CAB 31000 GVW	1	1
0227	TRUCK, TRACTOR TANDEM 75000 GVW	3	6
0230	TRUCK, C&C TANDEM 50000 GVW	3	3
0232	TRUCK,DUMP,4 AXLE 5000 GVW	9	28

3.1.2 Equipment Properties

The machine identification number on the oil analyses report was also an input in NCDOT equipment database system to extract the detailed physical description about the machine. Table 6 lists the machine information such as the functional location, construction year, manufacturer of asset, model number, maintenance plant, description of machine, along with the information referring to the engine type, engine capacity, and engine power.

Table 6: Available equipment description information

Equipment ID	The unique identification number of the vehicle (Ex. 3222222).
Functional location	Classification of equipment type and the class of machines.
Model number	The model number of the vehicle.
Description of machine	The machine type and gross vehicle weight.
Engine information	Information regarding the engine type and capacity.

Figure 8 is an excerpt of the data compiled into a spreadsheet about the equipment number, functional location, and inventory number, construction year, manufacturer of asset, model number, maintenance plant, description of technical object, engine type, engine capacity, and engine power.

Equipment	Functional Location	Inventory Number	Construction Year	Manufacturer of Asset	Model	Mainten	Description of Technical Object	Engine Type	Engine Capacity	Engine Power
30108047	1N1-TRKDMP-002240-0205	1215-6344-0205	2005	INTERNATIONAL	7300SFA	910	TRUCK, DUMP 33000 GVW	IL6	7.6	230
30108031	1N1-TRKDMP-002224-0205	1215-6328-0205	2005	INTERNATIONAL	7300SFA	510	TRUCK, DUMP 33000 GVW	IL6	7.6	230
30037027	1N1-TRKDMP-002007-0205	1215-6147-0205	2004	INTERNATIONAL	7300	710	TRUCK, DUMP 33000 GVW	IL6		230
30024025	1N1-TRKDMP-001778-0205	1064-4884-0205	2001	CHEVROLET	C7500	710	TRUCK, DUMP 33000 GVW			210

Figure 8: Available description of the equipment

3.1.3 Review Maintenance Records of Machines

At this stage, the oil age parameters in terms of gallons of fuel consumed and miles travelled by the equipment were obtained. Maintenance records of machines were reviewed to determine the schedule of oil changes throughout the service period of equipment. Examining the schedule, the data for the oil replacements conducted prior to the sample tests were utilized.

The cumulative odometer readings and fuel meter readings were determined on the dates the oil samples were collected. Later, the cumulative odometer reading and fuel meter readings for the equipment were determined on the date the oil replacements were conducted prior to the oil sample analyses. The measure of oil age in gallons of fuel consumed was calculated by the difference of cumulative fuel meter readings on the sample dates and on the dates the previous schedule of oil replacement was conducted on the equipment. Similarly, the measure of oil age in miles was calculated by the difference of cumulative odometer readings on the sample dates and date of previous schedule of oil replacements was conducted on the equipment.

Figure 9 gives a representation to the equipment number, the oil replacement date prior to the sample date were mentioned as pre-records. Also, the fuel and odometer readings on the sample date were represented as post-records. The calculated difference of fuel meter and odometer readings on the sample date and on the previous oil change date was represented as age of oil in gallons of fuel consumed and miles travelled by the equipment.

Equipment	Pre-records			Post-records			Oil Age	Oil Age
	Date	Fuel Meter Reading	Odometer Reading	Date	Fuel Meter Reading	Odometer Reading	(Gallons)	(Miles)
30108047	10/6/2006	3152	20007	2/28/2007	4044	24740	891	4733
	2/28/2007	4044	24740	5/8/2007	4426	26281	383	1541
	2/28/2007	4044	24740	9/19/2007	4884	29375	840	4635
30108031	9/21/2006	2173	14624	3/26/2007	2992	19795	819	5171
	9/21/2006	2173	14624	9/20/2007	3731	25166	1558	10542
30037027	9/29/2006	3971	20532	4/13/2007	4879	25573	908	5041
	4/11/2007	4864	25215	9/18/2007	5777	30838	913	5623
30024025	5/10/2006	6534	35317	12/21/2006	7180	39204	646	3887

Figure 9: Oil age parameters (Fuel meter readings and Odometer)

3.2 Selection of Study classes

The assessment of existence of a relationship between oil quality and oil age parameters for every class depends on the distribution of oil ages. To determine adequate distribution of oil ages, the given classes had to be filtered before conducting regression analysis. The important criteria for selection of classes was based on the number of oil analyses results and the number of machines. Moreover, the selection criteria were also determined after categorizing each equipment into classes that were selected based on the primary criteria.

3.2.1 Number of Oil Analyses Results

To assess the relationship between oil quality and oil age, sufficient data in each equipment class was required to conduct the analysis for research. The criteria for the selection of classes of equipment could be categorized based on the number of analysis results and the number of equipment in each class. Hence all equipment classes were carefully examined to evaluate whether a sufficient number of oil analyses results and machines were adequately available to be considered for analysis of the research. After the specified criteria have been analyzed, the following equipment classes were selected based on availability of adequate data to evaluate the relationship between oil quality and oil age.

3.2.2 Classification of Equipment in Each Class

The criteria for selection of a particular class also depended on the classification of equipment because not all the machines in the given classes yielded adequate data regarding oil quality and oil age parameters. The classes of machines were selected subsequently by reviewing the adequate number of machines from the specified categories. The following were the categories for the selection of class based on the classification of equipment.

1. Equipment no longer in use (deleted machines)
2. Equipment whose oil age parameters cannot be determined.
3. Equipment whose oil age parameters were estimated
4. Equipment whose oil age parameters were determined.

Equipment no Longer in Use (Deleted Machines):

Engine oils were sampled for the machines during the period of 2006 and 2009. However, some of the machines from a significant number of classes were removed from the fleet. Though the physical description of the equipment of these machines were available on the NCDOT equipment database, maintenance records for these machines were no longer available. Hence, the oil age parameters cannot be determined for this set of machines. These equipment in each class were not considered for further analyses.

Equipment whose Oil Age Parameters cannot be Determined:

Oil age (gallons and miles) for the machines were determined by reviewing the maintenance records of machines and deciding the schedule of oil change prior to the sample test conducted. This was performed to determine when the oil was introduced in the engine. However for some equipment, the first maintenance schedule of oil change were on the approximate date the sample tests were conducted. The oil age parameters for these equipment during that period of time cannot be determined. Hence, the sample tests for these equipment were not included.

Equipment whose Oil Age Parameters were Estimated:

Preventive maintenance includes activities such as changing oil, replacing oil and air filters, as well as checking the condition of vehicle and its parts. Oil change for the equipment is conducted for every 5,000 miles of equipment use. However, on examining the schedule records for a number of equipment, it indicated that the maintenance actions were being performed on the engine but it was unclear of the kind of maintenance that was being performed. For a number of machines, it was assumed that oil change was being performed even though the difference of cumulative odometer readings was in the range of 1,000 miles to 3,500 miles. Though the equipment oil age parameters were estimated, they were included in analyzing the relationship between oil quality and oil age.

Equipment whose Oil Age Parameters were Determined:

The difference in cumulative odometer readings of approximately 5,000 miles or closer determines that oil change had been included in the preventive maintenance actions conducted for equipment. On occasion, oil change was included in the preventive maintenance actions at a cumulative odometer difference of either greater or much greater than 5,000 miles. However, it was clear that oil change had been included in the preventive maintenance actions. For these categorized machines, the difference of cumulative odometer readings is either 5,000 miles or closer between the sample dates and the dates at which previous oil change was performed on the equipment. Hence, oil age parameters were calculated on the dates the sample oil had been introduced in each equipment. Thus, the equipment oil age parameters were utilized to analyze the relationship between oil quality measures and oil age parameters.

3.3 Distribution of Oil Ages in Selected Classes of Equipment

After classifying the machines and determining the selection of study classes, the oil age parameters for all the machines were either determined or estimated. There were several ranges of oil age values obtained both in terms of gallons of fuel consumed and miles travelled by the equipment for the selected classes. For each class, a distribution of oil ages in terms of miles travelled by the equipment were represented by a histogram. The histogram showed that the values of oil ages that are concentrated in specified intervals as well as the lower concentrations of the range of oil age values obtained. The understanding in distribution of oil ages would be utilized to interpret the nature of graphs obtained during the analyses of oil quality measures with respect to oil age parameters.

3.4 Analyses of Oil Quality with respect to Oil Age

The assessment of a relationship between oil quality and oil age for the current class of equipment was executed in two phases. In the first phase, regression analyses were conducted for every class of machines by examining each oil age measure as independent variable (gallons and miles) against each oil quality measures (viscosity and TBN) as dependent variables. The primary objective of the current analyses to assess the relationship was accomplished by examining results and graphs obtained of each oil quality measure with respect to each oil age parameter for the selected classes of equipment.

The graphs obtained from the regression analysis were examined in three steps. The first step was interpreting the distribution of oil ages. The second step was evaluating the nature of trend lines obtained from each graph. The trend lines in each graph would help to evaluate the relationship between oil quality measures and oil age parameters. The third step was to assess whether gallons of fuel consumed or miles travelled by the equipment could explain oil performance. This analysis was performed to determine whether the rates of oil degradation could be predicted for the selected classes of equipment.

3.4.1 Classification of Equipment Based on the Manufacturer

The machines from the classes 0205, 0206 and 0212 constituted equipment from different set of manufacturers. Hence, in the second phase of analysis, evaluation was done to determine whether the manufacturer of the machine had a role in assessing the relationship between oil quality and oil age. Therefore, the machines within these equipment classes were further classified based on the manufacturer.

Regression analyses were conducted for machines in the given classes utilizing similar oil quality measures and oil age parameters in the selected classes. However, the data points in the graphs obtained representing each equipment in the three classes were classified based on their type of manufacturer. There were separate trend lines in the analysis graphs, classified for each set of data points such as the International and Chevrolet in classes 0205 and 0206. Consecutively, separate trend lines were obtained for the data points classified as International and Sterling in class 0212. Each of the graphs for all the three classes were analyzed and evaluated to interpret whether the kind of manufacturer of the machine was significant in assessing the relationship between oil quality (viscosity and TBN) and oil age parameters of the equipment.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Selected of Equipment Classes Based on Oil Analysis Reports

NCDOT provided 495 analysis results of engine oil sampled periodically and infrequently for the purpose of managing the health of 202 machines that belong to 10 equipment classes. Development of a relationship between oil quality and oil age depended upon the distribution of oil ages. Hence, the class of machines were carefully selected for analysis and assessed the distribution of oil age (miles). The selection of the classes of equipment for the analysis also depended on the classification of machines in the particular class.

The initial criteria for selection of class depended upon the number of machines and number of oil analyses results for that particular class type. Table 7 lists the classes that had significant number of oil analyses results and machines to evaluate the relationship between oil quality and oil age. A total of 482 analysis results of engine oil and 194 equipment were considered for study from all the selected classes.

Table 7: Selected classes through analyzing oil sample reports

Class	Description of class	Sample size
205	TRUCK, DUMP 33000 GVW	129
206	TRUCK, MISC 32000 GVW	34
209	TRUCK, CREW CAB 32000 GVW	37
212	TRUCK, DUMP TANDEM 50000 GVW	235
217	TRUCK, TRACTOR TANDEM 50000 GVW	19
232	TRUCK,DUMP,4 AXLE 5000 GVW	28

4.2 Selection of class based on the classification of equipment

Table 8 lists the information for each selected class of equipment including the total number of machines, total number of deleted machines, number of equipment whose oil age cannot be determined, number of equipment whose oil age was estimated and the number of equipment whose oil age was determined. The total number of equipment from each class which were used in the final analysis of the study was also listed in Table 7.

Table 8: Classification of equipment in the selected classes

Class	**Total Equipment**	**Deleted Equipment**	**Unknown Oil Age**	**Estimated Oil Age**	**Known Oil Age**	**Equipment used in research**
0205	58	9	4	9	36	45
0206	15	0	0	4	11	15
0209	21	6	2	2	11	13
0212	84	11	3	16	54	70
0217	7	2	1	0	4	4
0232	9	0	0	1	8	9
Total	194	28	10	32	124	156

The above table depicted that oil age for 80 percent of total equipment were used in the research analysis and the oil age parameters for the remaining 20 percent of the equipment could not be calculated as they were classified as either deleted machines or machines with unknown oil age. It can be also be concluded that classes 0205, 0206, 0209, 0212 and 0232 possess adequate number of equipment and a total of 369 test results for the analysis possessing adequate distribution of oil ages so that oil quality was measured with respect to oil age parameters. Class 0217 was not considered in the current study due to inadequate number of equipment after the classification of equipment.

4.3 Distribution of Oil Ages

Determination of distribution of oil ages was fundamental in interpreting the nature of graphs obtained. There was broad range of oil age (miles) values obtained in each of the selected classes. However, the Figures 10 through 14 explain that 63 percent of all of the calculated oil age (miles) parameters from the selected equipment classes were obtained in an interval of 4000 miles to 6000 miles. It indicates that the distribution of oil age was concentrated in between 4000 and 6000 miles and sparsely distributed among the other interval of values. This signifies the unequal distribution of oil age (miles) throughout the entire range of oil age (miles) values obtained. The distribution of oil ages in selected classes is individually shown in the following histograms.

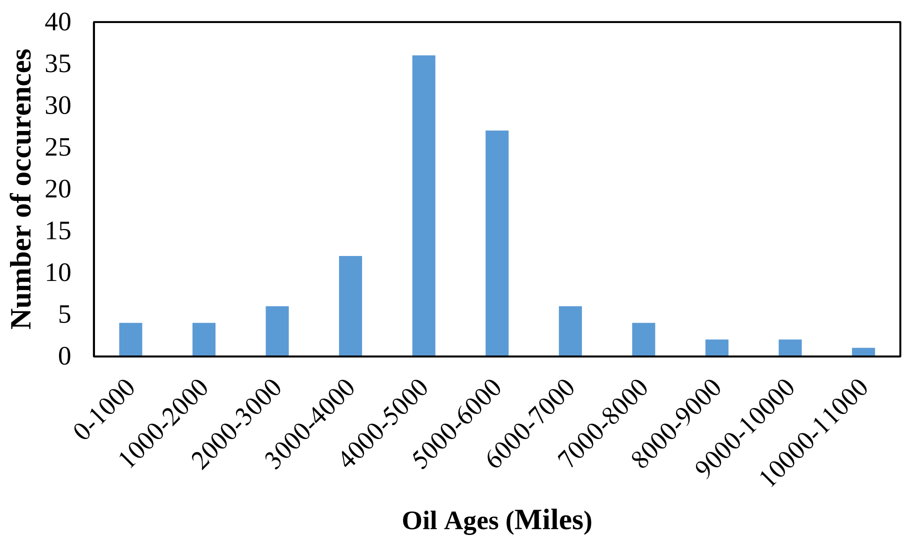

Figure 10: Distribution of oil age (miles) for class 0205

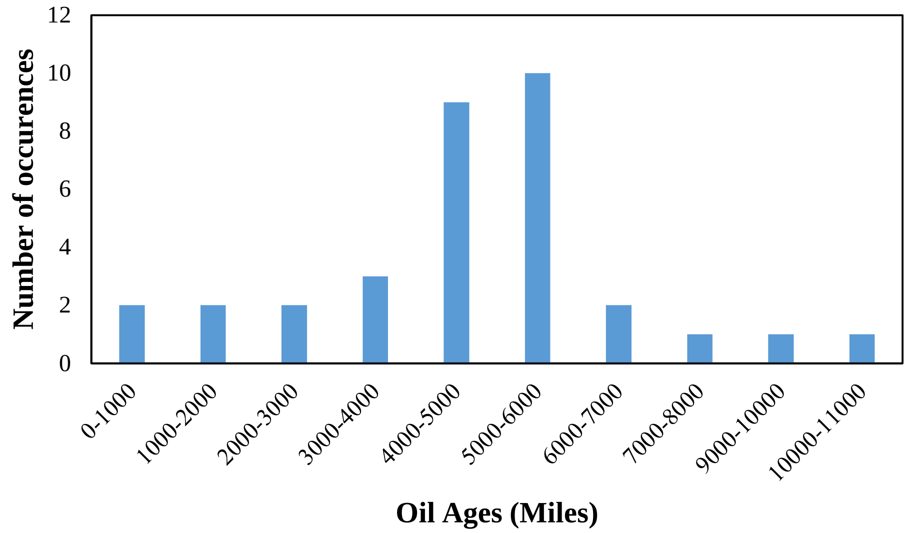

Figure 11: Distribution of oil age (miles) for class 0206

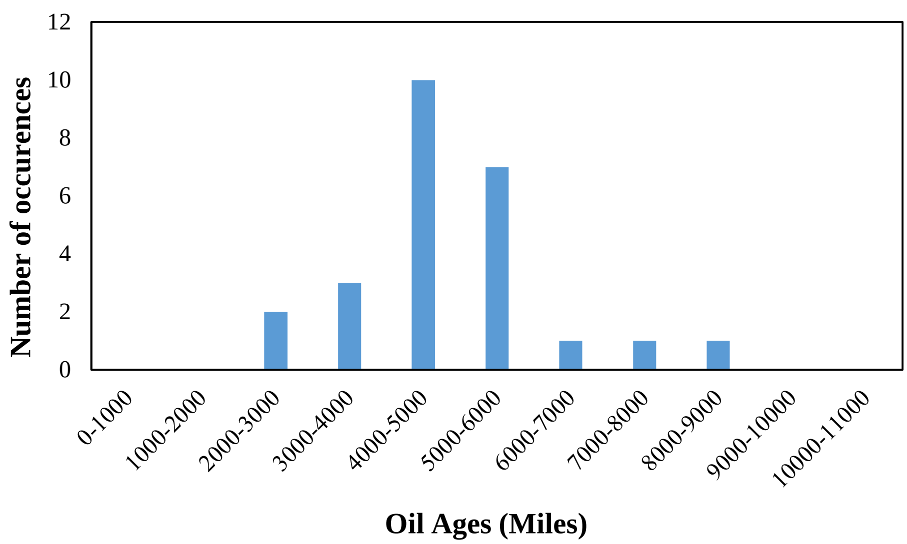

Figure 12: Distribution of oil age (miles) for class 0209

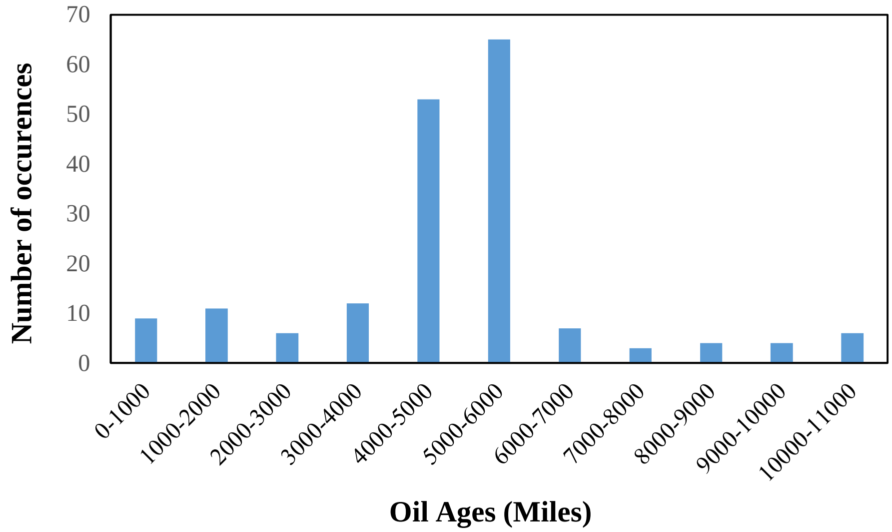

Figure 13: Distribution of oil age (miles) for class 0212

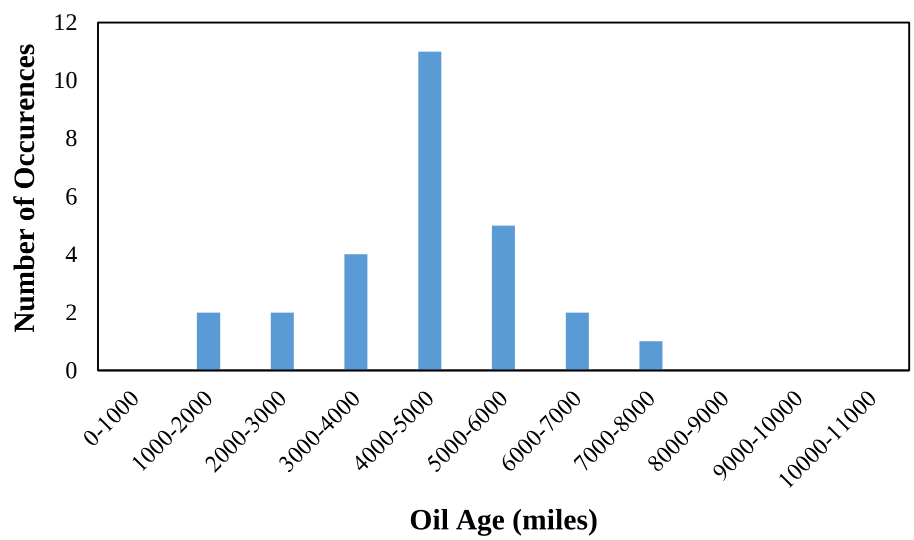

Figure 14: Distribution of oil age (miles) for class 0232

4.4 Analysis and Interpretation of Results

The analysis and interpretation of the results obtained could be explained in a sequential manner through regression analysis results and graphs of the selected dependent and independent parameter. Regression analysis results obtained for each class assessed the relationship between oil quality and oil age parameters as well as interpreted the nature of graphs obtained.

4.4.1 Regression Analyses Results

Table 9 lists the class number, the dependent parameter, independent parameter, b_0 (y-intercept), b_1 (age coefficient), t-test, p-value and the confidence intervals limits obtained for different values of b_1. It could be seen that the values of b_1 obtained in regression analyses were approximately equal to zero. A linear relationship could not be depicted for the given dependent and independent parameters. In fact, viscosity and TBN were seemingly unaffected by the chosen oil age parameters, gallons of fuel consumed and miles travelled by the equipment for the selected classes of equipment.

Table 9: Regression analysis results of dependent parameters and independent parameters

Class	Dependent variable	Independent variable	bo	b1	t-stat	p-value	Lower 95%	Upper 95%
0205	Viscosity	Gallons	12.9489	-0.0006	-1.2994	0.1967	-0.0016	0.0003
		Miles	12.5316	0.0000	-0.1407	0.8884	-0.0002	0.0001
	TBN	Gallons	9.5859	-0.0012	-1.6285	0.1072	-0.0026	0.0003
		Miles	9.0816	-0.0001	-0.7256	0.4701	-0.0003	0.0001
0206	Viscosity	Gallons	11.9683	0.0011	1.569	0.1271	-0.0003	0.0025
		Miles	12.5335	0.0000	0.3151	0.7549	-0.0002	0.0003
	TBN	Gallons	9.3215	-0.0005	-0.4806	0.6353	-0.0026	0.0016
		Miles	9.8965	-0.0002	-1.0308	0.3133	-0.0006	0.0002
0209	Viscosity	Gallons	13.5586	-0.0003	-0.5598	0.5813	-0.0012	0.0007
		Miles	13.6732	-0.0001	-0.6331	0.5332	-0.0003	0.0001
	TBN	Gallons	8.7985	0.0004	0.5668	0.5766	-0.001	0.0018
		Miles	8.5278	0.0001	0.7714	0.4487	-0.0002	0.0004
0212	Viscosity	Gallons	14.2463	0.0001	0.6042	0.5465	-0.0002	0.0004
		Miles	14.2933	0.0000	0.2859	0.7753	-0.0001	0.0001
	TBN	Gallons	8.7921	-0.0001	-0.3399	0.7344	-0.0008	0.0006
		Miles	9.0867	-0.0001	-1.0712	0.286	-0.0002	0.0001
0232	Viscosity	Gallons	14.6376	0.0001	0.2412	0.8114	-0.001	0.0012
		Miles	14.6291	0.0000	0.2895	0.7747	-0.0002	0.0002
	TBN	Gallons	9.3599	-0.0009	-0.7314	0.473	-0.0034	0.0016
		Miles	10.0645	-0.0003	-1.4727	0.1564	-0.0008	0.0001

4.4.2 Interpretation of Graphs

The relationship between oil quality and oil age could not be determined for the given classes of equipment which was explained by the nature of given oil analyses reports and oil age parameters obtained. The tests on oil samples for machines were conducted during the period of 2006 and 2009 for all of the machines. The analysis indicated that majority of the test results yielded approximately similar values because the oil samples from different machines were measured during the same approximate age interval, and for similar service period for all the machines. Hence, there were a significant number of repeated measures in oil quality values as observed in the graphs for the classes of machines.

The review of maintenance records of machines indicated that the oil samples for a significant number of machines were collected on the approximate dates on which preventive maintenance actions were conducted on the machines. Also, preventive maintenance is scheduled to be conducted on machine serviceability of approximately 5000 miles. The age of oil (miles) was calculated as the difference between the cumulative odometer readings on the sample date and on the previous schedule of preventive maintenance conducted and hence, the majority of oil age (miles) values were obtained in the interval of 4000 to 6000 miles. Therefore, the concentration of oil age (miles) were obtained in the interval of 4000 to 6000 miles and were sparsely distributed on the other values of oil age (miles) obtained.

In conclusion, a linear relationship could not be determined between the oil quality parameters and oil age parameters for selected classes of equipment. The fact that the majority of the oil ages obtained for all of the selected classes were concentrated between 4000 miles and 6000 miles signified the insufficient distribution among the range of oil age (miles) parameters obtained. Therefore, the data points on each graph obtained for both the oil age parameters were concentrated in one specified interval and sparsely distributed among the other interval values. Figures 15 through 22 shows the analysis graphs for classes 0205 and 0212. The analysis graphs of the classes 0206, 0209 and 0232 were shown in Figures 27 through 38 in Appendix A.

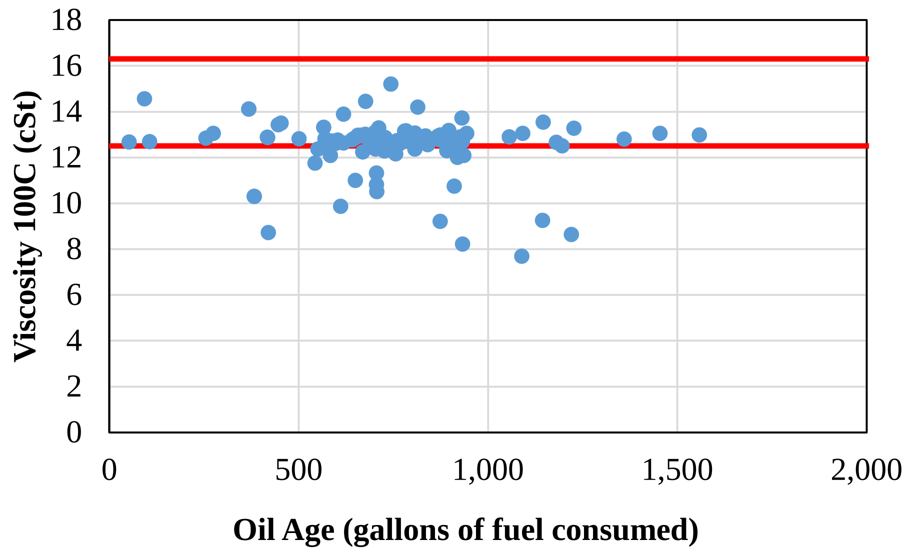

Figure 15: Scatter plot of viscosity and oil age (gallons) for Class 0205

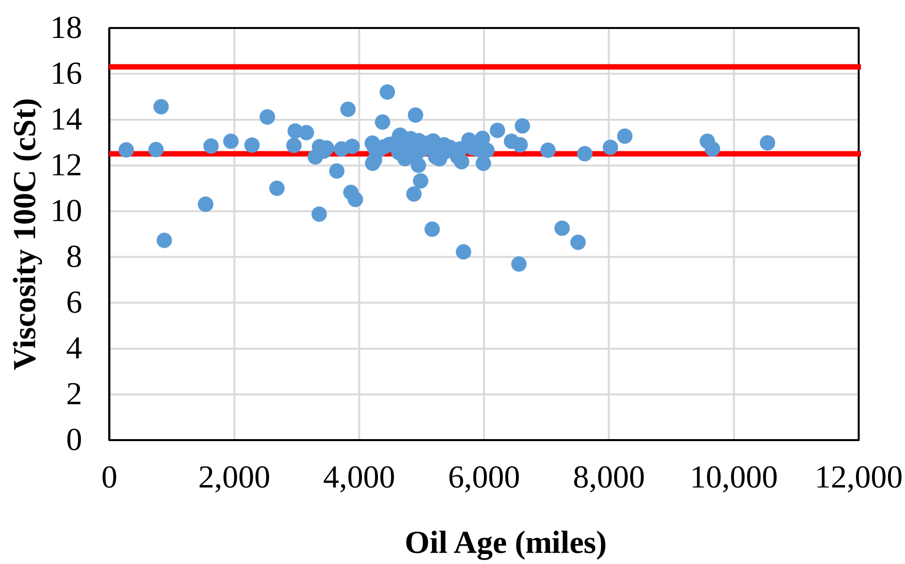

Figure 16: Scatter plot of viscosity and oil age (miles) for Class 0205

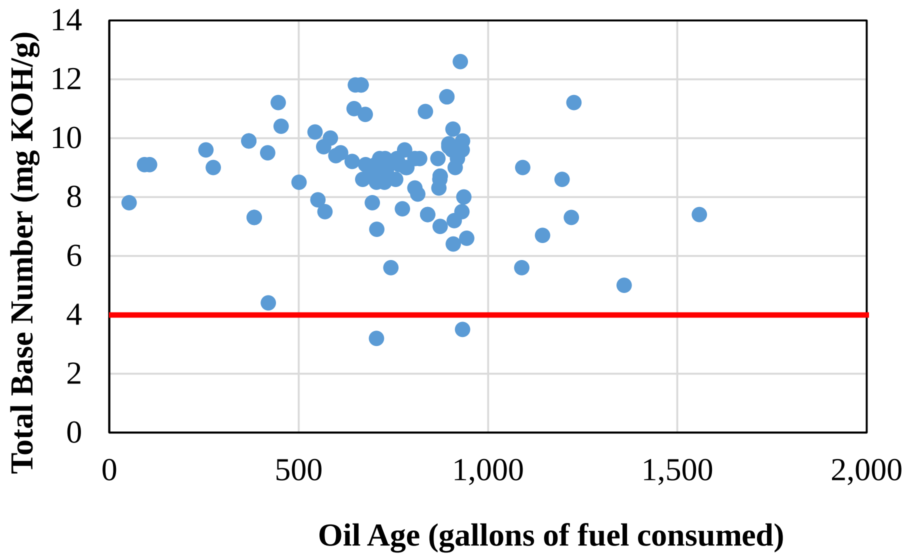

Figure 17: Scatter plot of TBN and oil age (gallons) for Class 0205

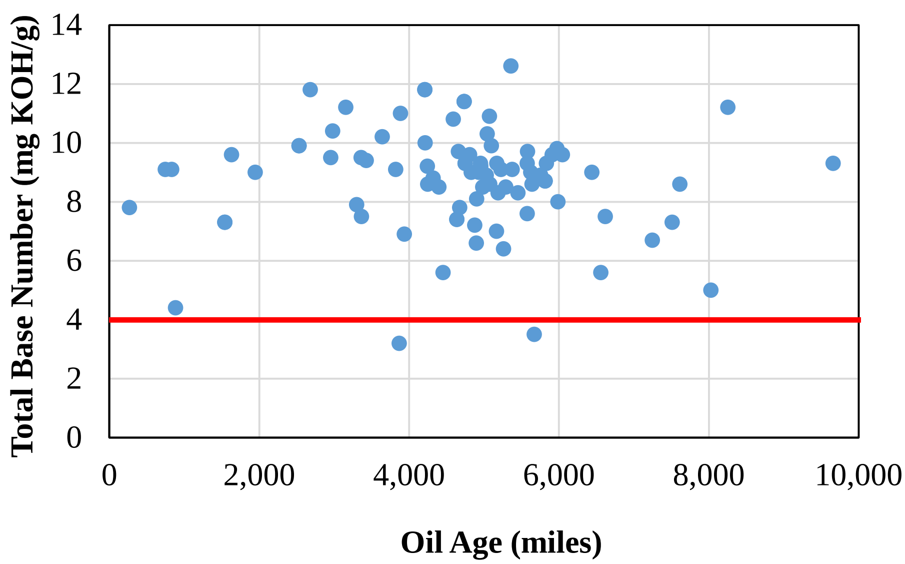

Figure 18: Scatter plot of TBN and oil age (miles) for Class 0205

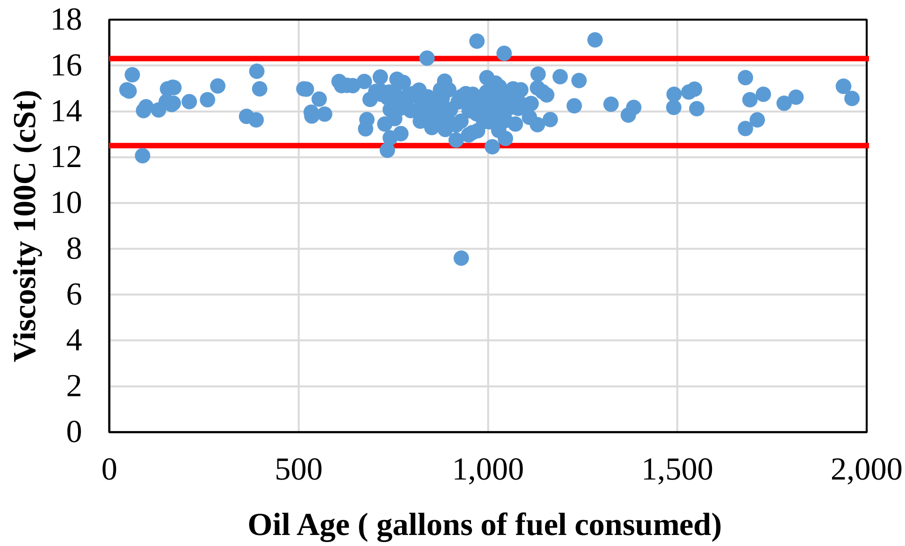

Figure 19: Scatter plot of viscosity and oil age (gallons) for Class 0212

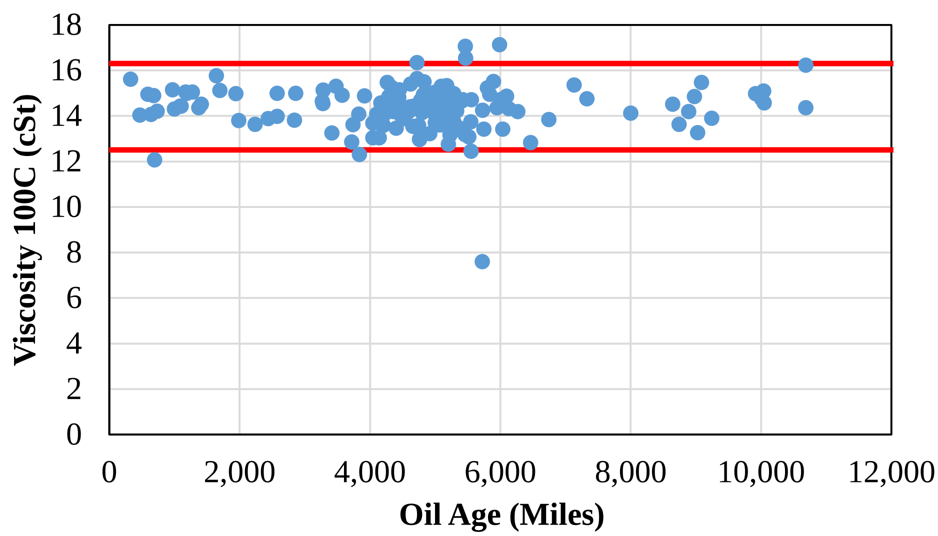

Figure 20: Scatter plot of viscosity and oil age (miles) for Class 0212

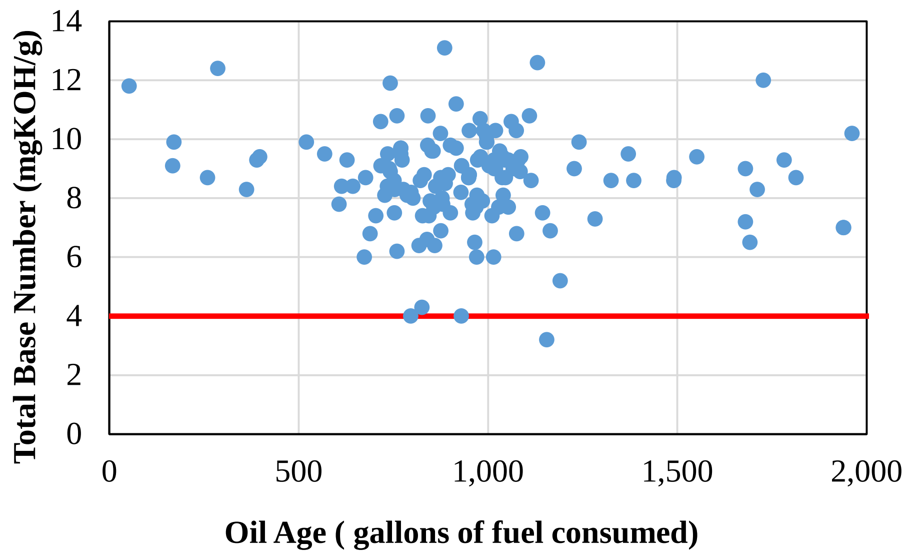

Figure 21: Scatter plot of TBN and oil age (gallons) for Class 0212

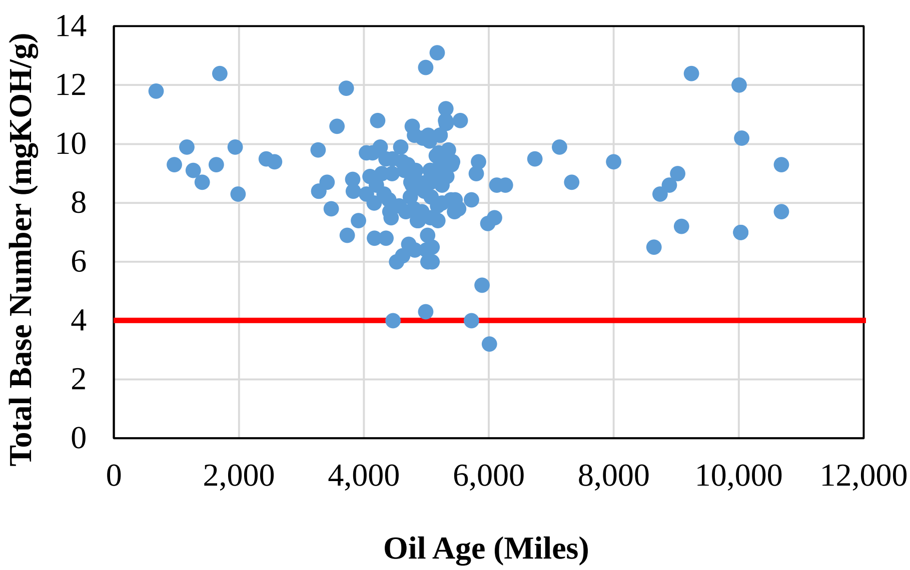

Figure 22: Scatter plot of TBN and oil age (gallons) for Class 0212

4.5 Classification of Machines Based on the Manufacturer

The manufacturers of equipment in the classes 0205, 0206 were International and Chevrolet. The manufacturers of equipment for class 0212 were International and Sterling. Table 10 lists the number of machines classified further based on the type of manufacturer.

Table 10: Number of machines based on the manufacturer

Class	**International**	**Chevrolet**	**Sterling**
0205	38	7	0
0206	12	2	0
0212	27	0	43

4.5.1 Analysis of Class 0212

The analysis for oil quality and oil age for machines classified based on the manufacturer in class 0212 were conducted. Each data point representing the machine was classified based on the manufacturer. Figures 23 through 26 show the analysis graphs for oil quality and oil age.

In addition to the graphs, regression equations were obtained for viscosity and TBN with respect to oil age (miles) for both International and Sterling machines separately. This was conducted to understand if there is any difference in the oil quality with respect to usage of oil (miles driven by equipment) between International and Sterling machines.

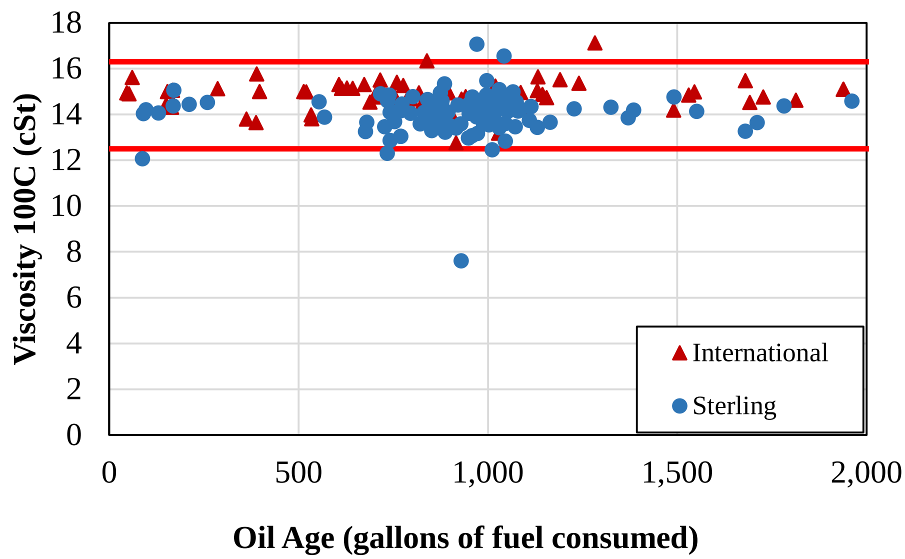

Figure 23: Scatter plot of viscosity and oil age (gallons) for Class 0212

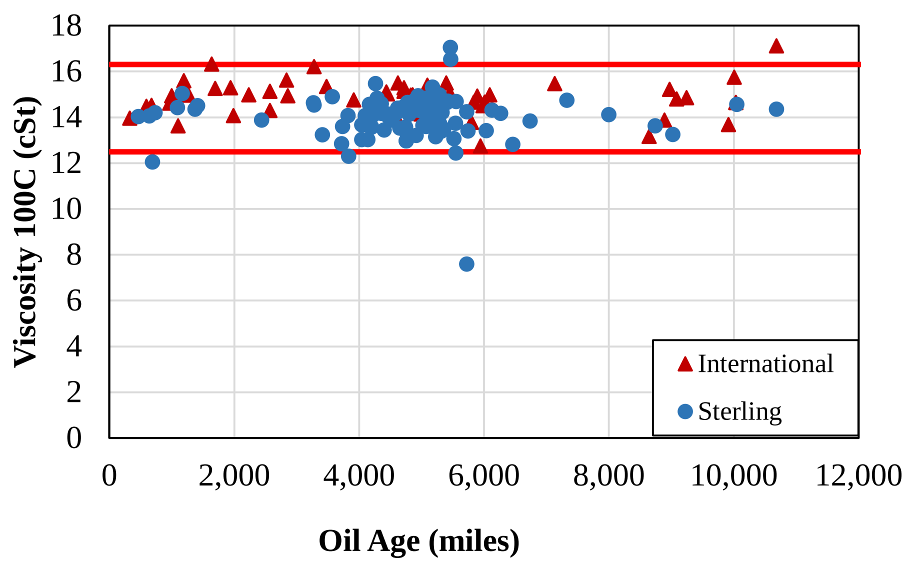

Figure 24: Scatter plot of viscosity and oil age (miles) for Class 0212

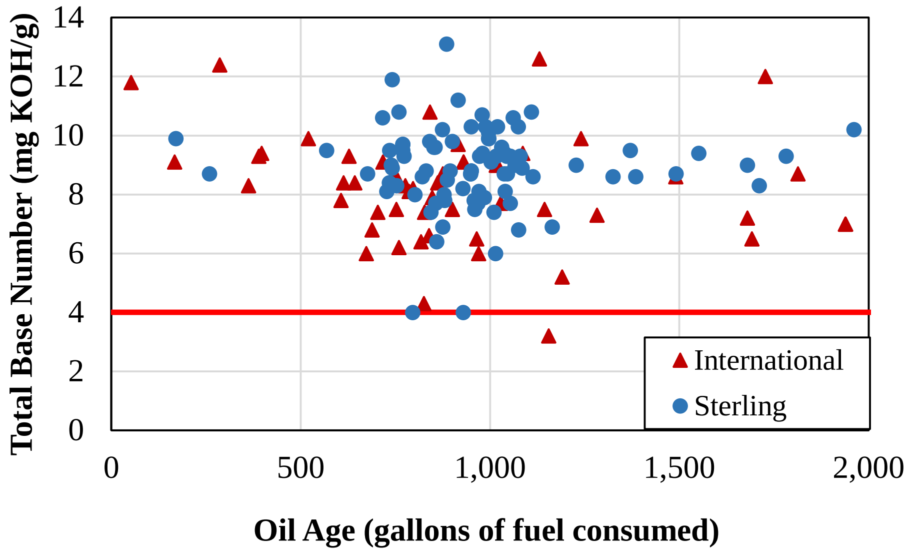

Figure 25: Scatter plot of TBN and oil age (miles) for Class 0212

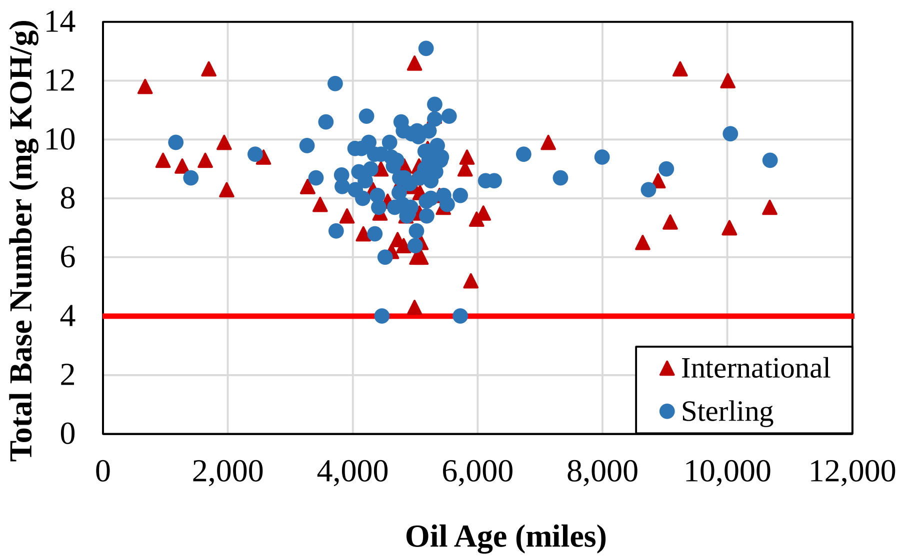

Figure 26: Scatter plot of TBN and oil age (gallons) for Class 0212

From Figure 24, the equations obtained for International and Sterling machines in Class 0212 for viscosity measured against oil age (miles) and were given as

INTERNATIONAL: Viscosity@100C = 14.731 + 0.000001 Oil Age (Miles)

STERLING: Viscosity@100C = 14.030 + 0.000001 Oil Age (Miles)

The p-value obtained in the regression analysis by adding "manufacturer" as a co-variable is 0.00. This implies that the manufacturer of machines had a significant role in the values of viscosity obtained. It could also be seen that viscosity of International machines was higher than viscosity of Sterling machines with a difference of 0.7 cSt. Hence, a substantial amount of statistical difference was observed from the equations obtained. However, the value of viscosity obtained in machines of each manufacturer were very well in permissible limits to indicate good quality oil. Therefore, it can be concluded that the statistical difference in the values of viscosity obtained does not make any practical inferences.

From Figure 26, the equations were obtained for International and Sterling machines for TBN measured against oil age (miles) and were given as

INTERNATIONAL: TBN = 8.661 - 0.000072 Oil Age (Miles)

STERLING: TBN = 9.279 - 0.000072 Oil Age (Miles)

The p-value obtained in the above analysis conducted by including "manufacturer" as a co-variable is 0.030. Even this implies that manufacturer had a role in the values of TBN obtained for machines of each manufacturer. The value of TBN obtained for Sterling machines is higher than for International machines with a difference of 0.62 mgKOH/g. However, even in this case the statistical difference does not yield any practical benefits as the value of TBN obtained indicates a good quality oil. Consequently, the analysis did not serve to determine a relationship between oil quality and oil age.

4.5.2 Classes 0205 and 0206

Figures 39 through 42 in Appendix B show the analysis graphs for oil quality measured against oil age for class 0205. The regression analysis was conducted for oil quality and oil age for International and Chevrolet machines separately. The p-value obtained in the analysis of viscosity and TBN measured with respect to oil age (miles) by including manufacturer as an independent variable were 0.824 and 0.152, respectively. It implies that the manufacturer did not have a significant role in the values of viscosity and TBN obtained.

Figures 43 through 46 in Appendix B shows the analysis graphs for oil quality measured against oil age for class 0206. The regression analysis was conducted for oil quality and oil age for International and Chevrolet machines separately. The p-value obtained in the analysis of viscosity and TBN measured against oil age (miles) by including manufacturer as an independent variable were 0.972 and 0.080, respectively. It implies that manufacturer did not have a significant role in the values of viscosity and TBN obtained.

From the analysis of 0212 machines, it was seen that manufacturer had a significant role in the values of viscosity and TBN obtained. It was observed in classes 0205 and 0206 that there were not a significant number of International and Chevrolet machines to explain the role of manufacturer. Hence, it could be concluded that the data was insufficient to determine the changes in viscosity and TBN against oil age for classes 0205 and 0206.

CHAPTER 5: CONCLUSIONS

Engine oil has a pivotal role in maintaining the serviceability and durability of the engine. Consequently, engine oil replacement is one of the most important and cost-consuming process of any preventive maintenance program conducted on the machines. Therefore, analyzing oil quality and understanding about the nature of oil degradation is very essential. This is achieved through sampling oil from machines to understand the condition of oil and supervise the health of machines.

The main aim of this research was to determine whether the engine oil sampled periodically and infrequently by NCDOT for the purpose of monitoring the health of individual machines could be used to estimate the rate of oil degradation. The data for oil quality parameters and oil age parameters obtained were limited to those available by NCDOT machines and equipment database system.

There were a total of 202 machines, 495 oil analysis tests from 10 equipment classes of NCDOT fleet. The final analysis was conducted on 369 oil analysis tests, 156 machines belonging to five equipment classes. The equipment which had been deleted from the analysis were either deleted equipment or equipment whose oil age cannot be determined. Clearly, only 77 percent of the machines and 75 percent of the oil analysis results were available to conduct regression analysis from the initial data obtained.

The distribution of oil ages (miles) obtained and analyzed on a histogram for selected classes revealed that 63 percent of all the oil age values obtained for the selected machines were concentrated between 4000 miles and 6000 miles. The uneven distribution of oil age was a significant factor in interpreting the results of analysis.

The primary conclusion from regression analysis depicted that neither gallons of fuel consumed nor miles travelled by the equipment could serve to explain oil performance for the selected classes of equipment. The horizontal trend lines obtained in the regression analysis graphs indicated that the rates of oil degradation could not be determined for the selected classes of equipment. The most important conclusion of the current analysis was the oil sampling analyses conducted for the purpose of monitoring the health of individual machines is insufficient to determine the rates of oil degradation for machines in the NCDOT fleet.

The machines from classes 0205, 0206 and 0212 were further classified based on the manufacturer type, it did not serve to assess the relationship between oil quality and oil age. However, there was a substantial difference in values of viscosity and TBN obtained for International and Sterling machines in class 0212 implying the role of manufacturer in determining oil quality. It was also observed in class 0205 that approximately 30% of the sample tests indicated lower levels of viscosity which might be attributed to fuel dilution problems in those machines.

The rate of oil degradation would be traditionally determined by regular and consistent oil sampling of particular machines. This is because the oil samples are analyzed for degradation over the service period of equipment for particular machines. During periodic and infrequent oil sampling, the machine health was being supervised by understanding the condition of oil. The current study concludes that oil is not allowed to degrade during periodic and infrequent oil sampling of machines. This is supported by observing no statistical relationship between oil quality and oil age for machines in NCDOT fleet.

CHAPTER 6: RECOMMENDATIONS

For the current research, oil quality was measured against each oil age parameter for the selected classes in order to determine whether the rate of oil degradation could be predicted. The analysis revealed that the oil quality measures namely viscosity and TBN were unaffected with respect to gallons of fuel consumed and miles travelled by an equipment.

However, the careful analysis of graphs depict that viscosity and TBN were in satisfactory limits until 6000 miles for almost all of the equipment in the selected class of equipment. Hence, it could be said that engine oil is in good condition until 6000 miles. Consequently, it can also be told be preventive maintenance schedule in terms of oil change could be conducted at 6000 miles instead of 5000 miles. This would be helpful in reduction of the cost occurred due to conducting preventing maintenance of several equipment in NCDOT fleet.

REFERENCES

Agoston, A., Ötsch, C., and Jakoby, B, (2005). “Viscosity sensors for engine oil condition monitoring—Application and interpretation of results.” *Sensors and Actuators A: Physical*, 121(2), pp. 327-332.

AMSOIL (2004). “Technical Service Bulletin.” TSB: MO-2004-07-02.

Angeles, R. (2003). “Tables on oil analysis.” http://www.rsareliability.com/Oil%20Analysis%20Tables.pdf (July 22, 2015).

Barnes, A. M., Bartle, K. D., & Thibon, V. R. (2001). “A review of zinc dialkyldithiophosphates (ZDDPS): characterization and role in the lubricating oil.” *Tribology International*, 34(6), pp 389-395.

Basu, A., Berndorfer, A., Buelna, C., Campbell, J., Ismail, K., Lin, Y., Rodriguez, L., Wang, SS. (2000). “‘Smart sensing’ of Oil Degradation and Oil Level Measurements in Gasoline Engines.” (No. 2000-01-1366). SAE Technical Paper.

Bergstra, R. J., Givens, W. A., Maxwell, W. L., & Richman, W. H. (1998). “Advanced synthetic passenger vehicle engine oils for extended oil drain performance.” (No. 981444). SAE Technical Paper.

Caines, A., and Haycock., (1996). “Automotive Lubricants Reference Book.” Society of Automotive Engineers, Warrendale.

Exxon Mobil Corporation (2009). “Oil Analysis – The Basics.” http://www.mobilindustrial.com/ind/english/files/tt-the-basics-of-oil-analysis.pdf (November 9, 2015).

Fitch, B. (2012). “Optimizing Oil Change Intervals in Heavy-Duty Vehicles.” Machinery Lubrication, Noria Corporation, October 12(5).

Fitch, B. (2013). “Anatomy of an Oil Analysis Report”. Machinery Lubrication, Noria Corporation, December 13(6).

Guan, L., Feng, X. L., Xiong, G., & Xie, J. A. (2011). “Application of dielectric spectroscopy for engine lubricating oil degradation monitoring.” *Sensors and Actuators A: Physical*, 168(1), pp 22-29.

Herbeaux, J. L., & VanArsdale, W. E. (1993). “Mechanical Degradation of Multi-Grade Engine Oils.” (No. 930690). SAE Technical Paper.

Hilligoss, D. (2012). “ICP-Optical Emission Spectroscopy.” http://www.perkinelmer.com/PDFs/Downloads/APP_Optima8300ElementsInOil.pdf (June 16, 2015).

Hosie R., Lawrence. D. (1979). “Field experience of extended oil drain intervals in off-highway diesel engines.” *The Zambian Engineer*, pp 21-23.

Jetter, S., Kelly, K., Ragomo, M., Morrow, R., Nycz, D., Karl, G., Gullett, R., Dussault, B., Butler, B., Becker, T. (1998). “Extended Oil Drain Performance Capabilities of Diesel Engine Oils.” (No. 982718). SAE Technical Paper Series.

Jun, H. B., Kiritsis, D., Gambera, M., & Xirouchakis, P. (2006). “Predictive algorithm to determine the suitable time to change automotive engine oil.” *Computers & Industrial Engineering*, 51(4), pp 671-683.

Kader, M., Ramani, T. L., Johnson, J. D., Speigelman, C., Zietsman, J., & Jacobs, T. (2014). “Fleet Equipment Performance Measurement Preventive Maintenance Model: Final Report.” No. FHWA/TX-13/0-6626-1. Texas A&M Transportation Institute, College Station, TX.

Kollmann, K., Gürtler, T., Land, K., Warnecke, W., & Müller, H. D. (1998). “Extended oil drain intervals-conservation of resources or reduction of engine life.” *(Part II)* (No. 981443). SAE Technical Paper.

Lynch T.R., (2007). “Process Chemistry of Lubricant Base Stocks.” CRC Press, Boca Raton.

Montgomery, D., & Peck, E. (1982). “Introduction to linear regression analyses.” New York: Wiley.

Moon, S. I., Paek, K. K., Lee, Y. H., Kim, J. K., Kim, S. W., & Ju, B. K. (2006). “Multiwall carbon nanotube sensor for monitoring engine oil degradation.” *Electrochemical and solid-state letters*, 9(8), H78-H80.

Mujahid, A., & Dickert, F. L. (2012). “Monitoring automotive oil degradation: analytical tools and onboard sensing technologies.” *Analytical and bioanalytical chemistry*, 404(4), pp 1197-1209.

Oil Analysis user guide. (2004). http://www.agatlabs.com/Brochures/Tribology Brochure Print.pdf (July 23, 2015).

Ramani, T., Kader, M., Johnson, J., Jacobs, T., Spiegelman, C., & Zietsman, J. (2015). “Incorporating On-Board Diagnostics into Fleet Preventive Maintenance Practices”. In *Transportation Research Board 94th Annual Meeting* (No. 15-4374).

Rudnick L.R., (2003). “Lubricant additives: chemistry and applications.” Marcel Dekker, New York.

Rudnick L.R., (2009). “Lubricant additives: chemistry and applications.” CRC Press, Boca Raton.

Singh, H., & Swaroop, S. (1997). “Oxidation behavior of base oils and their constituting hydrocarbon types.” *Preprints-American Chemical Society. Division of Petroleum Chemistry*, 42(1), pp 218-220.

Gulf coast filters (2005). “The gulf coast filters oil analysis program.” www.gulfcoastfilters.com/oil_analysis_.htm (June 16, 2015).

Trujillo, G. (2004). “Resetting oil analysis parameters for changing diesel engines.” *Practicing Oil Analysis Magazine, Noria Latin America,* January.

Wang, S. S. (2001). “Road tests of oil condition sensor and sensing technique.” *Sensors and Actuators B: Chemical*, 73(2), pp 106-111.

Wang, S. S., & Lee, H. S. (1997). “The application of AC impedance technique for detecting glycol contamination in engine oil.” *Sensors and Actuators B: Chemical*, 40(2), pp 193-197.

Totten, G. E., Westbrook, S. R., & Shah, R. J. (2003). “Fuels and lubricants handbook: technology, properties, performance, and testing.” *Training*, *2007*, ASTM, West Conshohocken, pp 08-21.

Youngk, R. D. (2000). “Automobile engine reliability, maintainability and oil maintenance.” In *Proceedings of Annual Reliability and Maintainability Symposium*, IEEE, pp 94-99.

APPENDIX A: OIL QUALITY MEASURES VERSUS OIL AGE PARAMETERS

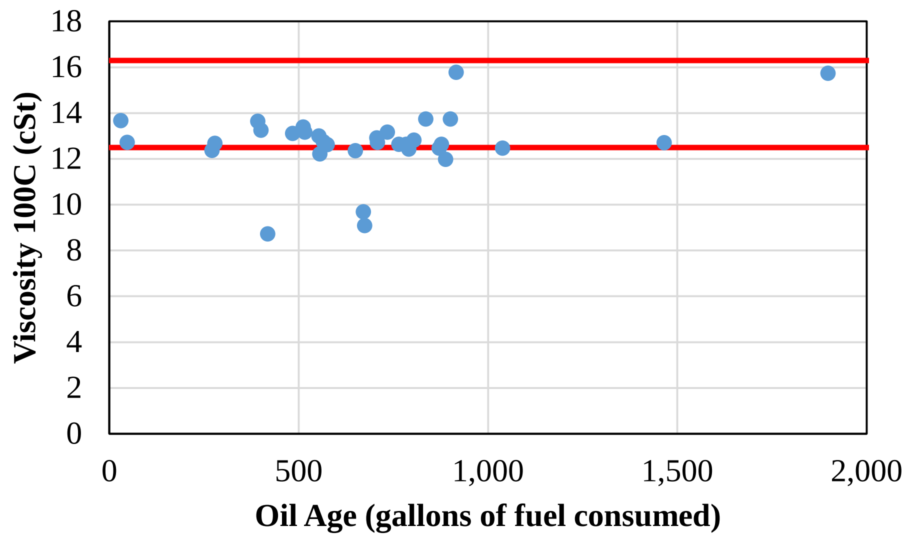

Figure 27: Scatter plot of viscosity and oil age (gallons) for Class 0206

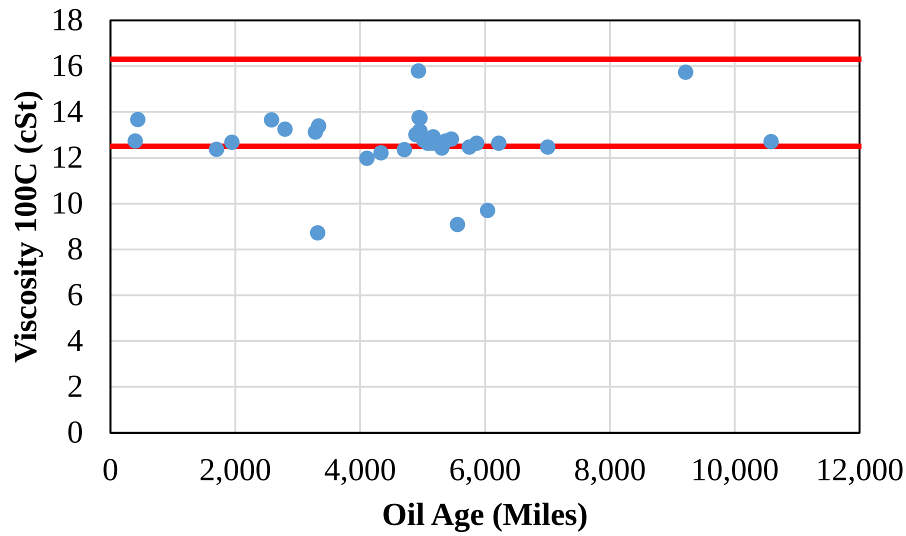

Figure 28: Scatter plot of viscosity and oil age (miles) for Class 0206

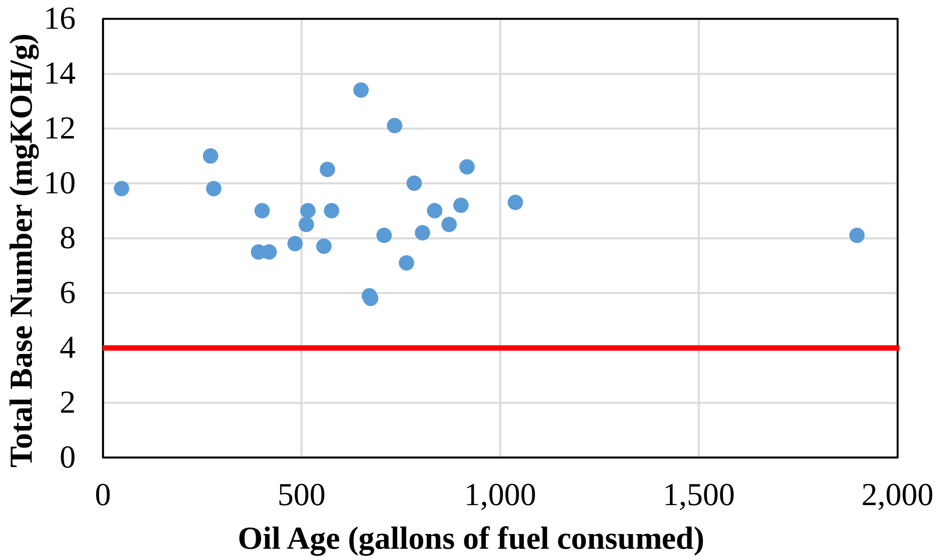

Figure 29: Scatter plot of TBN and oil age (gallons) for Class 0206

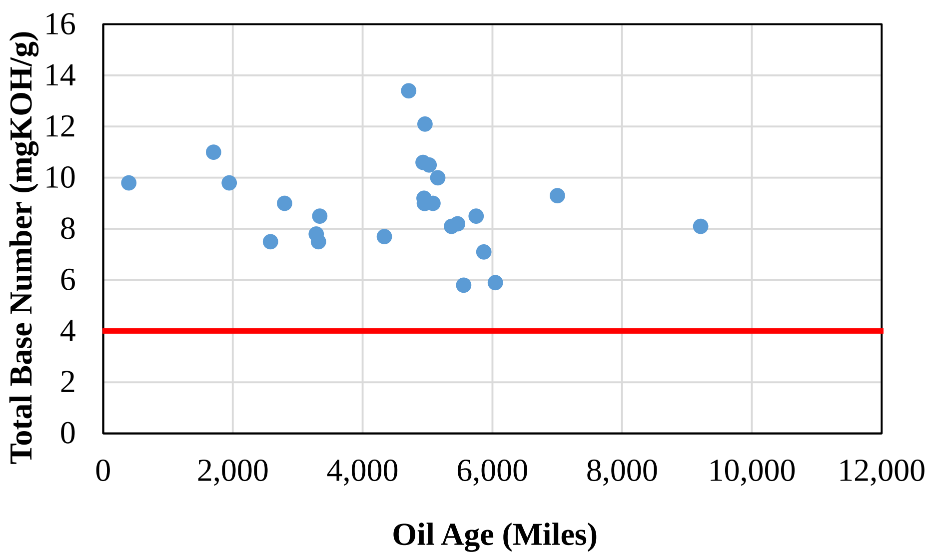

Figure 30: Scatter plot of TBN and oil age (miles) for Class 0206

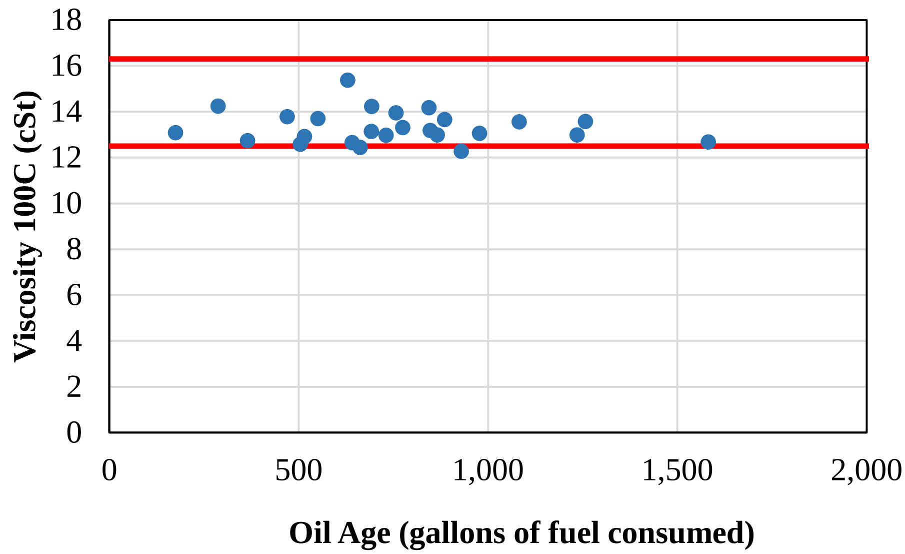

Figure 31: Scatter plot of viscosity and oil age (gallons) for Class 0209

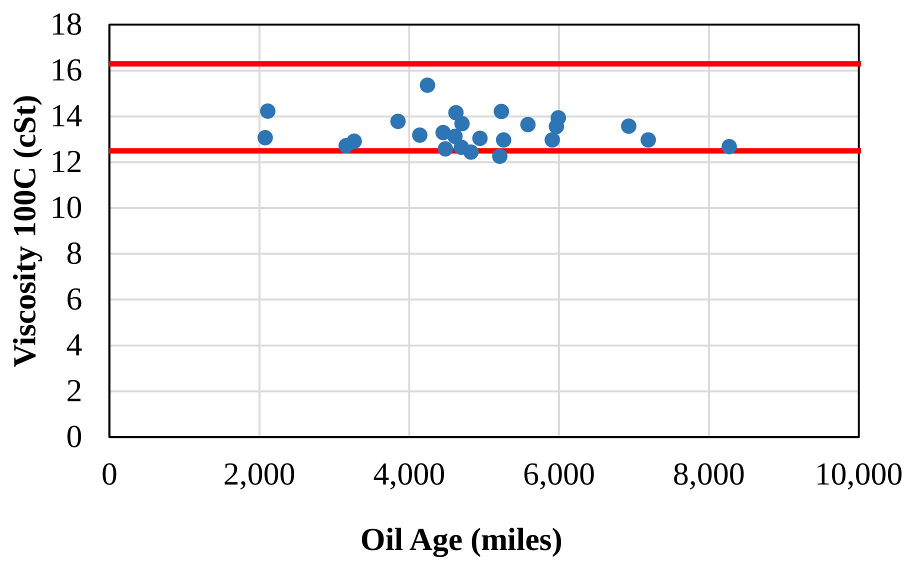

Figure 32: Scatter plot of viscosity and oil age (miles) for Class 0209

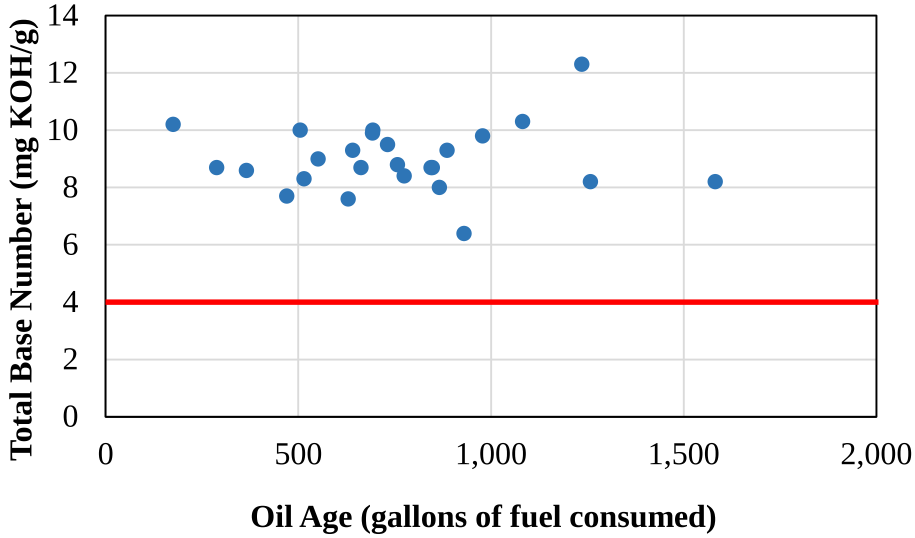

Figure 33: Scatter plot of TBN and oil age (gallons) for Class 0209

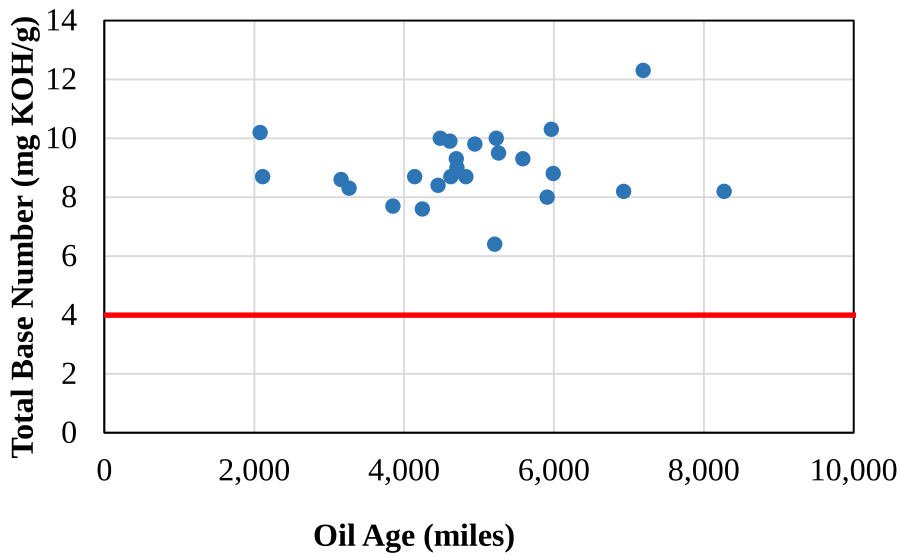

Figure 34: Scatter plot of TBN and oil age (miles) for Class 0209

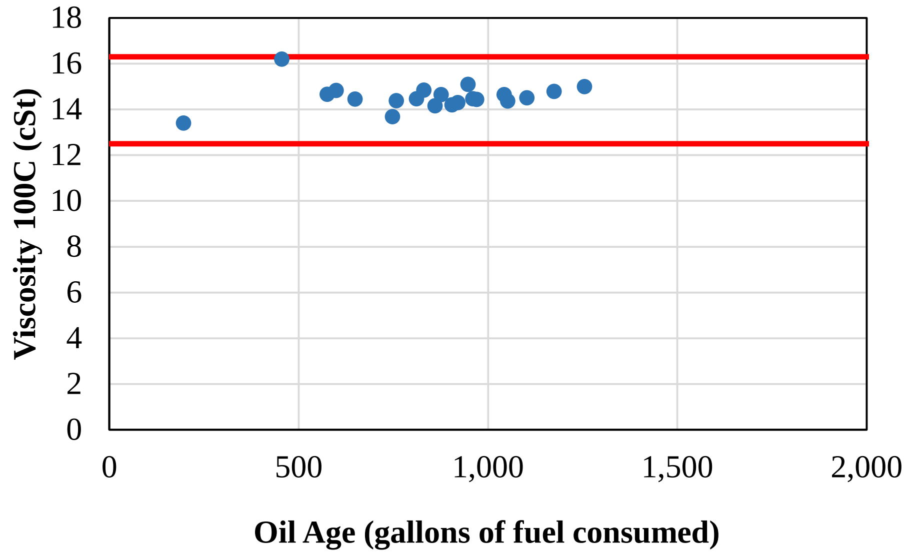

Figure 35: Scatter plot of viscosity and oil age (gallons) for Class 0232

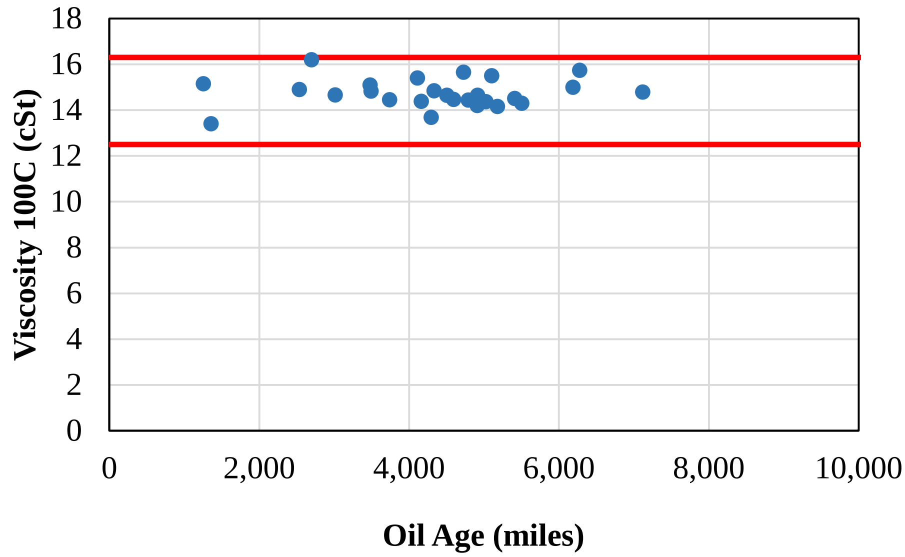

Figure 36: Scatter plot of viscosity and oil age (miles) for Class 0232

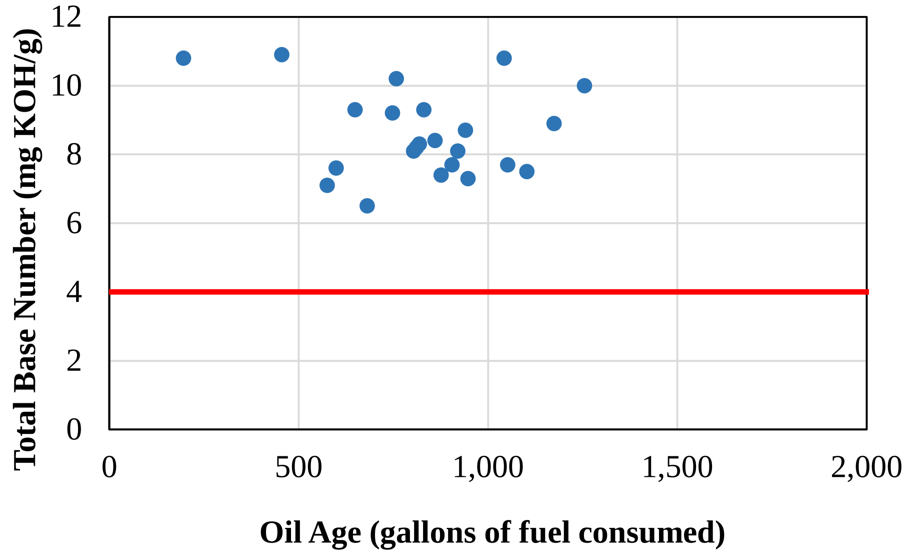

Figure 37: Scatter plot of TBN and oil age (gallons) for Class 0232

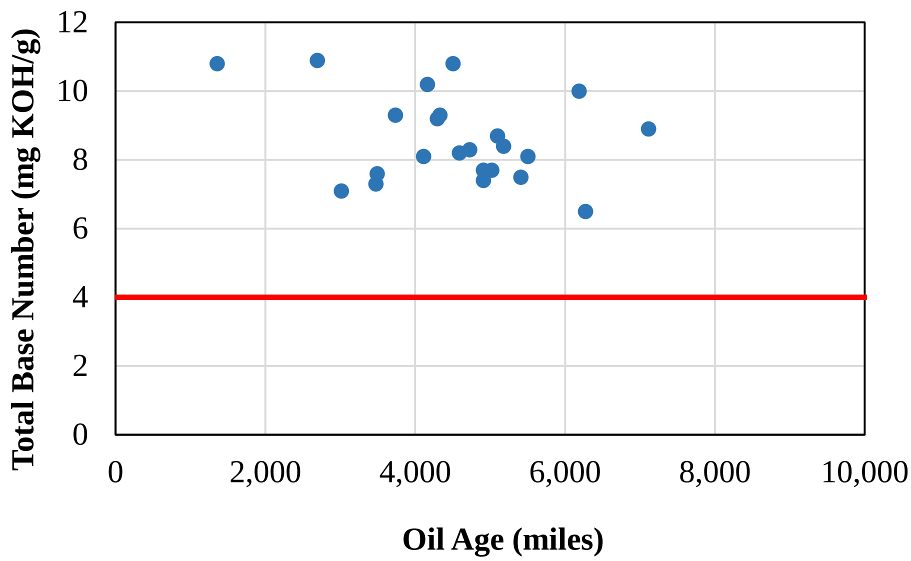

Figure 38: Scatter plot of TBN and oil age (miles) for Class 0232

APPENDIX B: OIL QUALITY AND OIL AGE ANALYZED AS THE MACHINES ARE CLASSIFIED BASED ON THE MANUFACTURER

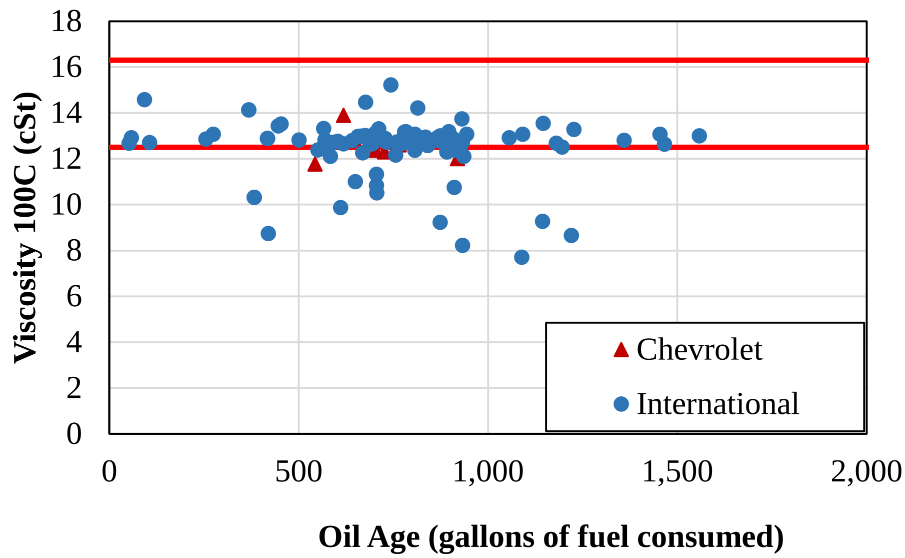

Figure 39: Scatter plot of viscosity and oil age (gallons) for Class 0205

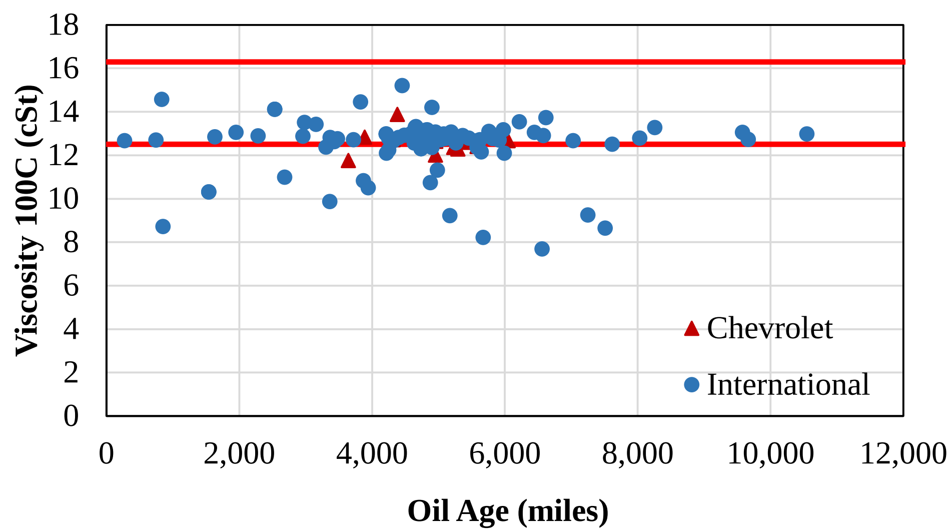

Figure 40: Scatter plot of viscosity and oil age (miles) for Class 0205

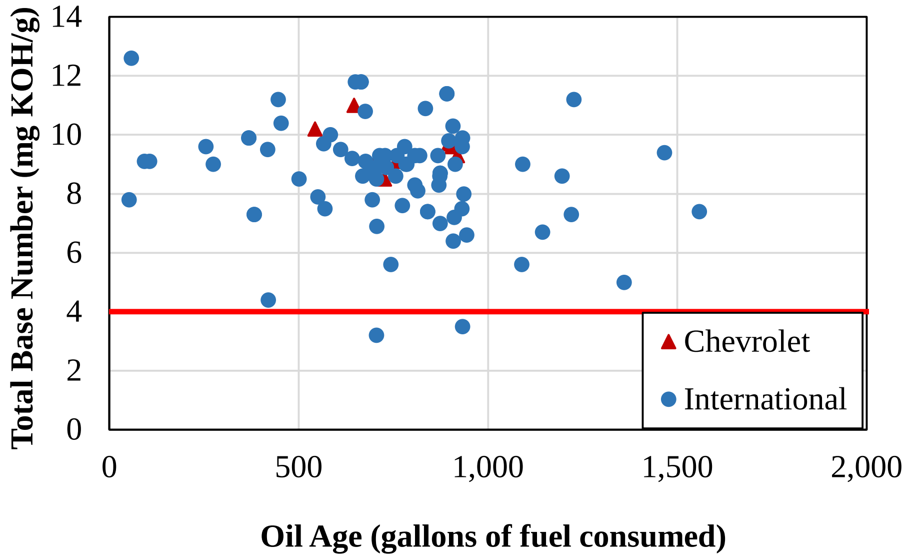

Figure 41: Scatter plot of TBN and oil age (gallons) for Class 0205

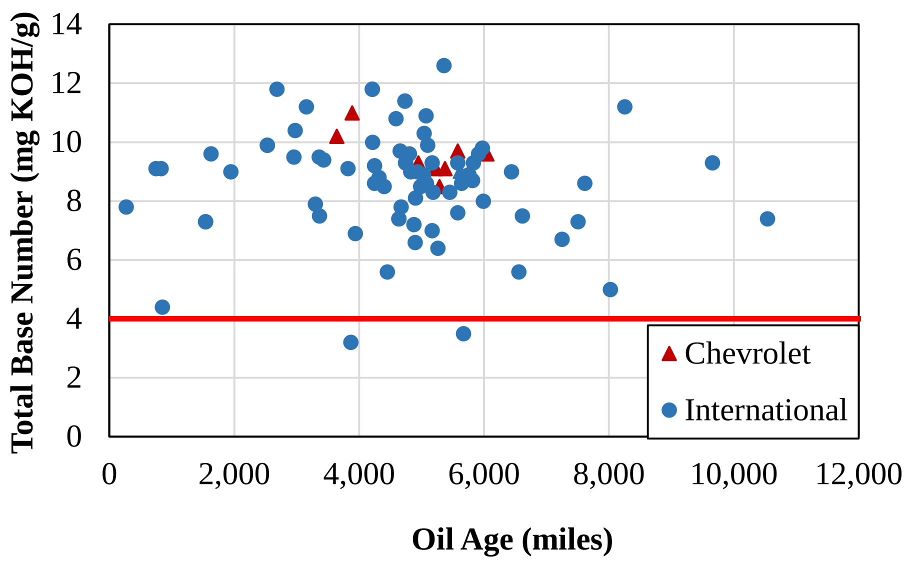

Figure 42: Scatter plot of TBN and oil age (miles) for Class 0205

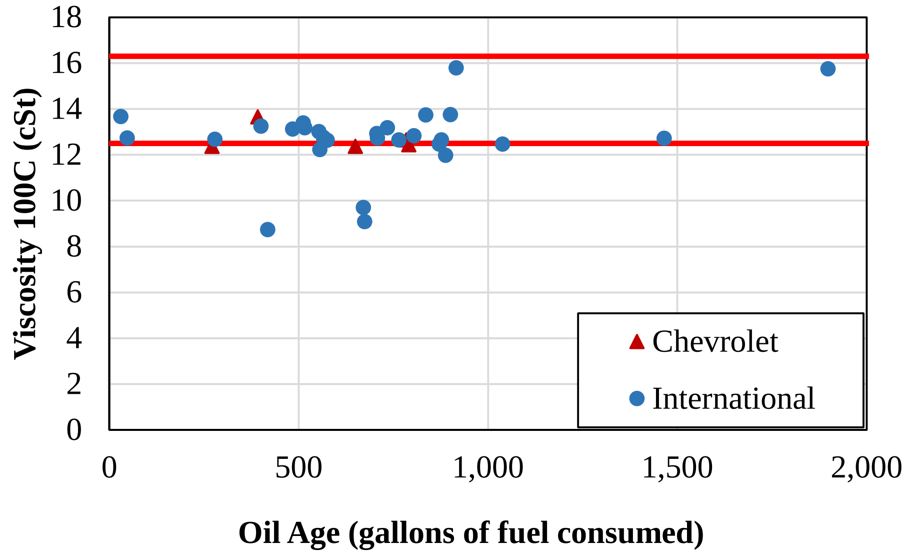

Figure 43: Scatter plot of viscosity and oil age (gallons) for Class 0206

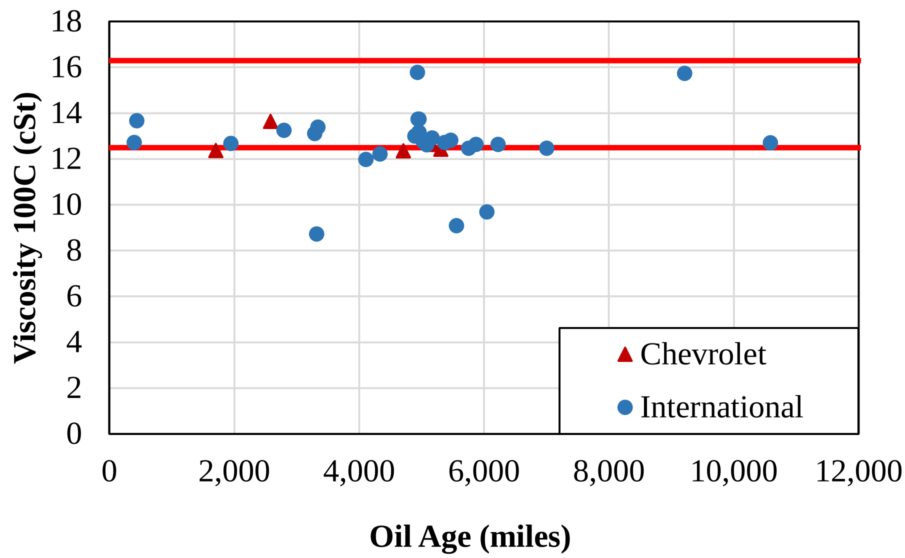

Figure 44: Scatter plot of viscosity and oil age (miles) for Class 0206

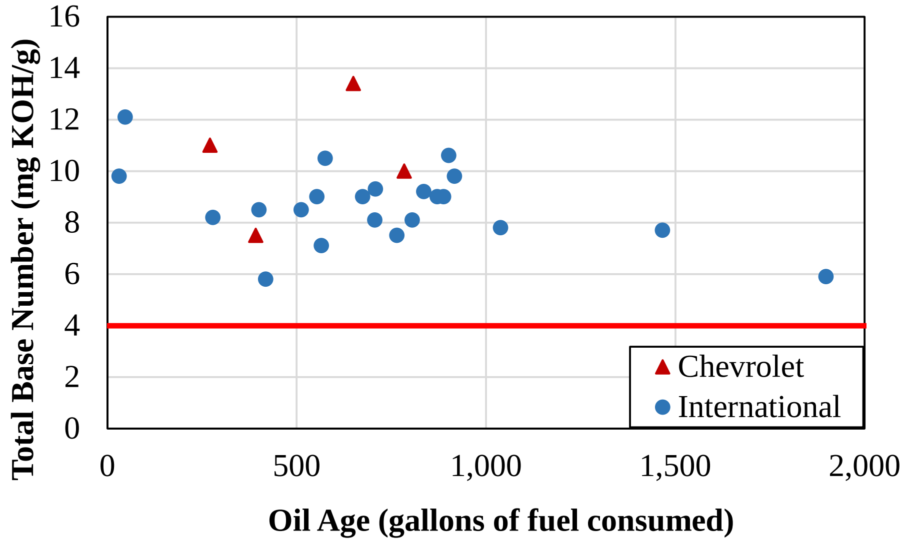

Figure 45: Scatter plot of TBN and oil age (miles) for Class 0206

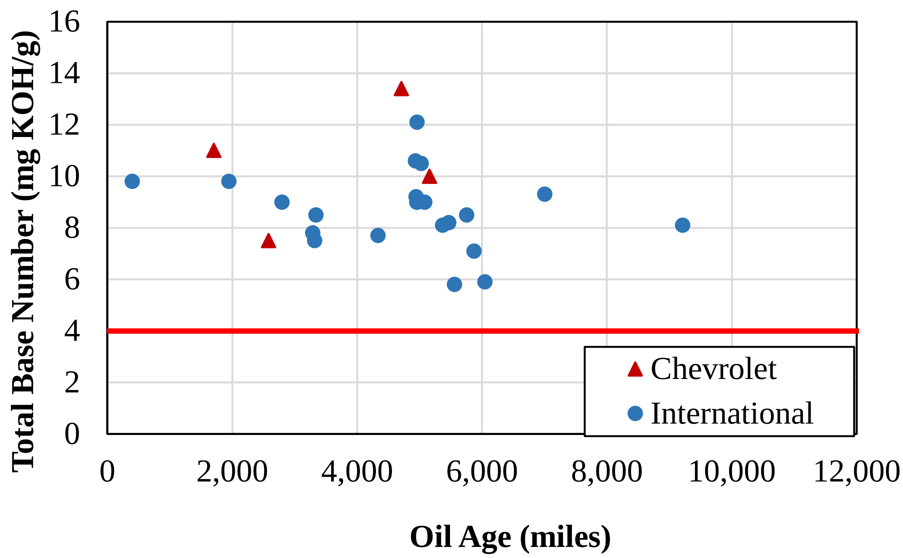

Figure 46: Scatter plot of TBN and oil age (miles) for Class 0206