ALTERNATE ENGINE PARAMETERS FOR MODELING OIL QUALITY

by

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ABSTRACT

JACOB TRAMMEL. Alternate engine parameters for modeling oil quality (Under the direction of DR. JOHN HILDRETH)

Oil changes in equipment is one of the most common preventative maintenance (PM) practices performed in fleet management. In addition to being a frequent cost item, the opportunity to optimize intervals could provide significant PM cost savings to an owner. This research investigated alternate variables for modeling oil degradation in an effort to improve oil change timing and potentially reduce PM cost. Throughout the course of the study, 952 samples were taken from North Carolina Department of Transportation (NCDOT) equipment. The samples were then analyzed using On-Site Analysis Inc. OSA4 TruckCheck oil analysis equipment. Additional data was acquired through the NCDOT's on board diagnostic monitoring systems. Total base number (TBN), was chosen as the variable to track oil degradation. As such, the analysis data was then combined with the on board diagnostic data to create the following models: miles or hours on sample versus TBN, fuel usage versus TBN, run time versus TBN, idle time versus TBN, percent idle versus TBN, as well as a number of combine models. The models were tested at a 95% confidence level to determine that currently the ideal model remains the standard miles/hours on sample. Other models such as fuel usage showed promise as alternate models. However, due to the implementation effort required to convert current standards, the alternate methods do not pose a great enough increase in model accuracy to warrant the implementation and use of new models.

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CHAPTER 1: INTRODUCTION

The construction and automotive industries perform regular preventive maintenance (PM) on a vast amount and large variety of vehicles and equipment in fleets around the world. To protect the equipment in the fleets, the practice of PM is completed to extend the lifespan of equipment by reducing unexpected failures, which in turns reduces the equipment's life cycle cost (Thorn et al. 1995). This practice of PM encompasses a variety of activities from basic oil changes and tire rotations, to complete engine rebuilds. Specifically for the purpose of this research project, the focus will be placed on the common and costly PM activity of oil changes (otherwise known as oil drain).

The North Carolina Department of Transportation currently performs oil changes

on its extensive fleet based on the accumulation of 5,000 miles or 200 hours, depending on the availability of odometer versus hour meter. The long-standing school of thought is that a PM schedule based on mile or hour intervals approximates the degradation of the oil. This amount of degradation is assumed to be directly correlated to the use of the engine.

However, neither miles nor hours accurately reflect the engine load under which a vehicle is placed. The reason being that the miles and hours form of measurement fails to capture how the engine was operated during the measured period. The problem which arises is due to the accumulation of high or low load applications the engine will be operated in during the oil's life. If the engine is operated at a constant load, in a manner similar to generators, the oil will degrade at a predictable rate and the drain interval can accurately be modeled using hours of operation. However, for equipment which is subjected to varying environments, the engine is not subjected to a constant load. Instead, the engine is constantly fluctuating between high and low load situations, and it becomes significantly more difficult to accurately model oil degradation using miles driven/hours ran. In these situations, measure of use that correspond with engine output, should be considered to model the oil degradation more accurately.

The lack of accuracy in the established intervals has led to the scholarly investigation of more accurate intervals parameters. To investigate this condition, The University of North Carolina at Charlotte (UNC Charlotte) has analyzed oil samples of heavy duty diesel trucks and tractors for the NCDOT. This analysis is being used to identify proper drain intervals as well as attempt to identify an alternate interval parameter. The research presented in the following thesis addresses the viability of fuel use as a new measure of engine load and create a new proposed PM tracking method based on new models using engine operation variables.

CHAPTER 2: PROBLEM STATEMENT

A current interest to fleet managers lies within optimizing maintenance schedules to reduce cost. This research focused on one aspect in particular, which is oil degradation modeling. Currently oil drain intervals for vehicles and equipment are tracked based on standard durations using miles or hours driven. These durations cause concern because they are based on arbitrary existing practices. These existing standards depend soley on miles or hours driven to reflect oil quality. With the increase in technology since the introduction of engine oil, the additives and physical properties of the oil have been advanced and improved on in terms of quality. This increase in oil additives and quality control has led to the ability to utilize oil for longer periods of time without increasing the potential of engine damage due to poor oil quality. Creating new drain intervals based on the performance advancements associated with modern lubricants, the potential exists to create considerable savings in maintenance time as well as PM budgets. New oil change intervals can be created by monitoring engine oil quality and by changing oil once it has reached a designated quality threshold. This threshold is defined by oil characteristics such as total base number (TBN) and viscosity, among others. Using the oil until it reaches the recommended thresholds allows for the oil to be used for the longest period of time without risking damage to the engine. The advantage to utilizing oil to its full life is mainly cost savings. Previous NCDOT research showed that ~$120,000 could be saved from extending oil change durations (Hildreth and Tymvios, 2016).

The optimal duration to utilize engine oil is dictated by a number of variables. The characteristics of oil quality include physical, chemical, and elemental properties of the used oil. The variables that address the three characteristics consist of TBN, viscosity, and contaminants in the oil (wear metals, dirt, and foreign materials). TBN measures the “alkaline additives in the lubricant,” which reduce the acidic compounds in the engine oil (Tribology, 2014). Jetter et al. 1998 recommends that TBN remains above 4 mg of KOH/g during use based on the corrosion which occurs below 4 mg of KOH/g (Jetter et al. 1998). Viscosity measures resistance to flow at the specific temperatures of 40C and 100C (SAE J300, 2015). As engine oil degrades, the viscosity fluctuates up and down based on contaminates in the engine. For the oil in question, 40 weight oil, SAE J300 lists the minimum value for viscosity as 12.5 centistokes while the maximum is 16.3 centistokes (SAE J300). The final characteristic to evaluate is wear metals produced from engine wear as well as foreign contaminants. The primary metals present in oil include aluminum, chromium, copper, iron, and tin (Tribology 2014). These metals are measured in parts per million (PPM) and function as warning signs for issues involving the moving components inside the engine (Tribology 2014).

The most accurate means to achieve the longest duration of oil life is accomplished by continuous monitoring of the oil. This method employs the use of sensors within the oil circulation system that measures such variables as wear metals and viscosity (Cambridge Viscosity’s Patented Sensor Technology, 2016). The issue with this method lies in the extremely expensive implementation cost for fleet use. Additionally, this method of analysis would determine that machines require PM on an inconsistent, individual basis that depends on the use of each piece of equipment. The next best alternative utilizes consistent short interval oil sampling of every machine. However, pulling an oil sample from every machine in the fleet every 1,000 to 1,500 miles would increase equipment down-time significantly and would adversely impact work flow. This leaves the final option for monitoring: short interval monitoring on a sample population in order to represent the entire fleet.

At this point, the factor which engine use has on oil quality must be discussed. When examining the duration a vehicle can travel before requiring an oil change, not every mile or hour during that period is the same. Not every mile of operation imparts the same wear on the oil due to the various manners in which the engine is operated and the physical conditions equipment perform under. In other words, if a truck travels up a mountain road carrying no load, the vehicle will travel X distance and use X force to travel that distance. The same truck carrying a 10,000lb load up the same road, will still travel X distance but will use considerably more force to travel that distance. Due to high load subjected to the engine, the oil will degrade more quickly than the low load situation.

This fact, that not every mile of vehicle operation is the same, is the root of this research project. The current miles or hours driven model of degradation, does not capture all of the involved variables within how a vehicle is operated. Therefore, it is necessary to examine alternate engine variables in order to identify more accurate methods of modeling degradation.

CHAPTER 3: RESEARCH OBJECTIVES

The purpose of this research was to address the concerns in oil degradation model accuracy. In order to achieve the goal of more accurate degradation models, a number of steps have been taken to facilitate the creation of multiple models and determine the most accurate model. The steps taken include the sampling and analysis of the NCDOT heavy duty diesel fleet. The analysis results were then combined with the NCDOT operation parameters to create models of degradation. The objectives below outline the major milestones undertaken to complete the goal of assessing the accuracy of oil degradation models.

Objective 1: Develop oil degradation models based on fuel usage, miles on sample, idle time, run time, and percent idle time. Using the data collected from the NCDOT create a models for oil degradation for miles on sample, fuel usage, idle time, run time, as well as combined models.

Objective 2: Assess the statistical significance of each model. From the models created in objective 1, determine the statistical significance of each model.

Objective 3: Identify the most effective model of oil degradation. Using the statistical significance of each model and the effort required for implementation determine the optimal model to propose for use by the NCDOT.

CHAPTER 4: RESEARCH SCOPE

Within these objectives, the reasearch will be limited to the following:

The investigations and hypothesis created in the course of this project is limited to the oil analysis data collected by UNC Charlotte from March 2015 to June 2016. This data is limited solely to the NCDOT Division 10, with samples taken from the equipment displayed in Table 4.1. This list of equipment will be used as sample population order to represent the entire population of equipment with the same engine configurations. Additionally, results and recommendations of this study should only be applied to the engines and equipment listed in Table 4.1.

TABLE 4.1: Equipment Utilized Throughout Study

Class Number	Equip ID	Year	Make	Model	Engine
0209	215-6074	2003	International	7300	Navistar DT466 7.6L I6
0209	215-6077	2003	International	7300	Navistar DT466 7.6L I6
0209	215-6255	2004	International	7300	Navistar DT466 7.6L I6
0209	215-6256	2004	International	7300	Navistar DT466 7.6L I6
0209	215-6258	2004	International	7300SFA	Navistar DT466 7.6L I6
0209	215-6260	2004	International	7300SFA	Navistar DT466 7.6L I6
0209	215-6374	2005	International	7300SFA	Navistar DT466 7.6L I6
0209	215-6375	2005	International	7300	Navistar DT466 7.6L I6
0209	215-6377	2005	International	7300	Navistar DT466 7.6L I6

TABLE 4.1: Equipment Utilized Throughout Study Cont.

Class Number	Equip ID	Year	Make	Model	Engine
0209	215-6511	2007	International	7300SFA	Navistar DT466 7.6L I6
0209	215-6883	2014	International	7300SFA	Navistar MAXXFORCE 7.6L I6
0210	462-0871	2008	Ford	F350	International (Powerstroke) 6.4L V8
0210	462-1196	2008	Ford	F350	International (Powerstroke) 6.4L V8
0210	462-1197	2008	Ford	F350	International (Powerstroke) 6.4L V8
0210	462-1198	2008	Ford	F350	International (Powerstroke) 6.4L V8
0210	462-1270	2008	Ford	F350	International (Powerstroke) 6.4L V8
0210	462-1271	2010	Ford	F350	International (Powerstroke) 6.4L V8
0210	462-1272	2010	Ford	F350	International (Powerstroke) 6.4L V8
0210	462-1523	2012	Ford	F350	International (Powerstroke) 6.7L V8
0210	462-2006	2012	Ford	F350	International (Powerstroke) 6.7L V8
0210	462-2302	2012	Ford	F350	International (Powerstroke) 6.7L V8
0210	462-2303	2013	Ford	F350	International (Powerstroke) 6.7L V8
0303	826-0394	2006	New Holland	TS115A	New Holland 6.7L 6-cyl
0303	826-0412	2007	New Holland	TS125A	New Holland 6.7L 6-cyl
0303	826-0417	2007	New Holland	TS125A	New Holland 6.7L 6-cyl
0303	826-0418	2007	New Holland	TS125A	New Holland 6.7L 6-cyl
0311	826-0579	2013	John Deere	7330	John Deere 6.8L 6-cyl

TA 4.1: Equipment Utilized Throughout Study Cont.

Class Number	**Equip ID**	**Year**	**Make**	**Model**	**Engine**
0311	838-0110	2000	John Deere	7600	John Deere 6.8L 6-cyl
0311	838-0111	2000	John Deere	7600	John Deere 6.8L 6-cyl
0311	838-0112	2000	John Deere	7410	John Deere 6.8L 6-cyl
0311	838-0113	2000	John Deere	7410	John Deere 6.8L 6-cyl
0311	838-0114	2000	John Deere	7410	John Deere 6.8L 6-cyl
0311	838-0115	2000	John Deere	7600	John Deere 6.8L 6-cyl
0311	838-0116	2000	John Deere	7600	John Deere 6.8L 6-cyl
0311	838-0117	2000	John Deere	7600	John Deere 6.8L 6-cyl
0311	838-0118	2000	John Deere	7600	John Deere 6.8L 6-cyl
0311	838-0166	2002	John Deere	7410	John Deere 6.8L 6-cyl
0311	838-0194	2003	John Deere	7615	John Deere 6.8L 6-cyl
0303	838-0311	2014	John Deere	6105M	John Deere 4.5L 4-cyl
0303	838-0312	2014	John Deere	6105M	John Deere 4.5L 4-cyl
0303	838-0313	2014	John Deere	6105M	John Deere 4.5L 4-cyl
0303	838-0314	2014	John Deere	6105M	John Deere 4.5L 4-cyl
0311	838-0320	2014	John Deere	6140M	John Deere 4.5L 4-cyl

CHAPTER 5: LITERATURE REVIEW

5.1: Engine Oil Basics

Engine oil is an essential lifeblood of modern combustion engines. It reduces internal friction forces through lubrication, removes contaminants from the engine, assists in heat dissipation, and inhibits corrosion. As the engine is used the oil will degrade and lose the ability to protect the engine in the methods listed above. As such the oil must regularly be replaced to maintain its beneficial properties. To keep the oil in optimal condition, manufacturers have specified recommended durations between oil changes measured in miles or hours on the oil. However, the specified drain intervals use the assumption that the engine will be operating in the worst case scenario and as such the drain interval can be extended depending on the engine's actual operating conditions (Agoston et al. 2005).

5.2: Oil Degradation

Engine oil breaks down as the oil is used by the engine to promote safe operations. As these operations occur the primary source of breakdown is the "chemical breakdown of additives and the subsequent interaction among the resultant components to produce corrosive acids and other undesired substances" (Al-Ghouti and Al-Atoum 2009). This process degrades the oil's ability to function as a basic compound and neutralize acid chemicals which enter the engine over the life of the oil. The measurement of this process uses the variable, TBN, which measures the alkalinity of the oil in (mg of KOH/g). In fresh oil, the TBN will vary from 9-11 mg of KOH/g, where the minimum desired TBN is at 4 mg of KOH/g (Jetter et al. 1998).

The additional breakdown will occur within the viscosity of the oil. As oil degrades it will become more or less viscous depending on the chemical environment within the engine. As viscosity is reduced the oil has less ability to penetrate the individual components inside of the engine, and as such, its ability to protect the engine is reduced. On the contrary, if the oil becomes more viscous, the oil breaks down and is unable to protect engine components ("Oil Analysis Guide" 2014). For the purposes of this research project, the threshold for minimum acceptable viscosity is set at 12 centistokes (cSt) as described in SAE J300 for 40 weight oils (SAE J300).

5.3: Preventative Maintenance

Preventive maintenance is the strategy and science of replacing components on a piece of equipment or plant before failure occurs. The US Army defines PM as the following: "the purpose of scheduled and/or preventive maintenance is to avoid premature failure of equipment and sustain the inherent reliability designed and manufactured in the equipment" (US Army 2013). Equipment purchasers estimated the amount of repairs which will be required over the life of the equipment, and it is the responsibility of the PM schedule to keep the repairs to a minimum. As such, if the PM schedule is ineffective and avoidable failures occur, the budget for the machine life cycle cost can be exceeded. With the equipment's budget dependant on the effectiveness of the PM schedule, it is essential that schedule be followed exactly. The importance of PM schedules is demonstrated by the North Carolina Department of Administrations's 1989 handbook on Motor Fleet Management Regulations, which states that "If maintenance is not performed within plus or minus 500 miles of the schedule the vehicle assignment is subject to termination" (NCDOA, 2015). In other words, if the operator of a vehicle neglects the maintenance schedule they will be removed from the vehicle due to the risk of premature failures caused by the missed PMs.

5.4: Preventative Maintenance Schedules

All machine components will fail given enough operation time, the science within PM aims to create a schedule that pushes the boundaries on the lifespan of components to extend service life without failure occurring. An alternative view can be taken from industrial applications where PM can be defined as, "The basic idea to perform PM is when the amount of deviation in the product quality characteristics used exceeds a predefined value. Therefore, it is possible to reduce the deviation from the target and consequently enhance quality by performing PM" (Shrivastava et al. 2016). For the purposes of construction, the "quality characteristic" variables can be a number of production variables. For example, in the case of an excavator the production variable would be the amount of earth excavated over a period of time. When the excavator experiences a simple failure such as a broken tooth on the bucket's cutting face, the machine remains operable. However, production will be reduced through the less efficient operation. The same analogy can be made in the case of a catastrophic failure such has a hydraulic system failure, which would cause a complete shutdown of the machine and production would be stopped until repairs can be made on the machine (Shrivastava et al. 2016).

Following this logic, the ideal situation is for a piece of equipment to be brought into a maintenance shop after hours or between jobs for service within a clean environment where mechanics can complete the required maintenance in the best possible environment to increase production rates. If the ideal schedule is not achieved, components have the potential to be replaced with considerable lifespan remaining, or the component will fail in the field (Guo et al. 2014).

For components replaced ahead of schedule, there are two outcomes. The first being that the component is replaced long before it fails, and subsequently a factor of safety is placed on the operation. The second outcome being that due to the early replacement, there is considerable life left in the component and the owner of the equipment is losing money due to the life left in the component. This method would likely be selected when equipment is being aggressively utilized to meet peak production rates. In this case, the safety factor of shorter PM intervals can better protect the equipment from the high wear rate induced through high production. However, if the machine is not a production driver, the increased PM cost due to the early replacements is unneeded overhead which can be reduced by extending the PM intervals (Guo et al. 2014).

The alternate to a conservative PM schedule is to extend the durations between PMs to attempt to obtain the full life of the component. This method is a more cost effective schedule. However, it can cause costly on-site repairs due to pushing the lifespan of components. The disadvantage of this method is that the components have the ability to fail in the field during production. When this occurs the machine is no longer capable of performing the required task and must experience downtime before it returns to service. As such, technicians will be required to either retrieve the equipment and haul it to a repair facility or perform the repairs in the field. Either option will cause longer downtime than the PM which would have reduced the possibility of the failure (Guo et al. 2014).

5.5: Extended Drain Intervals

For the purpose of this research, the focus of PM will be shifted to the specific item of oil drain intervals. When examining the PM schedules for oil drains, the intervals are measured in terms of hours, or miles driven depending on the odometer-type. Using the NCDOT as an example, the standard duration for oil changes is at 5,000 miles or 200 hours. Recent pushes for more environmentally conscious business practices have led to many organizations, including the NCDOT, examining its fleet management practices to create cost saving practices which also reduce the environment impact. Of the proponents for extended oil change intervals, California's Integrated Waste Management Board published research to support the move to extend oil changes. This research is based on data analysis of oil samples taken from passenger vehicles as well as heavy-duty diesel engines in a number of different machines as pictured in Table 5.1.

TABLE 5.1: California DTSC Oil Study Sample Population (Brown et al. 2008)

Fleet	Number and Vehicle and Engine Type	Engine Type	Sump Capacity	Oil Type and Grade	Filter Brand and Model
California Department of Corrections (CDC)	11 MCI Coach 102 Buses	Detroit Diesel 671	39	Mobil Drive Clean SAE 10W-30 Valvoline All Fleet Plus and Premium Blue SAE 15W-40 Chevron Lubricating Oil SAE 10W-30 Texaco Havoline Formula SAE 10W-30	puraDYN TF 40
	15 GM and Ford Vans	Gasoline GM V8, Ford V10	15	Chevron Supreme Motor Oil SAE 5W-30	OilGuard EPS 20
Department of General Services (DGS)	20 Chevy Cavaliers	Gasoline 4-cylinder	4	Conoco Phillips 76 Firebird LD SAE 10W-30 (re-refined oil)	Fram X2 Extended Guard
	20 Chevy Cavaliers	Gasoline 4-cylinder	4	" "	Standard
California Department of Forestry and Fire Protection (CAL FIRE)	5 1985-1997 17-Passenger Crew Carrying Vehicles	International Harvester 1954, 4700, 4900	44	Conoco Phillips 76 Guardol QLT SAE 15W-40 Chevron Delo 400 Multigrade SAE 15W-40	OilGuard EPS 60
	2 1999 Dodge BE 1500 ½ ton PU	Gasoline V8	6	" "	OilGuard EPS 20
	1992 GMC C7H042 16' Stakeside	Diesel	12	" "	OilGuard EPS 60
	1995 GMC K3500 BDSU 1Ton UB	Diesel	6	" "	OilGuard EPS 20
	1991 GMC K2500 ¾ Ton 4WD PU	Gasoline	6	" "	OilGuard EPS 20
	1988 Ford LT9000 Transport	Diesel	44	" "	OilGuard EPS 60
	1995 International F2574 Transport	Detroit Diesel 350		" "	OilGuard EPS 60
	1993 GMC K3599 Dozer Tender	Diesel		" "	OilGuard EPS 60
	2002 GMC Sierra 1500 ½ Ton PU	Gasoline V8	6	" "	OilGuard EPS 20
	1999 Dodge BE 1500 ½ Ton 4WD PU	Gasoline V8	6	" "	OilGuard EPS 20
	Dodge Ram 2500 ¾ Ton 2WD PU	Gasoline V8	6	" "	OilGuard EPS 20
	2002 Dodge Ram 1500 ½Ton PU	Gasoline V8	6	" "	OilGuard EPS 20
	2005 Ford F350 ¾ Ton PU	Gasoline V10	8	" "	OilGuard EPS 20
California Department of Transportation (Caltrans)	2000 Freightliner FC70 Herbicide Spray Truck	Cummins IBS	20	Conoco Phillips 76 Guardol QLT SAE 15W-40 Chevron Multigrade SAE 15W-40	OilGuard EPS 60
	1999 Navistar 4900 Safety Rail Repair	Caterpillar 3126	22-26	" "	OilGuard EPS 60
	2003 International Harvester 9400	Cummins N14	44	" "	OilGuard EPS 60
	2001 Freightliner FL70	Caterpillar 3126	18-20	" "	OilGuard EPS 60
	1996 International Harvester 4900	Detroit Diesel 466	22-26	" "	OilGuard EPS 60
Fresno Unified School District (FUSD)	14 Crown Coach Buses	Detroit Diesel 671, 6V92, Cummins 855	39	Chevron Heavy Duty Motor Oil SAE 15W-40	Luberfiner ZGard LFP9750
Long Beach Unified School District (LBUSD)	26 Crown Coach Buses	Detroit Diesel 671	32	Rosemead Soar SAE 15W-40 (re-refined oil)	Luberfiner ZGard LFP9750
Fresno Area Express (FAX)	10 Orion CNG Buses	Detroit Diesel 50 CNG	32	CITGARD CNG SAE 15W-40	OilGuard EPS 60

The research completed was performed to assess the drain intervals being used in the State of California for various government applications. The methodology of the study was to install secondary high-performance oil filters on the sample equipment and run the oil as long as possible until certain oil variables were deemed too low or high. To establish the metrics to be measured, the study consulted with various laboratories and manufacturers to create thresholds for each variable. The data sources and results of the thresholds are listed in Table 5.2.

TABLE 5.2: California DTSC Oil Parameters (Brown et al. 2008)

Oil Condition	Caterpillar[5]	Detroit Diesel[6]	Detroit Diesel/MTU	Cummins	Noria[7]	CTC Analytical Services	Chevron LubeWatch Diesel[8]	Chevron Diesel[9]	Herguth Laboratories
Physical/ Chemical									
Viscosity (cSt @ 100 C)	+/- 3.0	12.5 – 16.3	16.3		+/- 25%			+ 25%	16.8
TBN (mg KOH/g)	50%	2		2		3			2
Contaminants									
Soot (% wt)		3	3	3	3	3			1.5 – 3.0
Oxidation (Abs/cm)					25				30
Water FTIR (% vol)	0.5	0.3	0.3		0.25				0.1
Sulfination (Abs/cm)									30
Fuel (% vol)	4	2.5	2.5	5	3	3		5.0	5
Glycol (% vol)	0	0	0		Any				0.2
Metals (ppm)									
Iron		150	150	75 – 100		100	150	100	145
Aluminum				15		18	30	40	5
Chromium				15		12	25	40	5
Copper		30	30	20		30	50	40	21
Lead		30	30	30		30	50	100	10
Tin						18	25		8
Nickel						10	10		4
Silver							5		4
Antimony									
Silicon				15	20	20	25	20	20
Sodium				40	30			50	
Boron					20			20	
Zinc									
Phosphorus									
Calcium									
Magnesium									
Barium									
Molybdenum									
Potassium				40					

As shown in Table 5.2, the thresholds used for viscosity and TBN express a great deal of variance between differing laboratories. UNC Charlotte chose threshold values of 12.5-16.3 cSt for viscosity based on SAE J300 standards for 40 weight oil. Additionally, the conservative value of 4 mg of KOH/g was chosen based on the research of Jetter et al. 1998. The purpose of selecting the thresholds is to establish values which are considered safe operating levels to which the vehicles could be extended.

Once the study was put in place for one year, the data was compiled and new recommendations were created for the various engines and types of equipment. As can be seen from Table 5.3, the new oil drain intervals provide drastic increase over the existing intervals and will save considerable amounts of capital on PM.

TABLE 5.3: California DTSC Extended Oil Drain Results (Brown et al. 2008)

Participating Fleets	Number and Type of Vehicles	Filter Make and Model	Miles Accumulated During Study	Oil Samples Collected	Original Drain Intervals	Proposed Drain Intervals	Projected Payback Period (yrs)
Department of General Services (DGS)	40 passenger cars	Fram X2	798,000	212	6,000	10,000	0.2
California Department of Forestry and Fire Protection (CAL FIRE)	13 two- and three-axle trucks	OilGuard EPS 60	134,980	42	5,000	18,000	3.1
California Department of Transportation (Caltrans)	5 two- and three-axle trucks	OilGuard EPS 60	160,711	39	6,000	18,000	1.3
Fresno Area Express (FAX)	10 city transit buses	OilGuard EPS 60	179,099	56	6,000	18,000	3.7
Fresno Unified School District (FUSD)	14 school buses	Luberfiner ZGard LPF9750	116,618	34	9,000	36,000	2.5
Long Beach Unified School District (LBUSD)	26 school buses	Luberfiner ZGard LPF9750	505,115	57	10,000	36,000	6.8
California Department of Corrections (CDC)	11 coach buses	puraDYN TF 40	949,649	100	10,000	50,000	3.6

5.6: Engine Load

Standard oil drain intervals are based on the parameters previously stated as miles driven or hours of run time. What this parameter fails to capture is the level of output at which the engine is operating. Engine load has no single definition. However, for this study engine load will be defined as the internal resistance to angular acceleration with respect to the crankshaft of a given motor. While force required to move the vehicle increases, while engine output remains constant, the vehicle will decelerate. On the other hand, engine output increases while the force required remains constant, the vehicle will accelerate. In order for an engine to increase the output or load, it must inject more fuel

TABLE 5.4: Komatsu Engine Load (Komatsu 2009)

Construction
(1) Bulldozers

Range	Low		Medium		High	
Machine / Amount	U.S. Gal/hr.	ltr./hr.	U.S. Gal/hr.	ltr./hr.	U.S. Gal/hr.	ltr./hr.
D21A, P-8E0	0.4 ~ 0.85	1.6 ~ 3.2	0.85 ~ 1.3	3.2 ~ 4.8	1.3 ~ 1.7	4.8 ~ 6.4
D31EX, PX-22	0.9 ~ 1.8	3.3 ~ 6.7	1.8 ~ 2.6	6.7 ~ 10.0	2.6 ~ 3.5	10.0 ~ 13.3
D37EX, PX-22	1.0 ~ 2.0	3.8 ~ 7.6	2.0 ~ 3.0	7.6 ~ 11.4	3.0 ~ 4.0	11.4 ~ 15.1
D39EX, PX-22	1.2 ~ 2.4	4.5 ~ 8.9	2.4 ~ 3.5	8.9 ~ 13.4	3.5 ~ 4.7	13.4 ~ 17.9
D51EX, PX-22	1.4 ~ 2.8	5.2 ~ 10.5	2.8 ~ 4.1	10.5 ~ 15.7	4.1 ~5.5	15.7 ~ 21.0
D61EX, PX-15E0	1.7 ~ 3.4	6.4 ~12.9	3.4 ~ 5.1	12.9 ~19.3	5.1 ~ 6.8	19.3 ~ 25.7
D65E, P-12	2.1 ~ 4.1	7.8 ~ 15.6	4.1 ~ 6.2	15.6 ~ 23.4	6.2 ~ 8.2	23.4 ~ 31.1
D65EX, PX. WX-16	2.0 ~ 4.0	7.6 ~ 15.2	4.0 ~ 6.0	15.2 ~ 22.8	6.0 ~ 8.1	22.8 ~ 30.5
D85ESS-2A	2.2 ~ 4.4	8.4 ~ 16.8	4.4 ~ 6.7	16.8 ~ 25.2	6.7 ~ 8.9	25.2 ~ 33.6
D85EX, PX-15E0	2.5 ~ 5.1	9.6 ~ 19.2	5.1 ~ 7.6	19.2 ~ 28.8	7.6 ~ 10.1	28.8 ~ 38.4
D85EX, PX-15R	2.5 ~ 4.9	9.4 ~ 18.7	4.9 ~ 7.4	18.7 ~28.1	7.4 ~ 9.9	28.1 ~ 37.5
D155A-5	3.0 ~ 5.9	11.3 ~ 22.5	5.9 ~ 8.9	22.5 ~ 33.8	8.9 ~ 11.9	33.8 ~ 45.1
D155A-6	3.3 ~ 6.6	12.5 ~ 25.0	6.6 ~ 9.9	25.0 ~ 37.5	9.9 ~ 13.2	37.5 ~ 50.0
D155AX-6	3.0 ~ 6.0	11.4 ~ 22.8	6.0 ~ 9.0	22.8 ~ 34.2	9.0 ~ 12.0	34.2 ~ 45.6
D275A-5	7.7 ~ 10.9	29.2 ~ 41.3	10.9 ~ 14.1	41.3 ~ 53.5	14.1 ~ 17.4	53.5 ~ 65.7
D275A, AX-5E0	7.7 ~ 10.9	29.2 ~ 41.3	10.9 ~ 14.1	41.3 ~ 53.5	14.1 ~ 17.4	53.5 ~ 65.7
D275A-5R	7.6 ~ 10.8	28.8 ~ 40.8	10.8 ~ 13.9	40.8 ~ 52.8	13.9 ~ 17.1	52.8 ~ 64.8
D375A-5	10.6 ~ 15.0	40.2 ~ 56.9	15.0 ~ 19.5	56.9 ~ 73.7	19.5 ~ 23.9	73.7 ~ 90.4
D375A-6	11.3 ~ 16.0	42.8 ~ 60.6	16.0 ~ 20.7	60.6 ~ 78.5	20.7 ~ 25.4	78.5 ~ 96.3
D375A-5R	9.3 ~ 13.2	35.3 ~ 50.0	13.2 ~ 17.1	50.0 ~ 64.7	17.1 ~ 21.0	64.7 ~ 79.4
D375A-6R	10.9 ~ 15.4	41.3 ~ 58.4	15.4 ~ 20.0	58.4 ~ 75.6	20.0 ~ 24.5	75.0 ~ 92.8
D475A-5E0, -5SDE0	15.5 ~ 21.9	58.5 ~ 82.9	21.9 ~ 28.3	82.9 ~ 107.3	28.3 ~ 34.8	107.3 ~ 131.7
D575A-3	20.2 ~ 28.7	76.6 ~ 108.5	28.7 ~ 37.1	108.5 ~ 140.4	37.1 ~ 45.5	140.4 ~ 172.3
D575A-3SD	22.0 ~ 31.2	83.4 ~ 118.1	31.2 ~ 40.4	118.1 ~ 152.9	40.4 ~ 49.6	152.9 ~ 187.6

Low: Work where machine spend most of daily working hours idling or traveling with no load.

Medium: Average earth moving, scraper hauling, easy pushing
Object materials; Not hard to dig

High: Ripping, heavy pushing
Continuous use with engine at full throttle
Object materials; Blasted rock

and air into the cylinder for combustion. Komatsu’s performance manual defines engine load ranges by fuel intake of the motor; this can be seen in Table 5.4.

As depicted in Table 5.4, as engine load increases, the amount of fuel injected into the engine also increases. Engine load can also be viewed in terms of engine speed in RPM. As the RPM of the engine increases there will be an increase in the amount of fuel injected into the motor. This is due to the greater number of cycles the engine will undergo in a given time frame. This can then be extrapolated to the conditions under which the vehicle is operated. In a low load setting the vehicle will run at idle speed where engine RPM and fuel usage are at the lowest. On the opposite end of the spectrum, high load involves wide open throttle situations where the engine will be injected with the greatest amount of fuel possible and engine speed will be near the top end of the spectrum.

Additional points to address regarding engine load are the effects of high engine load on oil degradation. As engine load is increased, heat in the engine increases significantly past standard operating temperatures. Above 135º C, oxidization will become excessive along with a dramatic increase in nitration of the oil (Kader et al. 2014). On the contrary, an engine which is idled excessively will also suffer adverse conditions. Idling an engine is considered a “no-load condition” which can cause an “unbalanced erratic motion in the engine, which can lead to an increase in wear particles” (Kader et al. 2014). Additionally, if a vehicle is subjected to short trips as well as extended idling, the oils lifespan will be greatly reduced compared to constant low load situations (Kader et al. 2014).

This was demonstrated through the research of (Kollmann et al.1998), who presented the findings of a study in which engine operatational conditions and the effect of these conditions on oil quality. During the research project, the following graph was created to project the effects of adverse engine conditions on the oil change intervals.

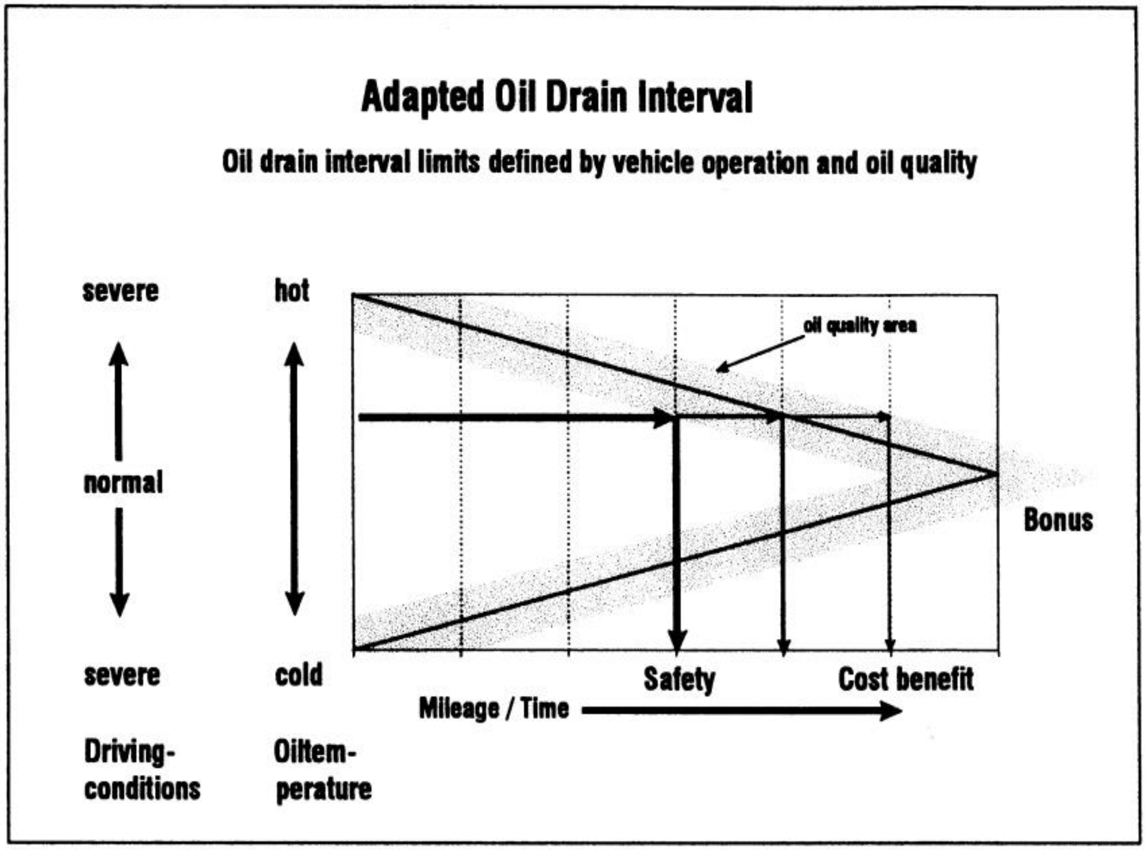

FIGURE 5.1: Effects of engine conditions on oil life (Kollmann et al. 1998)

In Figure 5.1, the theoretical effect of engine conditions on oil life is displayed. With oil life as the X-axis and engine conditions on the Y-Axis. The "V" drawn horizontally on the graph displays the possible oil life with normal engine conditions being the longest possible life, and the potential oil life decreasing as engine conditions go to either end of the severity spectrum. As such, severe conditions on either side of the spectrum, extremely light use with extended idling or heavy use with high operating temperatures, can significantly decrease the life of the oil.

Based on the summary presented, it is evident that the oil drain interval selected for proper oil life must account for the condition in which it has been operated. The simple measurement of using miles driven fails to capture how hard the engine was run during those miles. Additionally, it also fails to capture the duration of time which an engine is idled which has been shown to be just as harmful to oil quality as hard conditions (Kollmann et al. 1998). This is again repeated with hour meters. This type of meter simply cannot record how the engine has been run during the period. The answer to this problem is the focus of this research project which will establish the most accurate oil degradation model for the trucks within the study.

CHAPTER 6: RESEARCH METHODOLOGY

6.1: Data collection

The detailed description of this process starts with the equipment selection for the longitudinal study. Initially a large sample of the four equipment types were selected for the study. However, as the study progressed the number of equipment was reduced to what is listed in Table 4.1 for each class. From the equipment listed in Table 4.1, oil samples were manually collected through the dipstick port using a hand pump. When collecting oil from the equipment, three separate samples were collected on each occasion. UNC Charlotte has since recorded data from NCDOT equipment during the period of March 2015 to June 2016. During this time, 952 individual samples were collected and analyzed for chemical and physical analysis.

From the beginning of the study, a schedule had been determined on when to pull equipment for sampling. This schedule consisted of sampling at 5,000 miles or 200 hours depending on availability of odometer or hourmeter. After the initial sample, additional samples were taken every 1,500 miles 50 hours afterward. After the initial sample, the oil was continually monitored at the prescribed intervals until one or more oil quality variables became in danger of going above or below the established thresholds.

Once the oil sample was collected, it was then analyzed by lab equipment called OSA4 Truckcheck. This piece of testing equipment, manufactured by OSA, uses three separate test in order to analyze each sample. The equipment uses, dual atomic emission spectrometer, infrared spectrometer, and viscometer to determine oil quality as well as

test viscosity at both 40C and at 100C (Hildreth et al. 2015). The tests performed comply with ASTM D7417-10, which is the standard for testing in-service lubricants. In this test, three samples, collected from the equipment are tested. The OSA4 Truchcheck, creates an output which displays all the necessary data from the oil analysis. A sample output from the OSA4 TruckCheck can be seen in Appendix B.

Once the oil was collected from the equipment, additional diagnostic data needed to be acquired and organized. This data consisted of: mileage, hours, run time, idle time and, fuel usage. This data is regularly captured by the NCDOT through on board diagnostics. As such, it was available to be accessed using the fleet management software. This software was also used to track miles/hours on equipment within the study and to coordinate collection of samples from the NCDOT. The data was then accessed one piece of equipment at a time and downloaded for the life of the equipment. At this point, the data from the NCDOT was combined with the oil sample analysis as described by the process within the Data Analysis section.

6.2: Data Analysis

Once the data had been collected, both from the oil analysis as well as the NCDOT database, the next step was to compile the data and establish relations between the variables. The first step in this process was to bring everything into the spreadsheet used to organize the data, and to create a manageable spreadsheet database containing the large amount of information collected during this study. This was done by first organizing equipment by class codes. Once the data was separated into each equipment type, it was sorted by equipment ID and odometer/hour meter reading. This was performed so that at each sample point, all three separate samples could be grouped together and averaged into a single data point which should accurately represent the oil quality at the time of sampling. At this point, the data from the NCDOT was imported to match up with each truck at the time which corresponded to both diagnostic variables and oil analysis.

When importing the NCDOT data into the sheet, some manipulation of the data was required. An issue arose when the data had to be synchronized to the dates from the oil sampling, which did not match up with the dates that data was recorded from the machines. As such, interpolation was required to pair the datasets with the oil sample analysis. This process was completed using the following formula for fuel usage, run time and, idle time.

$$Variable\ at\ Sample\ Time = \left[\frac{SD - DS}{DE - DS} \times (VE - VS)\right] + VS$$

Where:

$$VS = Variable\ at\ Start\ Date$$

$$VE = Variable\ at\ End\ Date$$

$$SD = Sample\ Date$$

$$DS = Start\ Date$$

$$DE = Date\ End$$

Equation 6.1: Interpolation

Once the data was organized and sorted, the actual analysis could take place. The first step was to reorganize the data into separate data sets for each engine variation within classes. An example of the hierarchy put in place is displayed in Appendix B. The following data sets were created:

- *0209 Class - Navistar DT466 7.6L I6*
- *0210 Class - International (Powerstroke) 6.4L*
- *0210 Class - International (Powerstroke) 6.7L*
- *0303 Class - New Holland 6.7L 6-cyl*
- *0303 & 0311 Classes - John Deere 4.5L 4-cyl*
- *0311 Class - John Deere 6.8L 6-cyl*

Fuel usage, run time, idle time, percent idle time and, mileage on sample, were all measured against the TBN results from the oil analysis. Percent idle was calculated by dividing idle time by run time to represent the ratio which the equipment idled. TBN was selected due to the nature of the degradation as it occurs within the oil. This is demonstrated in Figure 6.1 and 6.2,in which the degradation of TBN and Viscosity for the 0210 6.7L datasets s displayed. As can be seen in the figures, TBN has a distinct trend

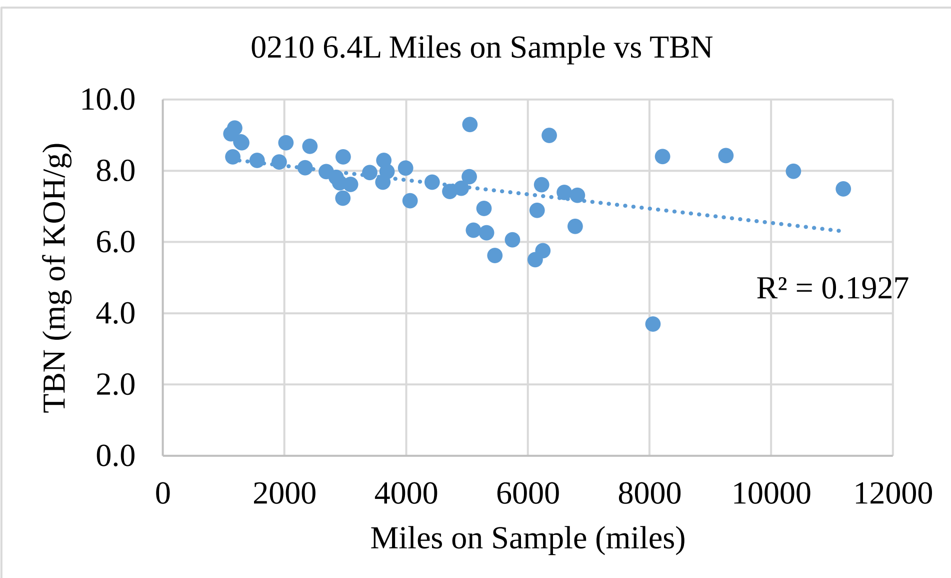

FIGURE 6.1: 0210 6.4: Miles on Sample vs Viscosity

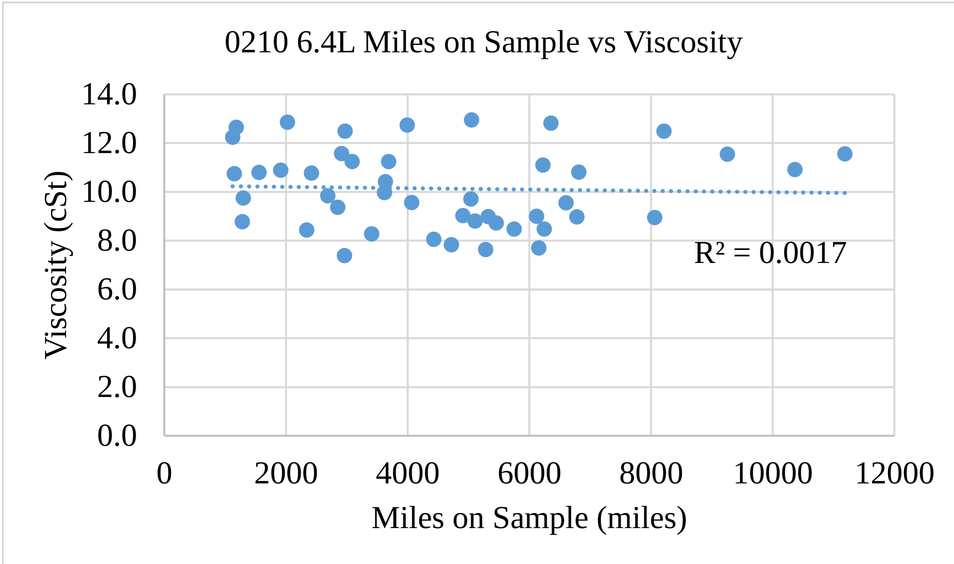

FIGURE 6.2: 0210 Miles on Sample vs TBN

while Viscosity stays fairly constant throughout the oil life. Based on these properties it was decided to use TBN for the regression analysis of the degradation models.

Once it was determined that TBN was the ideal variable to track, then the next step was to sort the individual data sets and isolate undesirable data. This was determined by dividing the Mileage on Sample by the Fuel Usage and sorting the data by miles per gallon. This allowed questionable data to be identified and numbers verified. Data was then trimmed from the samples on a case by case basis.

- *0209: Data points less than 3.0 MPG and greater than 17.0 MPG were removed from the set due to extremes of MPG. Additionally, truck 215-6377 had one oil change which performed abnormally well regarding oil degradation, so the run was removed.*
- *0210: Data points less than 6.0 MPG and greater than 14.0 MPG were removed due to extreme MPG.*
- *0303: Less than 2 Gallons per Hour or greater than 10 Gallons per Hour were removed.*
- *0311: Less than 1.7 Gallons per Hour or greater than 10 Gallons per Hour were removed.*

The deciding factor used to cut data was the consistantcy of results. For example, if a data set had consistant data that ranged from 4.0 MPG to 12.0 MPG, but then the next closest data points were at 2.0 and 14.0 MPG, then the data would be trimmed to included only data that ranged between 4.0 to 12 MPG.

Regression analysis was then performed on the data using Microsoft Excel as the analysis tool. The output of Excel's regression tool is displayed in Table 6.1.

TABLE 6.1: Sample Regression Output

0210 6.4L TBN vs Fuel Usage

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.404
R Square	0.163
Adjusted R Square	0.144
Standard Error	1.039
Observations	45.000

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	9.052	9.052	8.383	0.006
Residual	43	46.434	1.080		
Total	44	55.486			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	8.483	0.334	25.412	0.000	7.809	9.156
Fuel Usage	-0.002	0.001	-2.895	0.006	-0.003	-0.001

This analysis was performed on each data set for several configurations to ensure that all oil degradation models were addressed. The configurations tested as functions of TBN are listed below.

- 0209 & 0210 Classes
    - Run Time
    - Idle Time

- Fuel Usage
- Mileage on Sample
- % Idle/Run Time
- Run Time and Fuel Usage
- Run Time and Mileage on Sample
- Idle Time and Fuel Usage
- Idle Time and Mileage on Sample
- % Idle/Run Time and Fuel Usage
- % Idle/Run Time and Mileage on Sample
- 0303 & 0311 Classes
  - Fuel Usage
  - Hours on Sample

The 0209 & 0210 classes had significantly more tests performed due to the availability of the idle/run time data within the NCDOT database. It should be noted that a considerable number of additional tests were performed. However, due to the nature of the data, a great deal of correlation was present, and the validity of the models were then questioned. Then viability of each test was assessed using the p-value of the regression model at a 95% confidence level.

6.3: Results

As outlined in the previous section, regression analysis was performed in order to link oil analysis results for TBN to a variety of operational characteristics. The results of this effort produced the compilation of a number of oil degradation models. There were three main areas of focus within the regression analysis; Single Variable Models, Fuel Usage Combined Models, and Miles/Hours on Sample Combined Models. The summary of each regression analysis is displayed in Table 6.2. Additionally, this section presents the results for each engine within the study.

TABLE 6.2: Regression Results

Regression Analysis Results												
Class/Engine	Variable	Miles/Hours on Sample	Fuel Usage	Run Time	Idle Time	% Idle	Fuel Usage and Idle Time	Fuel Usage and Run Time	Fuel Usage and % Idle	Miles on Sample and Idle Time	Miles on Sample and Run Time	Miles on Sample and % Idle
0209 DT466	N	42	42	10	10	10	10	10	10	10	10	10
	P-Value	0.115	1.00E-03	0.756	0.87	0.564	0.207	0.19	0.466	0.893	0.828	0.846
	R-Squared	0.61	0.308	0.013	0.004	0.038	0.362	0.378	0.196	0.032	0.053	0.047
0210 6.4L	N	45	45	9	9	9	9	9	9	9	9	9
	P-Value	2.60E-03	5.90E-03	0.069	0.067	0.755	4.85E-05	3.21E-05	0.014	1.19E-04	4.21E-05	0.0385
	R-Squared	0.193	0.163	0.398	0.4016	0.015	0.964	0.968	0.76	0.951	0.965	0.662
0210 6.7L	N	61	61	26	26	26	26	26	26	26	26	26
	P-Value	5.77E-21	6.08E-17	0.367	0.389	0.216	1.98E-10	2.06E-10	9.88E-12	3.33E-12	3.35E-02	2.60E-12
	R-Squared	0.778	0.697	0.03	0.031	0.063	0.857	0.856	0.89	0.9	0.9	0.902
0303/0311 4.5L	N	47	47									
	P-Value	6.14E-12	1.74E-12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	R-Squared	0.654	0.673									
0303 6.7L	N	16	16									
	P-Value	0.002	0.002	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	R-Squared	0.509	0.497									
0311 6.8L	N	71	71									
	P-Value	3.65E-12	4.70E-09	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	R-Squared	0.394	0.506									

6.3: Discussion of Results

Modeling of the datasets returned a number of interesting results….. The first being the 0210 6.4L class and the difference in r-squared values when compared to the other classes within the study. The 6.4L class has r-squared values of 0.19 and 0.16 while the average r-squared value for miles on sample and fuel usage is 0.51. The data shows the there is considerable variability in the oil quality at all ages. This variability has been attributed to the nature of the 6.4L engine, which is known to be a problematic engine.

The next discovery is the p-value of the 0209-class data. Within the class only one model resulted in statistical significance. The sole model which is significant is the fuel usage versus TBN, with a p-value of 0.001. The proposed logic causing the variance is due to the manner which the 0209 class is utilized. The 0209 is a chassis description which is fitted with differing build outs in order to accomplish various task. As such, the trucks can be driven in very different manners varying from towing equipment and material to functioning as a repair trucks.

6.4: 0209 Results

The 0209 class consisted of 11 trucks utilizing the International 7.6L engine. Throughout the study 186 individual samples, which corresponds to 62 data points, were collected. Of the 62 data points, 20 were removed prior to regression analysis based on the criteria identified in the data analysis section 6.2. This left the remaining data to be analyzed as described in the previous section.

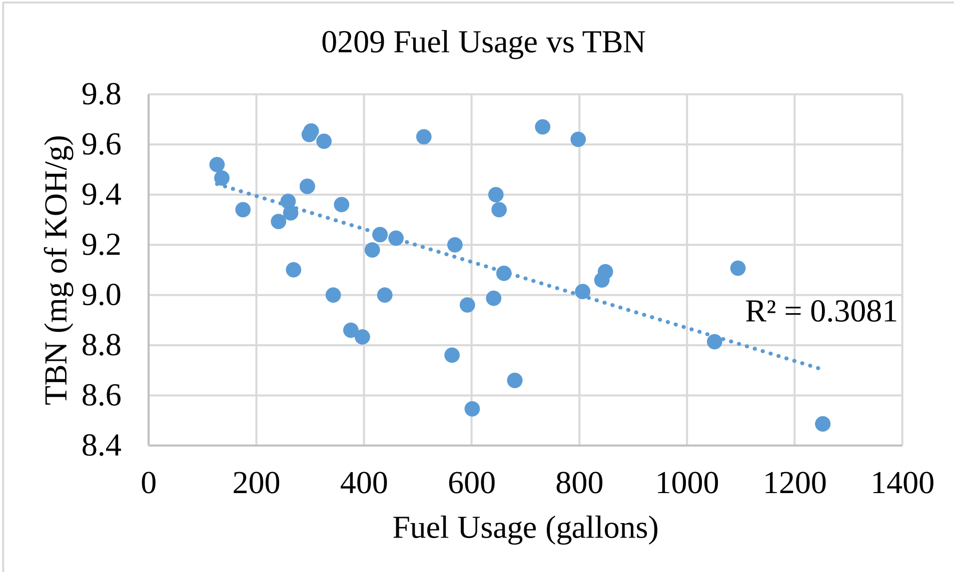

FIGURE 6.2: 0209 Fuel Usage vs TBN

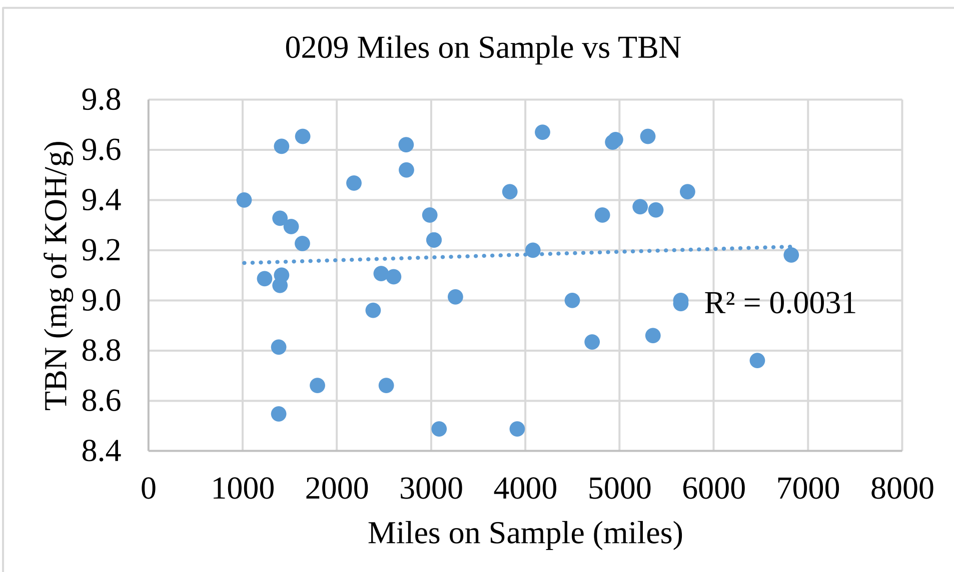

FIGURE 6.3: 0209 Miles on Sample vs TBN

The results of the analysis found that the best model, based on significance, is the fuel usage vs TBN model. This model resulted in a significance of 0.001 as shown in Table 6.2. Note that during the study a maximum p-value was set at 0.05. Despite the significance level being in the acceptable range, the R-squared value is very low meaning that a considerable amount of error is unexplained. This is the case for all models of the 0209 class and likely due to the variability within the data collected. Additionally, the sample size for the run and idle time analysis was reduced to only ten samples. This is due to the manner which the agency began recording in July of 2016. As such, many of the samples taken did not have a data point available early enough to accurately perform interpolation. This issue also influenced the strength of the analysis that could be performed with data collected for 0210 equipment with both engine classes.

6.5: 0209 Recommendations

Based on the results of the 0209 class analysis, the recommended model to use is the fuel usage versus TBN. The recommendation is based on the statistical significance of the model. However, there is concern when the corresponding r-squared value is examined and is shown to be very low. The low r-squared value then relates to an excessive amount of unexplained error within the model. As such, it would be recommended to repeat the study on the DT466 engine to ensure repeatability and validity of the model.

6.6: 0210 6.4L Results

While there was a great number of data points which were removed from the 0209 class, the 6.4L 0210 data set had only three points removed from the total 48 points. The first group of tests to examine is the single variable models; this is the most desirable model to use due to the simplistic nature of a single variable. For this dataset, mileage on sample proved to be the most statistically significant model carrying a significance level of 0.0026 which places the test in the realm of statistically significance at 95% confidence. In addition to miles on sample, the fuel usage vs TBN model was also significant at 0.0059. The graphical representation of both test is displayed in Figures 6.4

and 6.5. While neither model has high r-squared values, the miles on sample has the highest r-squared as well as the lowest p-value.

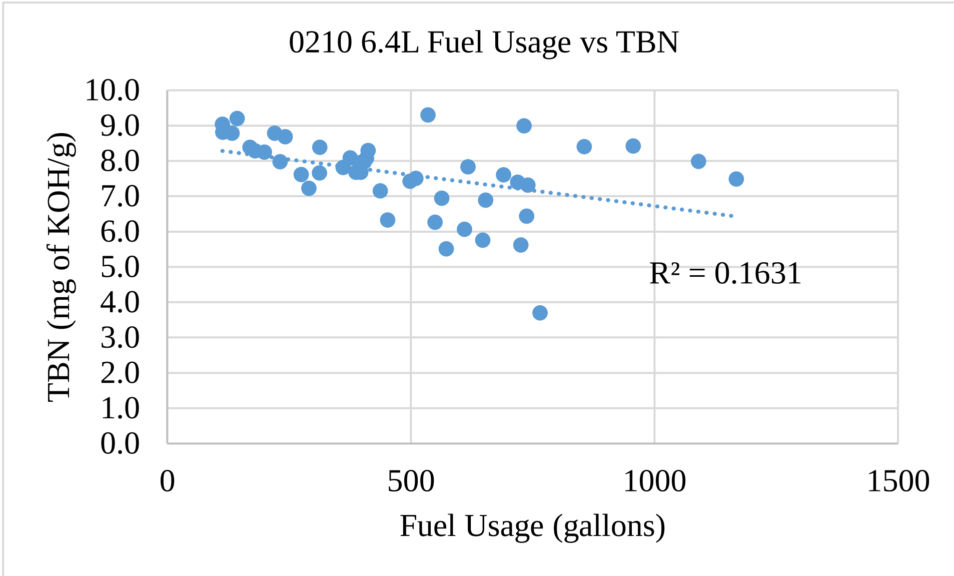

FIGURE 6.4: 0210 6.4L Fuel Usage vs TBN

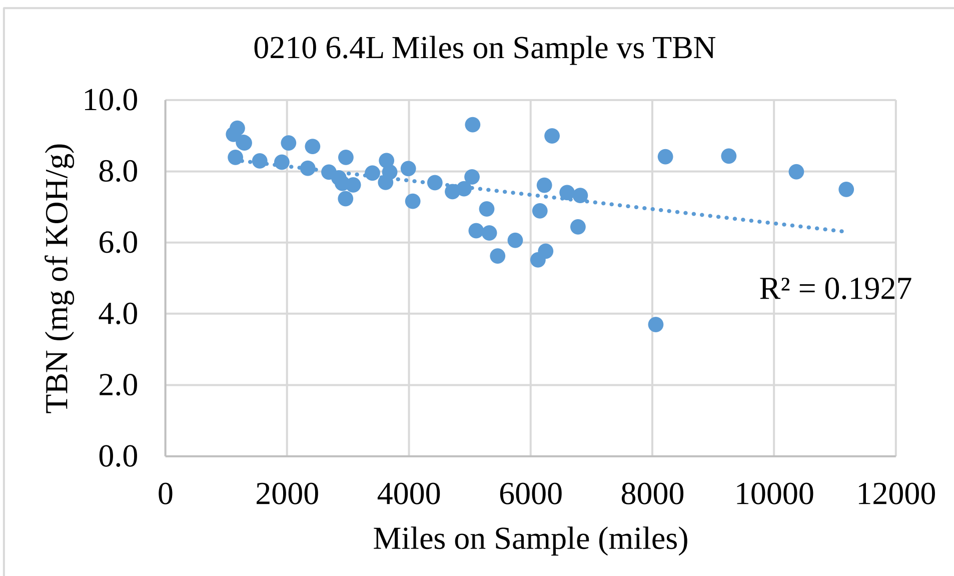

FIGURE 6.5: 0210 6.4L Miles on Sample vs TBN

The next series of tests that were conducted is the combined models, these models were made up of multiple variables to attempt to create the most accurate model. In the case of the 6.4L, all of the combined models were statistically significant. However, the most significant model of degradation is the TBN vs Fuel Usage and Run Time with a significance level of $3.21x10^{-5.}$ This model was followed closely by TBN vs Miles on Sample and Run time, as well as TBN vs Fuel Usage and Idle Time. The significance level of each test was $4.21x10^{-5}$ and $4.85x10^{-5}$ respectively. It should be noted that there considerable differences in the sample size when analyzing run time and idle time. While miles on sample and fuel usage had a total of 45 data points available for analysis, the run time and idle time only had nine data points.

6.7: 0210 6.4L Recommendations

Based on the criteria of statistical significance and r-squared value, the ideal model is fuel usage and run time versus TBN. Fuel usage and run time versus TBN has a p-value of 3.21E-05 and r-squared of 0.968. The next best model is another combined model of fuel usage and idle time versus TBN. The p-value and r-squared values are 4.85E-05 and 0.964 respectively. Despite the incredibly promising results, the issue arises when sample size is examined. With only nine data points for both models, the ability for the models to accurately represent the entire population is questioned. Without more data to confirm the models accuracy, then the next alternative must be taken, which is miles on sample versus TBN. This model has significance level of 2.60E-03 and r-squared of 0.193. This shows that the model is less desirable however the sample size of 45 ensures the models ability to represent the population accurately.

6.8: 0210 6.7L Results

The 6.7L data set for the 0210 class was the second largest data set that was collected during testing. There were 73 total data points with 12 being removed due to extreme mileage. This data set had a great number of models which would be acceptable for representing the class's oil degradation. The main focus is on three specific models, miles on sample versus TBN, fuel usage versus TBN, and miles on sample and idle time versus TBN. Miles on sample vs TBN had a p-value of 5.77E-21 and an r-squared of 0.778. While fuel usage had a p-value of 6.08E-17 and r-squared of 0.697. Finally miles on sample and idle time versus TBN had a p-value and r-squared of 3.33E-12 and 0.900.

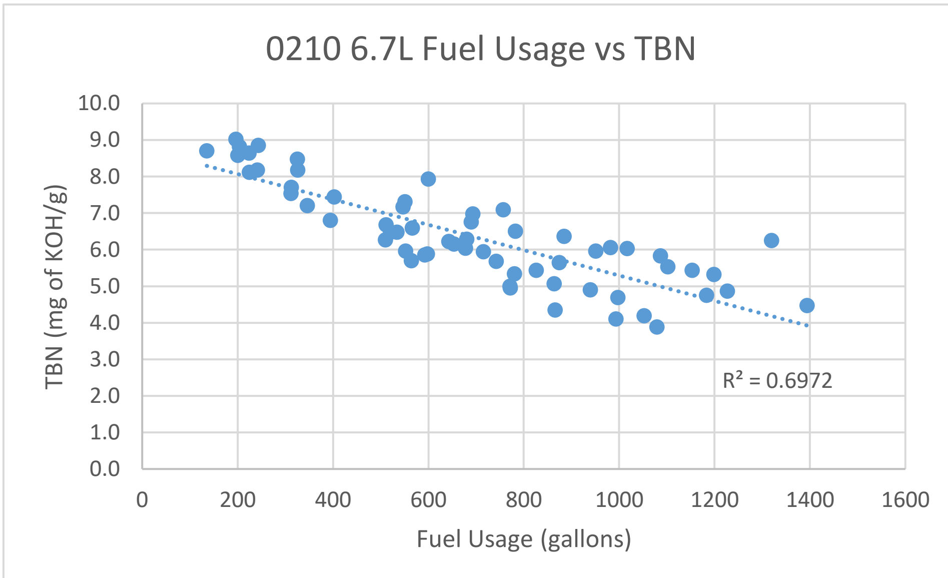

FIGURE 6.6: 0210 6.7L Fuel Usage vs TBN

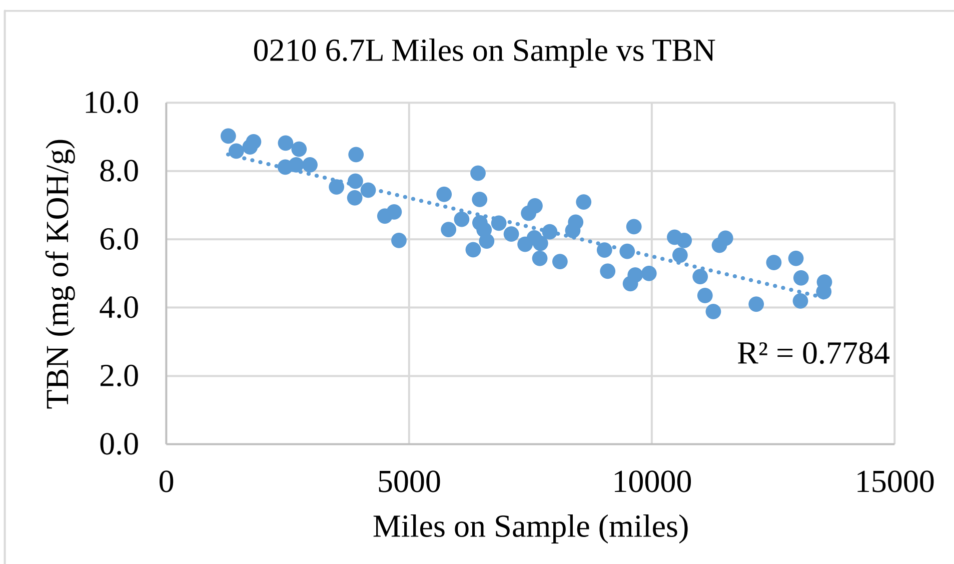

FIGURE 6.7: 0210 6.7L Miles on Sample vs TBN

6.9: 0210 6.7L Recommendations

Within the 0210 6.7L class, three models were selected as the most ideal. Between the three models, miles on sample versus TBN has been selected as the most ideal model of oil degradation. This decision was reached through a number of factors. The first is that miles on sample carries the highest significance of 5.77E-21 against the 6.08E-17 and 3.33E-12 for fuel usage and miles on sample and idle time. The next factor considered was the sample size. The miles on sample and fuel usage models had a sample size of 61 while the combined model had a sample size of only 26. This increase in sample size insures that the population will be accurately represented. The r-squared values were also examined to determine that miles on sample and idle time had the greatest amount of error explained by the model. However, the final consideration is the implementation effort. The effort required to create models to implement into the NCDOT fleet is extreme. While on the other hand, the miles on sample model is already being utilized by the fleet and requires no unit of measurement changes.

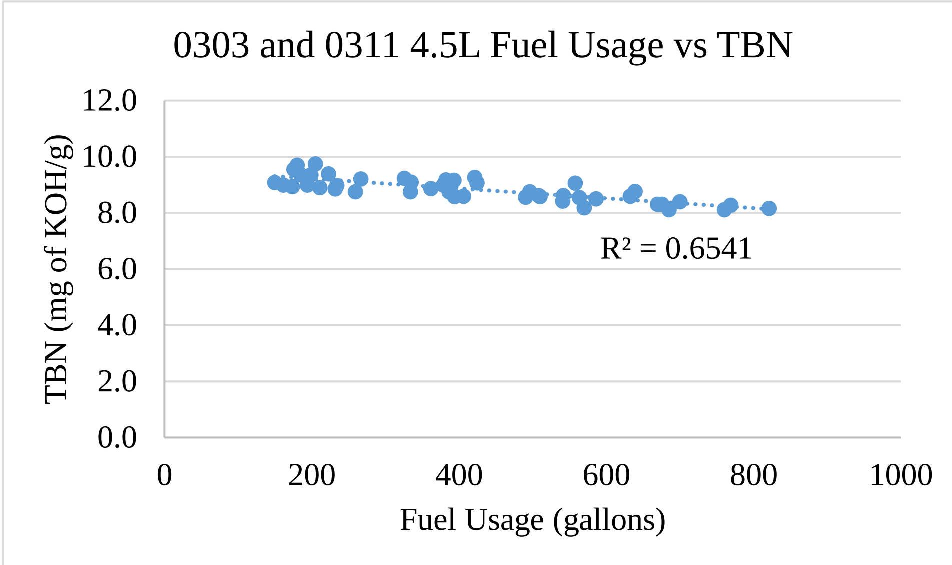

FIGURE 6.8: 0303 and 0311 4.5L Fuel Usage vs TBN

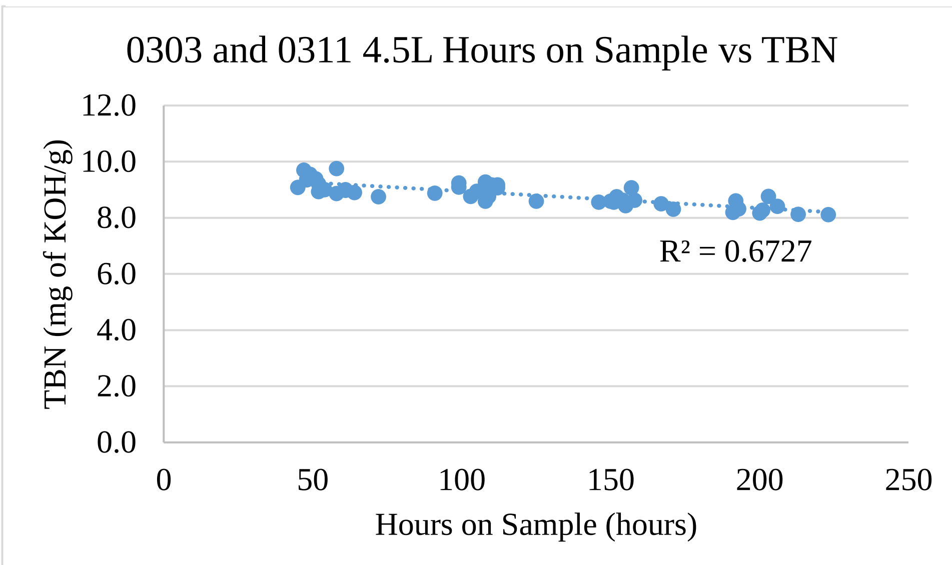

FIGURE 6.9: 0303 and 0311 4.5L Hours on Sample vs TBN

6.10: 0303 and 0311 4.5L Results

The 4.5L engine class for 0303 and 0311 tractors was the only the only class which did not require any trimming of the dataset. It should be noted at this point that for all tractors the only data available for analysis was the hours on sample, as well as the fuel usage. As such, the question for determining model viability is solely between fuel use and the hour meter. In this case the hour meter was the most accurate model with a P-Value of $1.74x10^{-12}$ while the P-Value of fuel usage was $6.14x10^{-12}$.

6.11: 0303 and 0311 4.5L Recommendations

Once the regression began on the tractor equipment classes, the only two variables available became Fuel Usage and Hours on Sample. With just two models to analyze the recommendation for the 4.5L engine is to use the existing hours on sample model. Fuel usage versus TBN showed a p-value of 1.74E-12 and r-squared value of 0.673. While the hours on sample model resulted in a p-value of 6.14E-12 and r-squared value of 0.654. As such, the fuel usage model has greater significance and less error in the model. However, the gain in significance and error is negligible once implementation effort is considered. Fuel usage would be the easiest alternate model to integrate into PM schedules and as such could be considered for use by the NCDOT.

6.12: 0303 6.7L Results

The 6.7L dataset was the smallest tested throughout the study with only 18 total data points and two points removed based on fuel data concerns. It should be noted that due to the small number of data points within this class, there is concern on the models ability to represent the equipment population. Once the regression analysis was performed hours on sample proved to be the more viable model with a P-Value of 0.0019 versus the 0.0023 of fuel usage. Additionally, the r-squared values showed that hours on sample has slightly more error explained by the model with 0.509 versus 0.497. The Tables 6.10 and 6.11 display the output from the regression test.

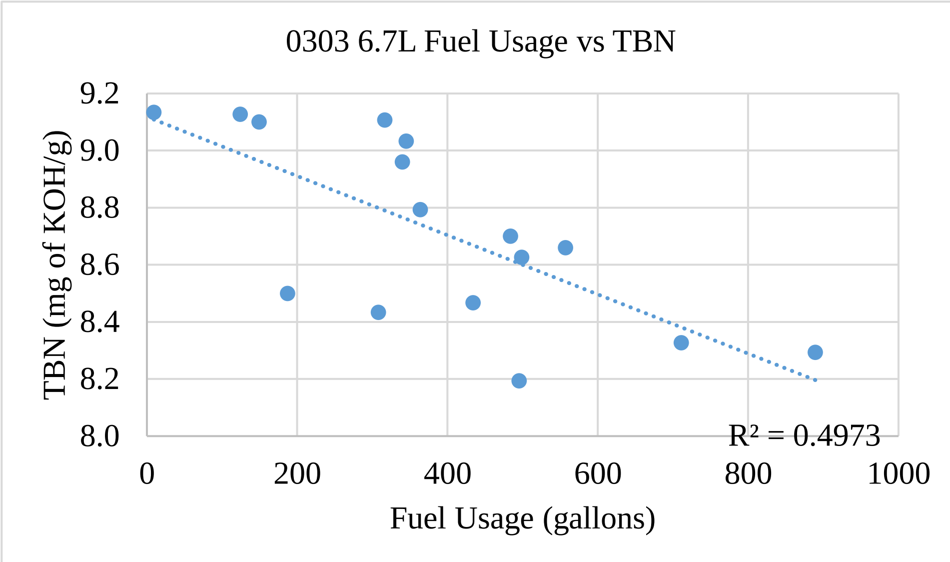

FIGURE 6.10: 0303 6.7L Fuel Usage vs TBN

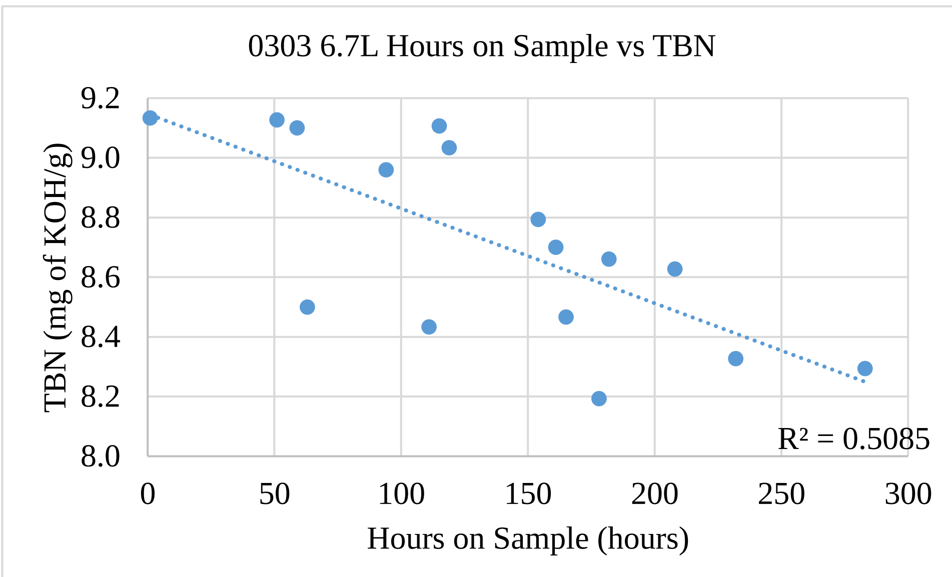

FIGURE 6.11: 0303 6.7L Hours on Sample vs TBN

6.13: 0303 6.7L Recommendations

The recommendation for the 6.7L engine is the hours on sample model. Hours on sample explained slightly more error in the model while also having greater significance. It should be noted that while the model for hours on sample was marginally more viable for use, both models are extremely similar and can both be used. While both models are viable, the hours on sample model is already in use and is the ideal model based on ease of implementation. One point which needs to be addressed is the sample size, the 0303 6.7L dataset consist of only 16 data points. Common practice recommends greater than 30 samples to represent a population, while this data set is half of that amount. As such, the class should be reexamined with a greater number of samples taken to ensure accuracy.

6.14: 0311 6.8L Results

The final data set is the 6.8L 0311 Class, within this class 74 data points were collected and only two were removed due to fuel data. Similar the other tractor class (0303), the only data available is hours on sample and fuel usage. The result of these two variables is that hours on sample has a p-value of 3.65E-12, three orders of magnitude more significant than fuel usage at 4.70E-09. While hours on sample is more significant, fuel usage explains greater error within the model with an r-squared of 0.506 versus 0.394. The results of the regression testing are displayed in Tables 6.12 and 6.13.

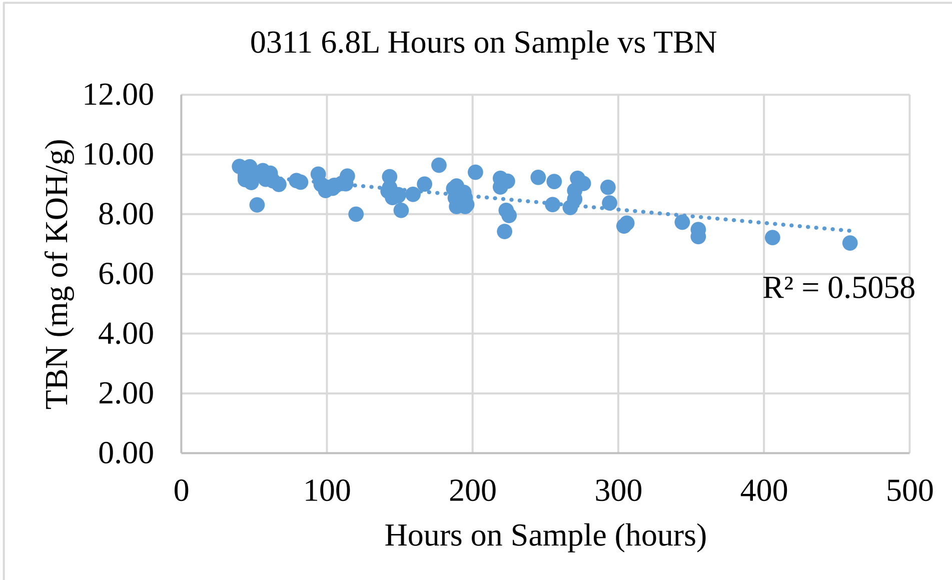

FIGURE 6.12: 0311 6.8L Hours on Sample vs TBN

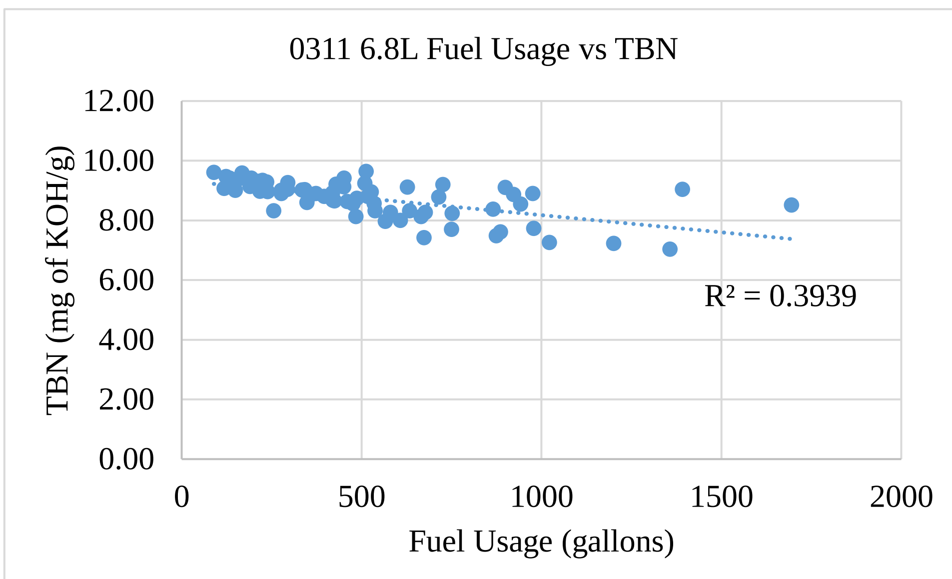

FIGURE 6.13: 0311 6.8L Fuel Usage vs TBN

6.15: 0311 6.8L Recommendations

The 0303 6.8L class consisted of only two models, the hours on sample as well as fuel usage. Both models had a large sample size of 71 which is adequate to represent the population. For the 0311 6.8L class the recommendation is to use the hours on sample model. This model is chosen due to the implementation effort required to switch PM scheduled to a fuel based system. Additionally, the hours on sample is three orders of magnitude higher than fuel usage with only 0.112 more error explained through the r-squared variable. Neither model is significantly greater than another, as such the ideal model is the one which is already in place and in use.

6.16: Implementation Effort

Throughout the recommendations the final factor of model selection was implementation effort. The implementation effort refers to the amount of time and energy which is required to overhaul the current PM system for both recording and implementing oil changes based on new variables. A rough examination of the implementation of fuel usage will be conducted as an example to outline the difficulty and to display the justification of implementation as a deciding factor.

The first step in integrating a new variable to schedule maintenance is the tracking of degradation. With fuel usage as the example, a physical gauge such as a flowmeter would need to be installed in the equipment to provide real time tracking of the variable. After the method of tracking the variable is integrated, PM would then have to be entered into the fleet management software in terms of gallons used instead of miles or hours driven. The next step, and potentially the most difficult, is the overhaul of the training protocols for personal. The current maintenance staff is deeply rooted in the methods of miles and hours based PM and would require a considerable effort to convince otherwise. The final step is that the NCDOT does not schedule PM based on the variable itself but the time estimate of when that variable threshold will be reached. As such, it is more difficult to predict a variable the staff is unfamiliar with. The combined steps create a very difficult task which must be measured against gains in model accuracy.

CHAPTER 7: CONCLUSION

Throughout this study, a number of different were developed and assessed in order to establish the most valuable model of oil degradation. Value was determined by the statistical significance, the r-squared value, and the implementation of the model. Statistical significance was assessed at the 95% confidence level. While r-squared was evaluated for the highest value. Next, the implementation of each model was assessed for the significance gained as well as the reduced error in the model. The gains were then compared to the effort required to introduce a new method of tracking PM as well as place the infrastructure required to model and coordinate PM events.

Through the course of evaluating oil degradation models, a number of viable solutions have been determined. However, a single model must be chosen for each classification. For the 0209 class with the DT466 engine, the miles on sample model was chosen. This decision was due to the fact that while the fuel usage model was more statistically significant than miles on sample, the r-squared value was half that of miles on sample. Therefore, neither model was found to be more valuable in determining oil degradation. As such, the existing miles on sample model should remain in place and the degradation model should be reexamined.

The 0210 class with the 6.4L Powerstroke engine had three possible models as suitable candidates. However, concerns with sample size led to the selection of miles on sample as the most viable model. The models decided against were more significant with considerably higher r-squared values. As such, with more data the fuel usage and run time combined model shows the most potential for implementation. An area for future research would be to re-examine the classes with greater sample size in order to confirm the viability of the combined degradation models.

Similarly, the 0210 6.7L dataset had a number of viable models including a combined model with sample sizes of 26. The miles on sample and idle time combined model proved to be a viable solution to increasing oil degradation models. However, the single variable model of miles on sample was more significant while having an r-squared value of 0.122 less than the combined model. As such, it was decided that the implementation effort required to incorporate the new model would outweigh the reduction in error.

For the tractor classes, 0303 and 0311, fuel usage proved to be a marginally more accurate model for modeling oil degradation. However, as with the previous classes, the effort required to implement a new PM model and schedule outweighs the minor benefits gained from the new models.

In conclusion, this study has shown that alternate models for oil degradation are a viable option for fleet management. However, the advantage gained from alternate models is likely over shadowed by the effort required to implement a new model and set up PM intervals based on the new models. Future research on oil degradation should reexamine alternate models with larger sample sizes in order truly assess the potential of alternate models.

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APPENDIX A: OSA4 PRINTOUT

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

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

FIGURE 8.1: OSA4 Printout

APPENDIX B: EXAMPLE DATA HIERARCHY

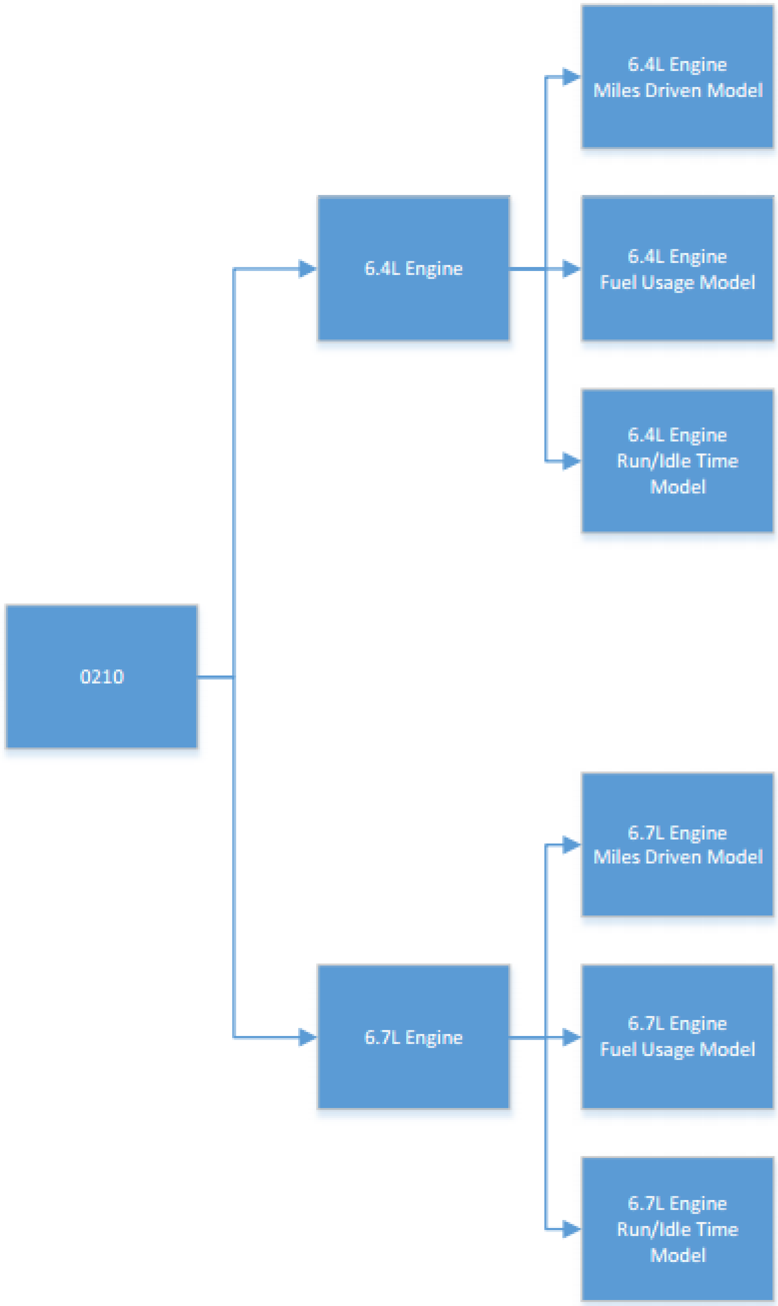

FIGURE 8.2: Example Data Hierarchy