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Modeling the residual useful life of railroad bearing grease

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MODELING THE RESIDUAL USEFUL LIFE OF

RAILROAD BEARING GREASE

A Thesis

by

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ABSTRACT

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Railroad bearing performance is often constrained by the life of its lubricant. The lubricant life is determined by tribomechanical processes that are present during bearing operation. No known physical models exist to predict the railroad bearing lubricant life. This thesis summarizes the efforts undertaken in the development of empirical models that can accurately predict the residual useful life of railroad bearing grease. Modeling techniques to be employed include regression, regression trees, and split plots. The grease samples used to populate this model come from healthy and faulty bearings that were run under different loads, speeds, and ambient conditions in a laboratory setting. Differential Scanning Calorimetry (DSC) values were used as indicators of the residual life of the grease after it has been in operation. This study was successful in developing empirical models which can be utilized to predict the residual life of railroad bearing grease for given operational parameters.

DEDICATION

I dedicate the completion of this thesis to my immediate and extended family, without their love and support I would not be where I am at today. To my mother, thank you for doing everything in your power to encourage me and help me as much as you could throughout all of these years. To my father, thank you for all the conversations and discussions you had with me that would lead me to generating new ideas, you are the smartest man in my life. To my brother, thank you for being the motivation for my success, I encourage you to be more successful than I am today. To my grandparents, thank you for always keeping me in your prayers, and for teaching me to turn to God when things get rough and to always thank him for what He gives me. To Dan, thank you for your words of encouragement and for always being there to put a smile on my face. The support from my family was beyond what I could ever begin to imagine, and for that I am forever grateful.

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I would also like to thank my colleagues. Arthur, thank you for assisting me in the analysis required to complete my research. Oscar, thank you for always being available to answer my questions and for helping me obtain the samples for my experiments.

The impetus for this work and the bearings we took samples from were provided by the Brenco bearing division of Amsted Rail Industries. A very special thanks to the University Transportation Center for Railway Safety which made this research possible through a USDOT Grant No. DTRT13-G-UTC59.

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CHAPTER I

BACKGROUND AND MOTIVATION

1.1 Background

In the United States of America, the freight system consists of 140,000 rail miles which are operated by more than 560 railroads. Together, the railroads share a fleet of approximately 1.5 million rail cars. Class I railroads make up 60 percent of those 140,000 rail miles and alone revenue more than $450 million a year. Train derailments can not only be devastating but also extremely costly [1].

According to data taken over the course of nine years, from 2001 to 2010, bearing failure is ranked number three within the top ten causes of freight train derailments. Table 1.1 shows that bearing failure accounts for 5.9 percent of freight train derailments.

Out of all the causes for bearing failure, over 50 percent of these causes involve the lubrication of the bearing. As shown in Figure 1.1, insufficient lubricant accounts for 15 percent, unsuitable lubricant accounts for 20 percent, and aged lubricant accounts for another 20 percent [2].

Railroad bearings must be properly lubricated during service operation. The function of lubrication is to reduce the contact friction between the bearing raceways and the rolling element that is not truly rolling [3]. Approximately 90 percent of all bearings are lubricated with grease; railroad bearings are among those. Some advantages of using grease as a lubricant over the alternative, oil, are the ease of use, its sealing action to keep debris out, the fact that it will not leak out of the seals like oil easily could, and that it protects against corrosion [4]. Inadequate lubrication can significantly affect the performance of the bearing and can affect the appearance of the components, but most importantly, it can lead to premature bearing failure.

Table 1.1. Top ten accident causes of freight train derailments from 2001-2010 [2]

	Freight Train Derailments	
	Main Line	
Rank	**Cause Group**	**Percentage**
1	Broken rails or welds	15.3
2	Track geometry (excluding wide gauge)	7.3
3	Bearing failure (car)	5.9
4	Broken wheels (car)	5.2
5	Train handling (excluding brakes)	4.6
6	Wide gauge	3.9
7	Obstructions	3.5
8	Buckled track	3.4
9	Track-train interaction	3.4
10	Other axle or journal defects (car)	3.3

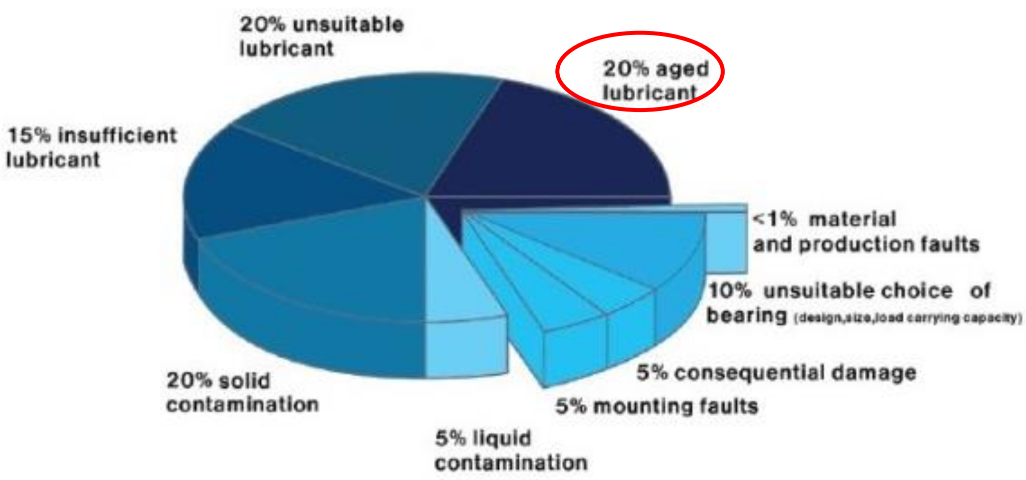

Figure 1.1. Breakdown of common bearing failure modes [5]

The Timken Company provides an outline of the progressive levels of bearing damage caused by inadequate lubrication. The Bearing Damage Analysis guide describes four levels of bearing damage which are pictured in Figures 1.2-1.5. The first level is “Discoloration”. This type of damage is caused by the metal-to-metal contact that occurs due to insufficient lubrication separating the rolling and sliding contacts. The contact produces friction which leads to excessive temperature which begins to discolor and aggravate the metal. Level 2 is described as “Scoring and Peeling” or “Micro-Spalling”. Insufficient or complete lack of lubrication mixed with high loads and elevated temperatures can cause metal to flake away and begin to create pits in the raceways and the rolling elements. The third level is “Excessive Roller End Heat”. Metal-to-metal contact due to inadequate lubrication can lead to localized high temperatures at the larger ends of the rollers. The heat damage on the rollers is not included in Level 1 because the rolling elements are usually made from a more resistant material than the remainder of the bearing components. The final and most critical damage done is Level 4, “Total Bearing Lockup”. The rise in the temperature can become extreme when the lubricant is exhausted. When those extreme temperatures are reached, it can alter the material properties and change the geometry, the rollers will get skewed, the cage will eventually get destroyed and this can ultimately lead to complete bearing seizure [6].

In industry, railcar maintenance is scheduled based on expected operating conditions. The schedules are set up after the railcar has run a predetermined number of miles [7]. That mileage is specified with an appropriate factor of safety, however, the mileage estimate for the railcars is made without proper consideration of the service operating conditions that those miles were run. This crude mileage estimation is a simple way of dealing with maintenance schedules, but unfortunately not all of the service operating conditions are optimal. There are cars that face optimal conditions, but there are also cars that endure harsher environments, and if these factors are not taken into account for maintenance cycles, it might lead to a catastrophic bearing failure if the lubricant is exhausted. In most cases, the serviceability of a bearing is dependent on the lubricant life since the lubricant has a limited life compared to the other bearing components. Therefore, relubricating the bearings is a part of the regular railcar maintenance.

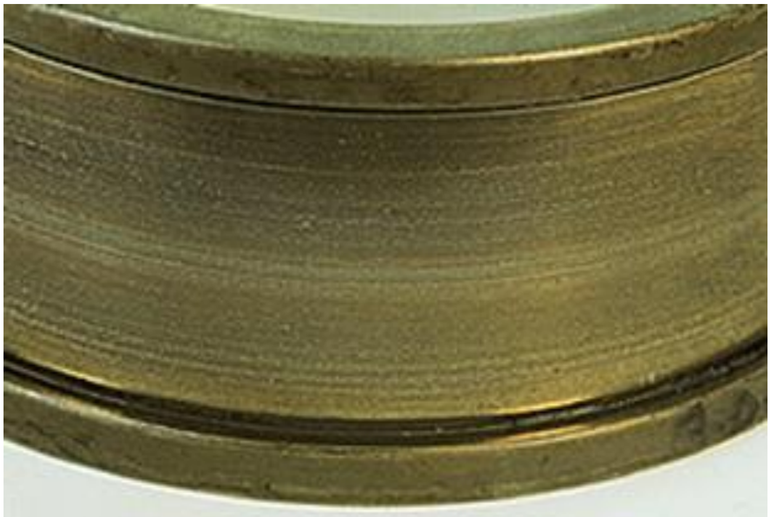

Figure 1.2. Level 1 – Discoloration

Figure 1.3. Level 2 – Scoring and Peeling

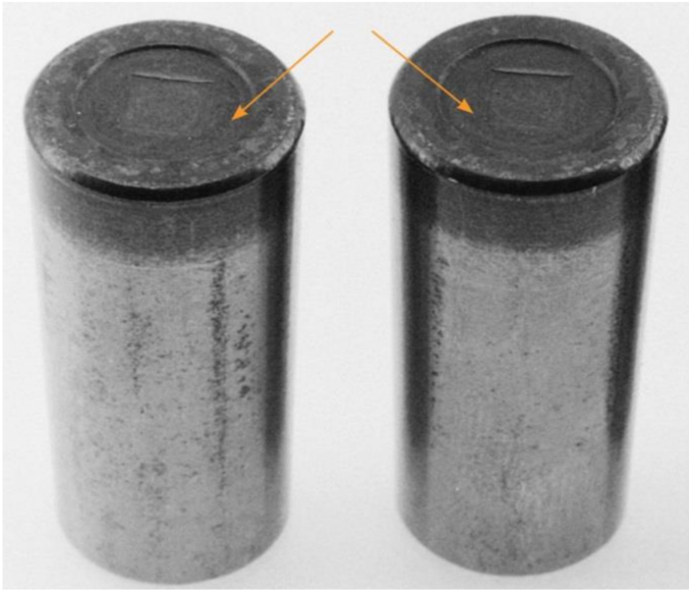

Figure 1.4. Level 3 – Excessive Roller End Heat

Figure 1.5. Level 4 – Total Bearing Lockup

The relubricating interval is generally recommended by the bearing or the grease manufacturer. The bearing manufacturer can recommend a method to assist in making a good estimate for relubrication interval for grease-lubricated bearings which is based on the estimated grease service life. Each of the existing estimates is only valid for the bearing type and the conditions that the manufacturer used to create the method [8]. There are several applied factors that influence grease service life; the effects of these are extremely complex to calculate for any application. It is, therefore, standard practice to use estimated grease service life based on empirical data [9]. No known methods exist for tapered-roller bearings under the conditions experienced in railroad service applications.

1.2 Motivation

Based on the above discussion, the study presented in this thesis is motivated by the need to develop a technique that can reasonably predict the residual life of bearing grease given a specified set of input parameters. The procedure used to gather the bearing grease samples, the variables monitored to devise the grease life estimation method, and the means to determine its residual life are imperative to ensure that an accurate method is developed. This thesis project takes advantage of the availability of a large number of healthy and faulty bearings that were run under varying operating conditions utilizing the dynamic bearing test rigs at the University Transportation Center for Railway Safety (UTCRS) at the University of Texas Rio Grande Valley (UTRGV). The data sets for this study were acquired from ongoing research efforts that focus on bearing life performance characterization.

Grease samples were obtained from strategic locations within the railroad bearings. The dynamic four bearing testers at UTRGV are monitored for temperature, vibration, applied load, and speed. Bearing measurements such as cage lift, cage shake, roller/cage spacing, and mounted and unmounted laterals as well as defective components are tracked carefully as a part of the performed experiments. Each grease sample was logged in a dataset along with the information of its respective experiment. The grease samples were analyzed in a differential scanning calorimeter (DSC) that provided oxidation induction time (OIT) and thermal decomposition (TD) results. The final dataset was populated by the grease bearing experiment variables and the response variables, OIT and TD, for over 200 samples. Modeling techniques that were employed to analyze the data for this thesis included simple linear regression, regression trees, and a complex split plot design.

The following chapters of this thesis outline how a large library of bearings with different operational variables was used to create a database of grease samples. This data was used as a basis to form a split-split plot model design. The response variables for this design, which are indicators of the residual life of the grease, are Oxidation Induction Time (OIT) and Thermal Decomposition (TD), which are indicators of the remaining life of the grease. The values for the OIT and TD are obtained from differential scanning calorimetry (DSC) analysis of the grease samples. Justifications and hypotheses that led to the decisions made within the span of this investigation, the resulting empirical equations for residual grease life, and suggestions for future work that can be done based on the acquired results are presented in the chapters hereafter.

CHAPTER II

EXPERIMENTAL SETUP AND PROCEDURES

2.1 Railroad Bearing Description

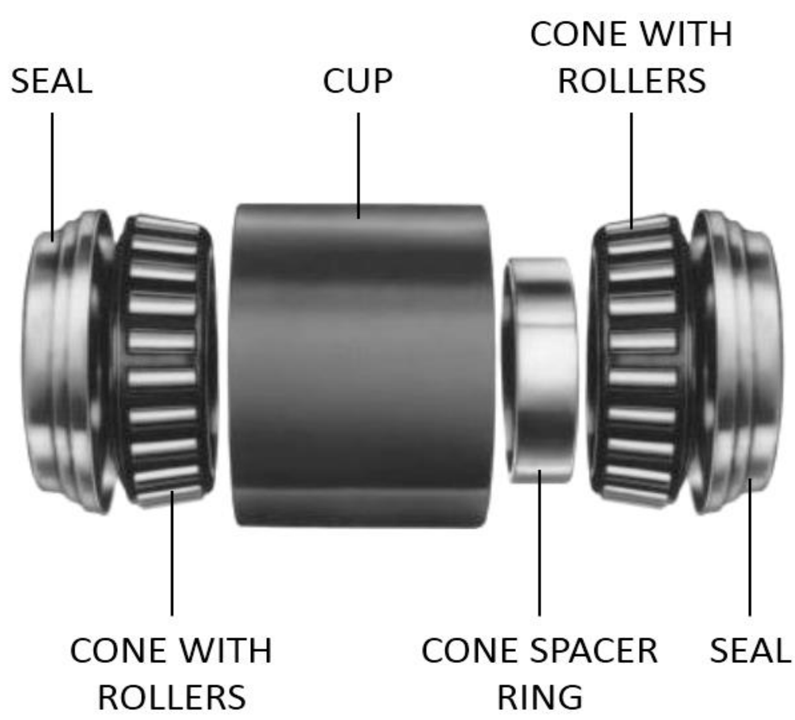

Figure 2.1. Tapered Roller Bearing Components [10]

In order to understand where the lubricant samples were collected from, one must first become familiar with the different components that make up the railroad bearing assembly. The tapered-roller bearings from which the grease samples were collected consist of several components. Figure 2.1 shows an exploded component view of a typical tapered-roller railroad bearing assembly. The bearing is composed of two cone assemblies (inner rings) with tapered rollers held by the roller cages, and separated by a spacer ring. The cup (outer ring) encloses the two cone assemblies and the spacer ring. The bearing components are lubricated with grease following the manufacturer's specified lubrication procedures, and the seals are placed at both ends to prevent lubricant leakage.

The bearings have three main components which influence the life of the lubricant differently. These components are the inboard and outboard cone (inner ring) assemblies and the spacer ring. Figure 2.2 shows a picture of the inner rings of two bearings, one clean (left) and one lubricated (right). Grease is sampled from both the inboard and outboard cone assemblies and from the spacer ring area.

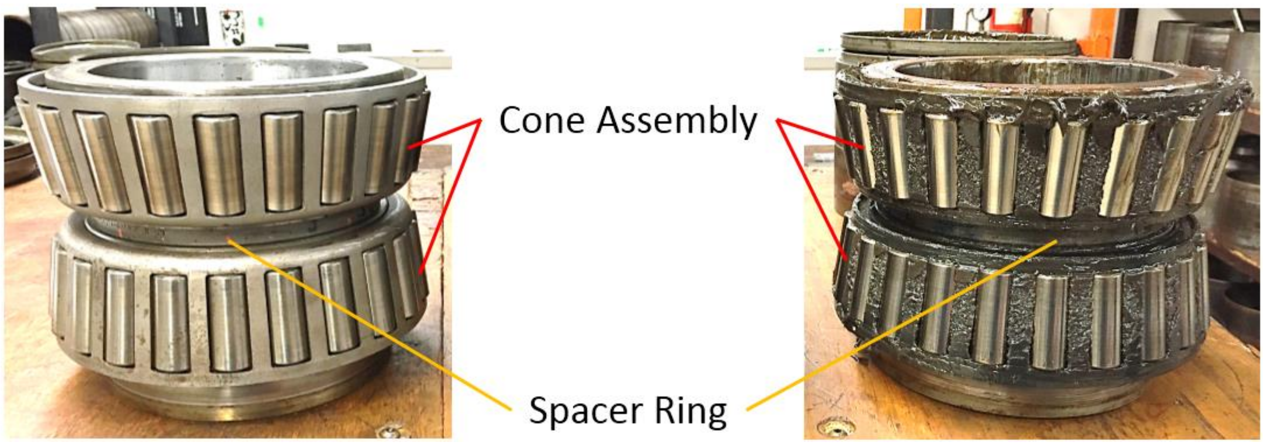

Figure 2.2. Photograph of clean (left) and lubricated (right) bearing components.

When a bearing is in service on a railcar, the cone assemblies are labeled either inboard or outboard depending on their position relative to the adjacent axle wheel; inboard cone assembly is the one which is closest to the adjacent wheel, while the outboard cone assembly is the one closest to the end cap facing outward. This investigation greatly benefits from the availability of a large number of bearings that are tested in the railroad bearing laboratory, under varying operating conditions, as part of several ongoing research projects at the University of Texas Rio Grande Valley (UTRGV) that focus on bearing life performance characterization. The collected grease samples come from bearings that were run utilizing the two dynamic four bearing test rigs located at UTRGV's railroad bearing laboratory. Figure 2.3 is a photograph of one of the two dynamic four-bearing test rigs present in the laboratory.

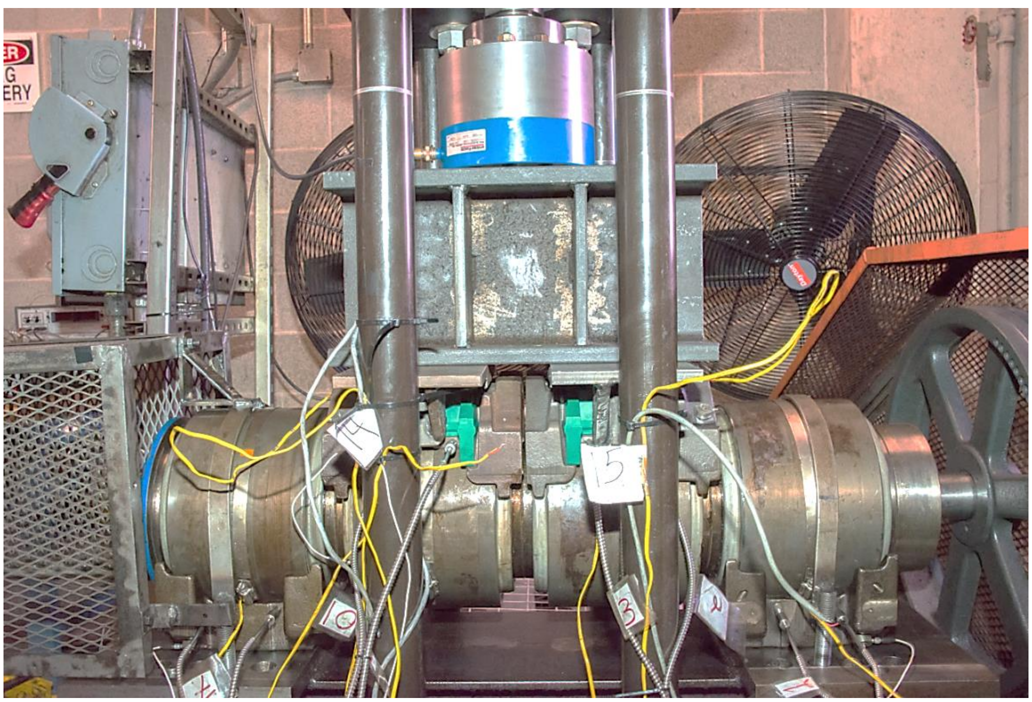

Figure 2.3. Photograph of one of the two dynamic four-bearing test rigs located at the UTRGV railroad bearing laboratory.

In the laboratory, the location of the cone assembly also has to do with the orientation of the bearing on the axle. Four bearings are pressed onto a test axle which is then mounted onto the test rig. There is a drive pulley at one end of the test axle that produces the rotational motion of the axle and an end cap equipped with an odometer to track the operation mileage at the other end of the test axle. Figure 2.4 shows a simplified schematic diagram of the test axle bearing setup. The cone assembly which is facing towards the drive pulley is designated as inboard, and the cone assembly which is facing towards the end cap is designated as outboard. The grease samples for the inboard and outboard raceways are carefully taken from the side of the raceway furthest from the spacer ring and the samples from the spacer ring area are taken from the middle region of the spacer. The four bearings on the test axle setup are numbered sequentially from 1 to 4 based on their location on the test axle relative to the drive pulley and the end cap. Bearing 1 is closest to the drive pulley and Bearing 4 is closest to the end cap, as shown in Figure 2.4.

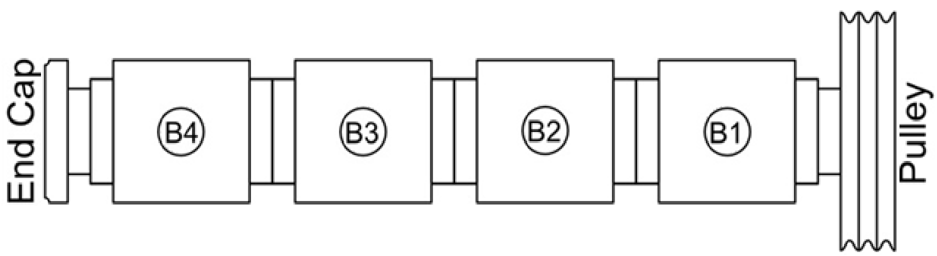

Figure 2.4. Diagram of Bearings on Test Axle

The bearings on the tester in the laboratory are subjected to variable operational characteristics. Healthy and defective (faulty) bearings are tested on the four-bearing test rig. The tester is capable of subjecting the bearings to variable load, speed, and ambient conditions. As a response to these conditions, the operating temperature of the bearings changes and these temperature histories are tracked and recorded by thermocouples that are strategically placed on the bearings, as shown in Figure 2.3. The load and rotational speed along with the bearing operating temperature were continuously recorded throughout all the bearing testing. The mileage at the end of each experiment was properly documented as well.

2.2 Expected Effects of Variables on Grease Life

During bearing operation, the cup (outer ring) is stationary while the axle rotates causing the cones (inner rings), rollers, and spacer ring to rotate. After careful consideration of the physical components of the bearing, it was hypothesized that lubricant contained within the cone assemblies, where the rollers are in constant contact with the raceways, is being subjected to more extreme conditions than the spacer ring grease. Therefore, it is expected that the grease contained within the raceways would experience mechanical shearing and friction caused by the interaction between the surfaces of the rollers and the raceways which, in turn, would contribute to higher temperatures in those areas. On the other hand, because of the limited contact between the spacer ring and the remaining internal components of the bearing, less severe mechanical and thermal conditions are expected for the grease contained within that area. Another factor that is expected to affect the lubricant is oxidation. It is predicted that oxygen diffusion will have a lesser effect on the grease contained within the central location of the bearing, in the spacer ring area, than it would on the grease contained within the cone assemblies and bearing raceways.

While the inboard and outboard raceway grease is subject to tribomechanical and chemomechanical processes, the spacer ring grease only carries with it the results of the thermal history of the bearing. Therefore, less residual life would be expected from the grease samples acquired from the inboard and outboard raceways than that of the spacer ring grease samples.

Whenever possible, grease samples were taken from all four bearings which were run under the same operating conditions on the test rig. It was expected that there would be performance differences between the four bearings and, therefore, bearing location on the test axle was one of the variables in the model. The performance of the bearings within the test axle can vary for one or more of the following factors: (1) because of the axle setup on the test rig, the two middle bearings (B2 and B3) are top-loaded while the outer bearings (B1 and B4) are bottom loaded, (2) even though efforts are made to maintain the same airstream across all four bearings, slight variations will occur due to obstruction of airflow by the hydraulic cylinder support beams (see Figure 2.3), and (3) some of the bearings tested may contain defective components of varying severity, while other bearings are healthy (defect-free).

The four-bearing test rig is capable of applying different loads and speeds to the test axle assembly (i.e., axle with the four mounted bearings). The grease is normally used for the duration of the bearing experiment while the loading conditions and the speed are varied, which results in fluctuations in the operating temperature of the bearings. The various experiments had different test durations based on the type of study performed. The mileage that each bearing ran was carefully tracked and documented throughout the entire test.. It is expected that grease life would be affected by operating mileage. That is, the grease samples which were run for extended periods accumulating higher mileage are expected to have less residual life. Moreover, the grease samples that experienced harsher operating conditions such as higher loads, higher speeds, and higher temperatures are expected to have less residual life.

Some experiments from which grease was sampled were run using a defective bearing along with healthy (defect-free) bearings. Normally, bearings can have defects on the inner ring (cone) raceways, outer ring (cup) raceways, and/or the rollers. For this study, the grease samples collected from defective bearings were taken from bearings with defects on the cup raceways only. The defects were small in size occupying less than 2% of the total area of the cup raceway which is $45in^2$. Research conducted at UTRGV shows that, for bearings containing small outer ring (cup) raceway defects, the average operating temperatures are consistently at or below the average operating temperatures of the healthy bearings run under the same operating conditions.

One possible explanation for this behavior is that the spalls on the cup raceways may favor the formation of pockets of grease which, in turn, enhances the lubrication of the rolling surfaces, and as a result, the operating temperature is slightly lower than that of healthy bearings [11]. This information suggests that the lubricant in bearings containing spalls that occupy less than 2% of the total raceway area are expected to have more residual life than that in healthy bearings run under the same exact service conditions. Even though this hypothesis seems counterintuitive, the lower operating temperature of the defective bearing is expected to slow the degradation of the grease. The data presented in this thesis and the developed bearing grease residual life model support and validate the aforementioned hypothesis.

CHAPTER III

LUBRICANT CHARACTERIZATION

3.1 Lubricant Structure

Lubricating grease is a complex combination of components. The lubricant being tested for this thesis is a lithium/calcium grease which has a temperature range of -10°C to 120°C and a viscosity of 143 centistokes at 40°C. The primary constituents of this and most greases are the lubricating molecules and antioxidants. Degradation of grease is a multifactorial process but is reasonably described by a simple two-stage degradation model which has previously been proposed [12]. In the first stage, carbon radicals form due to thermal or tribomechanical breakdown of lubricating molecules. Antioxidants in the grease inhibit bind to the free-radicals, preventing cascading oxidation of the lubricating molecules. After some time in service, the hydrocarbon radicals in the lubricant consume all the antioxidants and secondary degradation occurs as freed radicals rapidly decompose lubricant molecules leading to the viscosity increase and the formation of sludge and lacquer. Once the secondary degradation begins, the breakdown of the lubricant takes place in a very short time. The induction period of oxidation refers to the time until the secondary degradation begins [13]. When the antioxidants are consumed, the lubricating molecules begin to degrade.

3.2 Differential Scanning Calorimetry

Differential Scanning Calorimetry (DSC) is a technique which measures the difference between the heat flows into a sample and a reference over some controlled temperature range. DSC is an analytical method that can measure the onset of oxidation in grease. When compared to values of new grease, this method can be used to estimate the residual life of the grease [14].

A DSC was employed to test the samples for this investigation. A pressurized DSC has been used in prior studies but, in this study, a standard DSC was employed. Pressurized DSCs permit the use of a high concentration of oxygen in the chamber which accelerates oxidation, speeding up the test for samples that have high levels of antioxidants [14]. A standard DSC will yield the same type of results but takes longer to achieve decomposition of the grease. This improves the sensitivity of the measurement somewhat as differences between samples are more pronounced. Also, bearing operating conditions do not include oxygen at high pressures, so a standard DSC cell is more representative of operating conditions

In the DSC test, grease was sampled from the bearing components and stored in glass vials with air-tight lids to reduce oxygen exposure prior to testing. From the vials, a 2 milligram sample was placed on an aluminum pan to be tested in the DSC. Oxidation induction time tests performed in a DSC are kept at a constant temperature (isothermal) while changing the atmosphere of the sample. The test designed for assessing the grease samples proceeds as follows: First, nitrogen is flushed through the cell at a flow rate of 50 mL/min as the temperature of the sample is increased at a rate of 105°C/min to 210°C. This limits the oxidation of the sample until the test temperature is reached. At the test temperature, gas flow is switched to air, also at a rate of 50 mL/min. l. The consumption of the antioxidants of a used grease sample can take up to 30 minutes, therefore the chamber is kept isothermal with air for 60 minutes.

3.2.1 Oxidation Induction Time

The time taken for the antioxidants to be fully consumed in the DSC cell is known as the Oxidation Induction Time (OIT). OIT is a standard test performed using a DSC to measure the level of oxidation stabilizers in a sample. OIT was used in this investigation as a measure of residual life of the grease. Low OIT values suggest that after bearing operation only a few antioxidants remain in the sample and therefore less life remains in the grease. Residual life and OIT are directly proportional, samples with more residual life will yield higher OIT values and vice versa.

The OIT is determined from a plot of sample heat flow vs time. Figure 3.1 displays the graph for a DSC run performed on a grease sample. The introduction of air into the cell is indicated by the small step at 6.42 minutes. The exotherm which begins at 15.25 minutes indicates the end of the antioxidant consumption and the beginning of the decomposition of the lubricating molecules. The time elapsed between the two points is the OIT, in this case 8.83 minutes.

3.2.2 Thermal Decomposition

As mentioned previously, lubricating grease is composed of two main structures: the lubricating molecules and the antioxidants. The antioxidants in the grease prevent the breakdown of the lubricants. During operation the grease is degraded and the first structure to get broken down are the antioxidants. When the antioxidants are consumed, secondary degradation begins and the lubricating molecules begin to degrade. Thermal decomposition takes place as soon as the antioxidants have all been consumed, this can be seen in the DSC plot of heat flow versus time as the exotherm occurs. In Figure 3.2 decomposition begins at the exotherm at 15.39

minutes, the area under the exotherm is the heat of decomposition, in this case 902.1 J/g. The decomposition energy is essentially the chemical energy of combustion of the remaining hydrocarbon lubricating molecules. The longer those molecules are, the greater the energy released in decomposition.

Decomposition was used in this investigation as an additional measure of residual life of the grease. Decomposition can show that during operation some of the lubricant molecules were degraded and therefore less of the molecules are left to be degraded in the DSC cell. Residual life and decomposition are directly proportional, samples with more residual life will yield higher decomposition values and vice versa.

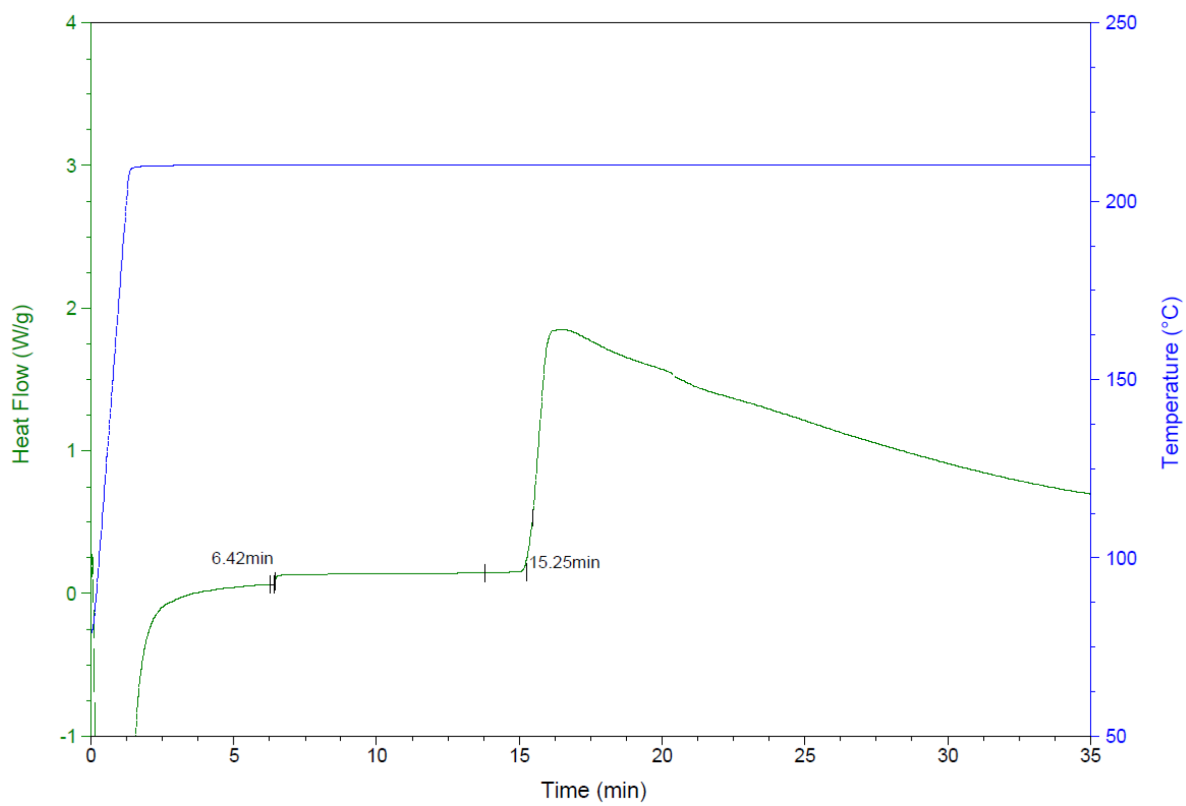

Figure 3.1. OIT in DSC Plot of Heat Flow vs. Time

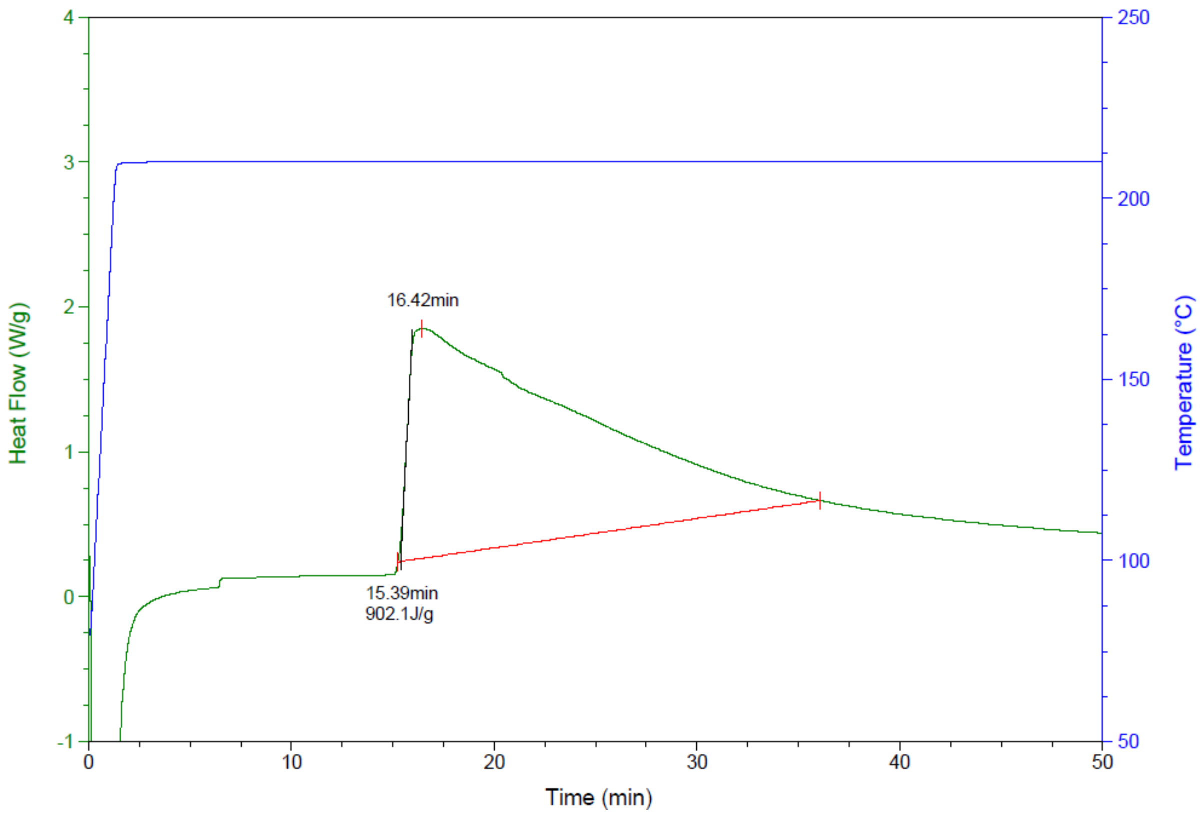

Figure 3.2. Decomposition in DSC Graph of Heat Flow vs. Time

CHAPTER IV

DEVELOPMENT OF LUBRICANT MODEL

4.1 Initial Dataset

Table 4.1. Dataset Variable Nomenclature

Variable	Description	Units
P	Average load experienced by sampled bearing	lb/in^2
s	Average speed experienced by sampled bearing	*mph*
m	Total mileage run by the sampled bearing	*miles*
T	Average temperature experienced by the sampled bearing	*°C*
L_{grease}	Location of grease within the bearing (Inboard raceway / Outboard raceway / Spacer ring)	N/A
$L_{bearing}$	Location of sampled bearing on the axle (B1 / B2 / B3 / B4)	N/A
BC	Sampled bearing condition (defective / defect-free)	N/A
$lat_{mounted}$	Measurement of maximum translation in bearing of one cone assembly with respect to the other	*inches*
$lat_{average}$	Measurement of maximum possible translation on the axle of bearing with respect to bearing	*inches*
m_{loaded}	Mileage that the bearing spent under loaded condition	*miles*
$m_{unloaded}$	Mileage that the bearing spent under unloaded condition	*miles*
OIT	Oxidation induction time	*minutes*
TD	Thermal decomposition energy	*J/g*

To construct an empirical model, a dataset is required that contains all the information needed for the model. The dataset was populated with the operational variables gathered in the laboratory from the dynamic tester. The variables were placed with their respective grease sample and response variable, OIT or TD. The variables used throughout the thesis and their definitions are provided in Table 4.1.

Grease was taken from three areas of each bearing: inboard raceway, outboard raceway, and spacer ring. Therefore, the original dataset contains three values defining the grease location within the bearing, L_{grease}. The value for this column in the dataset could be inboard, outboard, or spacer. Another value in this dataset is $L_{bearing}$, for the bearing location on the tester axle. The values for this column would be 1, 2, 3, or 4, as shown in Figure 2.4, these number are representing the nominal values for the location of the bearing that the grease sample was taken. The average load and average speed for the all four bearings on the axle, and the average temperature for every location in the bearing are recorded for each experiment the grease was used in along with the mileage of that experiment. There were occasions when the bearing was used in more than one experiment therefore the weighted average for load, speed, and temperature, and the total mileage were recorded for the entire time that that grease was in operation. The weighted averages for load, P, speed, s, and temperature T, along with the total mileage, m, for the grease sample were recorded on the initial dataset.

4.2 Preliminary Data Analysis

Several statistical techniques were used in order to analyze the data and better understand the relationships between the operational characteristics and the response variable oxidation induction time (OIT). Only OIT was used to analyze the first set of data, this was done to better understand the first stage of degradation, as mentioned in Chapter 3. The first empirical technique used was simple linear regression of each of the individual variables versus OIT. The second approach was regression trees that take into account all variables simultaneously. The third approach takes the data structure into account and uses a complex split plot design.

4.2.1 Linear Regression

A simple linear regression analysis was conducted to investigate the relationship between the independent factors (*P*, *s*, *m*, and *T*) with the response variable OIT to be able to analyze if the variables affected grease life as it was expected. Figures 4.1-4.4 display the linear regressions to of the four variables along with the line equation and the R-square values.

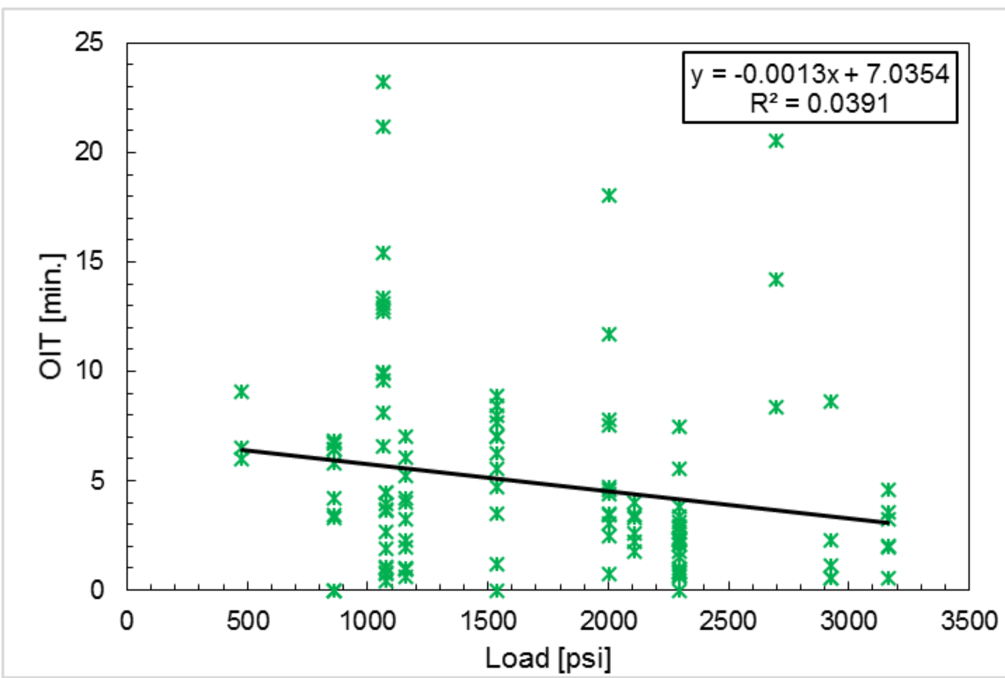

Figure 4.1. Linear Regression of OIT vs. Average Load for 118 samples of the initial dataset.

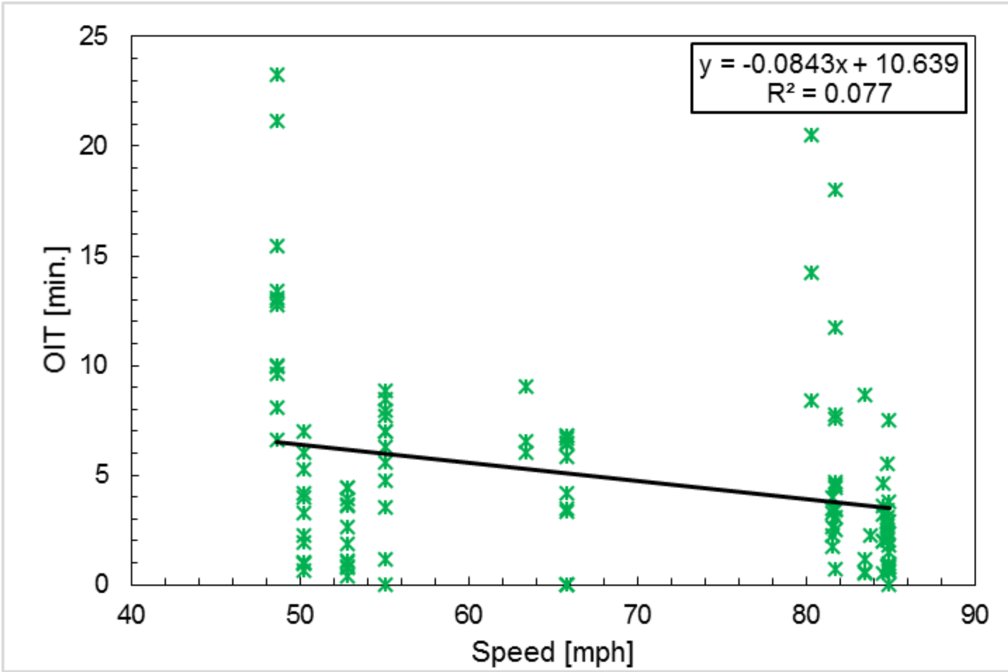

Figure 4.2. Linear Regression of OIT vs. Average Speed for 118 samples of the initial dataset.

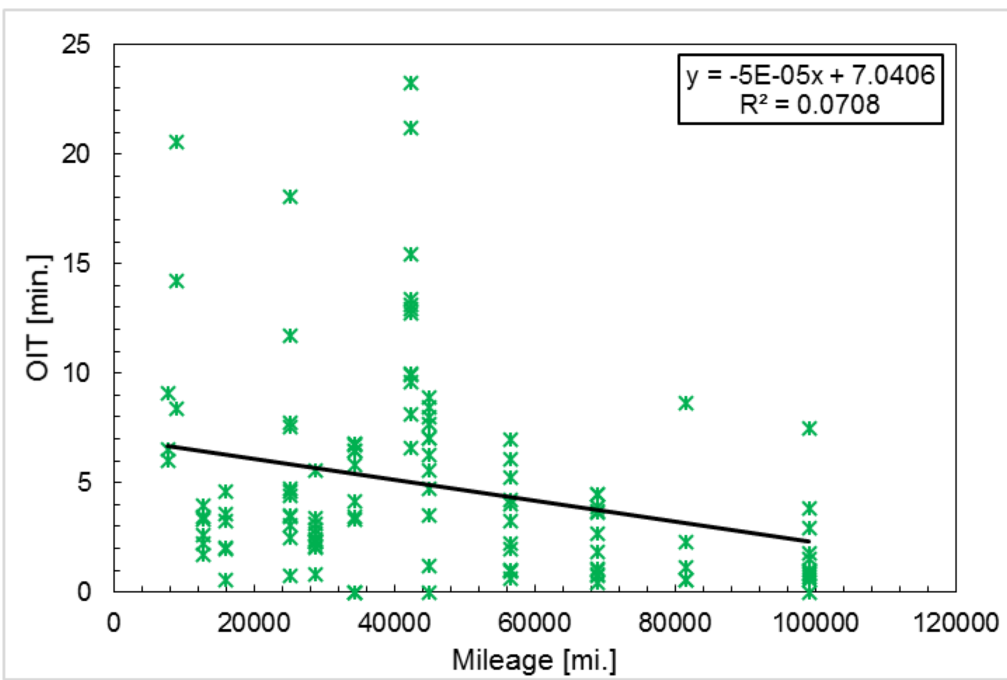

Figure 4.3. Linear Regression of OIT vs. Mileage for 118 samples of the initial dataset.

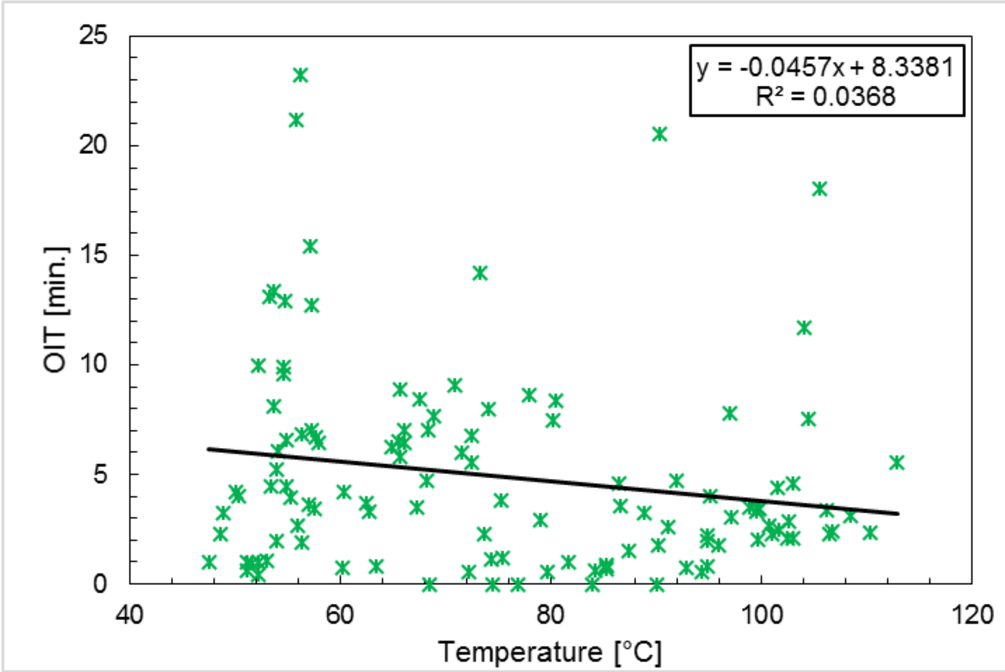

Figure 4.4. Linear Regression of OIT vs. Average Temperature for 118 samples of the initial dataset.

The fitted regression lines have negative relationship with the OIT. This is relationship was expected because higher loads, speeds, temperature, and mileage, will place the bearing at a harsher conditions and this is expected to shorten the length of the remaining life of the grease. Even though the negative relationships that were expected were observed, the small R-square values indicate that the models are not very predictive and alternative models should be investigated.

4.2.2 Regression Trees

Regression trees are a method to create decision trees that identify nodes with similar values of OIT created by binary splits of the independent factors [15]. A regression tree for the grease data is shown in Figure 4.5. JMP software was used to create this regression tree.

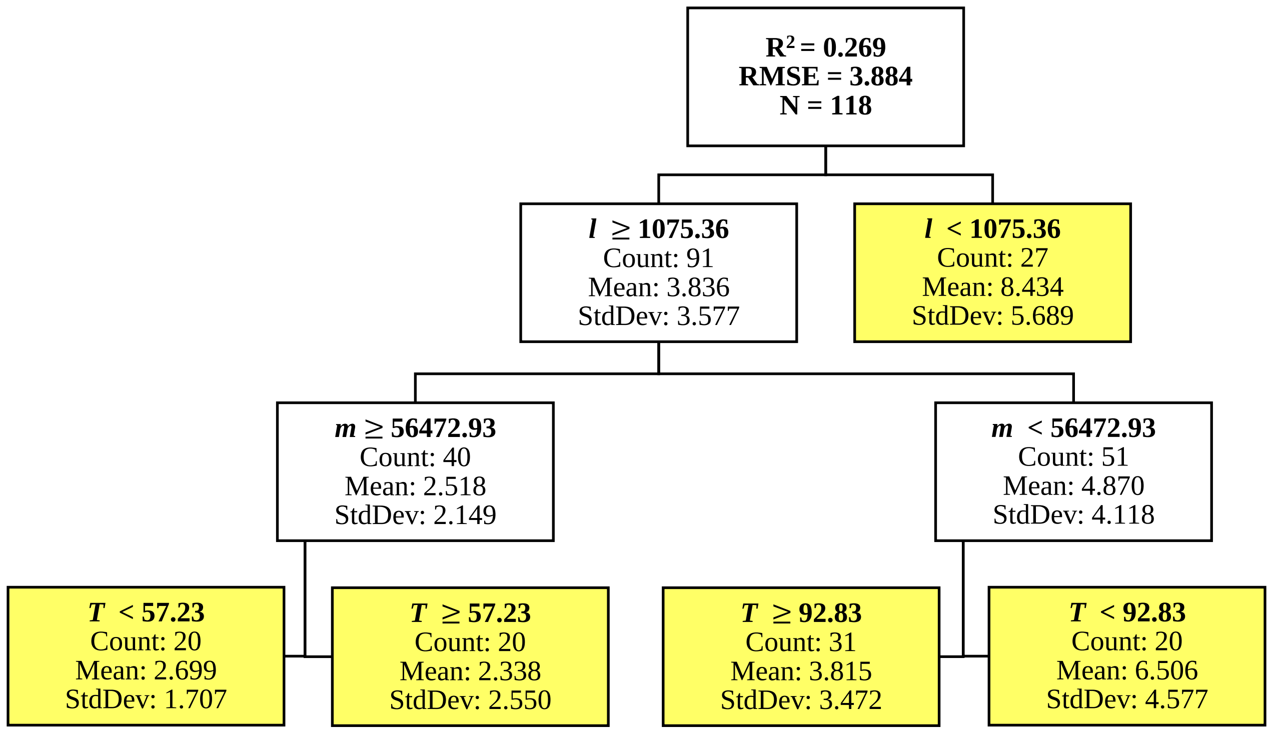

Figure 4.5. Regression Tree

The regression tree displayed in Figure 4.5, contains five nodes, indicated by the yellow highlighted boxes. The first split in this regression tree is based upon load and observations with average loads of less than 1075.36 psi form the first node. The average OIT value for the first node is 8.43. The observations with average load (≥1075.36 psi) are then split by total miles and then average temperature. Thus the factors that seem to determine OIT are load, mileage and temperature. Unfortunately, the value of R-square is 0.269 indicating most of the variability in the dataset is not captured in the model and the model does not do a very good job of capturing the relationship between the operating settings and OIT. Both the R-square values for the linear regressions and the regression trees pointed towards the models not being predictive enough and not doing a proper job of data mining.

4.3 Split Plot Design

Upon examining the method that the data was collected, it was recognized that the data collection was not completely randomized. Montgomery [16] classifies experiments run in this fashion as split-plot designs. In fact, this experiment is a split-split plot design. The whole plot is an axle or setup. There are three whole plot factors: speed, load and mileage. On each axle, there are four bearings. The bearings are the sub plots. There are four possible bearing locations on each axle. The sub-sub plots are the locations within the bearings from which grease is sampled (inner raceway, outer raceway and spacer ring). The temperature measured within each bearing is a sub-sub plot factor. Figure 4.6 shows the structure of the data.

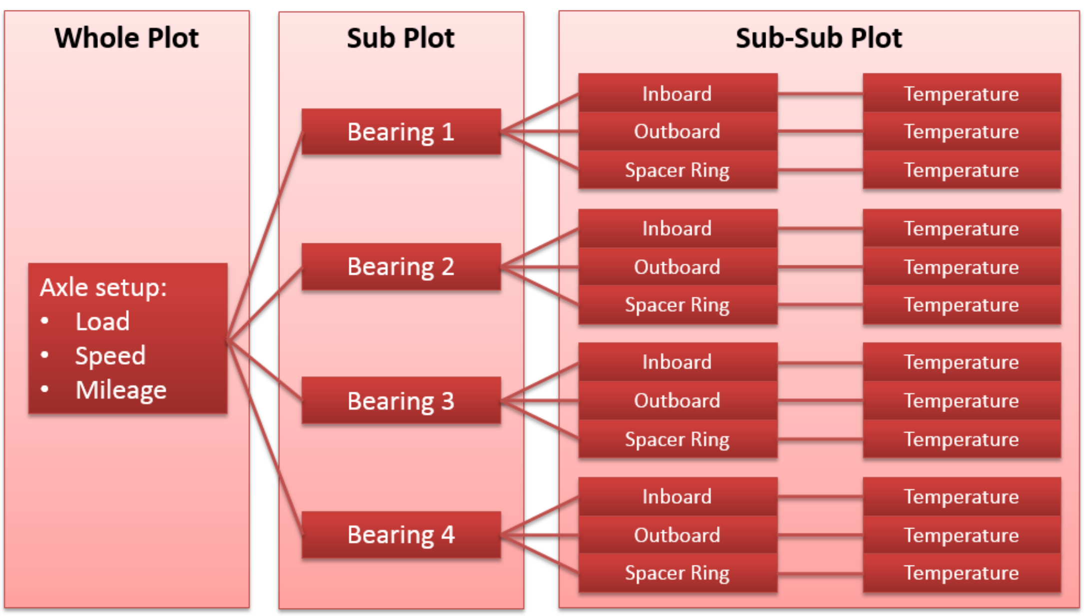

Figure 4.6. Data Structure for Model

A single replicate of the data was collected. That is, there are no repeated observations. Further the data is unbalanced. A complete axle setup should provide twelve observations (the product of four (bearing locations) and three (grease sampling locations) yields twelve observations). However, samples from all four bearing locations were not always collected. Thus, for some of the axle setups, there will be less than the expected twelve observations. Unbalanced data will affect the p-value for the model terms and the distributional results used to calculate probability values is no longer exact but approximate.

4.3.1 Split Plot Dataset

A linear regression model for the split-split plot design will be utilized for this analysis. To incorporate quantative variables such as the bearing location and grease locations, indicator (or dummy) variables must be utilized [17]. The bearing location variable has four possible values and requires three indicator variables. Table 4.2 provides the relationship between the three dummy variables representing the bearing location and the actual bearing location. For the preliminary split plot model, the location of the grease sample has three possible values and requires two indicator variables as shown in Table 4.3. The parameter estimates for the linear regression models were constructed restricted maximum likelihood (REML) technique using Matlab [18].

Additional to the indicator variables for L_{grease}, $L_{bearing}$, and BC (bearing condition), the split-split plot models utilize coded variables for the remainder of the nominal variables. Equations 4.1-4.8 describe the terms that will be used for all the split-split models included in this thesis. Where, P, s, m, T, $lat_{mounted}$, $lat_{average}$, m_{loaded}, $m_{unloaded}$, are the actual data values for the sample which can be gathered from the operating histories: average load experienced by sampled bearing in psi, average speed experienced by sampled bearing in miles per hour, mileage run by sampled bearing in miles, average temperature experienced by sampled bearing in °C, mounted lateral measurement of sampled bearing in inches, average lateral spacing measurement of sampled bearing in inches, miles run by sampled bearing in the loaded condition in miles, and miles run by sampled bearing in the unloaded condition in miles. The maximum and minimum values in the equation refer to the maximum and minimum value of that variable in the whole dataset that was used for that specific model.

Table 4.2. Indicator Variables for Bearing Location

$L_{bearing}$	x_4	x_5	x_6
1	0	0	0
2	1	0	0
3	0	1	0
4	0	0	1

Table 4.3. Indicator Variables for Grease Location

L_{grease}	x_7	x_8
Inboard	0	0
Outboard	1	0
Spacer	0	1

$$P' = \frac{P - \left(\frac{P_{max} + P_{min}}{2}\right)}{\frac{P_{max} - P_{min}}{2}} \tag{4.1}$$

$$s' = \frac{s - \left(\frac{s_{max} + s_{min}}{2}\right)}{\frac{s_{max} - s_{min}}{2}} \tag{4.2}$$

$$m' = \frac{m - \left(\frac{m_{max} + m_{min}}{2}\right)}{\frac{m_{max} - m_{min}}{2}} \tag{4.3}$$

$$T' = \frac{T - \left(\frac{T_{max} + T_{min}}{2}\right)}{\frac{T_{max} - T_{min}}{2}} \tag{4.4}$$

$$lat_{mounted}' = \frac{lat_{mounted} - \left(\frac{lat_{mounted_{max}} + lat_{mounted_{min}}}{2}\right)}{\frac{lat_{mounted_{max}} - lat_{mounted_{min}}}{2}} \tag{4.5}$$

$$lat_{average}' = \frac{lat_{average} - \left(\frac{lat_{average_{max}} + lat_{average_{min}}}{2}\right)}{\frac{lat_{average_{max}} - lat_{average_{min}}}{2}} \tag{4.6}$$

$$m_{loaded}' = \frac{m_{loaded} - \left(\frac{m_{loaded_{max}} + m_{loaded_{min}}}{2}\right)}{\frac{m_{loaded_{max}} - m_{loaded_{min}}}{2}} \tag{4.7}$$

$$m_{unloaded}' = \frac{m_{unloaded} - \left(\frac{m_{unloaded_{max}} + m_{unloaded_{min}}}{2}\right)}{\frac{m_{unloaded_{max}} - m_{unloaded_{min}}}{2}} \tag{4.8}$$

4.3.2 Preliminary OIT Split-Split Plot Model

The preliminary model data consists of 118 samples. The dataset contains 6 variables for each of the 118 samples, average load experienced by the sample, total mileage run by the sample, average speed experienced by the sample, grease sample bearing location on axle, grease sample location within the bearing (where 1 is inboard raceway, 2 is outboard raceway, and 3 is spacer ring), and average temperature experienced by the sample, along with a response variable

Oxidation Induction Time (OIT). A statistical summary for the 118 data point variables is shown in Table 4.4.

Table 4.4. Statistical Summary for Preliminary Model Data

	Minimum	**Maximum**	**Mode**	**Average**	**Standard Deviation**
Average Load [psi]	476.2	3162	1537.9	1702.7	715.2
Average Speed [mph]	48.7	84.9	55.1	68.2	15
Average Temperature [°C]	47.5	112.9	72.4	75.4	19.1
Total Miles	7709	99082.9	45006.2	45196.6	25486.5
Bearing Location	1	4	4	2.5	1.1
Grease Location	1	3	2	2	0.8
OIT [min]	0	23.26	0	4.89	4.56

The initial model contains 16 terms, load, speed, mileage, bearing location (x_4, x_5, x_6), grease location (x_7, x_8), temperature, and two factor interactions between load, mileage and speed and two factor interactions between temperature, load, mileage, and speed.

The terms that are statistically significant, according to the p-value threshold of $p < 0.1$ from Preliminary Model 1 are mileage, mileage × speed, x_4, x_7, temperature and the mileage × temperature interaction. All other terms do not appear to be statistically significant.

Preliminary Model 2 was fitted containing only the terms found statistically significant ($p < 0.05$) from Preliminary Model 1. In the second model, the terms speed and the mileage × speed interaction are not statistically significant and can be removed from the model.

The statistically significant terms ($p < 0.05$) from Preliminary Model 2 were used to create the Preliminary Model 3. In this model, the mileage × temperature interaction is not statistically significant and can be removed from the model.

The Final Preliminary Model was obtained by removing the mileage × temperature interaction and fitting a model to the remaining terms. The terms and p-values with the p-value threshold for Preliminary Models 1 through 4 are given in Table 4.5.

Table 4.5. Preliminary Model p-values

Term		P-value Thresholds			
		p < 0.1	p < 0.05	p < 0.05	p < 0.1
		Model 1	**Model 2**	**Model 3**	**Model 4**
P'		0.84			
m'		**0.02**	**0.03**	**0.04**	**0.05**
s'		0.72	0.39		
$P' \times m'$		0.26			
$P' \times s'$		0.54			
$m' \times s'$		**0.07**	0.15		
$L_{bearing}'$	x_4	**0.01**	**0.02**	**0.02**	**0.03**
	x_5	0.53			
	x_6	0.11			
L_{grease}'	x_7	**0.00**	**0.00**	**0.00**	**0.00**
	x_8	0.53			
T'		**0.01**	**0.01**	**0.01**	**0.02**
$P' \times T'$		0.45			
$m' \times T'$		**0.04**	**0.01**	0.24	
$s' \times T'$		0.50			

The final model contains five terms and utilizes coded variables for the mileage and temperature variables. The equation for the predicted value of OIT is Equation 4.9. Where the coefficients *m'* and *T'* are Equations 4.3 and 4.4 respectively.

$$\widehat{OIT} = 2.3872 - 3.8116m' + 1.7551x_4 + 2.7443x_7 - 3.388T' \quad (4.9)$$

In this preliminary equation x_4 is 1 if bearing location is 2 and 0 for other bearing locations, and x_7 is 1 if the grease sampling location is the spacer ring and 0 for either the inner or outer raceway. The coefficient for mileage contains a negative value that indicates the OIT value decreases as mileage increases. This relationship seems valid based upon our understanding of how grease degrades as a function of usage. The second term in the model for the variable x_4 indicates that the model predicts higher values of OIT for bearings in location 2 than the other three bearings. This relationship was not understood and required more research. The coefficient for the term x_7 is positive and suggests that grease in the spacer ring will have larger values of OIT than grease sample from the inner or outer raceways. This relationship is consistent with our understanding of the physical model. The coefficient for the temperature term in the model is negative. This indicates that as the temperature increases, the OIT decreases. This relationship is consistent with our understanding of the physical system.

4.3.3 Additional Variables for Model Improvement

The preliminary data analysis helped in the understanding of the behavior of the variables. Load, speed, temperature, mileage, bearing location, and grease location were the original variables that were being investigated for their relationship with Oxidation Induction Time (OIT). Additional variables were considered as an attempt to improve the dataset.

Prior to testing, the bearings are checked twice for lateral measurements, once before the bearings are pressed onto the axle and again once all four bearings are mounted on the axle. The values of lateral and mounted lateral are known for all bearings on the dataset; therefore, a column for lateral, $lat_{average}$, and a column for mounted lateral, $lat_{mounted}$, were also added to the dataset.

For the experiments run on the tester rig, there were defective and healthy bearings. Table 4.6 shows the indicator variables for bearing condition, when the bearing is healthy the value will be 0, when the bearing is defective, meaning it has a defect of size that is less than 2% of the total area of the raceway, the values will be 1. Grease samples in the dataset were taken from several of these defective bearings; therefore, an additional column was added to the dataset for this variable.

Table 4.6. Indicator Variables for Bearing Condition

	BC
Healthy	0
Defective	1

The split-split plot analysis gave the preliminary equation in which all but one coefficient made sense with the physical model. The equation suggested that grease contained in bearing location 2 would have more residual life than the other three bearings, this response was not expected and further analysis of the physical model had to be done. Adding the new variable of the presence of a spall in the bearing, uncovered the answer. For the experiments where a defect was present in one of the four bearings the defective bearing was usually placed on bearing location 2. This could possibly explain why bearing location 2 would give higher OIT values in the preliminary split-split plot equation.

The preliminary equation also suggests that grease in the spacer ring will have larger values of OIT than grease sampled from the inner or outer raceways. In the data there was not a large discrepancy between the OIT values for the inboard and outboard raceways than between the values of spacer ring grease and the raceways. For this reason, instead of comparing the three areas to each other (inboard raceway vs. outboard raceway vs. spacer) the new dataset would only compare spacer ring grease to raceway grease. For the new model, the location of the grease sample has two possible values which require an indicator variable, shown in Table 4.7.

Table 4.7. New Indicator Variables for Grease Location

L_{grease}	
Raceway	0
Spacer	1

4.3.4 Second OIT Split-Split Plot Model

The second model data consists of 161 samples. The dataset contains 9 variables for each of the 118 samples, average load experienced by the sample, total mileage run by the sample, average speed experienced by the sample, bearing mounted lateral measurement, bearing average lateral spacing, bearing condition (where 1 means the bearing contains a small defect as described in Chapter 2 and 0 means the bearing is healthy), grease sample bearing location on axle, grease sample location within the bearing (where 1 is inboard raceway, 2 is outboard raceway, and 3 is spacer ring), and average temperature experienced by the sample, along with a response variable Oxidation Induction Time (OIT). A statistical summary for the 161 data point variables is shown in Table 4.8.

The second model contains 17 terms, load, speed, mileage, bearing location (x_4, x_5, x_6), mounted lateral, lateral spacing, bearing condition, grease location, temperature, and two factor interactions between load, mileage and speed and two factor interactions between temperature, load, mileage, and speed.

Table 4.8. Statistical Summary for Second Model Data

	Minimum	Maximum	Mode	Average	Standard Deviation
Avg. Load [psi]	476.2	3162	1538.4	1638.4	581.9
Total Miles	4452.9	99032.7	44983.3	37224.6	25201
Avg. Speed [mph]	47.6	85.7	55.1	69.6	15.6
Avg. Temperature [°C]	47.5	113.3	N/A	78	18.6
Mounted Lat. [inches]	0	0.012	0	0.005	0.004
Lateral Spacing Avg. [inches]	0.02	0.027	0.024	0.024	0.001
Bearing Condition	0	1	0	0.15	0.36
Bearing Location	1	4	3	2.6	1.1
Grease Location	1	3	3	2	0.8
OIT [min]	0	23.7	0	5.3	4.3

The terms that are statistically significant according to the p-value threshold from the Second Model 1 are load, mileage, speed, x_4, lateral spacing, bearing condition, grease location, temperature, and the mileage × temperature interaction. All other terms do not appear to be statistically significant.

Table 4.9. Second Model p-values

Term	p-value thresholds				
	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
P'	**0.03**	**0.04**	0.21		
m'	**0.01**	**0.00**	**0.01**	**0.02**	**0.02**
s'	**0.05**	0.07			
$P' \times m'$	0.06				
$P' \times s'$	0.06				
$m' \times s'$	0.07				
x_4	**0.03**	**0.02**	0.15		
$L_{bearing}'$ x_5	0.07				
x_6	0.06				
$Lat_{mounted}'$	0.08				
$Lat_{average}'$	**0.04**	0.06			
BC'	**0.00**	**0.00**	**0.04**	**0.01**	**0.01**
L_{grease}'	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
T'	**0.00**	**0.00**	**0.00**	**0.01**	**0.03**
$P' \times T'$	0.09				
$m' \times T'$	**0.00**	**0.01**	**0.05**	0.17	
$s' \times T'$	0.07				

Model 2 was fitted containing only the terms found statistically significant from Model 1. In this model, the terms speed and lateral spacing are not statistically significant and can be removed from the model.

The statistically significant terms from Model 2 were used to create Model 3. In this model, load and x_4 are not statistically significant and can be removed from the model.

Model 4 was fitted containing only the terms found statistically significant from Model 3. In this model, the term for the mileage × temperature interaction is not statistically significant and can be removed from the model to fit the Final Model for the second set of models. The terms and p-values with the p-value threshold for the Second Models 1 through 5 are given in Table 4.9.

The final model contains four terms and utilizes coded variables for the mileage and temperature variables. The equation for the predicted value of OIT is Equation 4.10. Where the coefficients *m'* and *T'* are Equations 4.3 and 4.4 respectively.

$$\widehat{OIT} = 2.5637 - 3.6829m' + 2.2569BC + 2.6208L_{grease} - 2.6066T' \qquad (4.10)$$

In this equation *BC* is 0 if the bearing sampled from is a healthy bearing and 1 if the bearing sampled contains a defect as described earlier. L_{grease} is 1 if the grease sampling location is the spacer ring and 0 a raceway. The coefficient for mileage contains a negative value that indicates the OIT value decreases as mileage increases. This relationship seems valid based upon our understanding of how grease degrades as a function of usage. The second term in the model for the variable BC indicates that the model predicts higher values of OIT for bearing conditions with small defects. This relationship makes sense with the predicted behavior based on the research that was described in Chapter 2. The coefficient for the term L_{grease} is positive and suggests that grease in the spacer ring will have larger values of OIT than grease sample from the raceways. This relationship is consistent with our understanding of the physical model. The coefficient for the temperature term in the model is negative. This indicates that as the temperature increases, the OIT decreases. This relationship is consistent with our understanding of the physical system.

4.4 Tertiary Model

4.4.1 Load Condition

For the first few models, the load variable referred to the average load experienced by the bearing over the length of the experiment. An average of the load experienced even as a weighted average, represents no real significance in industry. In industry and even at the University Transportation Center for Railway Safety laboratory, the only load condition that is monitored is whether the car was loaded or unloaded. Therefore, the load variable was changed for the new dataset. The new load variable is m_{loaded}, referring to the amount of miles the sampled bearing spent at a loaded condition. In the loaded condition, the tester is simulating a fully loaded car this corresponds to a load of 34,400 lb per bearing (Per AAR standards for Class F and K railroad Bearings).

4.4.2 Tertiary OIT Split-Split Plot Model

The Tertiary OIT model data consists of 206 samples. The dataset contains 9 variables for each of the 206 samples, the number of miles at loaded run for the sample, total mileage run for the sample, average speed experienced by the sample, bearing mounted lateral measurement, bearing average lateral spacing, bearing condition (where 1 means the bearing contains a small defect as described in Chapter 2 and 0 means the bearing is healthy), grease sample bearing location on axle, grease sample location within the bearing (where 1 is inboard raceway, 2 is outboard raceway, and 3 is spacer ring), and average temperature experienced by the sample, along with a response variable Oxidation Induction Time (OIT). A statistical summary for the 206 data point variables is shown in Table 4.10.

The initial model contains 17 terms, loaded miles, speed, mileage, bearing location (x_4, x_5, x_6), mounted lateral, lateral spacing, bearing condition, grease location, temperature, and two factor interactions between loaded miles, mileage and speed and two factor interactions between temperature, loaded miles, mileage, and speed.

The terms that are statistically significant according to the p-value threshold from Model 1 are loaded miles, mileage, speed, mileage × speed, x_4, x_5, mounted lateral, bearing condition, grease location, temperature, and the loaded miles × temperature interaction. All other terms do not appear to be statistically significant.

Table 4.10. Statistical Summary for Tertiary OIT Model Data

	Minimum	**Maximum**	**Mode**	**Average**	**Standard Deviation**
Miles at Loaded	3137.5	99032.7	39983.3	32138.2	23612.7
Total Miles	19173.3	99032.7	84983.3	48892.4	21117.9
Avg. Speed [mph]	47.6	85.7	55.1	68	15.6
Bearing Location	1	4	3	2.52	1.08
Mounted Lat. [inches]	0	0.012	0	0.0046	0.0036
Lateral Spacing Avg. [inches]	0.02	0.027	0.024	0.024	0.0014
Bearing Condition	0	1	0	0.23	0.42
Grease Location	1	3	3	2	0.8
Avg. Temperature [°C]	40.8	113.3	N/A	74.8	18.2
OIT [min]	0	26	0	7	5.6

Model 2 was fitted containing only the terms found statistically significant from Model 1. In this model, the terms mileage × speed, x_4, mounted lateral and the loaded miles × temperature interaction are not statistically significant and can be removed from the model.

The statistically significant terms from Model 2 were used to create Model 3. In this model, the term for speed is not statistically significant and can be removed from the model.

Model 4 was fitted containing only the terms found statistically significant from Model 3. In this model, the term x_5 is not statistically significant and can be removed from the model to fit the Tertiary Model. The terms and p-values with the p-value threshold for the Tertiary OIT Models 1 through 5 are given in Table 4.11.

Table 4.11. Tertiary OIT Model p-values

Term	p-value thresholds				
	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
m_{loaded}'	**0.01**	**0.01**	**0.01**	**0.02**	**0.05**
m'	**0.04**	**0.01**	**0.03**	**0.02**	**0.05**
s'	**0.01**	**0.02**	0.05		
$m_{loaded}' \times m'$	0.09				
$m_{loaded}' \times s'$	0.07				
$m' \times s'$	**0.05**	0.09			
x_4	**0.05**	0.07			
$L_{bearing}'$ x_5	**0.02**	**0.02**	**0.03**	0.06	
x_6	0.09				
$Lat_{mounted}'$	**0.05**	0.07			
$Lat_{average}'$	0.09				
BC'	**0.01**	**0.01**	**0.01**	**0.01**	**0.04**
L_{grease}'	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
T'	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
$m_{loaded}' \times T'$	**0.04**	0.06			
$m' \times T'$	0.07				
$s' \times T'$	0.08				

This model equation contains five terms and utilizes coded variables for the loaded miles, mileage, and temperature variables. The equation for the predicted value of OIT is Equation 4.11. Where the coefficients m', T', and m_{loaded} are Equations 4.3, 4.4, and 4.7 respectively.

$$\widehat{OIT} = 3.0353 - 3.7074m'_{loaded} - 1.4175m' + 1.8871BC + 3.7745L_{grease} - 4.7629T' \quad (4.11)$$

In this equation *BC* is 0 if the bearing sampled from is a healthy bearing and 1 if the bearing sampled contains a defect as described earlier. L_{grease} is 1 if the grease sampling location is the spacer ring and 0 a raceway. The coefficient for mileage contains a negative value that indicates the OIT value decreases as mileage increases. This relationship seems valid based upon our understanding of how grease degrades as a function of usage. The second term in the model for the variable BC indicates that the model predicts higher values of OIT for bearing conditions with small defects. This relationship makes sense with the predicted behavior based on the research that was described in Chapter 2. The coefficient for the term L_{grease} is positive and suggests that grease in the spacer ring will have larger values of OIT than grease sample from the raceways. This relationship is consistent with our understanding of the physical model. In the model the coefficient for the temperature and for the loaded mile terms are negative. This indicates that as the temperature increases and as the load increases, the OIT decreases. These relationships are consistent with our understanding of the physical system.

4.4.3 Thermal Decomposition Split-Split Plot Analysis

In order to understand the second stage of degradation in which the grease molecules begin to decompose, a thermal decomposition model was built. The data for this model consists of 206 samples. The dataset contains 9 variables for each of the 206 samples, the number of miles at loaded run for the sample, total mileage run for the sample, average speed experienced by the sample, bearing mounted lateral measurement, bearing average lateral spacing, bearing condition (where 1 means the bearing contains a small defect as described in Chapter 2 and 0 means the bearing is healthy), grease sample bearing location on axle, grease sample location within the bearing (where 1 is inboard raceway, 2 is outboard raceway, and 3 is spacer ring), and average temperature experienced by the sample, along with a response variable Thermal Decomposition (TD). A statistical summary for the 206 data point variables is shown in Table 4.12.

Table 4.12. Statistical Summary for TD Model Data

	Minimum	**Maximum**	**Mode**	**Average**	**Standard Deviation**
Miles at Loaded	3137.5	99032.7	39983.3	32138.2	23612.7
Total Miles	19173.3	99032.7	84983.3	48892.4	21117.9
Avg. Speed [mph]	47.6	85.7	55.1	68	15.6
Bearing Location	1	4	3	2.52	1.08
Mounted Lat. [inches]	0	0.012	0	0.0046	0.0036
Lateral Spacing Avg. [inches]	0.02	0.027	0.024	0.024	0.0014
Bearing Condition	0	1	0	0.23	0.42
Grease Location	1	3	3	2	0.8
Avg. Temperature [°C]	40.8	113.3	N/A	74.8	18.2
TD [J/g]	152.3	1397.7	1225.5	856.3	320

A model with the 206 samples was built for the response variable of Thermal Decomposition (TD). The model contains 17 terms for loaded miles, speed, mileage, bearing location (x_4, x_5, x_6), mounted lateral, lateral spacing, bearing condition, grease location, temperature, and two factor interactions between loaded miles, mileage and speed and two factor interactions between temperature, loaded miles, mileage, and speed.

Table 4.13. TD Model p-values

Term		p-value thresholds			
		$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
		Model 1	Model 2	Model 3	Model 4
m_{loaded}'		**0.00**	**0.00**	**0.00**	**0.00**
m'		0.10			
s'		**0.01**	**0.02**	0.23	
$m_{loaded}' \times m'$		0.06			
$m_{loaded}' \times s'$		**0.02**	0.06		
$m' \times s'$		0.06			
	x_4	0.06			
$L_{bearing}'$	x_5	**0.03**	**0.02**	0.17	
	x_6	0.10			
$Lat_{mounted}'$		**0.05**	0.06		
$Lat_{average}'$		**0.05**	0.06		
BC'		**0.04**	**0.01**	**0.05**	**0.05**
L_{grease}'		**0.00**	**0.00**	**0.00**	**0.00**
T'		**0.00**	**0.00**	**0.02**	**0.00**
$m_{loaded}' \times T'$		**0.02**	**0.02**	0.83	
$m' \times T'$		0.07			
$s' \times T'$		**0.02**	**0.01**	0.17	

The terms that are statistically significant according to the p-value threshold from Model 1 are loaded miles, speed, loaded miles × speed, x_5, mounted lateral, lateral spacing, bearing condition, grease location, temperature, and the loaded miles × temperature and speed × temperature interactions. All other terms do not appear to be statistically significant.

Model 2 was fitted containing only the terms found statistically significant from Model 1. In this model, the terms mileage × speed, mounted lateral, and lateral spacing are not statistically significant and can be removed from the model.

The statistically significant terms from Model 2 were used to create Model 3. In this model, the terms for speed, x_5, miles × temperature and speed × temperature interactions are not statistically significant and can be removed from the model to fit the TD Model. The terms and p-values with the p-value threshold for the TD Models 1 through 5 are given in Table 4.13.

$$\widehat{TD} = 643 - 289m'_{loaded} + 100BC + 141L_{grease} - 236T' \tag{4.12}$$

In this equation *BC* is 0 if the bearing sampled from is a healthy bearing and 1 if the bearing sampled contains a defect as described earlier. L_{grease} is 1 if the grease sampling location is the spacer ring and 0 for a raceway. The term in the model for the variable BC indicates that the model predicts higher values of TD for bearing conditions with small defects. This relationship makes sense with the predicted behavior based on the research that was described in Chapter 2. The coefficient for the term L_{grease} is positive and suggests that grease in the spacer ring will have larger values of TD than grease sample from the raceways. This relationship is consistent with our understanding of the physical model. The coefficient for the temperature and for the loaded miles terms in the model are negative. This indicates that as the temperature increases and as the load increases, the TD decreases. These relationships are consistent with our understanding of the physical system.

CHAPTER V

LUBRICANT MODEL VALIDATION AND GENERALIZATION

5.1 Validation of Final Models

In order to validate the final model, several samples which were not a part of the datasets were tested for oxidation induction time (OIT) and thermal decomposition (TD) values. Using service history conditions for those samples in model Equations 4.11 and 4.12, expected OIT and TD values were calculated and compared to the experimentally obtained values.

5.1.1 Validation of Final OIT and TD Models

Equation 4.11 was used to calculate the OIT values of 40 samples that are not a part of the 206 data points that were used to fit the model. These 40 samples were also analyzed in the DSC to determine experimental OIT values. Figure 5.1 shows a plot where the 40 experimental values and their corresponding calculated values are compared. The green line represents a perfect match between the models and experimental results. In this plot it can be seen that 60 percent of the calculated values fall below their corresponding actual values.

Equation 4.12 was used to calculate the TD values of 40 samples that are not a part of the 206 data points that were used to fit the model. These 40 samples were also analyzed in the DSC to obtain experimental TD values. Figure 5.2 shows a plot where the 40 experimental TD values and their corresponding calculated values are compared. The green line represents a perfect match between the model and experiment values. In this plot it can be seen that 80 percent of the model predictions fall below their actual values.

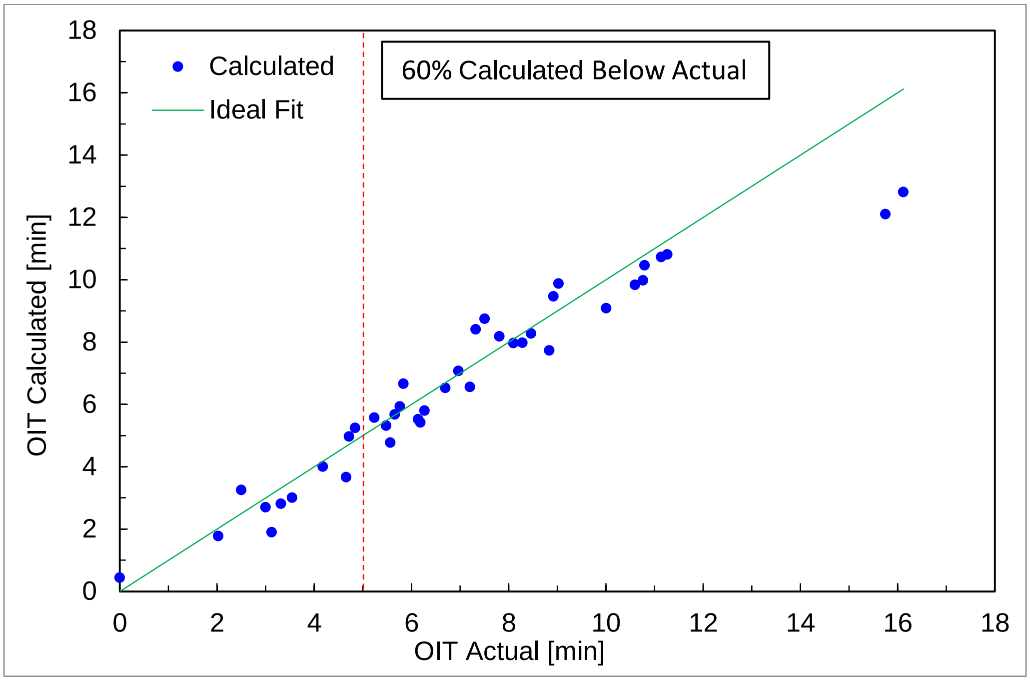

Figure 5.1. OIT experimental values for 40 samples in comparison to their corresponding OIT calculated values (obtained using Equation 4.11).

In practice, grease will be replaced when its appearance changes substantially. The dotted vertical red line in both plots represents the limit of grease life based on visual inspection. Bearing grease with appearance similar to samples to the left of this line would be regreased while grease with appearance similar to samples to the right would likely be left in service. Experiments show that there is still significant residual lubricant in samples which would be replaced and the model is predictive of life below this threshold. It can be seen from the two plots that a majority of the calculated values fall below their corresponding experimental values, 60% for OIT and 80% for TD. This suggests that the model is most often conservative and will predict a slightly lower residual life than can be expected in service.

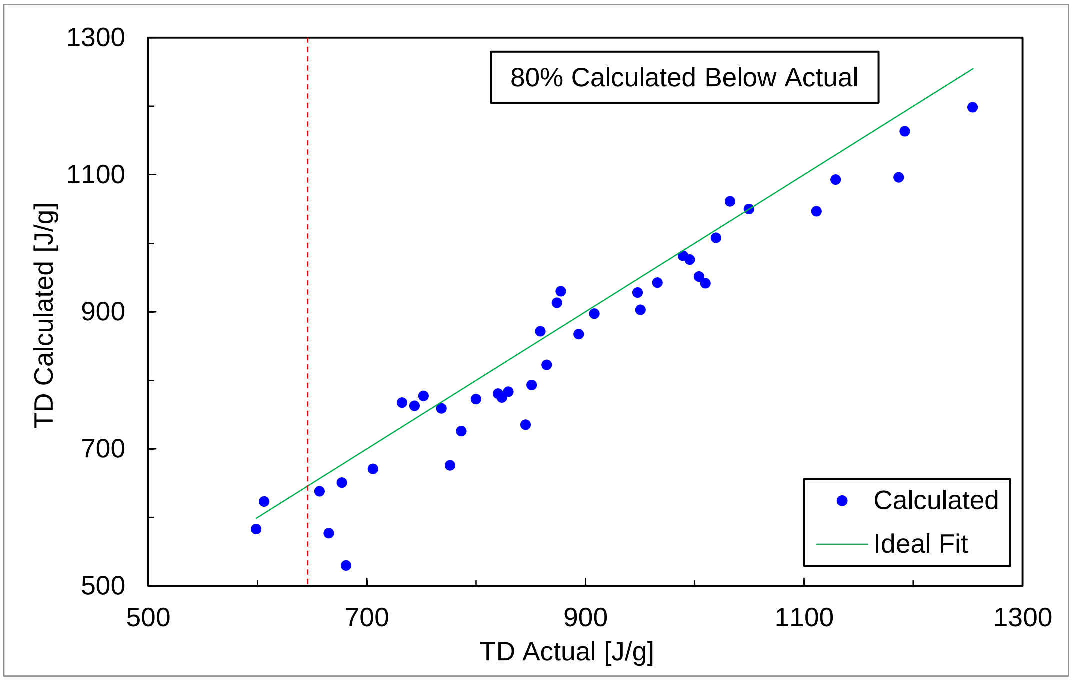

Figure 5.2. TD experimental values for 40 samples in comparison to their corresponding TD calculated values (obtained using Equation 4.12).

5.2 User Model Dataset

The objective of this thesis was to create a model which could be easily applied to service situations using inputs which would be readily available to a rail operator or maintainer. The final model obtained contained the terms for miles in the loaded condition, total mileage, bearing condition, grease location within the bearing and average temperature. Of these, average temperature is not currently available for most bearings in service in the field. Whether current or future wayside temperature monitoring can provide a dense enough history of temperature to apply this model is unknown. The models were built with continuously monitored bearings running in the laboratory where temperature data is readily available. In addition, the grease location variable would not apply to all bearing classes as many are not normally greased in the spacer ring. Therefore, including the grease location in the equation is not helpful to all end users and the value of this variable is assessed in the next section.

5.3 Preliminary User Models

Table 5.1. Final OIT Model with Model 6 p-values

Term	p-value thresholds					
	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**
m_{loaded}'	**0.01**	**0.01**	**0.01**	**0.02**	**0.05**	**0.02**
m'	**0.04**	**0.01**	**0.03**	**0.02**	**0.05**	**0.01**
s'	**0.01**	**0.02**	0.05			
$m_{loaded}' \times m'$	0.09					
$m_{loaded}' \times s'$	0.07					
$m' \times s'$	**0.05**	0.09				
x_4	**0.05**	0.07				
$L_{bearing}'$ x_5	**0.02**	**0.02**	**0.03**	0.06		
x_6	0.09					
$Lat_{mounted}'$	**0.05**	0.07				
$Lat_{average}'$	0.09					
BC'	**0.01**	**0.01**	**0.01**	**0.01**	**0.04**	**0.00**
L_{grease}'	**0.00**	**0.00**	**0.00**	**0.00**	0.00	
T'	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.05**
$m_{loaded}' \times T'$	**0.04**	0.06				
$m' \times T'$	0.07					
$s' \times T'$	0.08					

User friendly models were created by removing the grease location factor from the final models from Chapter 4 and fitting the models with the remaining terms. The final OIT model from chapter 4, Model 5, contained 5 terms, Model 6 was constructed by removing the grease location term and fitting the model. Table 5.1 shows initial 5 models along with Model 6 and the remaining terms and their p-values.

Model 6 contains four terms and utilizes coded variables for loaded miles, mileage, and temperature variables. The equation for the predicted value of OIT is Equation 5.1. Where the coefficients *m'*, *T'*, and m_{loaded} are Equations 4.3, 4.4, and 4.7 respectively.

$$\widehat{OIT} = 5.0019 - 0.3608m'_{loaded} - 4.1304m' + 1.9051BC - 1.0611T' \quad (5.1)$$

Table 5.2. Final TD Model with Model 6 p-values

Term		p-value thresholds				
		$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
		Model 1	Model 2	Model 3	Model 4	Model 5
m_{loaded}'		**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
m'		0.10				
s'		**0.01**	**0.02**	0.23		
$m_{loaded}' \times m'$		0.06				
$m_{loaded}' \times s'$		**0.02**	0.06			
$m' \times s'$		0.06				
$L_{bearing}'$	x_4	0.06				
	x_5	**0.03**	**0.02**	0.17		
	x_6	0.10				
$Lat_{mounted}'$		**0.05**	0.06			
$Lat_{average}'$		**0.05**	0.06			
BC'		**0.04**	**0.01**	**0.05**	**0.05**	**0.03**
L_{grease}'		**0.00**	**0.00**	**0.00**	**0.00**	
T'		**0.00**	**0.00**	**0.02**	**0.00**	**0.04**
$m_{loaded}' \times T'$		**0.02**	**0.02**	0.83		
$m' \times T'$		0.07				
$s' \times T'$		**0.02**	**0.01**	0.17		

The final TD model from Chapter 4, Model 4, contained four terms; Model 5 was constructed by removing the grease location term and fitting the model again. Table 5.2 shows initial four models along with Model 5 and the remaining terms and their p-values.

Model 5 contains three terms and utilizes coded variables for loaded miles and temperature variables. The equation for the predicted value of TD is Equation 5.2. Where the coefficients T' and m_{loaded} are Equations 4.4 and 4.7 respectively.

$$\widehat{TD} = 705 - 257m'_{loaded} + 100BC - 130T' \tag{5.2}$$

5.3.1 Validation of Preliminary User Models

These preliminary user friendly models were validated using the same method as the previous models. Several samples which were not a part of the datasets were tested on the differential scanning calorimeter for oxidation induction time (OIT) and thermal decomposition (TD) values. Application of the user-friendly Equations 5.1 and 5.2 to their respective service histories produced expected OIT and TD values for comparison to the experimental values.

Equation 5.1 was used to calculate the OIT values of 40 samples that are not a part of the 206 data points that were used to fit the model. These 40 samples were also analyzed in the DSC for actual OIT values. Figure 5.3 shows a plot where the 40 actual values and their corresponding calculated values are being compared. The green line represents a perfect match between experimental values and model prediction. In this plot it can be seen that 75 percent of the calculated values fall below their corresponding actual values.

Equation 5.2 was used to calculate the TD values of 40 samples that are not a part of the 206 data points that were used to fit the model. Experimental TD values for these 40 samples were obtained via DSC. Figure 5.4 shows a plot of the 40 experimental values and plotted against their corresponding calculated values. Again, the green line represents a perfect match between experimental values and model prediction. In this plot it can be seen that 80 percent of the calculated values fall below their corresponding actual values.

The dotted vertical red line in both plots represents the limit of grease life based on visual inspection. Bearing grease with appearance similar to samples to the left of this line would be regreased while grease with appearance similar to samples to the right would likely be left in service. It can be seen from the two plots that a majority of the calculated values fall below their corresponding experimental values, 75% for OIT and 80% for TD. This suggests that the model is most often conservative and will predict a lower residual life than can be expected in service.

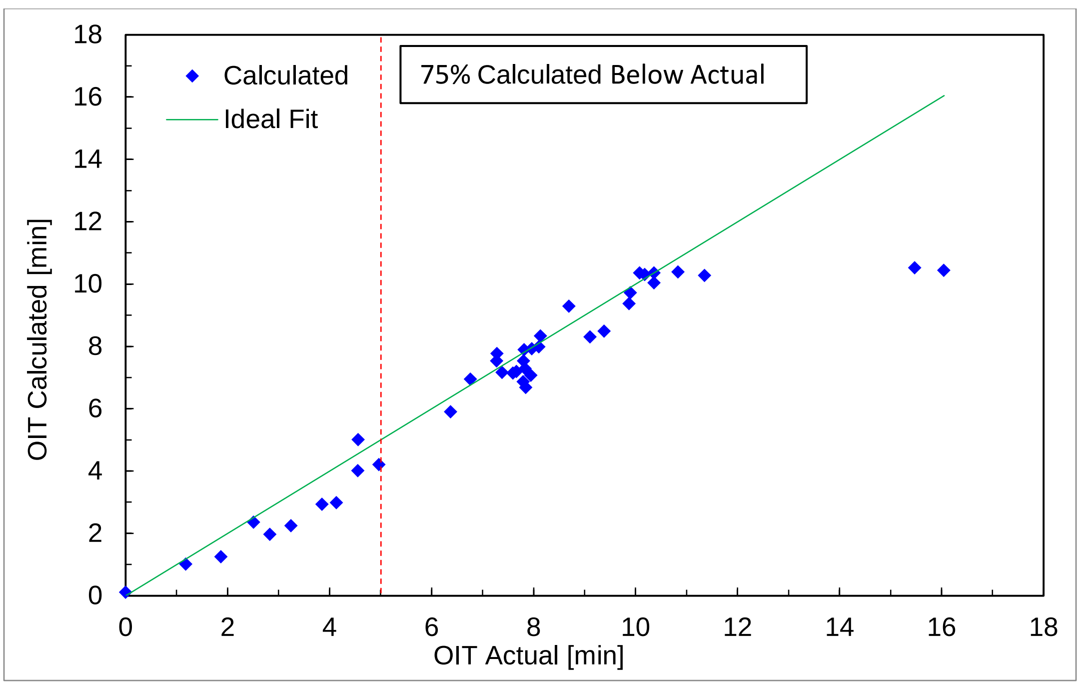

Figure 5.3. OIT experimental values for 40 samples in comparison to their corresponding OIT calculated values (obtained using Equation 5.1).

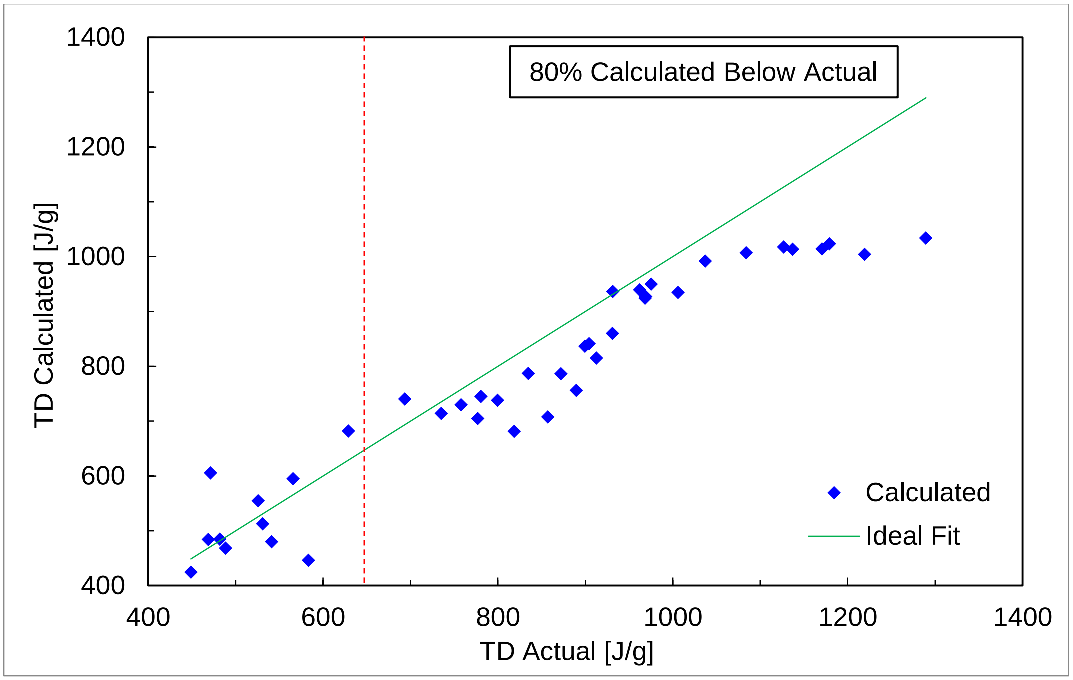

Figure 5.4. TD experimental values for 40 samples in comparison to their corresponding TD calculated values (obtained using Equation 5.2).

5.4 Building the Final User Models

After running the preliminary user models and comparing the Tertiary Model OIT Equation 4.11 to the Preliminary Model Equation 5.1, it can be seen that removing the grease location factor reduces the significance of the loaded miles term while the mileage variable became relatively more significant. This change could only be explained by considering that the mileage that the bearing spent loaded is always a percentage of the total mileage, meaning that loaded miles were included in the model twice. Therefore, instead of having miles loaded and total mileage, one final dataset was built using loaded mileage, m_{loaded}, and unloaded mileage, $m_{unloaded}$.

The location of the grease within the bearing was originally a part of the dataset in order to confirm that the expected physical response characteristics were visible in the models. The grease location variable for all the models confirmed that our understanding of the physical system was as expected with raceway grease showing greater degradation (Table 5.3) due to a combination of thermal history and tribomechanical damage while spacer grease only showed effects of thermal history.

Table 5.3. Average OIT and average TD for 206 samples. Comparing Raceway and Spacer ring location in the bearing.

Bearing Location	Average OIT	Average TD
Raceway	5.03	818.1
Spacer	8.08	868.4

By simply removing the grease location term to fit the preliminary user model, the 206 samples were lumped together without taking that difference into account. Therefore, the spacer ring samples were skewing the dataset. Since many bearings are only greased in the raceways, the spacer samples will not always be available. Thus this variable and the associated samples were removed from the final model.

In order to build the final user model one final dataset was built taking this new information into account. Instead of having miles loaded and total mileage, the final dataset was built using loaded mileage, m_{loaded}, and unloaded mileage, $m_{unloaded}$. Additionally, rather than removing the term for bearing location, all samples which were taken from the spacer ring were removed from the dataset, resulting in a dataset of 137 samples which were all taken from the bearing raceway.

The dataset used to build this model contains 8 variables for each of the 137 samples, the number of miles run in the loaded condition for the sample, the number of miles run in the unloaded condition for the sample, average speed experienced by the sample, bearing mounted lateral measurement, bearing average lateral spacing, bearing condition (where 1 means the bearing contains a small defect of less than 5% or raceway area as described in Chapter 2, and 0 means the bearing has no measurable surface defects), and average temperature experienced by the sample, along with response variables Oxidation Induction Time (OIT) and Thermal Decomposition (TD). A statistical summary for the 137 data point variables is shown in Table 5.4.

Table 5.4. Statistical Summary for Final User Model Data

	Minimum	Maximum	Mode	Average	Standard Deviation
Miles Loaded	3137.5	99032.7	39983.3	32085.6	23646.1
Miles Unloaded	0	45000	0	16784.5	14287.9
Avg. Speed [mph]	47.6	85.7	55.1	68	15.6
Bearing Location	1	4	3	2.53	1.08
Mounted Lat. [inches]	0	0.012	0	0.0046	0.0036
Lateral Spacing Avg. [inches]	0.02	0.027	0.024	0.024	0.0014
Bearing Condition	0	1	0	0.23	0.42
Avg. Temperature [°C]	40.8446	110.327	N/A	73.4	17.6
OIT [min]	0	17.1	0	5.9	4
TD [J/g]	157.6	1388.5	1226	818.2	294.8

The final user model contains 16 terms, loaded miles, unloaded miles, speed, bearing location (x_4, x_5, x_6), mounted lateral, lateral spacing, bearing condition, temperature, and two factor interactions between loaded miles, unloaded miles and speed and two factor interactions between temperature, loaded miles, unloaded miles, and speed.

5.4.1 OIT Final User Model

Table 5.5. Final OIT User Model p-values

Term		p-value thresholds				
		p < 0.1 Model 1	**p < 0.05 Model 2**	**p < 0.05 Model 3**	**p < 0.05 Model 4**	**p < 0.05 Model 5**
m_{loaded}'		**0.07**	**0.00**	**0.00**	**0.00**	**0.00**
$m_{unloaded}'$		**0.09**	0.09			
s'		**0.05**	**0.04**	0.42		
$m_{loaded}' \times m_{unloaded}'$		0.17				
$m_{loaded}' \times s'$		0.12				
$m_{unloaded}' \times s'$		0.17				
	x_4	0.16				
$L_{bearing}'$	x_5	**0.02**	**0.02**	0.20		
	x_6	0.12				
$Lat_{mounted}'$		0.12				
$Lat_{average}'$		0.12				
BC'		**0.00**	**0.00**	**0.01**	**0.00**	**0.00**
T'		**0.09**	**0.03**	**0.00**	**0.03**	**0.00**
$m_{loaded}' \times T'$		**0.03**	**0.05**	**0.05**	0.09	
$m_{unloaded}' \times T'$		0.11				
$s' \times T'$		0.11				

The terms that are statistically significant according to the p-value threshold from Model 1 are loaded miles, unloaded miles, speed, location x_5, bearing condition, temperature, and the loaded miles × temperature interaction. All other terms do not appear to be statistically significant.

Model 2 was fitted containing only the terms found statistically significant from Model 1. In this model, the term for unloaded miles is not statistically significant and can be removed from the model.

The statistically significant terms from Model 2 were used to create Model 3. In this model, the terms for speed and location x_5 are not statistically significant and can be removed from the model.

Model 4 was fitted containing only the terms found statistically significant from Model 3. In this model, the loaded miles × temperature interaction term is not statistically significant and can be removed from the model to fit the remaining terms in the Final User Model. The terms and p-values with the p-value threshold for the Final OIT Models 1 through 5 are given in Table 5.5.

The final model contains three terms and utilizes coded variables for the loaded miles and temperature variables. The equation for the predicted value of OIT is Equation 5.3. Where the coefficients T' and m_{loaded} are Equations 4.4 and 4.7 respectively.

$$\widehat{OIT} = 3.4679 - 3.9399m'_{loaded} + 2.3053BC - 3.1031T' \qquad (5.3)$$

The coefficient for loaded miles contains a negative value that indicates the OIT value decreases as the amount of miles the bearing spends in the loaded condition increases. This relationship seems valid based upon our understanding of how grease degrades as a function of usage. In this equation *BC* is 0 if the bearing sampled from is a healthy bearing and 1 if the bearing sampled contains a defect as described in earlier chapters. This term in the model for the variable BC indicates that the model predicts higher values of OIT for bearing conditions with small defects. This relationship is consistent with prior experience with bearings with defects covering less than 5% of the raceway area as was discussed in Chapter 2. The coefficient for the temperature term in the model is negative. This indicates that as the temperature increases and as the load increases, the OIT decreases. These relationships are consistent with our understanding of the physical system.

5.4.2 TD Final User Model

The terms that are statistically significant according to the p-value threshold from Model 1 are loaded miles, unloaded miles, speed, the loaded miles × speed interaction, the unloaded miles × speed interaction, locations $x_{4 \text{ and }}$ x_5, mounted lateral, lateral spacing average, bearing condition, temperature, the loaded miles × temperature interaction, and the unloaded miles × temperature interaction. All other terms do not appear to be statistically significant.

Model 2 was fitted containing only the terms found statistically significant from Model 1. In this model, the terms for unloaded miles, the unloaded miles × speed interaction, mounted lateral, lateral spacing average, the loaded miles × temperature interaction, and the unloaded miles × temperature interaction are not statistically significant and can be removed from the model.

The statistically significant terms from Model 2 were used to create Model 3. In this model, the terms for the loaded miles × speed interaction and locations x_4 and x_5 are not statistically significant and can be removed from the model.

Model 4 was fitted containing only the terms found statistically significant from Model 3. In this model, the term for speed is not statistically significant and can be removed from the model to fit the remaining terms in the Final User Model. The terms and p-values with the p-value threshold for the Final TD Models 1 through 5 are given in Table 5.6.

Table 5.6. Final TD User Model p-values

Term		p-value thresholds				
		p < 0.1 Model 1	**p < 0.05 Model 2**	**p < 0.05 Model 3**	**p < 0.05 Model 4**	**p < 0.05 Model 5**
m_{loaded}'		**0.04**	**0.00**	**0.00**	**0.00**	**0.00**
$m_{unloaded}'$		**0.09**	0.08			
s'		**0.06**	**0.04**	**0.05**	0.30	
$m_{loaded}' \times m_{unloaded}'$		0.11				
$m_{loaded}' \times s'$		**0.06**	**0.05**	0.12		
$m_{unloaded}' \times s'$		**0.09**	0.08			
$L_{bearing}'$	x_4	**0.06**	**0.05**	0.59		
	x_5	**0.04**	**0.03**	0.30		
	x_6	0.12				
$Lat_{mounted}'$		**0.08**	0.08			
$Lat_{average}'$		**0.07**	0.07			
BC'		**0.04**	**0.04**	**0.05**	**0.05**	**0.05**
T'		**0.06**	**0.05**	**0.00**	**0.00**	**0.00**
$m_{loaded}' \times T'$		**0.08**	0.07			
$m_{unloaded}' \times T'$		**0.09**	0.09			
$s' \times T'$		0.12				

The final model contains three terms and utilizes coded variables for the loaded miles and temperature variables. The equation for the predicted value of TD is Equation 5.4. Where the coefficients T' and m_{loaded} are Equations 4.4 and 4.7 respectively.

$$\widehat{TD} = 652 - 292m'_{loaded} + 98.8BC - 276T' \quad (5.4)$$

The coefficients for loaded miles and temperature are negative indicating that as mileage and average operating temperature increase, the TD decreases. These relationships are consistent with the mechanisms of physical degradation as a function of usage. In this equation *BC* is 0 if the bearing sampled from is from a flaw free bearing and 1 if the bearing sampled contains a small surface defect as described in earlier chapters. This term in the model for the variable BC indicates that the model predicts higher values of TD for bearing conditions with small defects. This is the same relationship observed with the corresponding OIT model and is consistent with prior results discussed in Chapter 2.

5.5 Validation of Final User Models

The final user models were validated using the same method as the previous models. Several samples which were not a part of the datasets were tested for oxidation induction time (OIT) and thermal decomposition (TD) values. Using the variables for those samples and inputting them into Equations 5.3 and 5.4 from the final user friendly models, OIT and TD values were calculated and compared to the actual experimental values.

5.5.1 Validation of User OIT Model

Equation 5.3 was used to calculate the OIT values of 30 samples that are not a part of the 137 data points that were used to fit the model. These 30 samples were also analyzed in the DSC for actual OIT values. Figure 5.5 shows a plot where the 30 actual values and their corresponding calculated values are being compared. In this and the plot of TD values, the green line represents a perfect match between model and experimental values. In this plot it can be seen that 87 percent of the calculated values fall below their corresponding actual values.

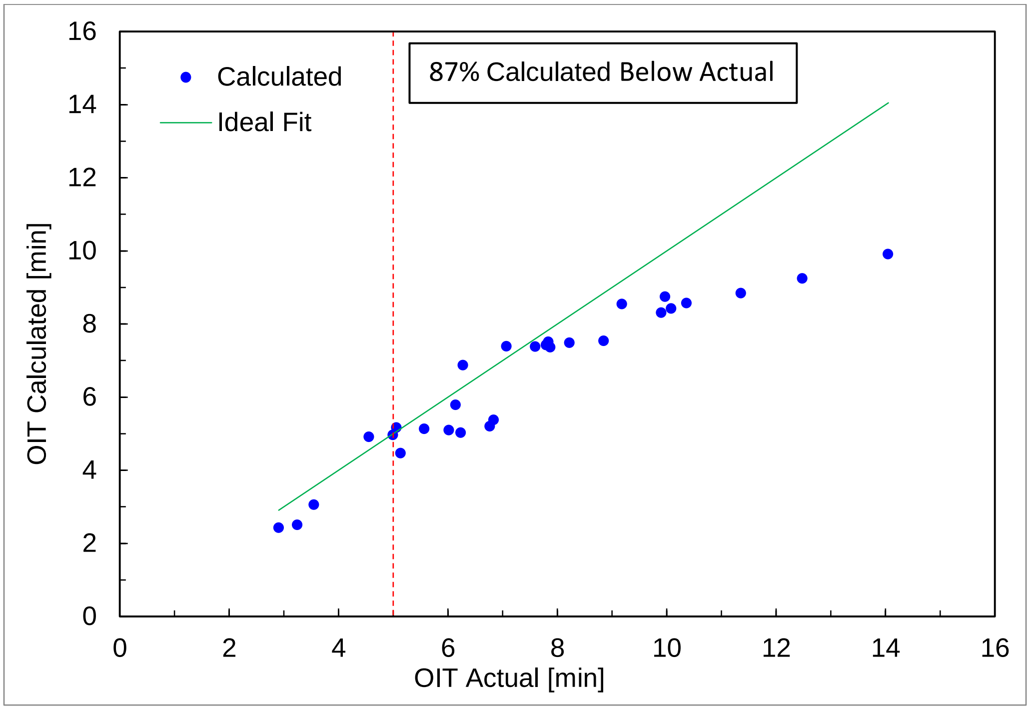

Figure 5.5. OIT experimental values for 30 samples in comparison to their corresponding OIT calculated values (obtained using Equation 5.3).

5.5.2 Validation of User TD Model

Equation 5.4 was used to calculate the TD values of 30 samples that are not a part of the 137 data points that were used to fit the model. These 30 samples were also analyzed in the DSC for actual TD values. Figure 5.6 shows a plot where the 30 actual values and their corresponding calculated values are being compared. In this plot it can be seen that 80 percent of the calculated values fall below their corresponding actual values.

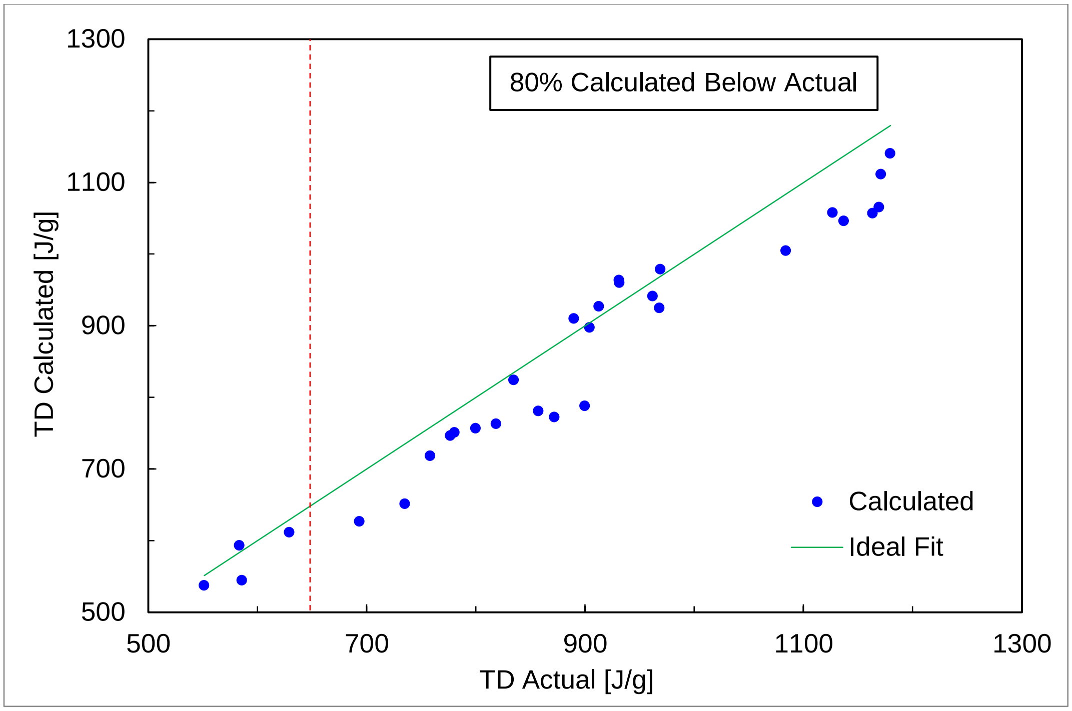

Figure 5.6. TD experimental values for 30 samples in comparison to their corresponding TD calculated values (obtained using Equation 5.4).

The dotted vertical red line in both plots represents the limit of grease life based on visual inspection. Bearing grease with appearance similar to samples to the left of this point would be regreased while grease with appearance similar to samples to the right would likely be left in service. It can be seen from the two plots that a majority of the calculated values fall below their corresponding experimental values, 87% for OIT and 80% for TD. This suggests that the model is most often conservative and will predict a lower residual life than can be expected in service.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

The objective of this thesis research was to create a multivariate residual life model for railroad bearing lubricating grease which could be applied in service situations by using inputs which would be readily available to the maintainer, both in industry and at the University Transportation Center for Railway Safety (UTCRS) at the University of Texas Rio Grande Valley (UTRGV).

The dataset used to fit the split-split plot models contained 11 different operational variables of the bearings which were sampled for grease. The models that are outlined in this thesis proved that not all of the variables are significant enough to influence lubricant life. The final Equations 5.3 and 5.4 can be solved for oxidation induction time (OIT) and thermal decomposition (TD), respectively, by inputting three values. These values are miles run in the loaded condition, average temperature experienced by the bearing, and the condition of the bearing whether defective or healthy, these three variables were found to be most influential on the degradation of the lubricant.

The resulting models provide the equations to solve for the lubricant's oxidation induction time (OIT) and thermal decomposition (TD) values, which are both indicators of its residual life. A lubricant sample, of the type studied in this thesis, that has never been used (virgin grease) will have an average OIT value of 35 minutes and an average TD of about 1330

J/g. A used grease sample which has an OIT of 17.5 minutes or a TD of 665 J/g can be said to have 50% residual life since these are half of the values for a virgin grease sample.

Figures 5.5 and 5.6 from Chapter Five provide validation plots, a means by which Equations 5.3 and 5.4 were validated. The figures show that the equations are conservative, that is, they tend to calculate lower values of OIT and TD than the actual values. The equations suggest a lower residual life value than that which would result if the grease were tested to acquire an actual residual life value. It can be seen from the validation plots that the model is most accurate in the middle section, between the limit of grease life based on visual inspection and the high residual life values. It is crucial that the model works well between these two points, since it is most important to be able to predict the grease life once it has been used for a substantial period of time but before the appearance of the lubricant begins to change significantly.

This model can be applied to schedule bearing maintenance in order to prevent the lubricant from being the cause for bearing failure. The three variables needed for this model are not all readily available for bearings operating in the field. The monitoring of all of the variables as was done for the samples used to build the model is possible but it is unknown if it can be achieved. Future work includes fitting the model using available wayside operational histories for inputs. As for the bearings being run on the dynamic testers at UTRGV, the operational variables can be gathered at any point in time as all of the necessary variables are monitored throughout the experiments. A user wanting to know whether it is time to re-lubricate a bearing or not, can simply solve for the OIT and TD values for given operating conditions, using Equations 5.3 and 5.4. Rather than having to go through the time consuming process of stopping the dynamic tester, removing the bearings from the axle, and disassembling the bearing to check the grease, the equations will predict a residual life value with some safety factor provided by the conservativism of the model. This will save time and will prevent unnecessary interruptions to experiments whose completion is crucial to the ongoing research.

Although the model was successful in predicting residual life of the railroad bearing lubricant when three known operational characteristics were used as inputs, a few steps can be taken to improve the understanding of the physical responses as well as improve the model itself. These steps include, (1) add a second bearing condition variable which deals with the defects on the inner ring (cone) raceways, (2) evaluation of a nonlinear temperature dependent term to better fit the behavior of the model in its entirety. Additionally, this model can provide a basis to future work on forensics of bearing failure by gathering grease samples from a failed bearing, the grease can then be assessed and a model can be used to figure out what the conditions of the bearing were which lead to failure.

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BIOGRAPHICAL SKETCH

Thania Alejandra Martinez was born on September 26, 1992 in Matamoros, Tamaulipas, Mexico to Jose and Esmeralda Martinez. She moved to the United States at the age of 6 and obtained her US citizenship while living in Mercedes, Texas. She attended Mercedes High School and through the Dual Enrollment Engineering Academy at South Texas College obtained her Associate of Science in Engineering degree along with her high school diploma in May of 2011. After which she attended The University of Texas-Pan American where she graduated with her Bachelor of Science in Mechanical Engineering in 2013. Her time at The University of Texas-Pan American not only included attending classes, she also served as a research assistant for two years on the Biomechanics Team where she was a co-author to two conference papers. She continued her education at The University of Texas Rio Grande Valley and earned a Master of Science Degree in Mechanical Engineering in December 2015. During her time at The University of Texas Rio Grande Valley she worked as a graduate research assistant at The University Transportation Center of Railway Safety where she had the opportunity to co-author a conference paper and present her research at the 2015 Joint Rail Conference. Thania can be reached by e-mail at mtzthania@gmail.com.