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DEVELOPING EMPIRICAL MODELS OF RAILROAD BEARING GREASE

Thania A. Martinez
Mechanical Engineering Department
University of Texas Pan American
Edinburg, Texas 78539

Dr. Doug Timmer
Manufacturing Engineering Department
University of Texas Pan American
Edinburg, Texas 78539

Dr. Robert Jones
Mechanical Engineering Department
University of Texas Pan American
Edinburg, Texas 78539

Dr. Constantine Tarawneh
Mechanical Engineering Department
University of Texas Pan American
Edinburg, Texas 78539

ABSTRACT
The degradation of the grease used to lubricate railroad bearings is believed to be caused by two processes: the mechanical processes occurring within the bearing and a diffusion process. Appropriate lubrication of the bearings is critical during railroad service operation. The study presented here will focus on 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 data set used in the development of the model consists of more than 100 samples of grease that were taken from railroad bearings. The bearings have been subjected to experimental variables such as load conditions, rotational speed, temperature, and mileage all of which have been observed in a laboratory setting. The mileage parameter is consistent with the total miles that were run using the grease from which the sample has been taken. Load, speed, and temperature values fluctuate within the total service operation of the bearing; therefore, a high value, a low value, and a weighted average are taken for the aforementioned parameters. The grease samples are taken from critical locations of the bearing, the inboard raceway, the outboard raceway and the spacer ring area, meaning that there are three samples collected from each railroad bearing, each having their own set of corresponding parameters. The oxidation induction time (OIT) of the grease is an indicator of the residual life of the grease; therefore, the OIT for each sample had been acquired using a differential scanning calorimeter (DSC). OIT is dependent upon mileage, load, speed, and temperature. This study was successful in developing an empirical model which can be utilized to predict the residual life for given operational characteristics.

INTRODUCTION
Railroad bearings must be properly lubricated during service operation. This is crucial to prevent accidents such as derailments. The grease usually employed in railroad bearings for lubrication includes a thickening agent that has been introduced to the grease. Some advantages of using grease as a lubricant are the ease of use, its sealing action, it will not leak out and it protects against corrosion [1]. But the life of the bearing depends on the grease life and the grease has a limited life. Additionally, there is no known absolute value for grease life. The end of the life of grease is defined by the point in time where the grease can no longer lubricate the mechanism [2].

The life of grease is affected by many factors. While observing the influences on grease life, Farcas and Gafitanu [3] took into account speed and temperature in one graph. In their overall study, they varied, speed, load and temperature. They also investigated the difference between oil and grease as a lubricant. Farcas and Gafitanu also use bearing revolutions as an indicator of service life because their experiments consist of running the bearings to failure. Cann [4] investigated the effects of the temperature, the speed and the additive package on lubrication life.

Currently, some grease life estimates exist. For example, for lubricated-for-life bearings in which the life of the grease exceeds the life of the bearing is one example. The manufacturer publishes a catalog that can be used to estimate grease life. The primary parameters of these models are bearing type, bearing size, speed and operating temperature [5]. Even though the bearing manufacturer will provide a tool for estimating grease life, the scientific developments for this are still very limited and there is still much to be done for the development of a true physical grease life model. All existing models are empirical and based on grease life testing [6].

The bearing experiments performed at The University of Texas – Pan American (UTPA) were conducted to develop empirical model(s) of grease life based upon operational settings or factors. The factors being observed for this study are the temperature of the bearings, the speed of the bearings, the load placed on the bearings, and the total mileage of the test. Additionally, variables denoting the setup of test rig such as the location of the bearing upon the axle and the location that the grease was sampled are also recorded. In the UTPA study, the bearings are not being run to failure. Rather, the total revolutions of the bearing, that is the mileage, is observed and used as an independent variable in the grease model(s). This approach allows for the analysis of the effects of the independent factors have upon the grease and enable an estimate of the usable life of grease to be generated. The project benefits from the availability of a large number of bearings subjected to varying operating histories provided by the ongoing research into bearing life performance.

EXPERIMENTAL TESTING

Grease used to lubricate railroad bearings is subjected to different operational settings that allow a model of the useful life of the grease to be estimated. Because of their structure, railroad bearings provide the opportunity to sample greases from three locations: the inboard raceway, the outboard raceway, and the spacer ring area as shown in the diagram in Figure 1.

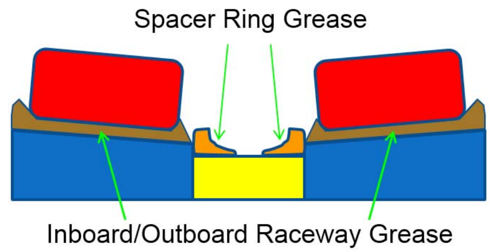

Figure 1. Diagram of the Three Locations in the Bearing

It is hypothesized that grease contained within the raceways is subjected to mechanical shearing, high temperatures in the contact zone and forced convention of grease which may transport oxygen from the seal area. In contrast, grease contained within the spacer is subjected to less severe conditions with little or no convection and oxygen diffusion is believed to be limited.

Four bearings are pressed onto an axle which is then mounted onto the experimental tester, there is a pulley at one end of the axle which drives the rotation of the axle (see Figure 2).

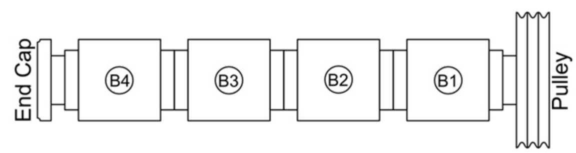

Figure 2. Diagram of Bearings on Axle

The tester simulates the operating conditions of railroad bearings. The bearing locations are determined by the location relative to the pulley. The bearings are assigned nominal values of 1, 2, 3 and 4; they are placed in order with bearing 1 being closest to the pulley and bearing 4 being furthest away from the pulley. The bearings are then subjected to variable load conditions and rotational speeds in the tester. Load and speed can be varied within each experiment. Therefore, a weighted average is taken for load and speed. Three thermocouples are placed on each of the four bearings to collect temperature measurements throughout the length of the experiment; a weighted average is also taken for the temperature of the bearing. The mileage of the bearings is recorded for every experiment. For the cases in which the same grease is used in more than one experiment, meaning the grease is not cleaned out and replaced by unused grease, the mileages for the experiments the grease was used in are added up; thus, giving the total mileage of that batch of grease. The same applies when averaging the load, speed and temperatures, all conditions of all experiments the grease was used for are taken into account. The different locations that the grease is being collected from, the locations of the bearing, the average load, the average speed, the average temperature and the mileage of the grease are all influential variables which are to be addressed within the multivariate model.

Oxidation Induction Time

The oxidation induction time (OIT) is used as a measure of the remaining life of the grease. To measure the oxidation levels of the grease samples, a differential scanning calorimeter (DSC), produced by TA Instruments, is being employed. After the samples are collected from the inboard raceway, outboard raceway and spacer ring area, they are stored in glass vials with hermetic lids to reduce oxygen exposure. Two milligrams of grease are taken from each sample and placed in an aluminum pan. The pans is then placed into the DSC for oxidation induction time testing. OIT testing measures the level of thermal stabilizers in the material. The sample is rapidly heated to the test temperature and the temperature is held there. The DSC produces the graph of heat flow vs time, shown on Figure 3 which will be examined to gather the OIT of the sample.

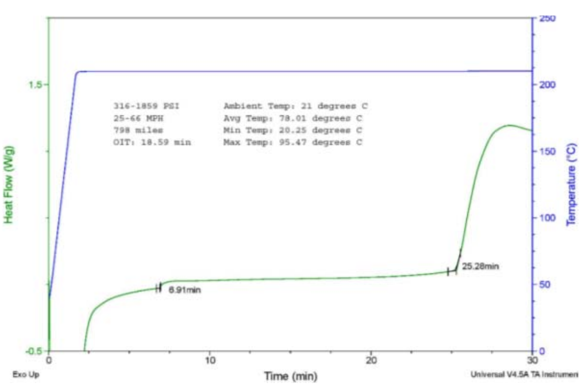

Figure 3. Graph of Heat Flow vs Time

The time elapsed between the introduction of air into the cell and the decomposition of the sample (indicated by the presence of an exothermic peak) reveals the time to oxidation, that time is then recorded as OIT.

The oxidative aging of bearing grease is a process with several governing factors. The lubricant additive package includes anti-oxidants or stabilizers. These usually work by scavenging oxygen in the grease, thus, preventing oxidation of the hydrocarbon molecules which actually provide lubricant activity. Note that the additives provide protection from oxidation which occurs at a lower temperature than thermal decomposition, thus, having the effect of allowing the grease to operate at a higher temperature or for longer times. However, if the thermal decomposition temperature is reached, even the stabilizers will not protect the grease. The breakdown of these stabilizers is governed by the availability of oxygen. There are a number of rate determining factors in the problem. The rate of oxygen uptake is controlled by 1) the rate of oxygen penetration of the external bearing seal which is influenced by whether the bearing is in motion, the age of the seal, and the temperature and 2) rate of oxygen transport through the grease which is governed by bearing function which stirs the grease in the contact zone. Since aging in the bearing is a diffusion limited process, miles of operation, speed history, load history, and thermal history will be primary determinants of residual grease life.

DATA ANALYSIS AND MODEL BUILDING

Statistical techniques are utilized in the section to build empirical models to better understand the relationship between the operational settings and the response variable OIT. The first empirical technique utilized is simple linear regression. The second approach is to utilize a data-mining technique called Regression Trees. The third approaches is based upon a design of experiments approach and utilizes split plot designs.

Linear Regression

A simple linear regression analysis was conducted to investigate the relationship between the independent factors (speed, load and mileage) with the response variable OIT. Figure 4 displays a fitted line plot of OIT versus speed with the sampling location of each observation denoted as a triangle square or circle. The fitted regression line has a weak negative relationship with the OIT. The negative relationship is to be expected because higher speeds impart higher mechanical energy and temperature to the grease and shorten the length of the remaining life of the grease. However, the model is not very predictive and alternative models are investigated.

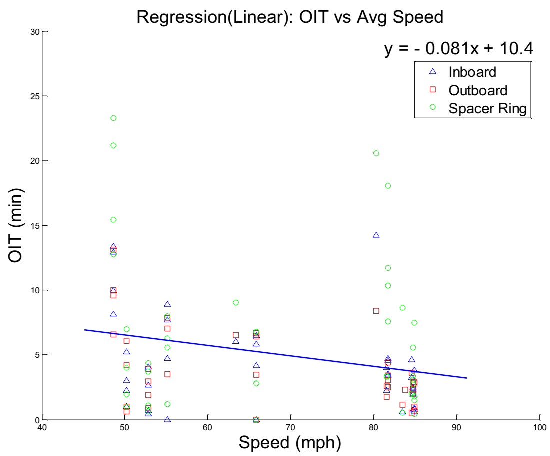

Figure 4. Simple Linear Regression of OIT vs. Speed

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. A regression tree for the grease data is shown in Figure 5. JMP software was used to create this regression tree. The regression tree displayed in Figure 5, contains five nodes. The first split in the regression tree is based upon load and observations with 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 high load (>=1075.36 psi) are then split by total miles and then average temperature. Thus the factors that seem to determine OIT are load, miles 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.

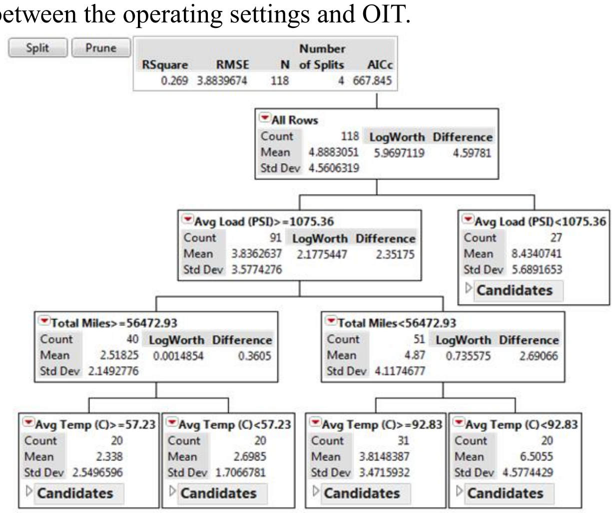

Figure 5. Regression Tree

Split-Plot Designs

Upon examining the method that the data was collected, it was recognized that the data collection was not completely randomized. Montgomery [7] 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 subsub 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 subsubplot factor.

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 (four bearings locations times three grease sampling locations yields twelve observations). However, sometimes values from all four bearing locations were not 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 *p*-values is no longer exact but approximate.

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 [8]. The bearing location variable has four possible values and requires three indicator variables. Table 1 provides the relationship between the three dummy variables representing the bearing location and the actual bearing location. The location of the grease sample has four possible and requires two indicator variables as shown in Table 2. The parameter estimates for the linear regression models were constructed restricted maximum likelihood (REML) technique using Matlab [9].

Table 1. Representation of Bearing Location

	Dummy Variables		
Bearing	**X4**	**X5**	**X6**
1	0	0	0
2	1	0	0
3	0	1	0
4	0	0	1

Table 2. Representation of Grease Location

	Dummy Variables	
Grease Location	**X7**	**X8**
1	0	0
2	1	0
3	0	1

The initial model contains 16 terms including two factor interactions between load, mileage and speed and two factor interactions between temperature, load, mileage and speed and the results are shown in Figure 6. The terms that are statistically significant from the initial model are mileage, mileage*speed, x_4, x_7, temperature and the mileage*temperature interaction. All other terms do not appear to be statistically significant.

	Term	Coef	se(Coef)	t-statistic	approx p-val	
wp terms (approx error df = 6)	Intercept	1.0737	3.7641	0.2853	0.7850	
	load	1.5122	7.1931	0.2102	0.8405	
	mileage	-13.2989	4.3152	-3.0819	0.0216	**
	speed	1.7393	4.5440	0.3828	0.7151	
	load*mileage	-9.3852	7.4705	-1.2563	0.2557	
	load*speed	-4.6215	7.1840	-0.6433	0.5438	
	mileage*speed	16.6564	7.5960	2.1928	0.0708	*
sp terms (approx error df = 24)	x4	2.8713	0.9978	2.8776	0.0083	**
	x5	0.6385	1.0011	0.6378	0.5296	
	x6	1.6466	0.9917	1.6604	0.1099	
ssp terms (approx error df = 72)	x7	2.9221	0.6333	4.6141	0.0000	**
	x8	-0.3409	0.5432	-0.6276	0.5323	
	temperature	-8.7969	3.2085	-2.7417	0.0077	**
	load*temperature	-3.9283	5.1582	-0.7616	0.4488	
	mileage*temperature	-7.8488	3.6546	-2.1476	0.0351	**
	speed*temperature	2.7801	4.1258	0.6738	0.5026	

Analysis of coded variables

	Obs	Approx DF	Approx Error DF
WP	13	13	6
SP	40	27	24
SSP	118	78	72

Variance Component	Estimate
wp	15.337
sp	1.871
ssp	5.593

Variance Ratios	Estimates
eta1	2.7421
eta2	0.3346

Figure 6. Initial Split Plot Model

A second model was fitted containing only the terms found statistically significant from model 1. The results for model 2 are shown in Figure 7. 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 from the second term were used to create the third model shown in Figure 8. In this model, the mileage*temperature interaction is not statistically significant and can be removed from the model.

The final model was obtained by removing the mileage*temperature interaction and fitting a model to the remaining terms. The final model given in Figure 9, contains a term for the y-intercept, mileage, bearing location, grease sampling location and temperature.

	Term	Coef	se(Coef)	t-statistic	approx p-val	
wp terms (approx error df = 9)	Intercept	0.6999	1.5747	0.4445	0.6672	
	mileage	-8.0003	3.1156	-2.5678	0.0303	**
	speed	1.6769	1.8711	0.8962	0.3935	
	mileage*speed	6.0180	3.7871	1.5891	0.1465	
sp terms (approx error df = 26)	x4	1.9142	0.7417	2.5808	0.0159	**
ssp terms (approx error df = 75)	x7	2.9134	0.5294	5.5032	0.0000	**
	temperature	-6.6029	2.4734	-2.6696	0.0093	**
	mileage*temperature	-6.2692	2.4603	-2.5481	0.0129	**

Analysis of coded variables

	Obs	Approx DF	Approx Error DF
WP	13	13	9
SP	40	27	26
SSP	118	78	75

Variance Components	Estimate
wp	13.680
sp	2.052
ssp	5.497

Variance Ratios	Estimates
eta1	2.4885
eta2	0.3733

Figure 7. Second Split Plot Model

	Term	Coef	se(Coef)	t-statistic	approx p-val	
wp terms (approx error df = 11)	Intercept	1.8964	1.3727	1.3815	0.1697	
	mileage	-3.9511	1.9252	-2.0523	0.0423	**
sp terms (approx error df = 26)	x4	1.8173	0.7385	2.4608	0.0208	**
ssp terms (approx error df = 75)	x7	2.7981	0.5002	5.5940	0.0000	**
	temperature	-5.0227	1.9157	-2.6219	0.0106	**
	mileage*temperature	-3.5885	3.0580	-1.1735	0.2443	

Analysis of coded variables

	Obs	Approx DF	Approx Error DF
WP	13	13	11
SP	40	27	26
SSP	118	78	75

Variance Components	Estimate
wp	14.714
sp	2.089
ssp	5.500

Variance Ratios	Estimates
eta1	2.6753
eta2	0.3799

Figure 8. Third Split Plot Model

	Term	Coef	se(Coef)	t-statistic	approx p-val	
wp terms (approx error df = 11)	Intercept	2.3872	1.1846	2.0152	0.0690	*
	mileage	-3.8116	1.7281	-2.2057	0.0496	**
sp terms (approx error df = 26)	x4	1.7551	0.7521	2.3336	0.0276	**
ssp terms (approx error df = 76)	x7	2.7443	0.4986	5.5040	0.0000	**
	temperature	-3.7388	1.5485	-2.4145	0.0160	**

Analysis of coded variables

	Obs	Approx DF	Approx Error DF
WP	13	13	11
SP	40	27	26
SSP	118	78	76

Variance Components	Estimate
wp	11.311
sp	2.231
ssp	5.599

Variance Ratios	Estimates
eta1	2.0202
eta2	0.3984

Figure 9. Final Split Plot Model

DISCUSSION OF RESULTS

The final model contains five terms and utilizes coded variables for the mileage and temperature variables. The equation for the predicted value of OIT ($\hat{y}$) is

$$\hat{y} = 2.3872 - 3.8116 * mileage' + 1.7551 * x_4 + 2.7443 * x_7 - 3.388 * temperature'$$

where $mileage' = \frac{mileage - 53396}{45687}$, $temperature' = \frac{temperature - 80.16}{32.71}$, 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 is not understood and will require future 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.

FUTURE RESEARCH

The inclusion of the location of the bearing on the axle needs to be examined. From the modeling process, the second bearing location yielded higher OIT predictions. An examination of the physical system will be undertaken to determine if a physical reason exists for this term be included in the model.

Additional examination of the split-split plot regression model needs to be undertaken. A first step is to calculate R-square values to provide a measure of the amount of total variability the model is explaining. Residual analysis is the usual diagnostic tool to determine if the model assumptions are satisfied. Residual analysis of a split-split plot design is complicated because there are three error estimates; one for the whole plot, a second for the sub plot and a third for the subsub plot. Additionally, a linear regression model is employed and examination of the relationships between mileage and temperature variables with OIT needs to be conducted.

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