SURVIVAL ANALYSIS OF REAL-WORLD TIRE AGING DATA

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ABSTRACT

This paper focuses on tire aging and tire failures due to increased chronological tire age, miles driven, and harsher environmental conditions. Fundamental material failure mechanism is presented first to illustrate why tires are aging faster under higher loads or temperatures. Then Kaplan-Meier curves and Log-rank tests are used to compare various risk factors that may lead to tire aging. Similarly, Weibull analysis is used to predict the tire failure probability against tire age or mileage. Finally, Cox proportional hazard model is utilized to explore the tire aging relative risk with statistical significances. It is found that greater chronological tire age, higher mileage, initial tire loads, and manufacturing characteristics or tire types all contribute to tire aging or failures.

INTRODUCTION

While crash data such as the National Motor Vehicle Crash Causation Study (NMVCCS) and Fatality Analysis Reporting System (FARS) indicate that tire failures contribute to vehicle crashes and to approximately 400 fatalities per year (around 1% of total motor vehicle fatalities in US), relatively little is known about the risk of tire aging/tire failure due to increased chronological tire age, miles driven, and harsher environmental conditions (tire aging). This paper investigates the various reasons or risks, numerically and graphically, that lead to tire failures over certain time or mileages, using survival analysis or reliability engineering techniques.

The research data used in this paper comes from National Highway Traffic Safety Administration (NHTSA) Vehicle Research and Test Center (VRTC). VRTC has been collecting and analyzing in-service tires from the southwest area of US. The research background and motivations were earlier introduced by MacIsaac and Feve. [1, 2] Phoenix, Arizona was selected for the tire collection site due to its high average ambient temperatures and large population. It is believed, from earlier tests [1, 2, 3], that thermo-oxidative degradation within the tires is the main risk factor that leads to tire aging, and that this thermo-oxidative degradation rate is proportional to the temperature.

Earlier work at VRTC provided rich data for this current research. [3] There are four phases of this ongoing tire aging program at VRTC [2, 3]: Phase one of the project consisted of the engineering analysis of six different tire models collected from on-vehicle service in Phoenix during March to April 2003. From the point of view of reliability and test validation, 250 collected tires of six different tire models were studied to provide details about their material properties and degradations. The results were then compared against 82 new, unused, same versions of the tire models to quantify the amount of degradation in each measured property. The results of phase one provided some insight of service-related tire degradation, and can be served as the real-world 'baseline' reference for the future laboratory-based tire test.

One typical reliability method, so called step stress test, or accelerated test, was performed for each tire at VRTC. Fundamental fatigue theory of materials is used as the guideline, and the test loads, or speeds were gradually increased, step-by-step, which were then associated with increased mechanical stress and higher temperatures within the tires under test. Accelerated tests are normally done by means of dynamic or vibration test, and by thermal chamber or oven test. Figure 1 shows one of such road-wheel dynamic test setup used in the VRTC research [2]. The experimental data patterns are compared to verify the effects of some possible tire relative risk factors, especially, greater tire chronological age, high mileage, initial tire load, and tire types or manufacturing characteristics.

Figure 1: Tire Aging Roadwheel Test Used by VRTC [2]

For phase two testing carried out by VRTC researchers, a thermal oven (Figure 2) was utilized, and this thermal test can realistically simulate the tire aging process, with the oven internal temperature varying from low to high, for instance, 55-70°C degrees for a period of 3-12 weeks [2]. It is observed, from repeated experiments, that only the oven thermal test during Phase two could replicate the tire material properties of the six Phoenix retrieved tire models [2].

Phase three and Phase four testing, proposed by VRTC, further validated the oven test results and model parameters derived from Phase two test based on the accelerated test theory. This paper will not address the details of Phase three and Phase four testing, but the theoretical analysis of this paper can be a useful hint.

More detailed statistical analyses are done in this paper compared with earlier Phase one work, two main experimental data sets derived from Phase one test at VRTC are used for the survival analysis in this study: the first dataset, 'Step Load', contains data from the stepped-up load road-wheel durability test performed on 127 unique tires (with no repeated tests). The second main dataset, 'Step Speed', contains data from the stepped-up speed road-wheel durability test performed on 95 unique tires (no repeated tests). Both step stress tests, either step load or step speed, were done to tire failures with associated higher stress, from each step of either higher load or faster speed. The main outcome variables of the above two data sets are time to failure (hours), mileage at failure (kilometers), and millions of cycles at failure. Some continuous data, such as tire age or mileage, are also categorized if needed in the modeling for the purpose of group comparison.

Figure 2: Oven Thermal Test to Simulate Tire Aging Used by VRTC [2]

The objectives of this research are listed as follows:

- Simply asking why tires fail, especially why tires fail much faster in hotter regions like Phoenix. Fundamental failure mechanisms, related to temperature and dynamic loads, are introduced first.
- Comparing the tire survival or failure probabilities of various factors leading to tire aging or failures, these factors are tire age, tire mileage, tire types and others, that are examined by paired comparison using Kaplan-Meier curves and Log-rank test.
- Predicting tire aging and failure probability using Weibull failure probability plots.
- Comparing the relative risks or hazard ratios of various factors and their statistical significances with p-values using Cox Proportional Hazard model.
- Providing some hints for future tire accelerated tests based on real-world data, failure theory of thermal and dynamic loads, and survival analysis.

EXPLORE TIRE AGING FROM A PERSPECTIVE OF AN ACCELERATED TEST

Tires fail because of high stress from a point of view of mechanical and reliability engineering. Stress-Cycle relationship or 'S-N curve' is used here to explain the tire failures, the tire failure happens when the following condition, Eq.(1), is met [6] –

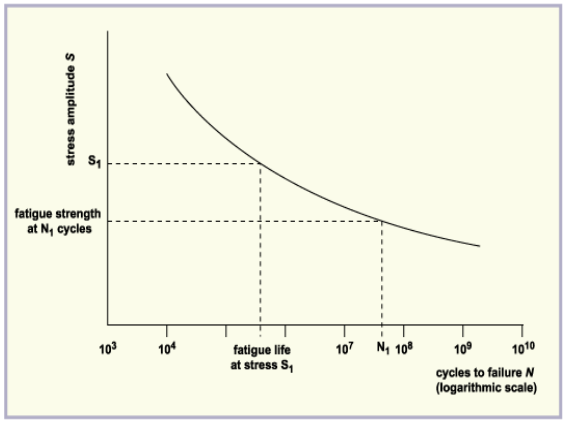


Figure 3: Stress-Life Curve (S-N Curve)

$$\sum_{i=1}^{K} \frac{n_i}{N_i} = 1 \qquad (1)$$

Where n_i is the test cycles performed at stress S_i while N_i is the maximum cycles before failure at stress S_i. Mechanical stresses in tires are mainly from two sources: stress caused by dynamic loads (for example, driving at high speeds), and stress caused by high temperature (for instance, driving in Phoenix during the summer or tire testing in a hot oven, Figure 2).

The tire aging can be much accelerated if used at a higher temperature than at a lower one. Accelerated temperature stress is described by an accelerated factor, or, $AF_{thermal}$, as following [6] (page 472-474) –

$$AF_{thermal} = \exp(E_a * TDF) \qquad (2)$$

Where

$$TDF = \frac{11605}{temp._{low}\ ^{o}K} - \frac{11605}{temp._{high}\ ^{o}K} \qquad (3)$$

In Eqs. (2-3), temp.^{o}K (absolute temperature) = (temp.^{o}C + 273.15), and 'E_a' is the activation energy in electron volts (eV). 'TDF' is defined as 'Temperature Differential Factor' from the Arrhenius Time-Acceleration Model. [6]

One example using Eqs. (2-3) is presented here - if a tire is exposed at a higher oven temperature of 65°C (or temp.^{o}K $_{high}$ = 65 + 273.15 =338.15), compared to being tested at a lower 50°C (or temp.^{o}K $_{low}$= 50 + 273.15 = 323.15), TDF=1.59 from above Eq.(3), if 'E_a' is related to material and assumed to be 1.2eV (the proper 'E_a' value can be obtained only after careful study of tire material), then $AF_{thermal}$ = exp(1.2x1.59)=6.76 from Eq. (2). The interpretation of this numerical example is that exposure of a tire to a higher temperature of 65°C for one hour is equivalent to almost 6.76 hours at a lower temperature of 50°C in the thermal oven, assuming other test conditions remain the same.

Like oven thermal accelerated test, the tire aging can also be much accelerated if used under higher dynamic loads than the lower one, such as step speed test. Dynamic accelerated factor can be obtained by the following formula, similarly [6, 7] -

$$\frac{T_{low}}{T_{high}} = \left(\frac{G_{high}}{G_{low}}\right)^{m} \qquad (4)$$

$$AF_{dynamic} = \frac{T_{low}}{T_{high}} \qquad (5)$$

Where G_{high} is the higher dynamic load that results in shorter test time, T_{high}, and G_{low} is a lower dynamic load that leads to longer test time, T_{low} (see S-N curve of Figure 3) [6]. G_{low} or G_{high} is dynamic or vibration power spectral density (PSD) related to driving speed with a unit of g^2/hz, while 'm' is a constant relate to tire materials and S-N curve (normally between 2.5 to 6). [6] However, this short paper will not address detailed effects of dynamic loads, tire materials and tire structures on the tire aging.

One example using Eqs. (4-5) is shown here - if G_{low} =0.04 g^2/hz, and G_{high} =0.06 g^2/hz, assuming 'm'=4, then $AF_{dynamic}$ = $(0.06/0.04)^4$ = 5.06 (times). This example implies that a tire tested at a 50% higher dynamic level of 0.06g^2/hz for one hour is equivalent to almost 5 hours if tested at a lower level of 0.04 g^2/hz.

If both thermal and dynamic accelerated factors are considered, then the total accelerated test factor is [6] –

$$AF_{total} = AF_{thermal} \times AF_{dynamic} \qquad (6)$$

Eq (6) indicates that tires used under both higher temperature and higher dynamic loads, as two examples above, will have a total accelerated factor

of $AF_{total} = AF_{thermal} \times AF_{dynamic} = 6.76 \times 5.06 = 34.2$ (times). We can interpret this approximately - one day *fast* driving (assuming dynamic loads 50% higher) in *hot* Phoenix (assuming more than 15°C degrees hotter) is 'almost equivalent to' one month *normal speed* driving in *cool* Seattle. Again, the different assumptions of material related constants of 'E_a' and 'm' in Eq.(2) and Eq.(4) can lead to different acceleration factors. The actual AF_{total} might be much smaller than the value in this illustrative example.

COMPARING TIRE RELATIVE RISKS USING KAPLAN-MEIER CURVES

One important variable used for survival analysis is time, for instance, the test time until failure of a tire in the laboratory, or years of tires being used in the field, or the treatment time of a patient enrolled into a clinical trial [8]. In this paper, tire age is represented by the variable "DOT Age", which was determined by subtracting the build date in the DOT code from the date the tire was collected from service. This was considered a more accurate measure of tire age [3, 9]. Further, DOT Age (Year) is defined as (collection date - DOT Middle week Date) *(1/365.25).

The estimated mileage of the tire is represented by the variable "DOT Estimated Mileage". The value of this variable is zero miles for new tires, actual vehicle odometer mileage for original equipment manufacturer (OEM) tires. For replacement tires, DOT Estimated Mileage is defined as (Vehicle Mileage/Vehicle Age)*Tire Age.

It is of great interest to observe the tire failure, or survival probability varying over a test time. One of the most useful tools to compare the survival probability over time is a method proposed by Kaplan and Meier [4]. The Kaplan-Meier survival curve is described by the following formula:

$$\hat{S}(t) = \prod_{t_i <= t} (1 - \frac{d_i}{n_i}) = \prod_{t_i <= t} (\frac{s_i}{n_i}) \qquad (7)$$

Where 'd_i' is 'deceased' subject, or failure tires, and 'S_i' is the 'survivor' subject or tires still under testing, and 'n_i' is total subject number (total tires) in the study at the study moment.

The Log-Rank test, used to compare the Kaplan-Meier curves and statistical significance with p-value, is shown as follows [4, 8]

$$T_L^2 = \frac{\sum_{i=1}^{I} (O_i - E_i)^2}{\sum_{i=1}^{I} V_i} \qquad (8)$$

Where 'O_i' is the 'observed' while 'E_i' is the 'expected' values, and V_i is the variance. The Log-Rank test is similar to Chi-Square test. The survival analysis is done using SAS Procedure of 'LifeTest' [11] and the Kaplan-Meier plots (or K-M Curves) are done using open source package R library of 'Survival' (www.r-project.org).

There are several research questions related to tire aging to be asked, some are listed as follows –

- Are greater chronological age tires prone to fail more easily?
- Will tires with higher mileages fail sooner? (Or alternatively, what is the combined effect of the tire age and mileage on aging if using a 'Service Factor' that correlates with tire age and mileage, see details on page 7)
- Do different tire types have different risks?
- Are tires located at front or rear associated with different Risks?

The following results, in the format of graphics, are several typical hypothesis questions that are studied using Kaplan-Meier curves, one by one.

CASE STUDIES

- Hypothesis Question One: Do Older Tires Have the Same Failure Rates as Newer Tires?

The engineering tests and experimental data suggest that tires with greater chronological age may be failing earlier than the new ones. Kaplan-Meier test and Log rank test were performed on 'step load' data set, and the following Figure 4 compares the survival rate over time between the older and newer tires.

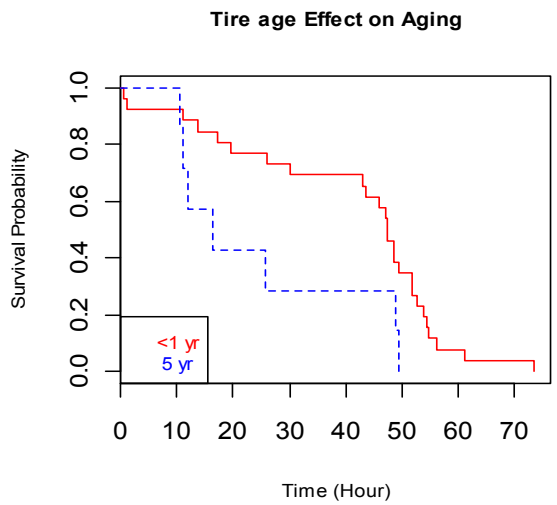


Figure 4 Survival Plot Comparing Older (dotted-line: >=5 years) and New Tires

The vertical axis of the above Figure 4 is the survival probability (0 to 1.0, or, 0-100%) and the horizontal axis is tire test time (0 to failure time, hours).

The results from Figure 4 indicate that there is a statistically significant difference (p-value=0.03 from Log rank test) between newer tires and older tires (>=5 years old) that failed much sooner from 'step load' data.

The same Kaplan-Meier test is also applied to 'step speed' data, and Figure 5 below indicates the same trend with 'step speed' data as Figure 4..

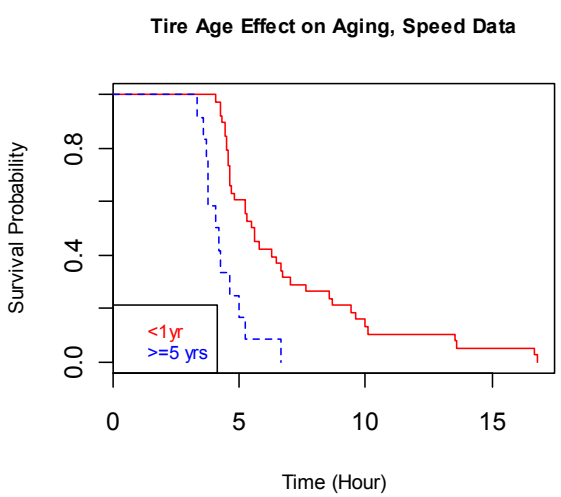


Figure 5 Survival Plots Comparing New and Old Tires (dotted-line)

- Hypothesis Question Two: Will High Mileage Tires Fail the Same as Lower Mileage Tires?

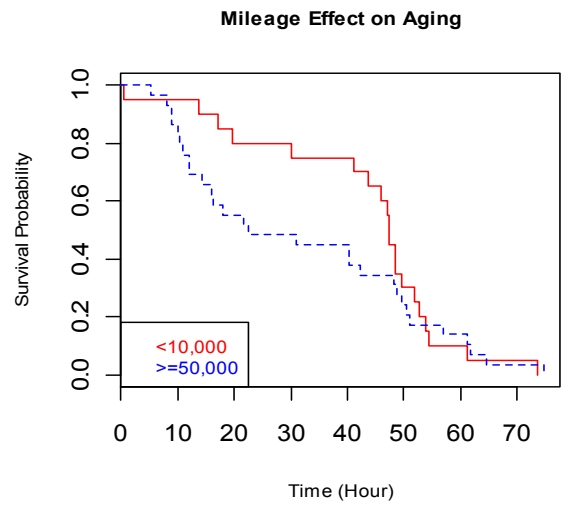


Figure 6 Survival Plots Comparing Low and High Mileage Tires (dotted-line: mileage<10,000)

The results from the above Figure 6 (using 'Step Load' data) indicate that there is a statistically significant difference between lower mileage tires (red curve) and higher mileage tires (p-value <5%).

- Hypothesis Question Three: Do Different Type Tires Have Same Failure Risks?

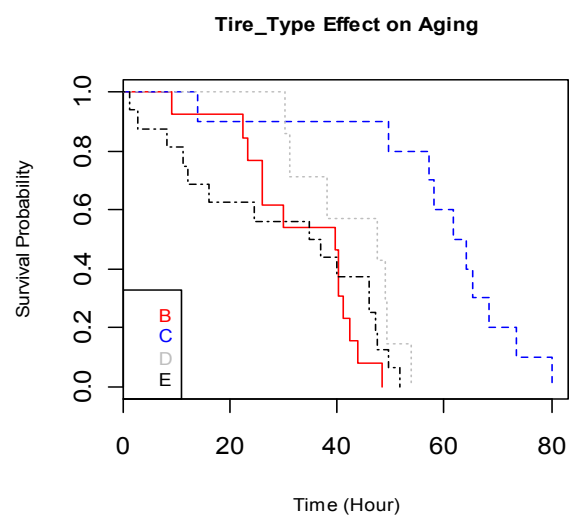


Figure 7 Survival Plots Comparing Various Tire Types

Figure 7 indicates (using 'Step Load' data) that there are significant differences among various tire types,

especially between best survival one (Type C, blue) vs. worst survival one (Type E, black).

- Hypothesis Question Four: Do Tires with Different Positions Have Similar Failure Risks?

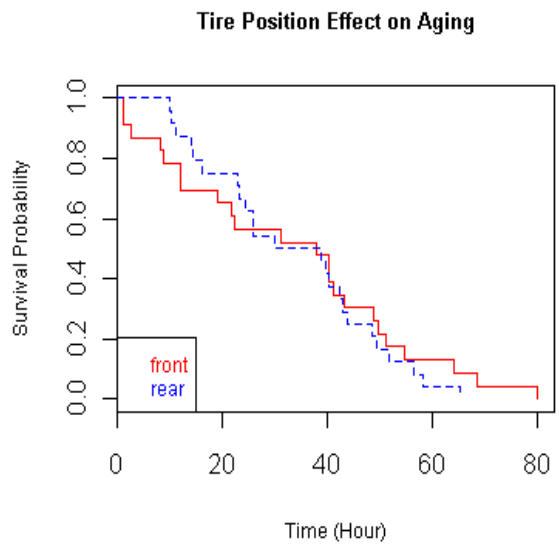


Figure 8 Survival Plots Comparing Positions (front/rear)

Figure 8 (from step load data) indicates a non-significant difference between the tires with different positions, 'front' vs. 'rear' position (p-value >10% from log-rank test).

More similar K-M curves also verify the significant effect of initial load although sample size is small. The effect of 'speed at failure' is also explored, and the results are not so statistically significant enough (p-value >0.05) if the speed is divided into two groups only (under, or above 170 km/hour), however, the speed can be divided into 3 or 4 groups later with a larger sample size, which may result in the greater aging differences between a very high speed group (with a higher relative risk) and a very low speed group. Some other parameters of tires, related to tire statuses, materials and structure, can also be explored in the similar procedure as above.

DISPLAY TIRE FAILURE PROBABILITY USING WEIBULL PLOT

The tire failure probability over test time, F(t), can be expressed by the following Eq. (9) in Weibull model:

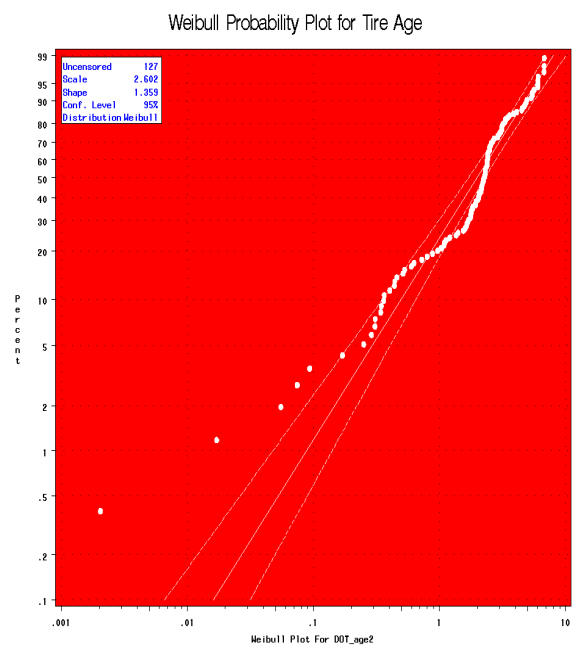
$$F(t) = 1 - e^{-(t/\alpha)^{\beta}} \qquad (9)$$

Or, equivalently it can be visualized by the following 'linear' transformation, as Eq. (10): [6, 8]

$$\log(-\log(S(t)) = \beta \log(t) - \beta \log(\alpha) \qquad (10)$$

In the above Eq.(10), S(t) is survival function, which can be estimated from the Kaplan-Meier curve discussed earlier. Note S(t) = 1-F(t), and F(t) of Eq. (9) is the accumulation of failure probability as time increases. Weibull failure probability plot from Eq. (10) can be visualized as a 'linear' plot described by 'Y=βX+Constant', where vertical 'Y'=log(-log(S(t)), 'X'=log(t), and 'Constant'=-βlog(α). 'β' is regarded as the 'Slope' of the linear plot, or 'Shape' parameter, and 'α' is a 'Scale' parameter and is related to the intercept of the linear plot.

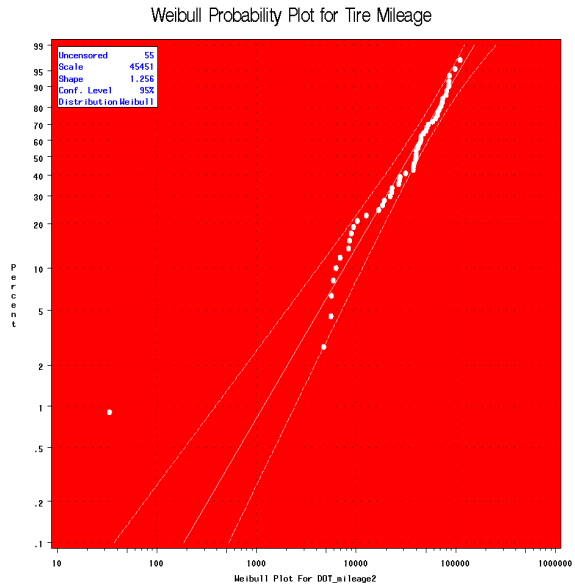
The following Figure 9 indicates that accumulation of tire failure probability increases with tire ages (step load data).



β =2.6 ('shape'), α =1.36 ('scale')

Figure 9 Failure Probability vs. Tire Age

The similar plot against mileage (Fig. 10 as below, using step speed data) indicates that accumulation failure probability also increases with tire mileages.



β =1.26 ('shape'), α =45451 ('scale')

Figure 10 Failure Probability vs. Tire Mileage

The following Tables 1-2 provide more results of slope (β) and scale (α) parameters, from additional Weibull modeling using different data sets. SAS Procedure of 'LifeReg' is used for Weibull analysis [11].

Table 1: Weibull Slope and Scale Parameters (Step Load data)

parameter	Failure vs Tire age	Failure vs Mileage
β (slope/shape)	2.6	1.37
α (scale)	1.36	41667
99% failure	@6.5 yrs	@110,000km

Table 2: Weibull Slope and Scale Parameters (Step Speed Data)

parameter	Failure vs Tire age	Failure vs Mileage
β (slope/shape)	1.17	1.26
α (scale)	2.46	45451
99% failure	@7 yrs	@105,000km

RELATIVE RISKS OF TIRE AGING BY COX PROPORTIONAL HAZARD MODEL

It is of interest to analyze the relative effect of aging, for example, older tires vs. the newer tires. Cox Proportional Hazard model has been very popular in modeling censor data and analyzing the relative risk. The mathematical form is simply as follows, [5]

$$h(t \mid X_1, X_2, X_3, ..X_n) = h_o \exp(\beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + ... + \beta_n X_n) \quad (11)$$

Where 'h_o' is the hazard at base time while 'h(t)' is the hazard at any given time, X_1, X_2, X_3, …, X_i are the possible risk factors of tire aging, such as tire age, mileage, tire types, tire status (Original, Replacement, or New, ORN) , tire position,…etc., β1, β2, …βi are regression parameter associated with the possible risk factors, and especially '$\exp(\beta_i)$' can be regarded as the relative hazard ratio associated to the risk factor of X_i when X_i is modeled as categorical data. In Eq. (11), the combined risk factor that correlates with tire age and mileage, 'Service Factor' [3], can also be considered, if tire age and mileage are not used simultaneously while assuming the possible correlation, or collinearity between the tire age and mileage, although the interpretation of 'Service Factor' is more indirect while 'tire age' and 'mileage' tend to be direct.

The following tables are obtained with SAS Procedure of 'PHReg'.[11] Table 3 comes from a modeling of 'step-load' data, and Table 4 comes from modeling 'step speed' data. Relatively small sample size makes it difficult to include multiple variables in Cox model.

Table 3: Cox Modeling of Hazard Ratios

Factor	p-value	Hazard ratio
Tire Age	0.03	0.78
Mileage	0.02	1.46
position	0.24	1.20

Table 4: Cox Modeling of Hazard Ratios

Factor	p-value	Hazard ratio
Tire Age	0.42	1.12
Status- ORN	0.04	0.66
Initial Loads	0.34	0.71
Mileage	0.20	1.32

One simple interpretation about 'Mileage' factor of Table 3: tires in a higher mileage group (20000 km vs. 10000 km group, for instance) have the aging risk 1.46 times (or 46% higher) compared with lower mileage group tires, with a significant p-value of 2%. Relatively small samples make it more difficult for Cox model with multiple risk factors.

Conditional probability of each risk predictor, X_i (such as tire age, mileage), or weight of each

predictor can be obtained from regression parameters and is as follows [5, 8] –

$$W_i = \frac{\exp(\beta_i X_i)}{\sum_{j=1}^{n} \exp(\beta_j X_j)} \quad (12)$$

The 'partial likelihood function', ℓ, is expressed as the product of all 'Conditional Probability of (X_i)'as the following formula that is similar to "Matched Case-Control" studies [5, 8] –

$$\ell = \prod_{i=1}^{m} \frac{\exp(\beta_i X_i)}{\sum_{j=1}^{n} \exp(\beta_j X_j)} \quad (13)$$

$$= p_{age}\, p_{mileage}\, p_{load}\, p_{pos}\, p_{type}\, p_{temp}$$

The tires are aging or failing faster if the above partial likelihood function ,ℓ, reached the maximum value, or conditional probability of each risk conditional probability, p_{age}, $p_{mileage}$, .., reaches a maximum value, *simultaneously*.

Three analytical methods used in this paper: Kaplan-Meier survival probability S(t) plots, Weibull failure probability F(t) Plots, and Cox Proportional Hazard, h(t), have the internal links to each other (as shown by Figure 11), and three approaches provide similar results of tire aging trends, and each model gives a point of view from different perspective. Some researchers are more interested in product failure rates from Weibull model, F(t), and the others may pay more attentions to survival rates over time from Kaplan-Meier curve, S(t), and relative hazard ratios, $h_1(t)/h_2(t)$, of various risk factors. Cox model studies the relative risks clearly as logistic model, and is a popular tool modeling reliability time data. [8]

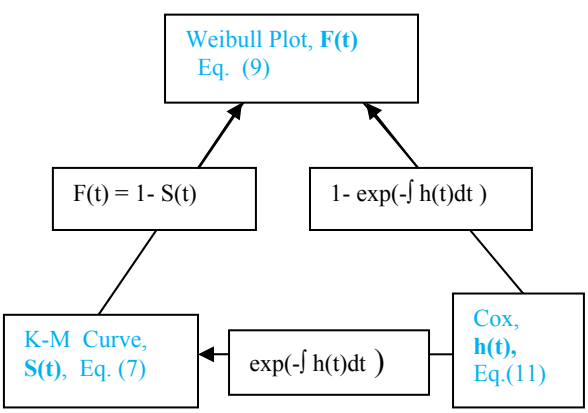


Figure 11 Linking Three Survival Models

CONCLUSIONS

- Greater chronological age tires are aging or failing faster than new tires, especially when tires older than five years are compared with new tires.
- Tires with higher mileages have higher aging risks.
- Different tire types or manufacturing characteristics lead to different aging risks. Also, tires with higher initial loads are prone to fail earlier.
- However, tires located at either front or rear vehicle positions have similar failure rates.
- Three analytical models discussed here, Kaplan-Meier survival curves, Weibull failure probability plots, and Cox Proportional Hazard Model, have the internal links to each other, and provide similar results.
- The statistical modeling of two data sets, step load and step speed, may provide different trends or statistical significances for certain parameters, and larger sample sizes may help multiple variable modeling. Furthermore, the tires studied are from the warmer Arizona area, and may have different characteristics from the tires of other areas.

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