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# FINITE ELEMENT ANALYSIS AND RELIABILITY STUDY OF MULTI-PIECE RIMS

Sandeep Chodavarapu
*University of Kentucky*, sandeepchodavarapu@yahoo.co.in

## ABSTRACT OF THESIS

# FINITE ELEMENT ANALYSIS AND RELIABILITY STUDY OF MULTI-PIECE RIMS

Multi-piece wheels or rims used on large vehicles such as trucks, tractors, trailers, buses and off-road machines have often been known for their dangerous properties because of the large number of catastrophic accidents involving them. The main causes for these accidents range from dislocation of the rim components in the assembly, mismatch of the components, manufacturing tolerances, corrosion of components to tires.

A finite element analysis of a two-piece rim design similar to one manufactured by some of the prominent rim manufacturers in the USA is undertaken. A linear static deformation analysis is performed with the appropriate loading and boundary conditions. The dislocation of the side ring with respect to the rim base and its original designer intent position is established using simulation results from ANSYS and actual rim failure cases.

Reliability of the multi-piece rims is analyzed using the failure data provided by the rim manufacturers in connection with a lawsuit (Civil Action No. 88-C-1374). The data was analyzed using MINITAB. The effect of an OSHA standard (1910.177) on servicing multi-piece rims was studied for change in failure patterns of different rims. The hazard functions were plotted and failure rates were calculated for each type of rim. The failure rates were found to be increasing suggesting that the standard had minimal effect on the accidents and failures. The lack of proper service personnel training and design defects were suggested as the probable reasons for the increasing failure rates.

Keywords: Multi-piece rims, accidents, finite element analysis, reliability, OSHA.

Sandeep Chodavarapu

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# FINITE ELEMENT ANALYSIS AND RELIABILITY STUDY OF MULTI-PIECE RIMS

By

Sandeep Chodavarapu

Dr.O.J.Hahn

------------------------------------------

(Director of Thesis)

Dr. George Huang

------------------------------------------

(Director of Graduate Studies)

12/09/2004

------------------------------------------

(Date)

# RULES FOR THE USE OF THESES

THESIS

Sandeep Chodavarapu

The Graduate School

University of Kentucky

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THESIS

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A thesis submitted in partial fulfillment of the requirements
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By

Sandeep Chodavarapu

Lexington, Kentucky

Director: Dr.O.J.Hahn, Professor of Mechanical Engineering

Lexington, Kentucky

2004

In loving memory of my mother,
Lakshmi Chodavarapu

# ACKNOWLEDGEMENTS

*Guru Brahma Gurur Vishnu*
*Guru Devo Maheshwaraha*
*Guru Saakshat Para Brahma*
*Tasmai Sree Gurave Namaha*

Meaning: Guru (the teacher) is verily the representative of Brahma (the creator), Vishnu (the sustainer) and Shiva (the destroyer). He creates, sustains knowledge and destroys the weeds of ignorance. I salute such a Guru.

The above Sanskrit verse is well known in Indian culture to truly honor a Guru (teacher). I am deeply indebted to my Guru, Dr.O.J.Hahn for providing me an opportunity to grow in every aspect of my life under his able guidance. I thank him from the bottom of my heart for having given me a chance to be a part of this research. I have greatly benefited from my long hours of interaction with him each day. He has been a father figure to me ever since I set foot in the United States of America. He has pulled me out of many ignorant situations and has immensely supported and inspired me during my personal tragedy. I am at loss of words to truly honor such a great and exceptional man.

I am deeply obliged to Dr. Kozo Saito and Dr. J.D. Jacob for having agreed to be on my Thesis Committee. They have provided outstanding insights that have guided me to deliver a much better work. Their critical review is gratefully acknowledged.

It is only the unparalleled love, support and vision of my parents that has made this work a reality. I dedicate this work to my mother, Lakshmi Chodavarapu who has been my source of strength since childhood. She laid a strong foundation to my future, inspired me to take up engineering as a career and has sacrificed her life for my studies. I wish she was alive to see my work. I hope to keep up to her aspirations and pray for her soul to rest in almighty peace. My father, Saradhi Chodavarapu is another great person without whom this document would not have been a reality. He has endured many a difficult and testing times in life to help me achieve my goals. My brother, Kuldeep Chodavarapu deserves all the love and credit for his constant support and encouragement. Finally, I would like to thank all my friends who have understood and motivated me during the course of this work. It is their unconditional love that has sustained me through the last couple of years.

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# CHAPTER ONE

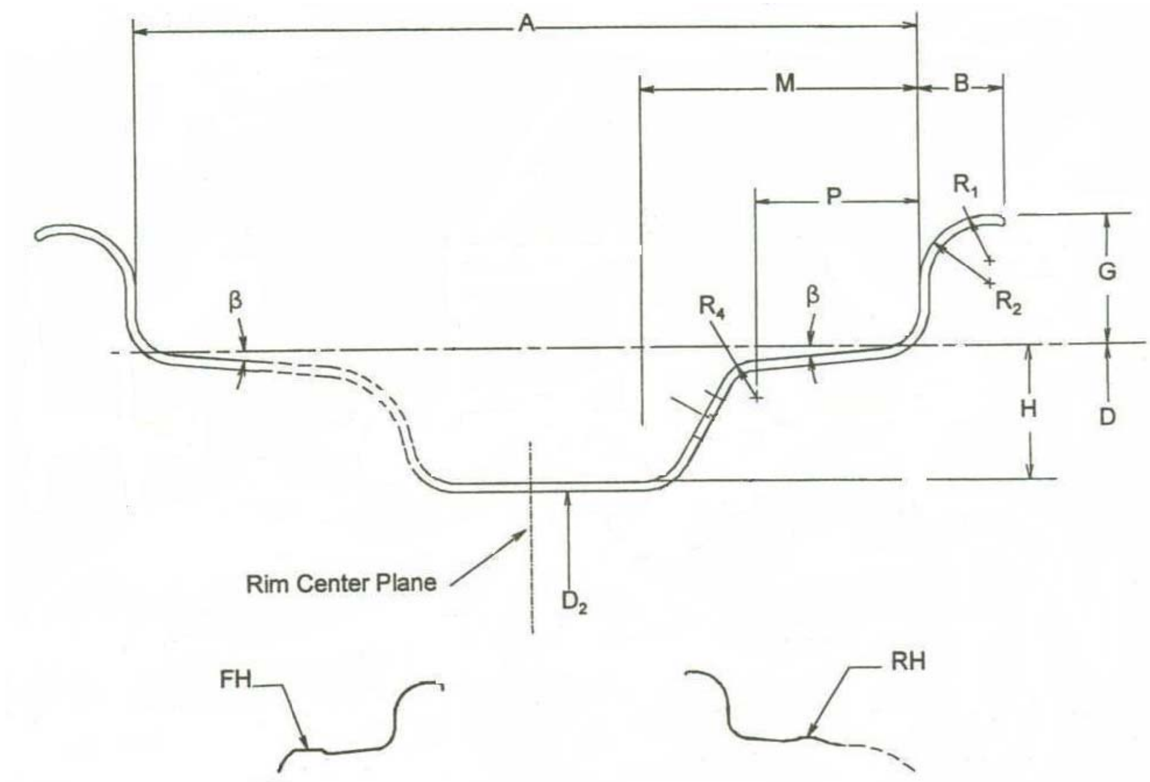
# INTRODUCTION

## 1.1 BACKGROUND

The earliest known wheel to the modern civilization was believed to be over fifty-five hundred years old, found in archeological excavations in what was Mesopotamia. Over the centuries, wheels have undergone gargantuan changes in manufacturing and application technology. We have moved over from the initial wooden wheels to manufacturing steel wheels to using different alloys for the same purpose for various functions and advantages. Successful designs have been established after years of experience, research and testing. These improvements have been aided by the development of several new scientific and analytical methods. The exact operating conditions can be simulated by finite element methods and computer programs. The reliability and safety considerations in operating a wheel can be configured with diverse analyses methods. The wheel over the centuries has come to become an inseparable part of human civilization. Wheels are also one of the most important components of automobiles from the view point of structural safety. As a result, wheels must be certified to have sufficient safety margins even under severe driving and operating conditions. Moreover, since other requirements such as lighter weight or more attractive design make the configuration of the wheel more complicated and sophisticated, it has become necessary to perform rigorous strength evaluations of the wheel in detail when a new wheel design is developed. A well designed wheel is the foundation which adds strength, stability and durability to a tire. Hence, the increased urge to make them safer and reliable.

## 1.2 WHEEL AND RIM ASSEMBLIES

The wheel, according to the SAE standard, SAE J393 OCT 91 is defined as a rotating load-carrying member between the tire and the hub. The main components of a wheel are the rim, the tire and the disk or the spokes. The rim and the tire in a wheel assembly are specially matched components. The hub is the rotating member that represents the attachment face for wheel discs. The rim is defined as the supporting member for the tire or tire and the tube assembly. The disc wheel is a permanent combination of the rim and the disc. The disc or the spider is defined as the center member of a disc wheel. There have been many rim designs in use. They can be broadly classified into- a single piece rim and a multi-piece rim. A single-piece rim is a continuous one-piece assembly. The multi-piece rims are essentially two or more pieces assembled together according to a concentric fit design. The assembly consists of a rim base and either a side ring or a side and lock ring depending on the number of pieces making the whole rim. In two-piece assemblies, the side ring retains the tire on one side of the rim. The fixed flange supports the other side. The side ring in a two-piece assembly could be either continuous or split. The split side ring is designed so that it acts as a self-contained lock ring as well as a flange. Some of the rims have a drop centre, where the central portion of the rim base is a drop of a certain angle from the main contour of the rim. The area where the drop starts is usually a hump which is of two types- Flat Hump (FH) or the Round Hump (RH). The rim is designated by either one of these along with the angle of the drop. A couple of these types have been illustrated in the figure below.




Dimensions: A – Rim width

B – Flange width

D – Rim diameter

$D_2$ – Rim inside diameter

G – Flange height

H – Well depth

M – Well position

P – Bead seat width

$R_1$ – Flange compound radius

$R_2$ – Flange radius

$R_4$ – Well top radius

FH – Flat hump

RH – Round hump

β – Bead seat angle

Figure 1.1: Rim

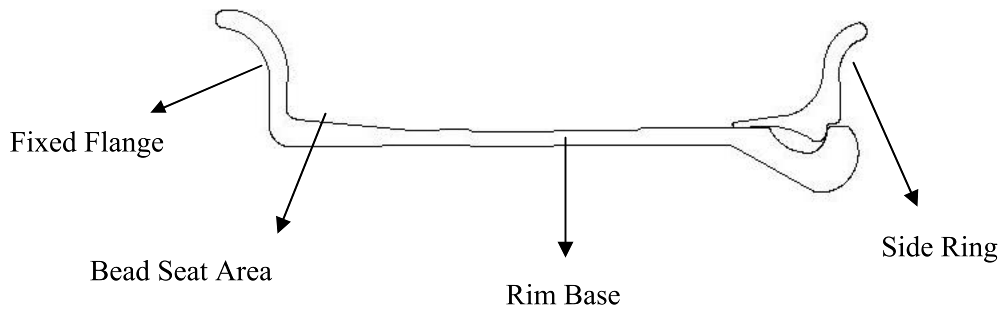



Figure 1.2: Two-piece rim outline.

In three-piece assemblies, the flange or continuous side ring supports the tire on one side of the rim. The continuous side ring is, in turn, held in place by a separate split lock ring. All lock rings are split. In three-piece assemblies, the lock ring is designed to hold the continuous side ring on the rim.

The safety or efficient operation of the rims relies to a large extent on the component parts of the rims. Some of the main causes for concern are the deformation of the rim base and the side ring. The deformation would not result in a good fit of the assembled parts and would thus lead to a failure. Mismatch of the components during the assembly is also an important cause for concern. The other major factors affecting the safety are the changes in the manufacturing tolerances for the components, road hazards, corrosion of the component materials and the tires. The safe operation of the tires play an important role in reducing the danger associated with the rims. The process of mounting a tire onto a rim is a very crucial process. It could lead to a potentially life threatening situation. The improper inflation and also the deflation of the tires also affect the safety of the rims. The multi-piece rims are essentially a concentric fit of two interlocking parts. If any of them are not in the precise location of the designer's intent when the rim and the tire assembly is inflated, it may result in a separation of the rim components.

The present work concentrates more on the stress and concentric displacement analysis of the two-piece rim components in use.

### 1.3 OBJECTIVE

Multi-piece wheels or rims used on large vehicles such as trucks, tractors, trailers, buses and off-road machines have often been known for their dangerous properties. This is because of the large number of catastrophic accidents that they have been involved in. The accidents have in most cases resulted in serious injury or even death to the workers. The main problem with these types of rims is when the tire is mounted or demounted from the rim, the assembly blows off. The cause of the actual blow off varies from mismatch of the parts during the assembly, wear of the components and improper design. Numerous product liability lawsuits have been put up seeking compensation for the damages and the complete removal of these rims from the market. Though there has been a strong demand for a ban on the multi-piece rims, the wheel industry was successful in avoiding it by supporting an awareness and educational program brought out by the Occupational Safety and Health Administration (OSHA). The OSHA introduced a guideline in 1980 for servicing multi-piece and single rims. This guideline contains the servicing equipment that is recommended and the training that is required by the employee to work on the rims. It was also made mandatory to display this guideline in all the tire service stations and other places where the rims are assembled, mounted or demounted. The net result of this entire educational program was transfer of the liability from the manufacturer to the employees working on the rims.

Although OSHA guidelines require, among other things, the use of a safety cage during the tire mounting operation, accidents still occur after the wheel is removed from the safety cage, for example, when it explodes as it is being mounted on the vehicle. The warnings (which are part of the educational program) are not an adequate substitute for a safer design.

The present work seeks to analyze a two-piece rim similar to those manufactured by some of the most prominent rim manufacturers in the USA. The actual rim being analyzed is the 7.5 Type FL Rim, 2 Pc Design, Non-Demountable with and without valve hole. A linear static stress and deformation analysis would be performed to look into the areas of maximum stress development and also the areas of maximum deformation. Non-linear effects will not be considered in this investigation. Reliability of the rims and the effect of regulations enforced on the rims such as the Occupational Health and Safety (OSHA) guideline will be reviewed.

# CHAPTER TWO

# REVIEW OF PUBLISHED LITERATURE

## 2.1 BACKGROUND

The modern day truck wheel has undergone many changes in design to improve its overall performance on the road. Most of the earlier work on the analysis of tire rims was undertaken during the 1970s and 1980s. Bradley [1] traces the development of the modern truck disc wheel from the World War II times. Initially the flat base rim was the standard of the industry before 1945. In 1945 two types of rims- the advanced rim and the interim rim were introduced. The interim rim had a new side ring to the original flat base. This gave the tire additional support. The advanced rim was a three piece rim, side ring and lock ring combination. It had more advantages than the interim rim design. Bradley also discusses the development of the disc portion of the wheel, the tubed and the tubeless wheel assemblies. The bevel weld construction of the disc for weight reduction in tubed wheel assemblies is shown. The introduction of the drop centre single piece rim for tubeless tires was also discussed. The development of the duo rim has also been traced and its design features were clearly described. The duo rim could function both as a tubed or a tubeless rim.

## 2.2 STRESS ANALYSIS

Ridha [2] presented a finite element stress analysis of automotive wheels which could be applied not only to the rim but to the entire wheel. The rim cross-section was first modeled by an interconnected grid of fine triangular elements. The displacements of each element were calculated and then the strains and finally the stress distribution obtained. The formulation of the stiffness matrix of a constant strain triangular element for axisymmetric problems was given along with the modifications for non-axisymmetric problems. He concluded from the analysis that the largest principle stresses were located in the regions of sharp changes in the rim's contour, i.e., the flanges and the drop centre. He also discussed the effects of increasing the width of the rim for reducing the stress levels.

Morita et al [3] showed that the present FEM stress evaluation technique was a good and effective way to develop new designs for wheels. The induced stress of the wheel in the rotating bending fatigue test was simulated by a three dimensional finite element analysis of the wheel. The stress distribution was obtained and the results were compared to experimental results from strain gauges on a wheel. The comparison yielded similar results from both of them. The wheel that they had analyzed was a passenger car wheel (5-1/2 JJ x 14 WDC). The element used for the FEM modeling was a four-node iso-parametric shell element. The effect of different design parameters like the disc thickness, disc hat radius and rim thickness were also studied numerically. All the three parameters had an inverse proportional relation with the stress amplitude.

Stearns [4] investigated the effects of tire air pressure along with the radial load on the stress and displacement of aluminum alloy tire rims in his doctoral dissertation. The effects of providing an opening on the rim and also environmental degradation were also investigated. ALGOR was used in the modeling and analysis of the rim, which was a single piece type. Stearns' research revealed that the finite element analysis of the rim was more accurate with a brick element rather than a shell or a plate element. Critical areas were identified both on the rim and the disc. The Von Mises stresses in the disc were found to be much lower than that in the rim. The inboard bead seat area was identified to be the area of maximum stress. The stress was however below the endurance limit for the applied loading condition. The effect of providing a square opening resulted in 10% higher stress concentration when compared to a round hole opening at the same location.

Ridder et al [5] looked into the incorporation of reliability theory into a fatigue analysis algorithm. A design algorithm had been developed and the automotive wheel assembly was taken as an example to demonstrate its application. Using the program, failure vs. cycles curves had been developed for different alloys like 1010 Steel, DP Steel and 5454 Aluminum. The effects of driver and route variations and also material processing effects have been studied. Based on the information collected and the results from the analysis, the most reliable wheel spider of the three alloys in consideration was suggested. The effects of fatigue crack growth on durability have not been dealt with. This case study was concentrated only on component reliability for determination of the best possible material for the job.

The safety and salient features of both single and multi-piece rim types in the context of field performance were discussed by Watkins and Blate [6]. The failure of multi-piece rims was discussed with a theoretical approach. They had reviewed different finite element analyses discussed above to verify adequacy of the existing design. Results of multi-piece component analysis had not been presented. Statistical analysis of accident data had also been performed. The OSHA guideline on servicing different types of rims had come out only a year earlier and the authors expected the injuries to be minimized as a result of it.

The literature review reveals that most of the analysis and studies on rims had not clearly addressed the problem of failure of multi-piece rims and the huge accident data associated with them. The OSHA guideline was expected to minimize or control the number of accidents relating to multi-piece rims. The effect of OSHA standard on the actual serviceability would be revealed by a complete statistical analysis of the data after its implementation. This review provides a clear direction to the present study.

# CHAPTER THREE

# FINITE ELEMENT ANALYSIS

## 3.1 INTRODUCTION TO FEA

The finite element method is a numerical method for solving problems of engineering and mathematical physics. Typical problem areas of interest in engineering and mathematical physics that are solvable by the use of the finite element method include structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential. This method is used to solve complex problems that are difficult to be satisfactorily solved by other analytical methods. It actually originated as a method of analyzing the stress distribution in different systems.

The concept of Finite Element Analysis was initially proposed by Courant in 1941 [7]. In a work published in 1943, he used the principle of stationary potential energy and piecewise polynomial interpolation over triangular sub regions to study the Saint-Venant torsion problem. Approximately ten years later engineers had set up stiffness matrices and solved the equations with the help of digital computers. The exact behavior of a structure at any point can be approximated by using the numerical solutions at discrete points, called nodes. The nodes are connected by the elements. The approximate solution for each element is represented by a continuous function, which leads to a system of algebraic equations. The complete solution is then generated by assembling the elemental solutions, allowing for the continuity at the inter-elemental boundaries.

There are numerous element types that could be chosen for a given structure. The selection of the appropriate element type depends on the problem at hand. An element or mesh that works fine in a particular situation may not be as good for a different situation. The engineer should select the best element for a problem understanding well both the nature of the element behavior and the problem itself. The numerical hand calculations using this method become increasingly difficult with the complexity in the geometry of the structure and with increasing number of nodes. For this reason, several finite element computer programs have been developed by research organizations that can produce reliable approximate solutions, at a small fraction of the cost of more rigorous, closed-form analyses.

Out of all the numerous computer programs currently available to analyze finite element problems, ANSYS is very popular software. ANSYS can be efficiently used to analyze a number of models in most of the above mentioned areas in engineering and mathematical physics.

## 3.2 INTRODUCTION TO ANSYS

ANSYS Inc developed and maintains ANSYS, a general purpose finite element modeling package for numerically solving static/dynamic structural analysis (both linear and non-linear), fluid and heat transfer problems as well as electromagnetic and acoustic problems.

From the available element library in ANSYS, the element used for modeling the rim section is the SOLID95 type. SOLID95 is a higher order version of the 3-D 8-node solid element SOLID45 [8]. It can tolerate irregular shapes without as much loss of accuracy. SOLID95 elements have compatible displacement shapes and are well suited to model curved boundaries. The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. The element may have any spatial orientation. Elements are generated using free/mapped/automatic meshing. The convergence of results is ensured by *refining mesh size* (increasing the number of elements) i.e. h-FEA is adopted. The p-method is more tolerant for element distortion and geometry quality such as aspect ratio, skew ness angle etc. Also the number of elements is much less compared to h-method; hence no mesh refinement is needed for complicated geometry.

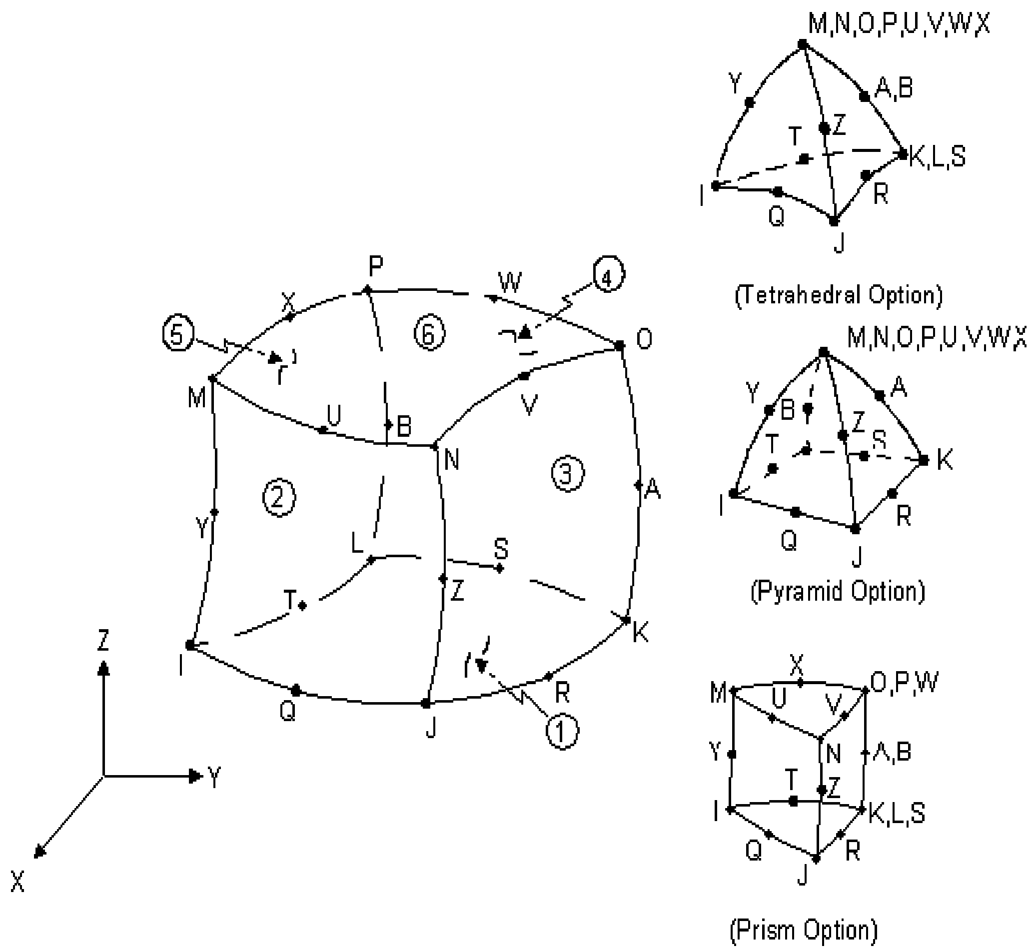



Figure 3.1: SOLID95 3-D 20-Node Structural Solid

(Courtesy: ANSYS, Inc. Theory Reference)

### 3.3 INTRODUCTION TO PRO/E

Solid modeling, as a field is the result of several convergent developments like automated drafting systems, free-form surface design and graphics and animation. The incorporation of component design intent in a graphical model by means of parameters, relationships and references is known as the parametric design. Pro/E is one of the most widely used parametric solid modeling software available today. It can be efficiently used for modeling complex parts, features and assemblies. The wheel rim is one such complex component which can be easily modeled using Pro/E.

### 3.4 MODELING USING PRO/E

The two-piece rim used for the analysis is modeled using Pro/E. The rim as already discussed contains two parts- the rim base and the side ring. The two-piece design is a concentric fit of these two combining parts. First, the rim base is modeled as a part using the 'revolve' option in Pro/E. Then, the side ring is also modeled as a part. The two parts are then assembled using the 'components assemble' option. The assembly is checked for the accurate fit of the two parts in the proper designated location. The two-piece rim is modeled as a $360^0$ solid as shown in the figure 3.2. But due to the symmetry in the geometry, a $2^0$ model is used for the analysis.

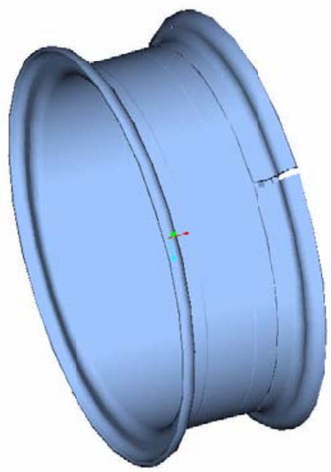


Figure 3.2: Tube-Type Demountable Rim Assembly (two-piece)

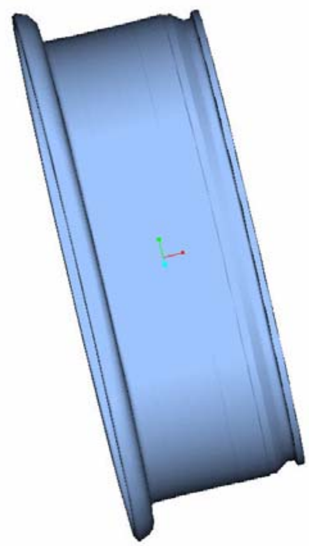


Figure 3.3: Rim Base

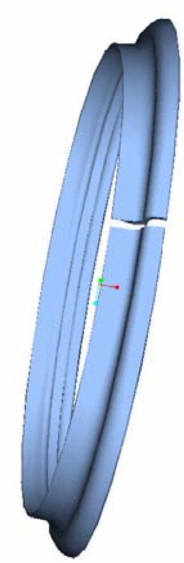


Figure 3.4: Split Side Ring

### 3.5 ANALYSIS OF TWO-PIECE RIM

The $2^0$ rim modeled in Pro/E is saved as a .iges file. It is then imported into ANSYS using the import file command. The import file command in ANSYS can import models from Pro/E in the .iges file mode.

The element type used for the model is chosen as SOLID 95 from ANSYS element menu. Previous research [4] has shown that the solid element is a better option to model the wheel and rim components than the shell elements. The model is then assigned the material properties like Young's Modulus, Poisson's ratio and density of steel. The meshing is done with the 'mesh tool' option in ANSYS. A free tetragonal mesh for volumes is generated. The total number of elements created as a result of the meshing process is 22896. Then the loading and the boundary conditions are applied to the model. The model is restrained in all degrees of freedom (ALL DOF) on the lower left side region of the rim base. This is the area where the disc or the spokes are attached or bolted to the rim connecting it to the hub. Since the $2^0$ model is used due to symmetry, the symmetry boundary conditions are applied to the side edges of each component in the two-piece assembly. A pressure loading of 90 psi is applied to the top cup surface of the model. This is the inflation pressure of the tire acting on the top surface of the rim.

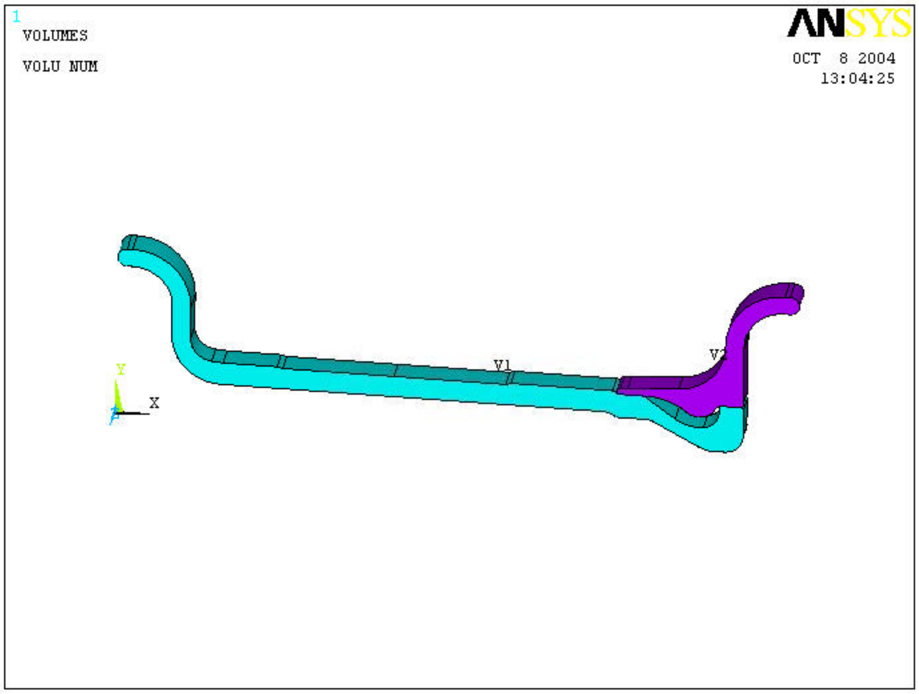



Figure 3.5: Two degree model of rim imported into ANSYS

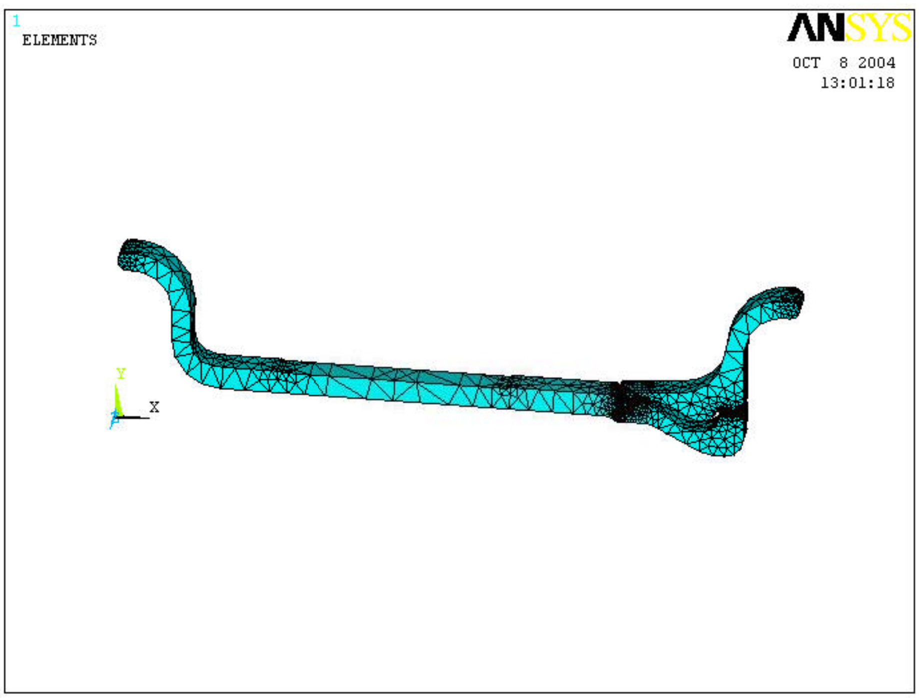



Figure 3.6: Elements generated using the meshing option in ANSYS

### 3.6 RESULTS AND DISCUSSION

The model is run for the applied boundary and loading conditions. Due to the complexity of the assembly model and the total number of the elements involved, the processing time is very high. The model solves for an approximate time of around two hours. The general post processing of the model yielded the deformation and the stress results. A result summary from the General post processing menu gave the overview of all the required results. The deformed shape of the rim assembly as a result of the pressure loading is shown below from the ANSYS plot, figure 3.7. Also, a plot of the deformed and the un-deformed shape of the assembly is shown in figure 3.8.

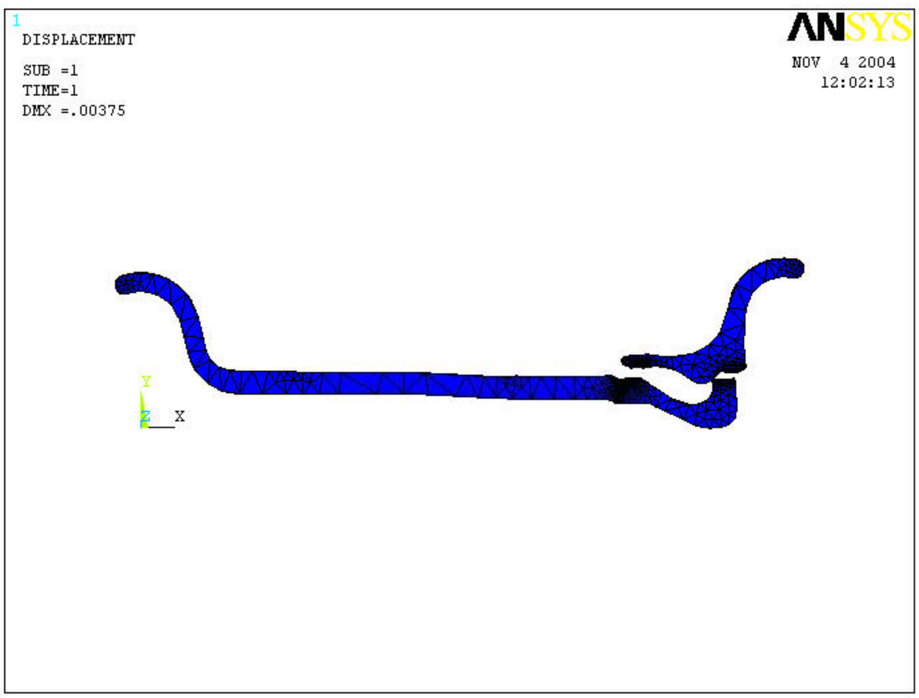



Figure 3.7: ANSYS plot of the deformed shape of the rim assembly.

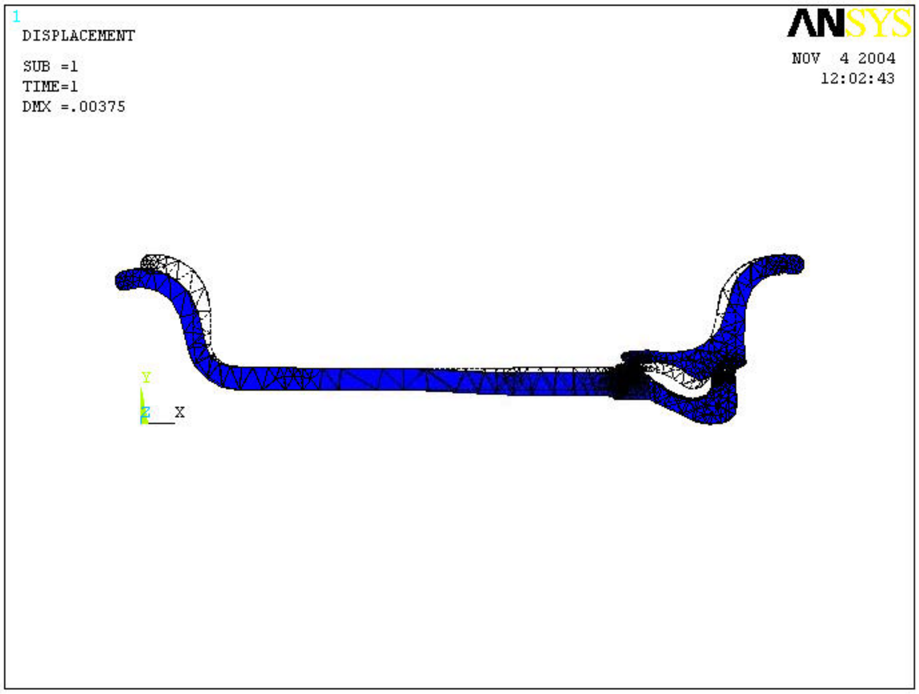



Figure 3.8: ANSYS plot of the deformed and un-deformed shape of the rim assembly.

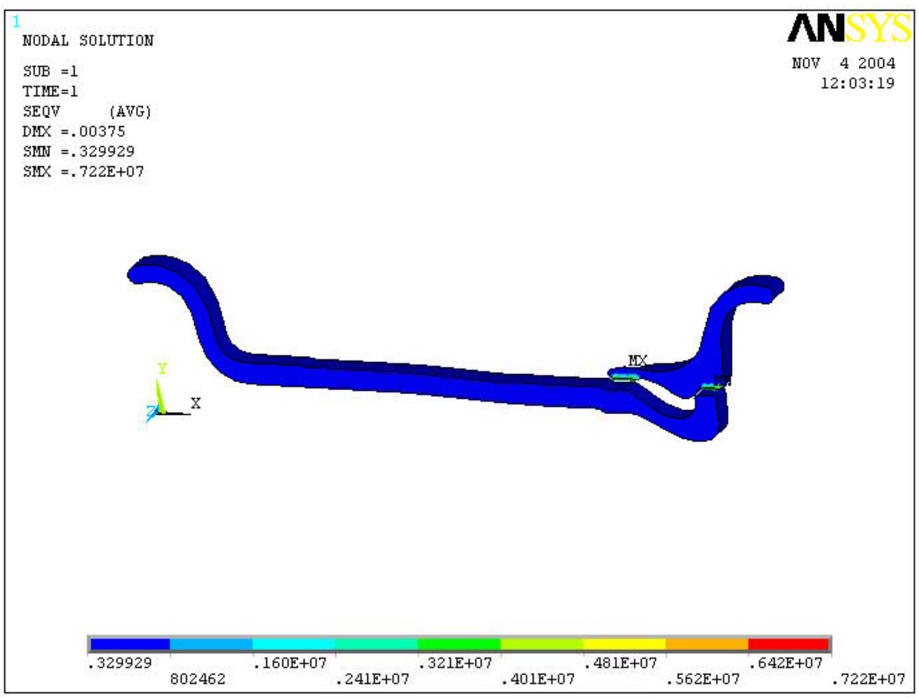



Figure 3.9: ANSYS plot of the Von-Mises stress profile of the rim assembly.

From the plots it is very clear that the assembly comes apart due to the inflation pressures of the tire on the rim. The figure 3.7 shows that the side ring is dislocated by 0.00375 inches. The tongue-in-groove principle of locking the two components, as the fit is usually referred to as, has the greatest challenge of retaining the side ring in the groove when the extreme pressure acts on the assembly. Roughly half the inflation pressures act on the side ring, imposing on it a very high force to move out of the groove. The axisymmetric inflation pressure acting on the rim produces an axial force on the side ring and also induces shearing and bending effects. The axial force causes the side ring to move in the 'x' direction and the bending moment causes it to dislocate from the original designer intent position. Also, the tire bead runs through the area of dislocation. The weakening of the tire bead, made up of drawn steel cables which carries most of the hoop stress further adds to the impulsive force against the side ring causing it to fail. The outward directed axial force acting on the side ring due to the pressure of inflation is very high and pushes the ring in the direction of the force acting. The plots from ANSYS are indicative of the type of dislocation that is expected due to the forces acting as a result of the inflation pressure.

The effect of changing the position of the side ring along the circumference of the rim base does not help the situation any further. The simulation run in ANSYS was done changing the position of the side ring, i.e., the dislocated area of the side ring is placed in a new position on the rim base and similar results have been obtained. The stress contour plot shows that the maximum stresses occur in the region of contact between the two components and the bead seat area. But due to the high stress acting on the side flange, a little deformation is observed on the base area which is in contact with the other component and through which runs the tire bead.

The results from the ANSYS simulation were checked with some actual rim failure pieces. The dislocation is very similar to the one that is obtained from the simulation. The ring or the flange is moved out of the position of intent. Figure 3.10 shows the original position of a side ring when the components are fit exactly. Figure 3.11 shows the rim components from a failure case. Clearly the movement of the ring off the base area is replicated from the ANSYS results shown in figure 3.13 and figure 3.14. The effect of changing the position of the area of dislocation was also done on the actual components and found to be not successful.

Figure 3.10: Original fit of the components in a multi-piece rim.

The figure above shows the original fit of the components in a multi-piece rim. The black portion of the picture is the side ring which is in exact concentric fit with the rim base, which is the brown portion of the picture. The side ring is snapped onto the rim base to form the exact fit. The figures 3.11 and 3.12 show the fit from a multi-piece rim whose side ring is dislocated from its original position. This is because of the effect of inflation pressures and other forces acting on it during its operation.

Figure 3.11: Dislocation of the ring portion from the rim base at position 1.

Figure 3.12: Rotational dislocation of ring portion from rim base at position 2.

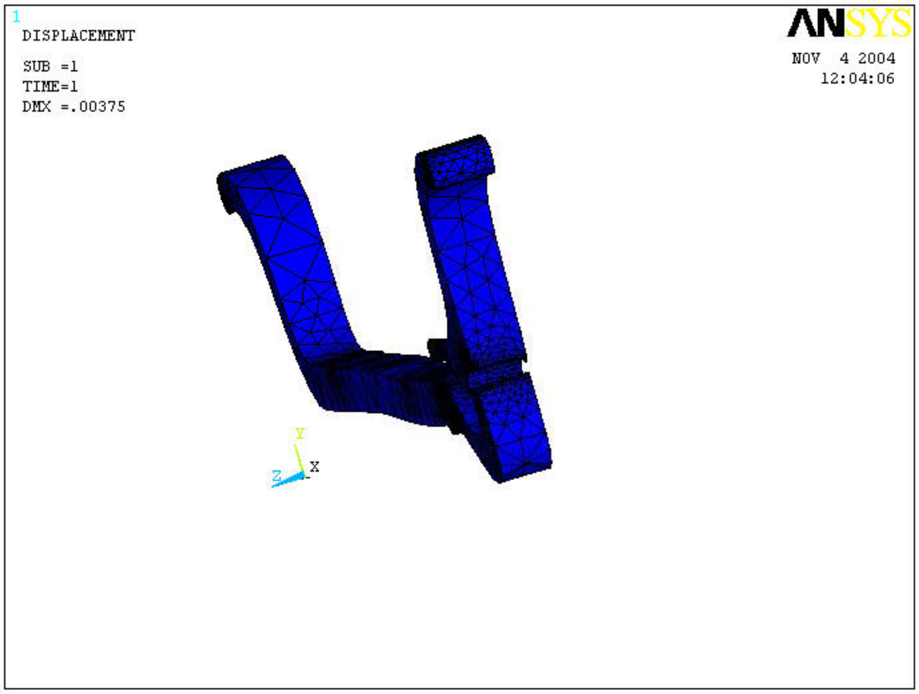



Figure 3.13: Separation of the side ring from the rim base from ANSYS simulation.

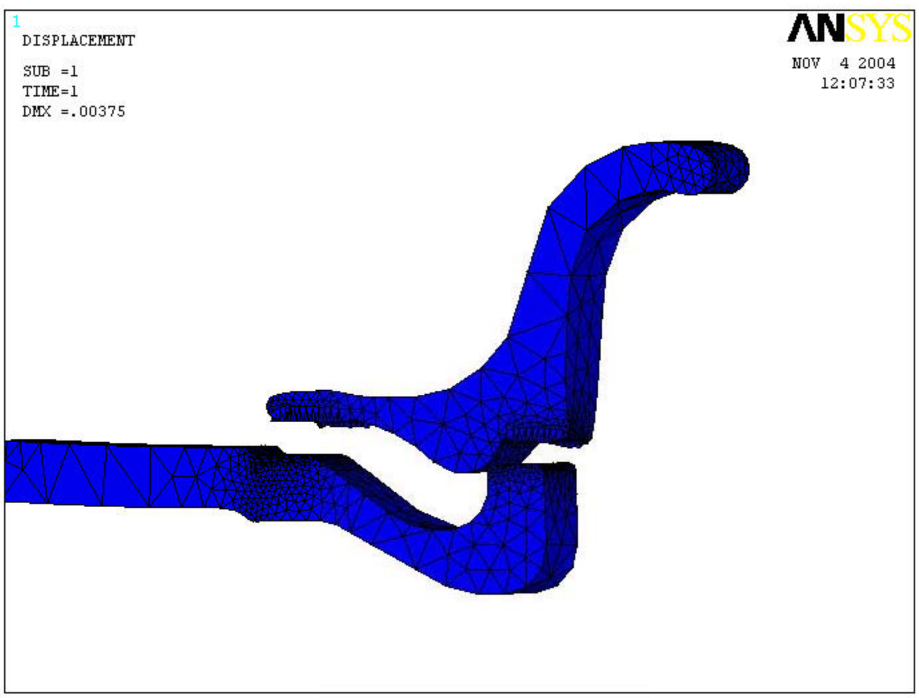



Figure 3.14: Dislocation of side ring from rim base from ANSYS simulation.

# CHAPTER FOUR

# RELIABILITY ANALYSIS

The term ‘Reliability’ is defined as the probability that a product or component can perform its desired function for a specified interval under stated conditions. The need for the reliability analysis of different components is important because of the demands for their safer operation. The data from the failures of components is initially organized into distributions and then analyzed for their failure rates, safety index etc.

## 4.1 STATISTICAL DISTRIBUTIONS

A reliability function and its related hazard function are unique. Each reliability function has a single hazard function and vice versa. All the failure related data can be fit into some of the common failure density functions, each having its related hazard function. Some of the most common among them are briefly discussed here.

### 4.1.1 Exponential Distribution:

The exponential distribution is widely used in reliability. The probability density function for an exponentially distributed random variable ‘t’ is given by

$$f(t)=(1/\theta)\, e^{-t/\theta}\ ,\ \ t \geq 0$$

where θ is a parameter called the mean of the distribution, such that θ>0, and

$$R(t) = e^{-t/\theta}\quad , \qquad t \geq 0$$

### 4.1.2 Log Normal Distribution:

The log normal density function is given by

$$f(t)=\frac{1}{t\sigma\sqrt{2\pi}}\ \exp\left[-1/2\left(\frac{\ln t-\mu}{\sigma}\right)^2\right]\quad , \qquad t \geq 0$$

where $\mu$ and $\sigma$ are parameters such that $-\infty < \mu < \infty$ and $\sigma > 0$ .

### 4.1.3 Weibull Distribution:

The cumulative distribution for a random variable, x, distributed as the three-parameter Weibull is given by,

$$F(x;\theta,\beta,\delta) = 1 - e^{-(\frac{x-\delta}{\theta-\delta})^{\beta}}, \qquad x \geq \delta$$

where $\beta > 0, \theta > 0$ and $\delta \geq 0$. The parameter $\beta$ is called the shape parameter or the Weibull slope, $\theta$ is the scale parameter or the characteristic life and $\delta$ is called the location parameter or the minimum life. The scale parameter is also sometimes indicated by η. The two-parameter Weibull has a minimum life of zero and the cumulative distribution is given by,

$$F(x;\theta,\beta) = 1 - e^{-(\frac{x}{\theta})^{\beta}}, \quad x \geq 0$$

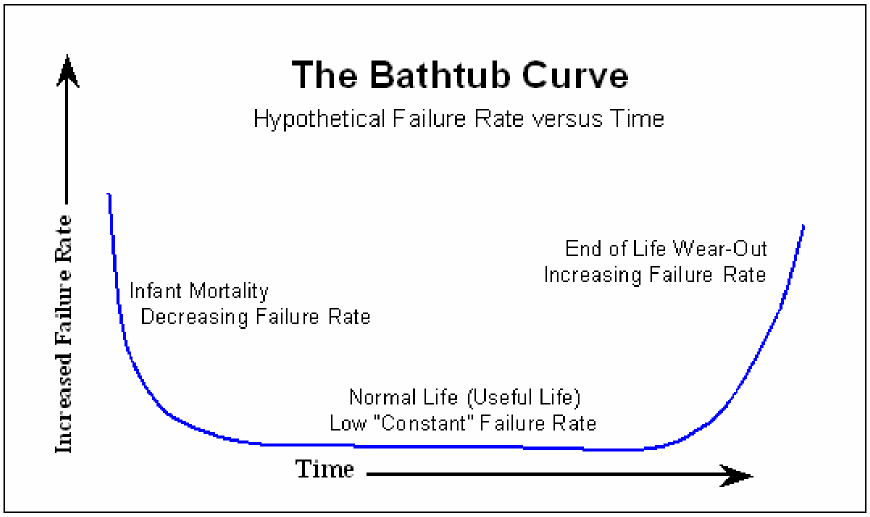
The three-parameter Weibull can be converted into the two-parameter distribution by a simple linear transformation. The Weibull probability density function for the two-parameter distribution is given as

$$f(x;\theta,\beta) = \frac{\beta}{\theta}(\frac{x}{\theta})^{\beta-1} e^{-(\frac{x}{\theta})^{\beta}}, \quad x \geq 0$$

The hazard function is given by

$$h(x) = \frac{\beta}{\theta}(\frac{x}{\theta})^{\beta-1}, \ x \geq 0$$

The hazard function is decreasing when $\beta < 1$ , increasing when $\beta$ >1, and constant when $\beta$ is exactly 1. The hazard function h(x) will change over the lifetime of a population of products somewhat as shown in the figure below. The first interval of time represents early failures due to material or manufacturing defects. Quality control and initial product testing usually eliminate many substandard devices, and thus avoid this initial failure rate. Actuarial statisticians call this phase of the curve “infant mortality”. The second phase of the curve represents chance failures caused by the sudden stresses, extreme conditions, etc. In actuarial terms this could be equated to the accidents encountered by the population of individuals on a day-to-day basis. The portion of the curve beyond this region represents wear out failures. Here the hazard rate increases as equipment deteriorates.




**4.2 GOODNESS-OF-FIT TESTS**

The failure data which is modeled into different distributions can be tested for the best fit distribution using a couple of methods. These are the Anderson Darling Test and the Goodness-of-fit test for a statistical distribution.

The Anderson-Darling test [9] is used to test if a sample of data came from a population with a specific distribution. It is a modification of the Kolmogorov-Smirnov (K-S) test and gives more weight to the tails than does the K-S test. The K-S test is distribution free in the sense that the critical values do not depend on the specific distribution being tested. The Anderson-Darling test makes use of the specific distribution in calculating critical values. This has the advantage of allowing a more sensitive test and the disadvantage that critical values must be calculated for each distribution. Currently, tables of critical values are available for the normal, lognormal, exponential, Weibull, extreme value type and logistic distributions. This test is usually applied with a statistical software program that will print the relevant critical values. The Anderson-Darling test is an alternative to the chi-square and K-S goodness-of-fit tests.

The Anderson-Darling test statistic is defined as

$$A^2 = -N - S$$

where $$S = \sum_{i=1}^{N} \left(\frac{2i-1}{N}\right)[\ln F(Y_i) + \ln(1 - F(Y_{N+1-i}))]$$

'F' is the cumulative distribution function of the specified distribution and $Y_i$ are the ordered data.

The critical values for the Anderson-Darling test are dependent on the specific distribution that is being tested. Tabulated values and formulas have been published [8] for a few specific distributions (normal, lognormal, exponential, Weibull, logistic, extreme value type 1). The test is a one-sided test and the hypothesis that the distribution is of a specific form is rejected if the test statistic, A, is greater than the critical value.

The second method for testing the goodness-of-fit is the Correlation Coefficient method. The correlation coefficient, $r^2$ (sometimes also denoted as $R^2$) is a quantity that gives the quality of a least squares fitting to the original data. It is defined by

$$r = \frac{n\sum xy - \sum x \sum y}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}$$

or can be stated in more simpler terms as $r^2 = \frac{SS_{xy}^2}{SS_{xx} SS_{yy}}$

where $SS_{xx}, SS_{yy}, SS_{xy}$ are the sum of squared values of a set of 'n' data points $(x_i, y_i)$ about their respective means. The correlation coefficient is also known as the product-moment coefficient of correlation or Pearson's correlation. The value of the maximum correlation coefficient for a set of failure data modeled using different distributions could be reasonably assumed to be the best fit distribution.

## 4.3 FAILURE DATA OF DIFFERENT TYPES OF RIMS

The large numbers of multi-piece rim accidents occurring over the last few decades have resulted in a number of product liability lawsuits being filed. The main objectives of these lawsuits were to seek the removal of the multi-piece tire rims from operation and to demand compensation for the accidents. The present set of data pertaining to the record of these wheel rim accidents has been produced by all the major rim manufacturers to The Circuit Court of Kanawha County, West Virginia, in relation to a lawsuit. The data was turned in as an exhibit in the Civil Action No. 88-C-1374 [10]. Each data file had the name of the victim and the date, time and place the accident had taken place. It also specified the type of rim causing the accident and the manufacturer in most cases. The resulting injury to the victim and the plaintiffs on behalf of the victim were also included in the details pertaining to each lawsuit. The total number of accident cases that were investigated in this study is 985. The time period involving the data was from 1955 to 1987.

The huge number of accidents involving the multi-piece wheel rims caused a lot of concern to the Occupational Health and Safety Administration (OSHA). OSHA is an organization of the U.S Department of Labor whose goal is to assure the safety and health of America's workers by setting and enforcing standards and encouraging continual improvement in workplace safety and health. OSHA initially sought to ban all the multi-piece rims but could not do so because of pressure from the wheel industry. Hence, they had brought out a standard for servicing multi-piece and single piece rim wheels in 1980 [11]. This was part of an educational program to increase the awareness among tire mounters and workers in the service stations.

The data has been thoroughly reviewed and organized into two sets. The first set of data contains the details of accidents before the OSHA guideline had come into effect and the second set of data contains the details of accidents after the guideline was enforced. A tabular format containing the number of various types of wheel rim accidents and the year of the accident for each set of data was created. The tabulated data has been first plotted for the accident curves with respect to the year of accident.

The summary of the number of cases is given below.

Total Number of Accident Cases Listed: 985.

Number of 'RH 5°' rim accidents: 411.

Number of Two Piece rim accidents: 147.

Number of Three Piece rim accidents: 43.

Number of Single Piece rim accidents: 44.

Number of Unknown rim type accidents: 340.

| Year | RH 5 Rim Accidents | Two Piece Rim Accidents | Three Piece Rim Accidents | Unknown Accidents |
|---|---|---|---|---|
| 1955 | 1 | | | |
| 1956 | | | | |
| 1957 | | | | |
| 1958 | | | | |
| 1959 | 1 | | | |
| 1960 | 2 | | | |
| 1961 | 2 | | | |
| 1962 | 1 | | | |
| 1963 | | | | |
| 1964 | 1 | | | |
| 1965 | 4 | | | |
| 1966 | 2 | | | 1 |
| 1967 | 4 | | | |
| 1968 | 4 | 2 | | 1 |
| 1969 | 11 | | | |
| 1970 | 10 | | | 4 |
| 1971 | 11 | 5 | | 8 |
| 1972 | 10 | 1 | | 13 |
| 1973 | 16 | 3 | | 27 |
| 1974 | 16 | 4 | 4 | 10 |
| 1975 | 16 | 4 | 2 | 10 |
| 1976 | 11 | 3 | 3 | 9 |
| 1977 | 23 | 8 | 2 | 22 |
| 1978 | 24 | 10 | 5 | 27 |
| 1979 | 23 | 11 | 6 | 34 |

Table 4.1: Accident statistics for different types of rims before OSHA Guideline

| Year | RH 5 Rim Accidents | Two Piece Rim Accidents | Three Piece Rim Accidents | Unknown Accidents |
|---|---|---|---|---|
| 1980 | 22 | 11 | 1 | 26 |
| 1981 | 46 | 9 | 2 | 36 |
| 1982 | 28 | 16 | 5 | 15 |
| 1983 | 29 | 17 | 5 | 21 |
| 1984 | 32 | 10 | 4 | 24 |
| 1985 | 19 | 10 | 2 | 15 |
| 1986 | 15 | 8 | | 9 |
| 1987 | 19 | 9 | 1 | 5 |

Table 4.2: Accident statistics for different types of rims after OSHA Guideline

| Year | Single Piece Accidents |
|---|---|
| 1969 | 2 |
| 1970 | |
| 1971 | 1 |
| 1972 | 1 |
| 1973 | |
| 1974 | 4 |
| 1975 | 2 |
| 1976 | 5 |
| 1977 | 4 |
| 1978 | 3 |
| 1979 | 2 |

Table 4.3: Accident statistics for single-piece rims before OSHA Guideline

| | Single Piece |
|---|---|
| Year | Accidents |
| 1980 | 5 |
| 1981 | 5 |
| 1982 | 4 |
| 1983 | |
| 1984 | 4 |
| 1985 | 1 |
| 1986 | 1 |
| 1987 | |

Table 4.4: Accident statistics for single-piece rims after OSHA Guideline

From the above data set, the failures relating to only the steel component failure are taken into consideration for the purpose of this investigation. The rubber failures like the tire blow-out during inflation or deflation, tire bead failures are eliminated. This is because the present investigation only deals with failure of rim components, i.e. steel components. The failure due to rubber is not considered here. Among the single-piece failures, the different modes of failure were found out to be failure during mounting, failure during assembly, moving vehicle incidents and separation during welding. From the above modes, only the separation during welding is considered as a steel component failure and the rest are determined to be rubber failures. Hence, looking into the separation due to welding failures in the single-piece rim data, only 1 failure was found. Thus this failure data is used for the single-piece rim analysis.

| | Single Piece |
|---|---|
| Year | Accidents |
| 1985 | 1 |

Table 4.5: Accident statistics for single-piece rims (non-rubber failures).

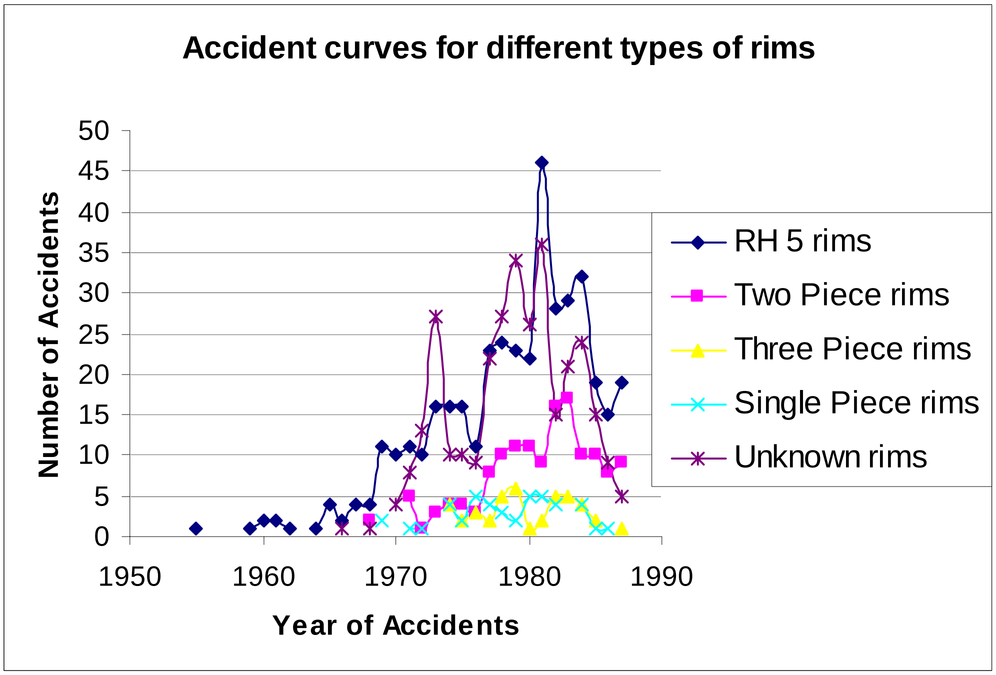



Figure 4.1: Graph for all the different types of rim accidents.

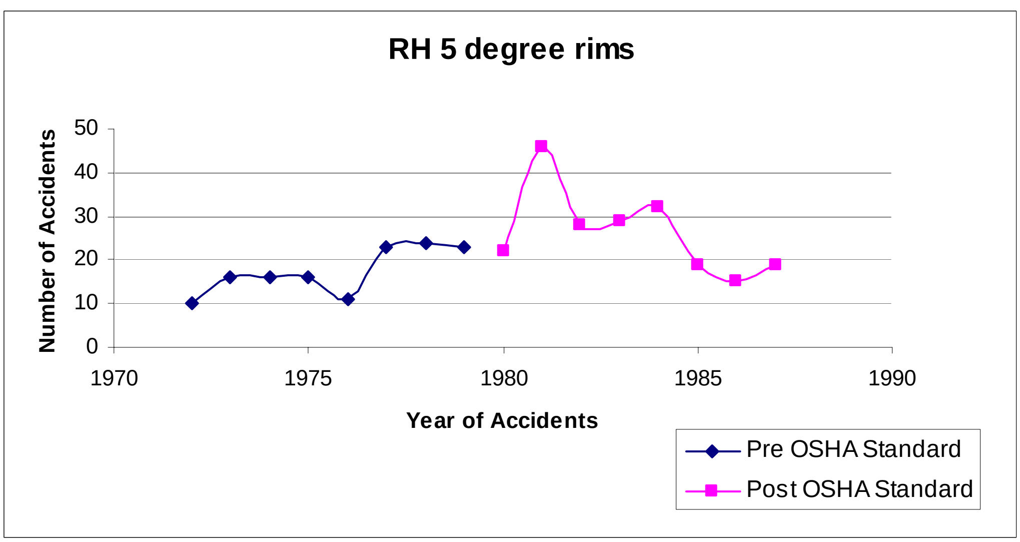



Figure 4.2: Accident Curves for RH 5 rims.

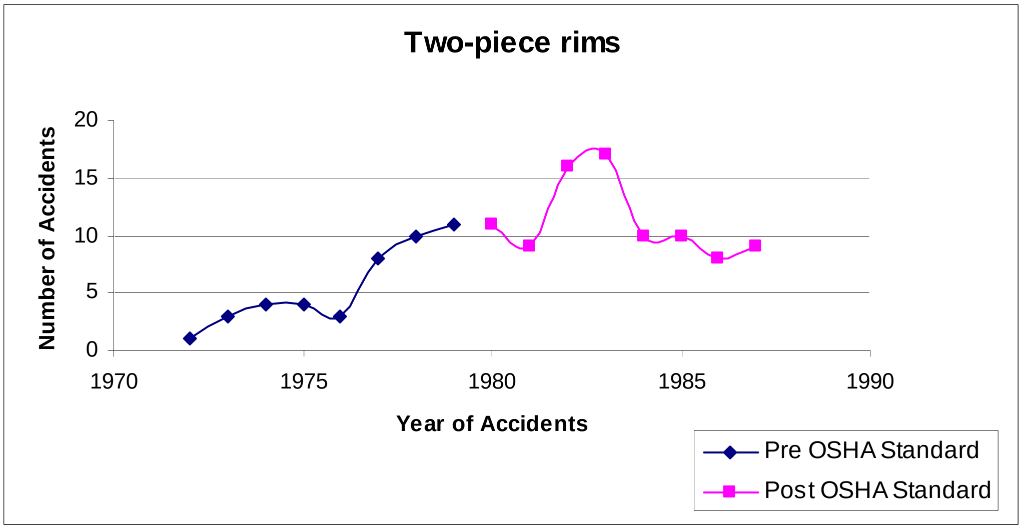



Figure 4.3: Accident Curves for Two Piece rims.

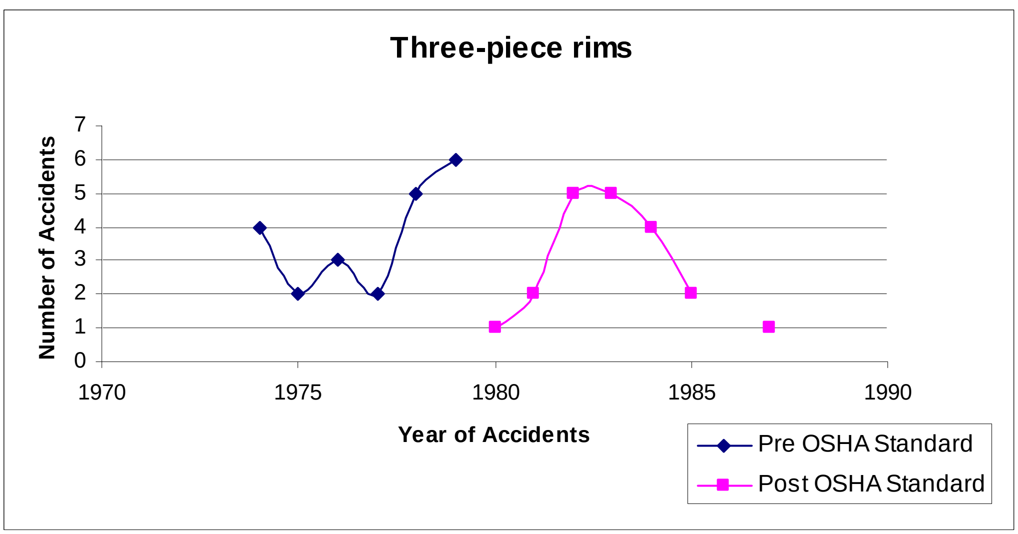



Figure 4.4: Accident Curves for Three Piece rims.

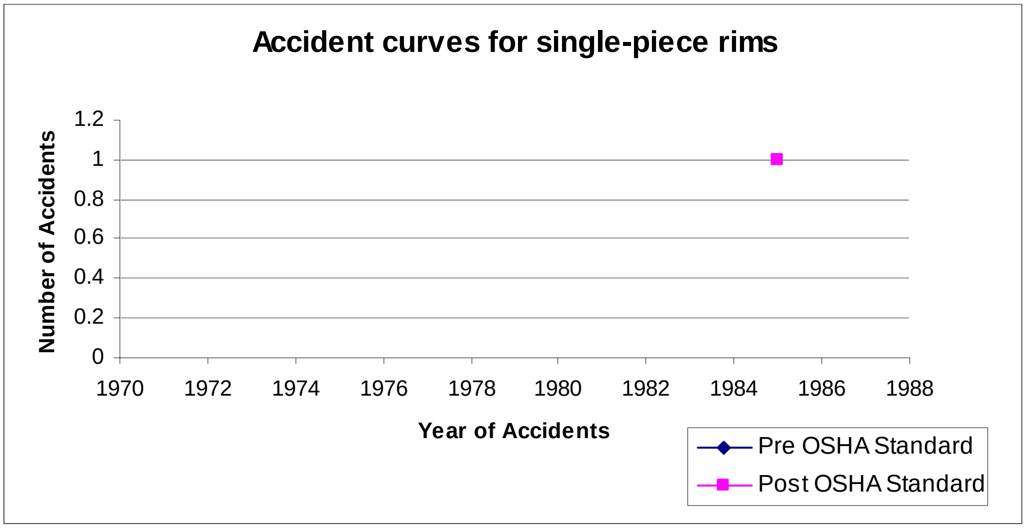



Figure 4.5: Accident Curves for Single Piece rims.

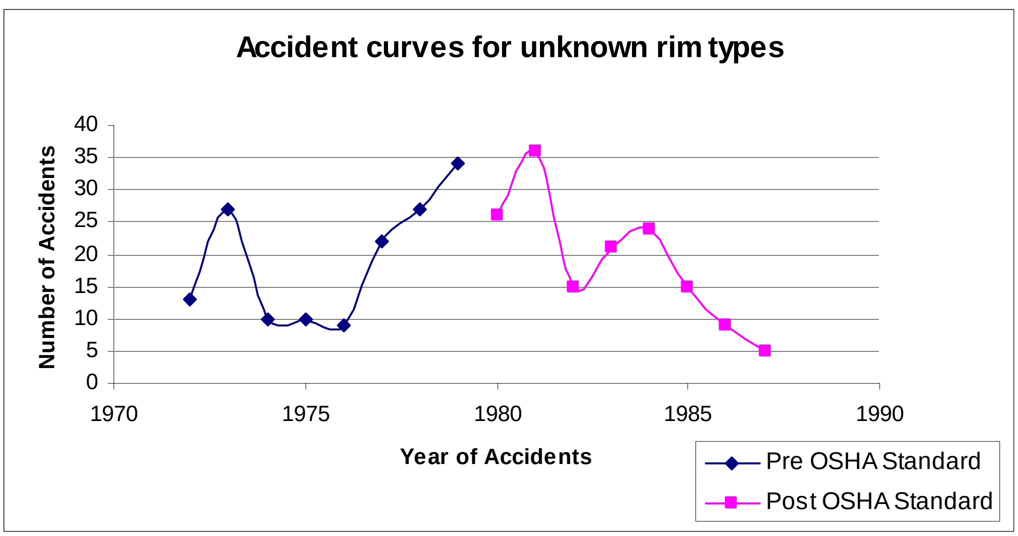



Figure 4.6: Accident Curves for Unknown type rims.

The above graphs are a simple representation of the failure data of the different rims. These graphs show that in most cases the accident curves have risen after the OSHA standard was introduced. This is particularly evident from the RH 5 degree and the two-piece rim curves.

## 4.4 ANALYSIS OF DATA USING MINITAB

The above failure data for different types of rims is analyzed using the statistical analysis software MINITAB 14. MINITAB is widely used software developed by MINITAB Inc. It can be used for various purposes like Statistical Process Control, Time Series and Forecasting, Reliability/Survival Analysis, Design of Experiments etc. [12]. Data is imported into a Minitab Project file from an Excel sheet using the options from the Minitab Software. The data is then re-grouped according to the types of rims and the year of consideration, i.e. the year in which OSHA introduced the guideline for servicing the multi-piece rims.

The data is first modeled into different distributions using MINITAB. Some of the distributions used were the 2 parameter Weibull, 3 parameter Weibull, exponential, normal, log-normal, log-logistic etc. After modeling the data, a best fit test was run. The tests used for determining the best fit were the Anderson-Darling test and the Correlation Coefficient method. For the Anderson-Darling test, the test statistic value should be the least in order for the data to best fit the distribution. The values of the computed Anderson-Darling test statistic for different rim data shows that the value for the 3 parameter Weibull is the least in most of the cases. The correlation coefficient value should be the highest, for a data to best fit the distribution. From this method also, it is sufficiently proved that the 3 parameter Weibull is the best fit distribution. The 3 parameter Weibull is widely known as the best fit distribution to model the failure data in most of the engineering situations. The values from the MINITAB analysis for the goodness-of-fit tests are given in the appendix.

Weibull distribution analysis is performed on the data. That is because mechanical products tend to degrade over a period of time and are more likely to follow a distribution with a strictly increasing hazard function. The Weibull distribution is a generalization of the exponential distribution that is appropriate for modeling lifetimes that have constant, increasing and decreasing hazard functions. A 95% confidence interval is chosen for the

Weibull analysis. The shape (β), the scale (θ) and the location (δ) parameters from the analysis of each set of data are investigated with greater detail.

The single-piece rim data used for the analysis is obtained from the Table 4.5. There is only one failure case that is appropriate to the present investigation. This data is insufficient for the analysis in MINITAB. It is difficult to perform a distributional analysis on a single point. Hence, the MINITAB plots for the single-piece rim data are not shown below.

RH 5 degree rim accident data analysis

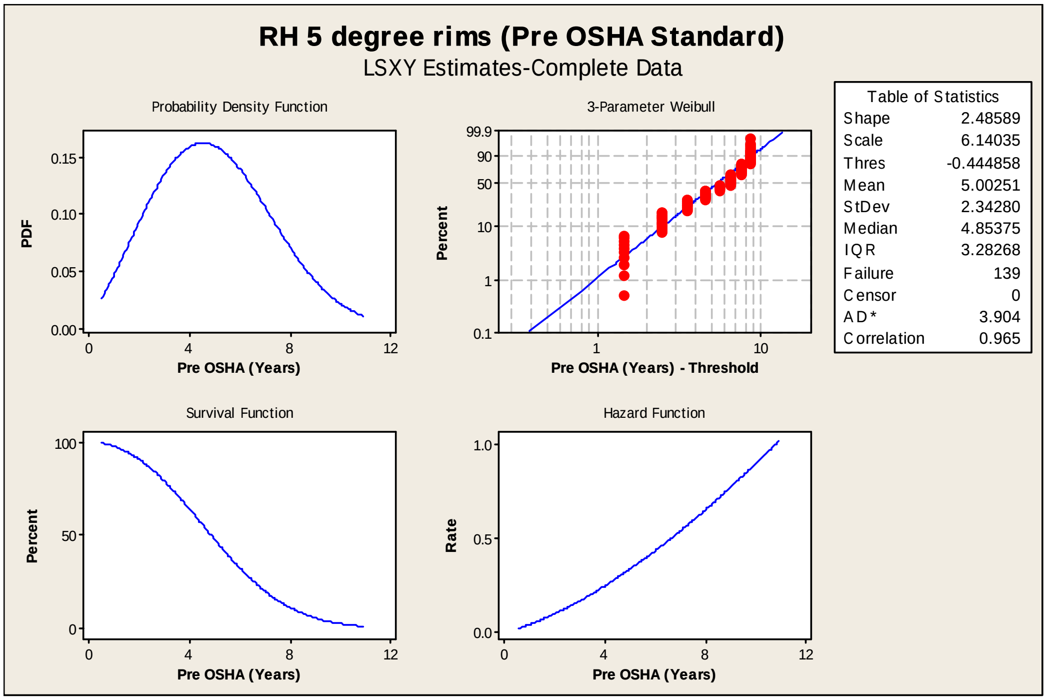



Figure 4.7: Distribution overview plot for RH 5 rim accident data (Pre OSHA Standard).

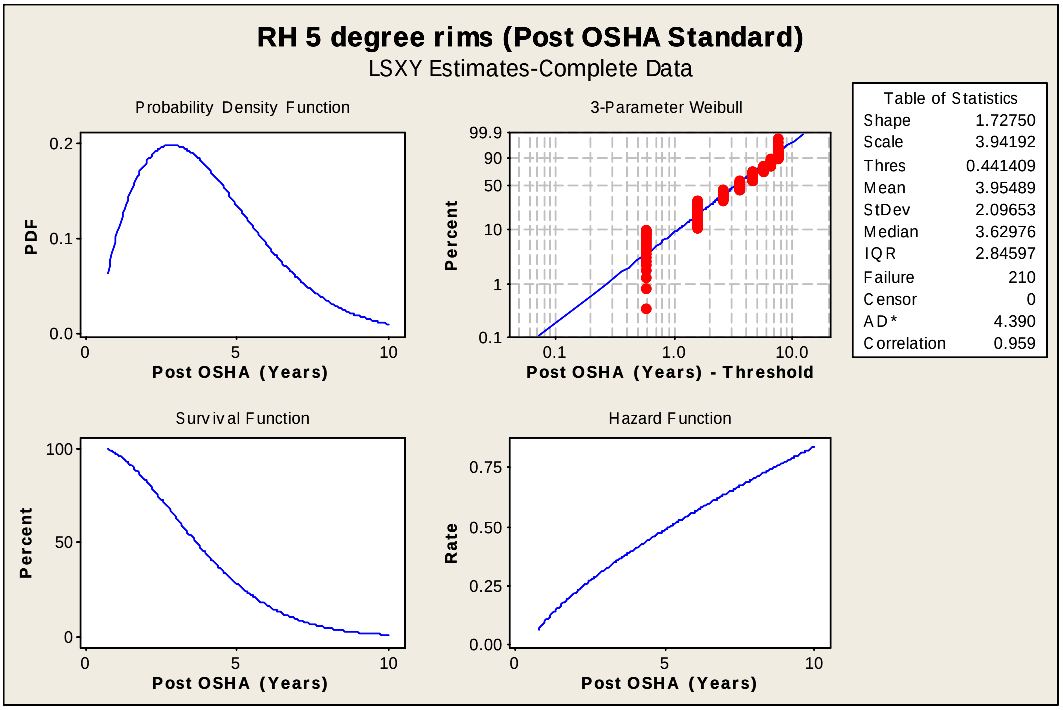



Figure 4.8: Distribution overview plot for RH 5 rim accident data (Post OSHA Standard).

Distribution Overview plot is hereafter referred to as D.O plot.

Two-piece rim accident data analysis

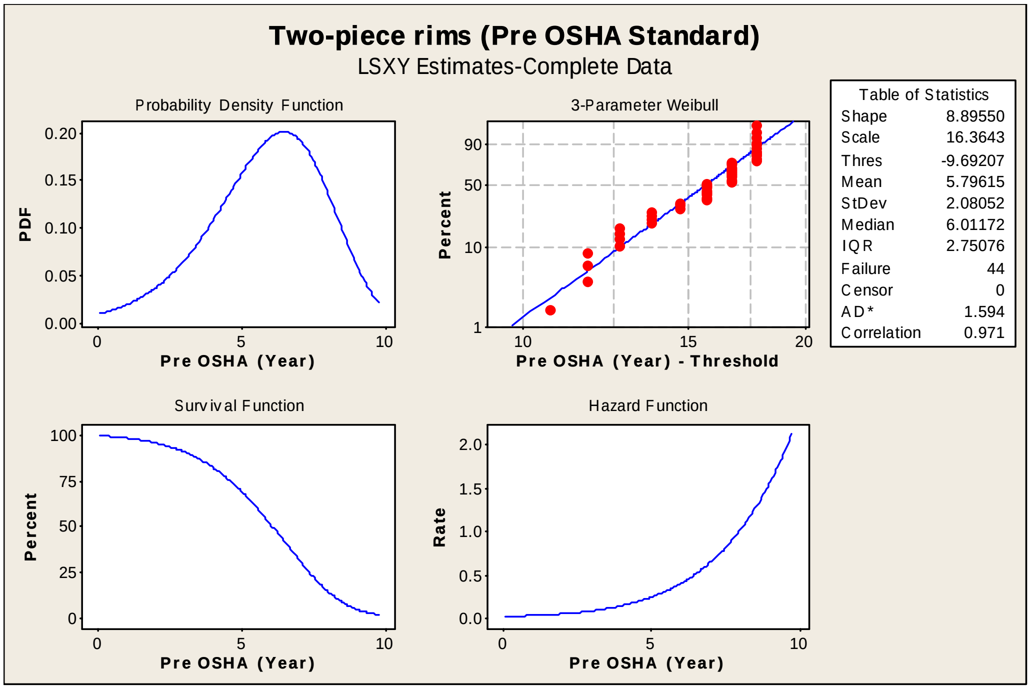



Figure 4.9: D.O plot for two-piece rim accident data (Pre OSHA Standard).

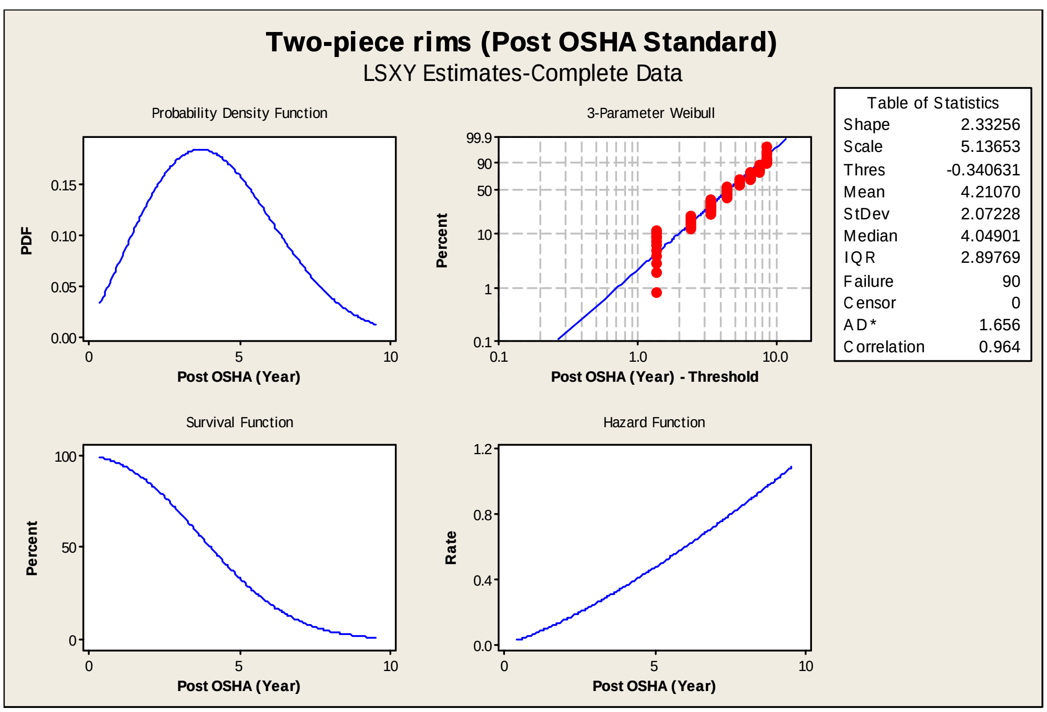



Figure 4.10: D.O plot for two-piece rim accident data (Post OSHA Standard).

Three-piece rim accident data analysis

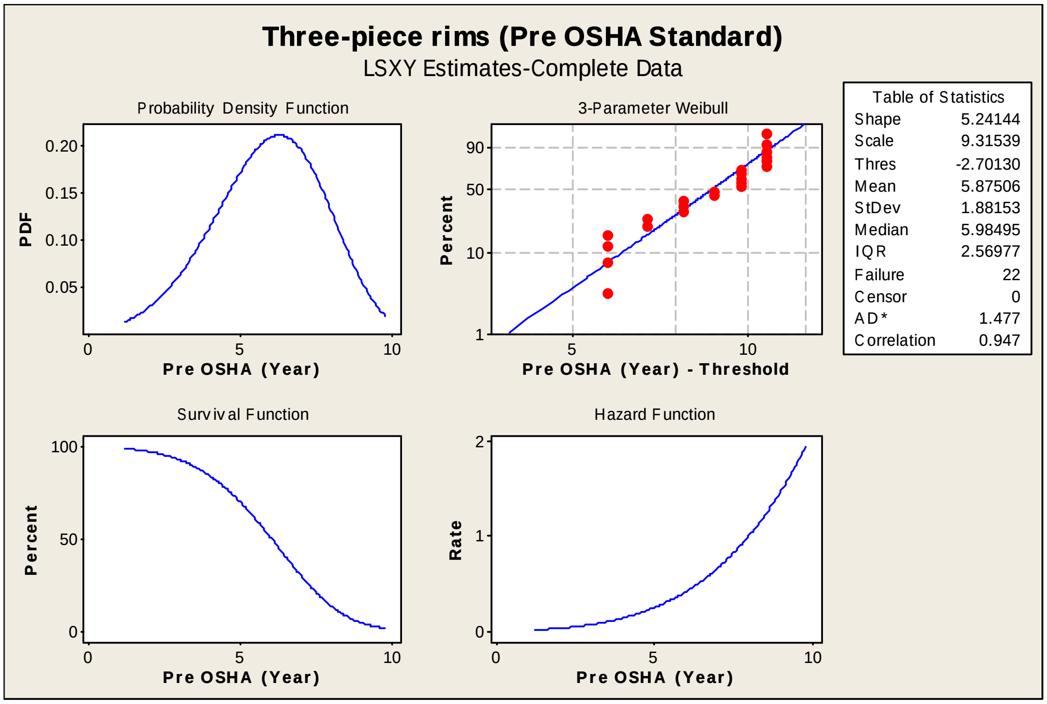



Figure 4.11: D.O plot for three-piece rim accident data (Pre OSHA Standard).

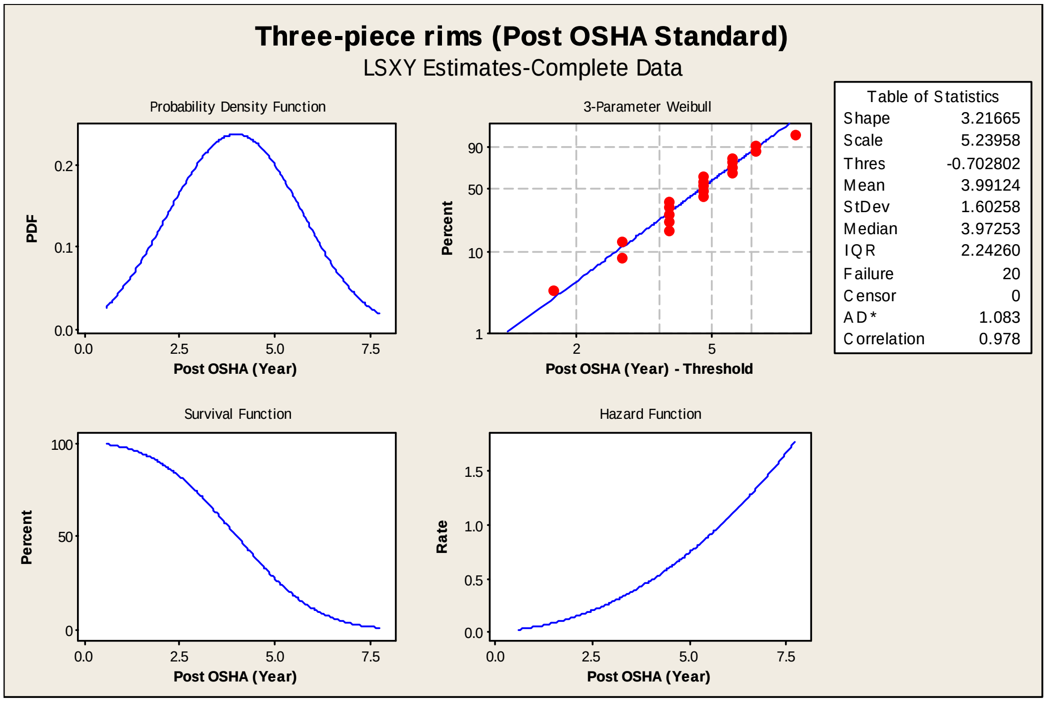



Figure 4.12: D.O plot for three-piece rim accident data (Post OSHA Standard).

Unknown rim type accident data analysis

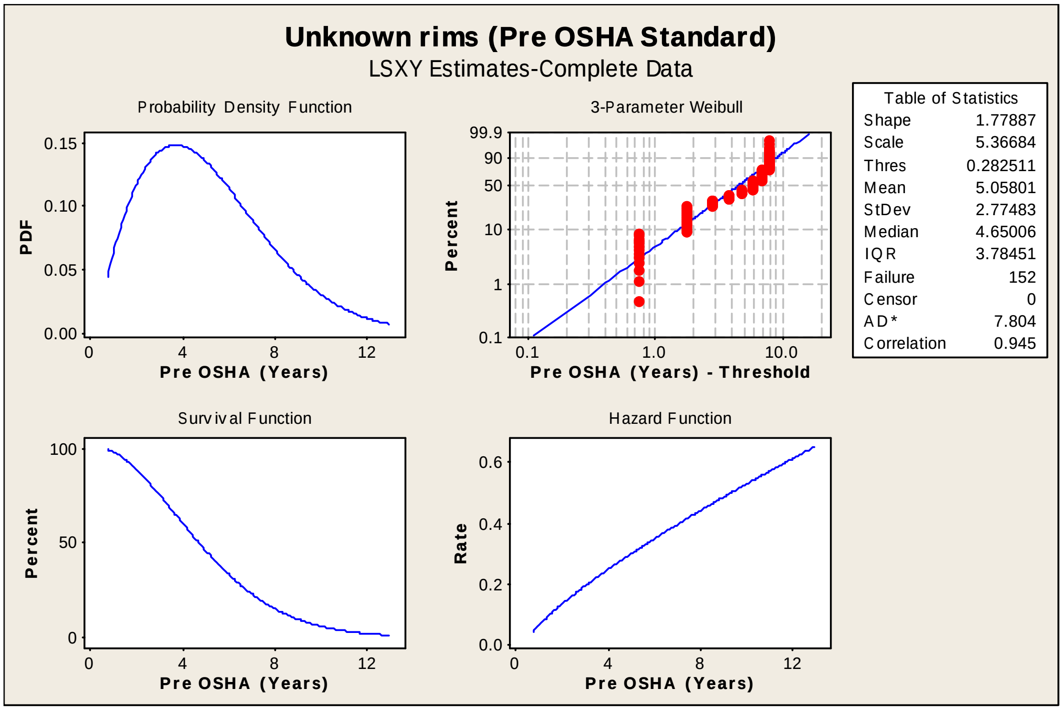



Figure 4.13: D.O plot for unknown rim accident data (Pre OSHA Standard).

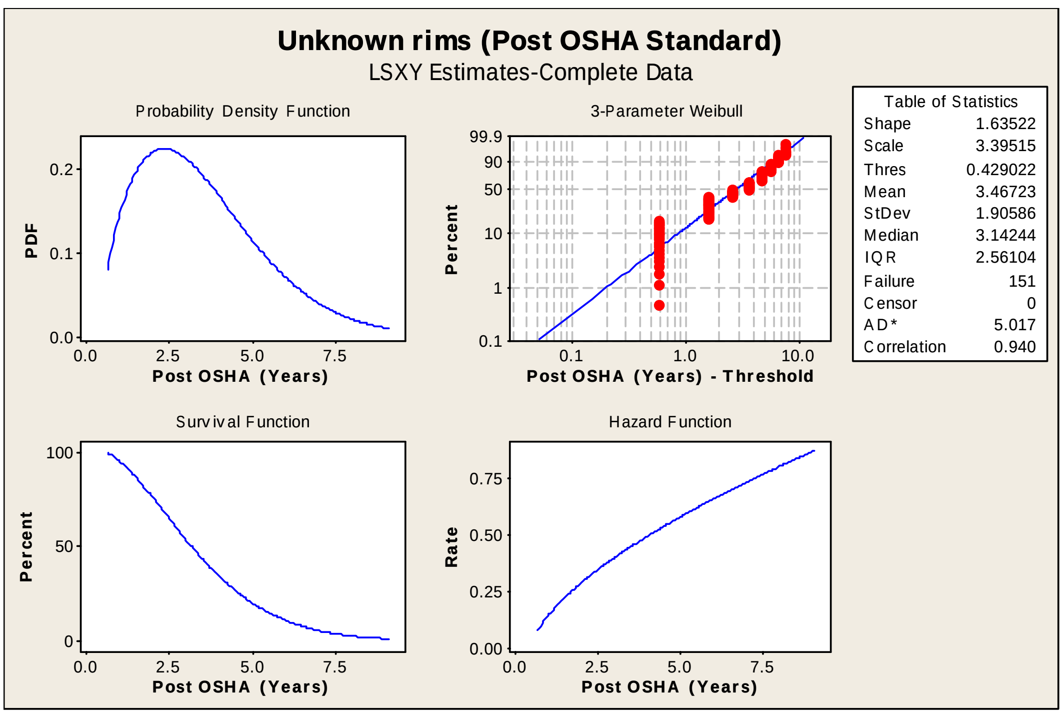



Figure 4.14: D.O plot for unknown rim accident data (Post OSHA Standard).

### 4.5 RESULTS AND DISCUSSION

The Weibull analysis from MINITAB yields the shape and scale parameter for fitting the particular data into a distribution. From the above analysis, we can state the results as follows:

| Type of rim: RH $5^o$ | | |
|---|---|---|
| Time period | Shape Parameter | Scale Parameter |
| Pre OSHA Standard (1972-1979) | 2.485 | 6.14 |
| Post OSHA Guideline (1980-1987) | 1.727 | 3.941 |

Table 4.6: Results from analysis of 'RH $5^0$' type rim data using MINITAB.

| Type of rim: Two piece | | |
|---|---|---|
| Time period | Shape Parameter | Scale Parameter |
| Pre OSHA Standard (1972-1979) | 8.895 | 16.364 |
| Post OSHA Standard (1980-1987) | 2.332 | 5.136 |

Table 4.7: Results from analysis of two-piece type rim data using MINITAB.

| Type of rim: Three piece | | |
|---|---|---|
| Time period | Shape Parameter | Scale Parameter |
| Pre OSHA Standard (1972-1979) | 5.241 | 9.315 |
| Post OSHA Standard (1980-1987) | 3.216 | 5.239 |

Table 4.8: Results from analysis of three-piece type rim data using MINITAB.

| Type of rim: Unknown | | |
|---|---|---|
| Time period | Shape Parameter | Scale Parameter |
| Pre OSHA Standard (1972-1979) | 1.778 | 5.366 |
| Post OSHA Standard (1980-1987) | 1.635 | 3.395 |

Table 4.9: Results from analysis of unknown type rim data using MINITAB.

From the above results it is clear that the shape parameter, β, is greater than 1 in all the cases. This indicates that the hazard function of the rim failures is an increasing function and the data do not represent an early-life or commissioning failures. The shape parameter, as the name implies, determines the shape of the distribution. When β is greater than 1, we can reasonably approximate the data to be characteristic of increasing failure rate or hazard function. In the case of RH $5^{o}$ type rims, the shape parameter changed from 2.485 in the time period before the OSHA guideline to 1.727 after the OSHA guideline. This implies that the failure data distribution has changed from being approximately log-normal before the guideline to somewhere in between exponential and log-normal distribution after the guideline. The β values for two-piece rim data have changed from 8.895 before the guideline to 2.332 after the guideline. The value of β for three-piece rim data before the OSHA guideline was 5.241. The β value for three-piece rims after the OSHA guideline had been introduced was obtained as 3.216. This implies that the distribution has an increasing hazard function and could be fairly approximated to be a normal distribution. The results for the single-piece rim data indicate that β changed from being 7.448 during the time when the OSHA guideline was not existent to 1.37 after 1980. Similarly, the β values for the unknown rim type data also changed from 1.778 before 1980 to 1.635 after 1980.

The distribution used for the analysis here is the 3 parameter Weibull distribution. The failure rate for a 3 parameter Weibull distribution is calculated by the following formula:

$$F.R = \frac{\beta}{\eta - \delta}\left(\frac{t - \delta}{\eta - \delta}\right)^{\beta - 1}$$

η here is the scale parameter which is also sometimes indicated by θ.

Using the above formula, calculations were made for the failure rates of different types of rims. The results at the end of the time period of 8 years for each set of data are tabulated below.

| Type of rim | Failure Rate (Pre-OSHA Standard) | Failure Rate (Post-OSHA Standard) |
|---|---|---|
| RH 5 degree rim | 0.546289 | 0.863966 |
| Two-piece rim | 0.01606 | 0.745866 |
| Three-piece rim | 0.266757 | 1.261069 |
| Unknown rims | 0.484256 | 0.999762 |

Table 4.10: Failure Rates of different types of rims before and after the OSHA Standard.

From the table shown above it is very clearly evident that the failure rates of the different rim types have increased after the OSHA Standard had come into effect. The failure rates in the case of two-piece, three-piece and single-piece rims show a drastic increase from before the standard to after its introduction. There has also been considerable increase in the failure rates of RH 5 degree rims and unknown rims. This shows that there had been very little effect of the standard on the number of accidents involving the multi-piece rims.

The beta values which are indicative of the slope of the curve for the data are very high. The beta values of some of the rim types have been compared with other published data of different engineering systems and components. Table 4.11 shows the low, typical and high beta values for these components. The results of the rim data when compared to these other components clearly fall on the higher side, which is not very desirable. The beta values should be reduced, so that the failure or hazard associated with them also decreases. The beta values can only be reduced with better efforts to maintain the rims and control the number of accidents.

| Item | Beta Values (Weibull Shape Factor) | | |
|---|---|---|---|
| | Low | Typical | High |
| Nuts | 0.5 | 1.1 | 1.4 |
| Pumps, lubricators | 0.5 | 1.1 | 1.4 |
| Vibration mounts | 0.5 | 1.1 | 2.2 |
| Compressors, centrifugal | 0.5 | 1.9 | 3 |
| Steam turbines | 0.5 | 1.7 | 3 |
| Gears | 0.5 | 2 | 6 |
| Two-piece rims | | | 8.8 |
| Three-piece rims | | | 5.2 |

Table 4.11: Beta values comparison of multi-piece rims with different engineering components.

# CHAPTER FIVE

# CONCLUSIONS

## 5.1 SUMMARY

The desired objective of looking into the rotational dislocation of the multi-piece rim components has been established and also the effect of OSHA standard on the failure rate of multi-piece rims has been investigated. The main contributions of this work are:

1. Establishment of the similar rotational dislocation of the rim components from actual multi-piece rim components and finite element simulations.
2. Documenting/modeling the failure data of different types of rims into statistical distributions.
3. Looking into the effect of the OSHA standard 1910.177 (Servicing multi-piece rims) on the failure rates of different multi-piece rims.

## 5.2 CONCLUSIONS

From the ANSYS simulation results, the dislocation of the side ring was very similar to that observed in an actual failed multi-piece rim. The inflation pressure and the radial force developed on the side flange cause it to move out of its desired location. The weakening and movement of the tire bead also adds to the causes for the dislocation of the side ring. The maximum deformation obtained from the ANSYS simulation is taken and the side ring is regenerated in Pro/E. The stresses caused a permanent deformation in the contour of the side ring. This is incorporated into the regeneration. The figures from Pro/E are shown below. The dislocation of the side ring is clearly evident from the plots. The effect of rotating the ring component on the rim base only changes the dislocation from one position to another. The designer intent fit is no longer present. This assembly when used to mount a tire and operate on a vehicle could lead to a catastrophic blowout. The huge number of accidents each year provides enough reason to re-look into the design of the multi-piece rim components. The rotation and separation of components is very dangerous when it is not contained. This could only be safe if it is restricted to being only on the truck. The separation and the subsequent blow-off of the rim components results in a much more extensive damage than the one that is contained to being on the truck itself.

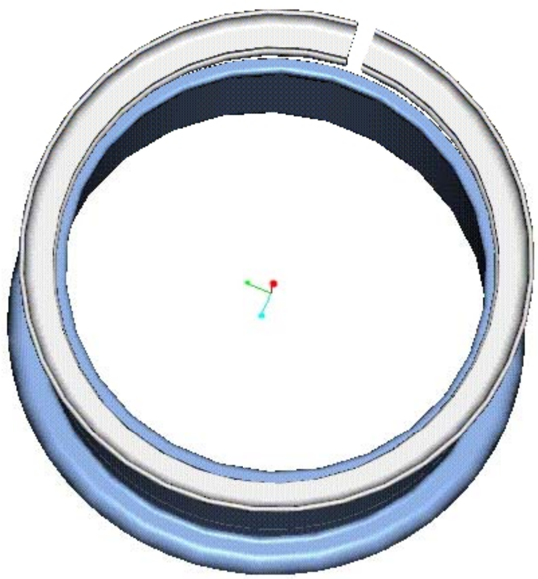


Figure 5.1: Regenerated side ring and rim base assembly.

Figure 5.2: Dislocation of side ring on regenerated assembly.

The failure data from different types of rims have been modeled into statistical distributions and the best fit distribution has been established using the Anderson-Darling test and the Correlation Coefficient method. The 3 parameter Weibull has been identified as the best fit distribution to model the data. The shape parameters for all the types of rims are greater than 1, which evidently proves an increasing failure rate. The survival function for different type of rims show that the rims have a decreasing survival trend and the hazard functions show that the hazard rate is increasing.

The failure rate for the RH 5 degree rims has increased from 0.546289 during the pre-OSHA standard period (1972-1979) to 0.863966 during the post-OSHA standard period (1980-1987). The corresponding values for the two-piece rim data increased from 0.01606 to 0.745866. The failure rate of the three-piece rims from the available data during the time when the OSHA standard was not in effect was 0.266757. The value for the failure rate after the standard came into effect for the three-piece rims is 1.261069. Similarly the failure rate values for the unknown rims increased from 0.484256 to 0.999762. The increase in the failure rate has been particularly drastic for the two-piece rims. The finite element analysis of the two-piece rim suggests the possible reason for this. The dislocation due to the ambient conditions causes the failure in most cases.

The probable reasons for the increasing failure rates could be because of the material properties of the components, i.e. the properties of steel, manufacturing and design defects, operator inefficiency and wear-out period failures. The material properties influence the change in the shape and contour of the components. The steel components when exposed to a consistent pressure loading after a considerable period of time could fail. The wear-out period of a rim also could be a possible reason for the increasing failure rates. The manufacturing and design defects also account for the increasing failure rates. Since the design of the multi-piece rims is based on a concentric fit, small tolerance defects could sufficiently transform into major problems while operation. Also the lack of proper training to the personnel operating on the multi-piece rims leads to failure. Even though there are regulations for a standardized working environment, improper training could often lead to a catastrophic failure. Products with similar increasing failure rates have been looked into, to focus on the reasons for such a trend or behavior. Electronic products like laser diodes, load-sharing power supplies and military equipment were some of the products which were found to have increasing failure rates. The reasons for such a trend varied from manufacturing and design defects, operator inefficiency to wear-out period failures. In some cases material properties also influenced failure rates for these products. The non-constant failure rate from the multi-piece rim data suggests that more inspection is needed along with new warnings. A small defect identified at an earlier stage can prevent a major failure.

The OSHA standard on servicing multi-piece rims which essentially has safety precautions like the usage of a cage during inflation, utilization of the proper tools for mounting and de-mounting the tire rim assembly, training of the workers on the exact procedure for handling the multi-piece rims has not had a positive effect. The situation had become worse indicating that more regulations and need for an effective inspection method be part of the OSHA standard. More investigation should also be carried out into the design features of the multi-piece rims and the method used for the rim components' assembly. The concentric fit of the components allows great risk in its handling and operation. A bolted type of multi-piece rim design could be investigated for effective functioning. The B-52 airplanes used by the military have the bolted type of rims in which the failure of the assembly contains the separation and do not lead to a blow-off of the components.

## APPENDIX A

### POST PROCESSING FROM MINITAB

<u>RH 5 degree rims accident data</u>

<u>Pre OSHA Standard (1972-1979)</u>

### Distribution ID Plot: Pre OSHA (Years)

Using frequencies in Failures_Pre

Goodness-of-Fit

| Distribution | Anderson-Darling (adj) | Correlation Coefficient |
|---|---|---|
| Weibull | 3.990 | 0.964 |
| Lognormal | 7.450 | 0.925 |
| Exponential | 40.151 | * |
| Loglogistic | 8.256 | 0.915 |
| 3-Parameter Weibull | 3.904 | 0.965 |
| 3-Parameter Lognormal | 4.380 | 0.959 |
| 2-Parameter Exponential | 26.701 | * |
| 3-Parameter Loglogistic | 6.189 | 0.941 |
| Smallest Extreme Value | 5.930 | 0.947 |
| Normal | 4.340 | 0.959 |
| Logistic | 6.148 | 0.941 |

Table of Percentiles

| Distribution | Percent | Percentile | Standard Error | 95% Normal CI Lower | 95% Normal CI Upper |
|---|---|---|---|---|---|
| Weibull | 1 | 0.670191 | 0.127203 | 0.461997 | 0.972206 |
| Lognormal | 1 | 1.16914 | 0.101072 | 0.986920 | 1.38501 |
| Exponential | 1 | 0.0356056 | 0.0025348 | 0.0309685 | 0.0409371 |
| Loglogistic | 1 | 1.03850 | 0.121927 | 0.825027 | 1.30720 |
| 3-Parameter Weibull | 1 | 0.520149 | 0.153743 | 0.218819 | 0.821479 |
| 3-Parameter Lognormal | 1 | -0.0100495 | 0.336319 | -0.669224 | 0.649124 |
| 2-Parameter Exponential | 1 | 1.02044 | 0.0022363 | 1.01607 | 1.02484 |
| 3-Parameter Loglogistic | 1 | -0.404587 | 0.380011 | -1.14939 | 0.340220 |
| Smallest Extreme Value | 1 | -1.88167 | 0.567364 | -2.99368 | -0.769656 |
| Normal | 1 | -0.0963191 | 0.350049 | -0.782403 | 0.589765 |
| Logistic | 1 | -0.512780 | 0.398322 | -1.29348 | 0.267918 |
| Weibull | 5 | 1.42775 | 0.184931 | 1.10764 | 1.84036 |
| Lognormal | 5 | 1.71780 | 0.120037 | 1.49793 | 1.96994 |
| Exponential | 5 | 0.181718 | 0.0129369 | 0.158052 | 0.208928 |
| Loglogistic | 5 | 1.73701 | 0.152663 | 1.46215 | 2.06354 |
| 3-Parameter Weibull | 5 | 1.41418 | 0.203340 | 1.01564 | 1.81272 |
| 3-Parameter Lognormal | 5 | 1.43766 | 0.272442 | 0.903681 | 1.97163 |
| 2-Parameter Exponential | 5 | 1.14538 | 0.0114135 | 1.12322 | 1.16797 |
| 3-Parameter Loglogistic | 5 | 1.50627 | 0.291899 | 0.934155 | 2.07838 |
| Smallest Extreme Value | 5 | 0.913260 | 0.404923 | 0.119625 | 1.70689 |
| Normal | 5 | 1.40506 | 0.280570 | 0.855151 | 1.95496 |
| Logistic | 5 | 1.47788 | 0.300158 | 0.889585 | 2.06618 |
| Weibull | 10 | 1.99390 | 0.206749 | 1.62720 | 2.44323 |
| Lognormal | 10 | 2.10889 | 0.131114 | 1.86695 | 2.38219 |
| Exponential | 10 | 0.373264 | 0.0265734 | 0.324651 | 0.429155 |
| Loglogistic | 10 | 2.19245 | 0.165816 | 1.89039 | 2.54276 |
| 3-Parameter Weibull | 10 | 2.03854 | 0.218509 | 1.61027 | 2.46681 |
| 3-Parameter Lognormal | 10 | 2.21732 | 0.242278 | 1.74246 | 2.69217 |

| | | | | | |
|---|---|---|---|---|---|
| 2-Parameter Exponential | 10 | 1.30916 | 0.0234443 | 1.26400 | 1.35592 |
| 3-Parameter Loglogistic | 10 | 2.38331 | 0.256308 | 1.88096 | 2.88567 |
| Smallest Extreme Value | 10 | 2.14757 | 0.335449 | 1.49010 | 2.80504 |
| Normal | 10 | 2.20544 | 0.248006 | 1.71935 | 2.69152 |
| Logistic | 10 | 2.37900 | 0.261349 | 1.86676 | 2.89124 |
| Weibull | 50 | 4.77880 | 0.222086 | 4.36275 | 5.23452 |
| Lognormal | 50 | 4.34805 | 0.208223 | 3.95851 | 4.77593 |
| Exponential | 50 | 2.45563 | 0.174821 | 2.13582 | 2.82333 |
| Loglogistic | 50 | 4.34805 | 0.217149 | 3.94261 | 4.79518 |
| 3-Parameter Weibull | 50 | 4.85375 | 0.214188 | 4.43395 | 5.27355 |
| 3-Parameter Lognormal | 50 | 5.01206 | 0.187311 | 4.64494 | 5.37918 |
| 2-Parameter Exponential | 50 | 3.08968 | 0.154236 | 2.80170 | 3.40726 |
| 3-Parameter Loglogistic | 50 | 5.00665 | 0.194452 | 4.62553 | 5.38777 |
| Smallest Extreme Value | 50 | 5.37787 | 0.176115 | 5.03269 | 5.72305 |
| Normal | 50 | 5.02878 | 0.186862 | 4.66254 | 5.39502 |
| Logistic | 50 | 5.02878 | 0.193934 | 4.64867 | 5.40888 |

Table of MTTF

| | | Standard | 95% Normal CI | |
|---|---|---|---|---|
| Distribution | Mean | Error | Lower | Upper |
| Weibull | 5.01666 | 0.206433 | 4.62795 | 5.43803 |
| Lognormal | 5.09936 | 0.259940 | 4.61451 | 5.63515 |
| Exponential | 3.54273 | 0.252214 | 3.08134 | 4.07321 |
| Loglogistic | 5.12897 | 0.249905 | 4.66183 | 5.64293 |
| 3-Parameter Weibull | 5.00251 | 0.197609 | 4.61520 | 5.38981 |
| 3-Parameter Lognormal | 5.03357 | 0.187351 | 4.66637 | 5.40077 |
| 2-Parameter Exponential | 4.01920 | 0.222515 | 3.60590 | 4.47986 |
| 3-Parameter Loglogistic | 5.02964 | 0.194238 | 4.64894 | 5.41034 |
| Smallest Extreme Value | 5.01657 | 0.190568 | 4.64306 | 5.39008 |
| Normal | 5.02878 | 0.186862 | 4.66254 | 5.39502 |
| Logistic | 5.02878 | 0.193934 | 4.64867 | 5.40888 |

Post OSHA Standard (1980-1987)

## Distribution ID Plot: Post OSHA (Years)

Using frequencies in Failures_Post

Goodness-of-Fit

| | Anderson-Darling | Correlation |
|---|---|---|
| Distribution | (adj) | Coefficient |
| Weibull | 5.395 | 0.956 |
| Lognormal | 5.809 | 0.960 |
| Exponential | 40.943 | * |
| Loglogistic | 7.360 | 0.946 |
| 3-Parameter Weibull | 4.390 | 0.959 |
| 3-Parameter Lognormal | 4.529 | 0.960 |
| 2-Parameter Exponential | 19.665 | * |
| 3-Parameter Loglogistic | 6.667 | 0.953 |
| Smallest Extreme Value | 19.910 | 0.904 |
| Normal | 5.328 | 0.965 |
| Logistic | 7.218 | 0.948 |

Table of Percentiles

| Distribution | Percent | Percentile | Standard Error | 95% Normal CI Lower | Upper |
|---|---|---|---|---|---|
| Weibull | 1 | 0.514905 | 0.0656523 | 0.401048 | 0.661087 |
| Lognormal | 1 | 0.845605 | 0.0651418 | 0.727101 | 0.983423 |
| Exponential | 1 | 0.0306260 | 0.0018391 | 0.0272254 | 0.0344514 |
| Loglogistic | 1 | 0.753826 | 0.0692144 | 0.629674 | 0.902457 |
| 3-Parameter Weibull | 1 | 0.716343 | 0.284941 | 0.441409 | 1.56209 |
| 3-Parameter Lognormal | 1 | 0.229242 | 0.231826 | -0.225129 | 0.683613 |
| 2-Parameter Exponential | 1 | 1.01551 | 0.0016106 | 1.01236 | 1.01868 |
| 3-Parameter Loglogistic | 1 | 0.0883854 | 0.198341 | -0.300355 | 0.477126 |
| Smallest Extreme Value | 1 | -2.16217 | 0.335752 | -2.82023 | -1.50411 |
| Normal | 1 | -0.820507 | 0.269383 | -1.34849 | -0.292527 |
| Logistic | 1 | -1.20988 | 0.286200 | -1.77082 | -0.648941 |
| Weibull | 5 | 1.10542 | 0.100044 | 0.925746 | 1.31997 |
| Lognormal | 5 | 1.27133 | 0.0785693 | 1.12630 | 1.43504 |
| Exponential | 5 | 0.156304 | 0.0093864 | 0.138949 | 0.175827 |
| Loglogistic | 5 | 1.29525 | 0.0886384 | 1.13267 | 1.48116 |
| 3-Parameter Weibull | 5 | 1.14773 | 0.149299 | 0.889431 | 1.48103 |
| 3-Parameter Lognormal | 5 | 1.04064 | 0.157726 | 0.731501 | 1.34978 |
| 2-Parameter Exponential | 5 | 1.12022 | 0.0082198 | 1.10422 | 1.13644 |
| 3-Parameter Loglogistic | 5 | 1.10477 | 0.151718 | 0.807410 | 1.40213 |
| Smallest Extreme Value | 5 | 0.341027 | 0.253044 | -0.154931 | 0.836985 |
| Normal | 5 | 0.598616 | 0.215880 | 0.175500 | 1.02173 |
| Logistic | 5 | 0.670189 | 0.210761 | 0.257104 | 1.08327 |
| Weibull | 10 | 1.54903 | 0.115711 | 1.33806 | 1.79326 |
| Lognormal | 10 | 1.58003 | 0.0863745 | 1.41949 | 1.75872 |
| Exponential | 10 | 0.321061 | 0.0192803 | 0.285412 | 0.361164 |
| Loglogistic | 10 | 1.65488 | 0.0976803 | 1.47409 | 1.85784 |
| 3-Parameter Weibull | 10 | 1.51284 | 0.107819 | 1.31562 | 1.73963 |
| 3-Parameter Lognormal | 10 | 1.53798 | 0.136078 | 1.27127 | 1.80469 |
| 2-Parameter Exponential | 10 | 1.25747 | 0.0168842 | 1.22481 | 1.29101 |
| 3-Parameter Loglogistic | 10 | 1.65868 | 0.137937 | 1.38832 | 1.92903 |
| Smallest Extreme Value | 10 | 1.44650 | 0.217517 | 1.02018 | 1.87283 |
| Normal | 10 | 1.35515 | 0.190800 | 0.981184 | 1.72911 |
| Logistic | 10 | 1.52124 | 0.182358 | 1.16383 | 1.87866 |
| Weibull | 50 | 3.74581 | 0.145377 | 3.47144 | 4.04186 |
| Lognormal | 50 | 3.40160 | 0.140450 | 3.13717 | 3.68833 |
| Exponential | 50 | 2.11220 | 0.126842 | 1.87767 | 2.37603 |
| Loglogistic | 50 | 3.40160 | 0.142418 | 3.13362 | 3.69251 |
| 3-Parameter Weibull | 50 | 3.62976 | 0.216814 | 3.22875 | 4.08059 |
| 3-Parameter Lognormal | 50 | 3.73692 | 0.154168 | 3.43476 | 4.03908 |
| 2-Parameter Exponential | 50 | 2.74966 | 0.111078 | 2.54035 | 2.97622 |
| 3-Parameter Loglogistic | 50 | 3.71884 | 0.143504 | 3.43758 | 4.00010 |
| Smallest Extreme Value | 50 | 4.33963 | 0.132087 | 4.08074 | 4.59851 |
| Normal | 50 | 4.02381 | 0.143697 | 3.74217 | 4.30545 |
| Logistic | 50 | 4.02381 | 0.146217 | 3.73723 | 4.31039 |

Table of MTTF

| Distribution | Mean | Standard Error | 95% Normal CI Lower | Upper |
|---|---|---|---|---|
| Weibull | 3.93917 | 0.134910 | 3.68343 | 4.21266 |
| Lognormal | 4.06842 | 0.181244 | 3.72825 | 4.43962 |
| Exponential | 3.04726 | 0.182994 | 2.70890 | 3.42788 |
| Loglogistic | 4.08715 | 0.179151 | 3.75068 | 4.45380 |
| 3-Parameter Weibull | 3.95489 | 0.148523 | 3.67424 | 4.25697 |
| 3-Parameter Lognormal | 4.01488 | 0.147623 | 3.72554 | 4.30421 |
| 2-Parameter Exponential | 3.52865 | 0.160251 | 3.22814 | 3.85714 |
| 3-Parameter Loglogistic | 4.01263 | 0.151047 | 3.71659 | 4.30868 |
| Smallest Extreme Value | 4.01604 | 0.140675 | 3.74032 | 4.29176 |

| | | | | |
|---|---|---|---|---|
| Normal | 4.02381 | 0.143697 | 3.74217 | 4.30545 |
| Logistic | 4.02381 | 0.146217 | 3.73723 | 4.31039 |

<u>Two-piece rims accident data</u>

<u>Pre OSHA Standard (1972-1979)</u>

## Distribution ID Plot: Pre OSHA (Year)

Using frequencies in Failures_Pre

Goodness-of-Fit

| Distribution | Anderson-Darling (adj) | Correlation Coefficient |
|---|---|---|
| Weibull | 2.070 | 0.960 |
| Lognormal | 3.436 | 0.892 |
| Exponential | 18.499 | * |
| Loglogistic | 3.583 | 0.892 |
| 3-Parameter Weibull | 1.594 | 0.971 |
| 3-Parameter Lognormal | 2.214 | 0.943 |
| 2-Parameter Exponential | 14.759 | * |
| 3-Parameter Loglogistic | 2.523 | 0.933 |
| Smallest Extreme Value | 1.592 | 0.970 |
| Normal | 2.190 | 0.944 |
| Logistic | 2.500 | 0.934 |

Table of Percentiles

| Distribution | Percent | Percentile | Standard Error | 95% Normal CI Lower | Upper |
|---|---|---|---|---|---|
| Weibull | 1 | 1.13910 | 0.382902 | 0.589436 | 2.20135 |
| Lognormal | 1 | 1.89389 | 0.226332 | 1.49841 | 2.39375 |
| Exponential | 1 | 0.0397497 | 0.0049407 | 0.0311554 | 0.0507148 |
| Loglogistic | 1 | 1.67821 | 0.314732 | 1.16202 | 2.42371 |
| 3-Parameter Weibull | 1 | 0.0648047 | 0.835550 | -1.57284 | 1.70245 |
| 3-Parameter Lognormal | 1 | 1.22895 | 0.551524 | 0.147984 | 2.30992 |
| 2-Parameter Exponential | 1 | 1.02434 | 0.0043552 | 1.01584 | 1.03291 |
| 3-Parameter Loglogistic | 1 | 0.756045 | 0.713123 | -0.641652 | 2.15374 |
| Smallest Extreme Value | 1 | -0.788502 | 1.13662 | -3.01624 | 1.43924 |
| Normal | 1 | 1.18056 | 0.568649 | 0.0660279 | 2.29509 |
| Logistic | 1 | 0.691576 | 0.736683 | -0.752297 | 2.13545 |
| Weibull | 5 | 2.12048 | 0.472446 | 1.37021 | 3.28159 |
| Lognormal | 5 | 2.56254 | 0.248144 | 2.11955 | 3.09811 |
| Exponential | 5 | 0.202868 | 0.0252156 | 0.159006 | 0.258830 |
| Loglogistic | 5 | 2.53942 | 0.352256 | 1.93490 | 3.33280 |
| 3-Parameter Weibull | 5 | 2.02686 | 0.865287 | 0.330930 | 3.72279 |
| 3-Parameter Lognormal | 5 | 2.55357 | 0.445094 | 1.68120 | 3.42594 |
| 2-Parameter Exponential | 5 | 1.16526 | 0.0222273 | 1.12250 | 1.20965 |
| 3-Parameter Loglogistic | 5 | 2.54616 | 0.538367 | 1.49098 | 3.60134 |
| Smallest Extreme Value | 5 | 1.87642 | 0.781661 | 0.344391 | 3.40844 |
| Normal | 5 | 2.53913 | 0.454779 | 1.64778 | 3.43048 |
| Logistic | 5 | 2.53318 | 0.548190 | 1.45875 | 3.60761 |
| Weibull | 10 | 2.79008 | 0.485376 | 1.98398 | 3.92371 |
| Lognormal | 10 | 3.01074 | 0.259872 | 2.54215 | 3.56570 |
| Exponential | 10 | 0.416707 | 0.0517949 | 0.326610 | 0.531657 |
| Loglogistic | 10 | 3.06312 | 0.361399 | 2.43072 | 3.86004 |
| 3-Parameter Weibull | 10 | 3.01459 | 0.909348 | 1.23230 | 4.79688 |

| | | | | | |
|---|---|---|---|---|---|
| 3-Parameter Lognormal | 10 | 3.26526 | 0.394776 | 2.49151 | 4.03901 |
| 2-Parameter Exponential | 10 | 1.35000 | 0.0456567 | 1.26342 | 1.44252 |
| 3-Parameter Loglogistic | 10 | 3.36509 | 0.464953 | 2.45380 | 4.27639 |
| Smallest Extreme Value | 10 | 3.05331 | 0.629706 | 1.81911 | 4.28751 |
| Normal | 10 | 3.26338 | 0.401302 | 2.47685 | 4.04992 |
| Logistic | 10 | 3.36682 | 0.470440 | 2.44477 | 4.28887 |
| Weibull | 50 | 5.72174 | 0.383649 | 5.01712 | 6.52532 |
| Lognormal | 50 | 5.31632 | 0.355593 | 4.66313 | 6.06102 |
| Exponential | 50 | 2.74144 | 0.340749 | 2.14871 | 3.49767 |
| Loglogistic | 50 | 5.31632 | 0.379372 | 4.62243 | 6.11439 |
| 3-Parameter Weibull | 50 | 6.01172 | 0.459415 | 5.11128 | 6.91216 |
| 3-Parameter Lognormal | 50 | 5.80688 | 0.301884 | 5.21520 | 6.39856 |
| 2-Parameter Exponential | 50 | 3.35840 | 0.300367 | 2.81840 | 4.00186 |
| 3-Parameter Loglogistic | 50 | 5.80471 | 0.315125 | 5.18708 | 6.42234 |
| Smallest Extreme Value | 50 | 6.13335 | 0.292156 | 5.56073 | 6.70597 |
| Normal | 50 | 5.81818 | 0.300534 | 5.22915 | 6.40722 |
| Logistic | 50 | 5.81818 | 0.313564 | 5.20361 | 6.43276 |

Table of MTTF

| | | Standard | 95% Normal CI | |
|---|---|---|---|---|
| Distribution | Mean | Error | Lower | Upper |
| Weibull | 5.84580 | 0.357499 | 5.18547 | 6.59020 |
| Lognormal | 5.86620 | 0.407716 | 5.11913 | 6.72229 |
| Exponential | 3.95506 | 0.491597 | 3.09993 | 5.04608 |
| Loglogistic | 5.90968 | 0.392406 | 5.18852 | 6.73107 |
| 3-Parameter Weibull | 5.79615 | 0.342117 | 5.12562 | 6.46669 |
| 3-Parameter Lognormal | 5.82186 | 0.301922 | 5.23011 | 6.41362 |
| 2-Parameter Exponential | 4.40688 | 0.433338 | 3.63438 | 5.34357 |
| 3-Parameter Loglogistic | 5.82097 | 0.314302 | 5.20495 | 6.43699 |
| Smallest Extreme Value | 5.78886 | 0.319662 | 5.16233 | 6.41538 |
| Normal | 5.81818 | 0.300534 | 5.22915 | 6.40722 |
| Logistic | 5.81818 | 0.313564 | 5.20361 | 6.43276 |

Post OSHA Standard (1980-1987)

## Distribution ID Plot: Post OSHA (Year)

Using frequencies in Failures_Post

Goodness-of-Fit

| | Anderson-Darling | Correlation |
|---|---|---|
| Distribution | (adj) | Coefficient |
| Weibull | 1.673 | 0.964 |
| Lognormal | 3.117 | 0.949 |
| Exponential | 19.216 | * |
| Loglogistic | 3.205 | 0.939 |
| 3-Parameter Weibull | 1.656 | 0.964 |
| 3-Parameter Lognormal | 1.642 | 0.965 |
| 2-Parameter Exponential | 11.690 | * |
| 3-Parameter Loglogistic | 2.044 | 0.962 |
| Smallest Extreme Value | 6.321 | 0.930 |
| Normal | 1.710 | 0.964 |
| Logistic | 2.228 | 0.960 |

Table of Percentiles

| Distribution | Percent | Percentile | Standard Error | 95% Normal CI Lower | Upper |
|---|---|---|---|---|---|
| Weibull | 1 | 0.510159 | 0.111582 | 0.332300 | 0.783214 |
| Lognormal | 1 | 0.886261 | 0.105382 | 0.702019 | 1.11886 |
| Exponential | 1 | 0.0323338 | 0.0029634 | 0.0270174 | 0.0386964 |
| Loglogistic | 1 | 0.775367 | 0.120524 | 0.571737 | 1.05152 |
| 3-Parameter Weibull | 1 | 0.374159 | 0.793413 | -0.340631 | 1.92922 |
| 3-Parameter Lognormal | 1 | -0.113620 | 0.578089 | -1.24665 | 1.01941 |
| 2-Parameter Exponential | 1 | 1.01710 | 0.0025960 | 1.01203 | 1.02220 |
| 3-Parameter Loglogistic | 1 | -0.409440 | 0.388820 | -1.17151 | 0.352633 |
| Smallest Extreme Value | 1 | -2.23479 | 0.565230 | -3.34262 | -1.12696 |
| Normal | 1 | -0.698404 | 0.430402 | -1.54198 | 0.145168 |
| Logistic | 1 | -1.15205 | 0.470541 | -2.07429 | -0.229803 |
| Weibull | 5 | 1.12572 | 0.171453 | 0.835194 | 1.51730 |
| Lognormal | 5 | 1.33797 | 0.127620 | 1.10983 | 1.61301 |
| Exponential | 5 | 0.165020 | 0.0151243 | 0.137887 | 0.197492 |
| Loglogistic | 5 | 1.34809 | 0.154470 | 1.07692 | 1.68754 |
| 3-Parameter Weibull | 5 | 1.09703 | 0.390058 | 0.332528 | 1.86153 |
| 3-Parameter Lognormal | 5 | 0.990575 | 0.337488 | 0.329111 | 1.65204 |
| 2-Parameter Exponential | 5 | 1.12832 | 0.0132492 | 1.10265 | 1.15459 |
| 3-Parameter Loglogistic | 5 | 1.02996 | 0.295073 | 0.451628 | 1.60829 |
| Smallest Extreme Value | 5 | 0.388259 | 0.418965 | -0.432899 | 1.20942 |
| Normal | 5 | 0.752838 | 0.343229 | 0.0801219 | 1.42555 |
| Logistic | 5 | 0.790498 | 0.343119 | 0.117998 | 1.46300 |
| Weibull | 10 | 1.59671 | 0.197891 | 1.25237 | 2.03574 |
| Lognormal | 10 | 1.66651 | 0.140599 | 1.41252 | 1.96617 |
| Exponential | 10 | 0.338964 | 0.0310665 | 0.283231 | 0.405665 |
| Loglogistic | 10 | 1.73163 | 0.169202 | 1.42982 | 2.09714 |
| 3-Parameter Weibull | 10 | 1.61677 | 0.245676 | 1.13525 | 2.09828 |
| 3-Parameter Lognormal | 10 | 1.62191 | 0.263849 | 1.10478 | 2.13905 |
| 2-Parameter Exponential | 10 | 1.27412 | 0.0272149 | 1.22188 | 1.32859 |
| 3-Parameter Loglogistic | 10 | 1.74494 | 0.260101 | 1.23516 | 2.25473 |
| Smallest Extreme Value | 10 | 1.54666 | 0.356343 | 0.848242 | 2.24508 |
| Normal | 10 | 1.52649 | 0.302180 | 0.934228 | 2.11875 |
| Logistic | 10 | 1.66983 | 0.294046 | 1.09351 | 2.24615 |
| Weibull | 50 | 3.98560 | 0.241887 | 3.53862 | 4.48904 |
| Lognormal | 50 | 3.61577 | 0.230359 | 3.19132 | 4.09666 |
| Exponential | 50 | 2.22998 | 0.204381 | 1.86332 | 2.66879 |
| Loglogistic | 50 | 3.61577 | 0.231932 | 3.18860 | 4.10016 |
| 3-Parameter Weibull | 50 | 4.04901 | 0.348364 | 3.36623 | 4.73180 |
| 3-Parameter Lognormal | 50 | 4.11232 | 0.261915 | 3.59898 | 4.62567 |
| 2-Parameter Exponential | 50 | 2.85915 | 0.179041 | 2.52891 | 3.23251 |
| 3-Parameter Loglogistic | 50 | 4.10547 | 0.224142 | 3.66616 | 4.54478 |
| Smallest Extreme Value | 50 | 4.57830 | 0.208509 | 4.16964 | 4.98697 |
| Normal | 50 | 4.25556 | 0.224469 | 3.81560 | 4.69551 |
| Logistic | 50 | 4.25556 | 0.226009 | 3.81259 | 4.69853 |

Table of MTTF

| Distribution | Mean | Standard Error | 95% Normal CI Lower | Upper |
|---|---|---|---|---|
| Weibull | 4.21835 | 0.225733 | 3.79833 | 4.68481 |
| Lognormal | 4.34035 | 0.298800 | 3.79250 | 4.96733 |
| Exponential | 3.21718 | 0.294859 | 2.68820 | 3.85026 |
| Loglogistic | 4.38127 | 0.289059 | 3.84982 | 4.98607 |
| 3-Parameter Weibull | 4.21070 | 0.224888 | 3.76993 | 4.65148 |
| 3-Parameter Lognormal | 4.25526 | 0.226042 | 3.81223 | 4.69830 |
| 2-Parameter Exponential | 3.68661 | 0.258302 | 3.21357 | 4.22928 |
| 3-Parameter Loglogistic | 4.25634 | 0.227739 | 3.80998 | 4.70270 |
| Smallest Extreme Value | 4.23923 | 0.222901 | 3.80235 | 4.67610 |

| | | | | |
|---|---|---|---|---|
| Normal | 4.25556 | 0.224469 | 3.81560 | 4.69551 |
| Logistic | 4.25556 | 0.226009 | 3.81259 | 4.69853 |

<u>Three-piece rims accident data</u>

<u>Pre OSHA Standard (1972-1979)</u>

## Distribution ID Plot: Pre OSHA (Year)

Using frequencies in Failures_Pre

Goodness-of-Fit

| Distribution | Anderson-Darling (adj) | Correlation Coefficient |
|---|---|---|
| Weibull | 1.483 | 0.946 |
| Lognormal | 1.871 | 0.925 |
| Exponential | 9.597 | * |
| Loglogistic | 2.031 | 0.914 |
| 3-Parameter Weibull | 1.477 | 0.947 |
| 3-Parameter Lognormal | 1.561 | 0.942 |
| 2-Parameter Exponential | 4.414 | * |
| 3-Parameter Loglogistic | 1.758 | 0.929 |
| Smallest Extreme Value | 1.551 | 0.945 |
| Normal | 1.556 | 0.942 |
| Logistic | 1.753 | 0.929 |

Table of Percentiles

| Distribution | Percent | Percentile | Standard Error | 95% Normal CI Lower | Upper |
|---|---|---|---|---|---|
| Weibull | 1 | 1.68110 | 0.513001 | 0.924363 | 3.05735 |
| Lognormal | 1 | 2.42037 | 0.354606 | 1.81624 | 3.22545 |
| Exponential | 1 | 0.0418506 | 0.0074901 | 0.0294686 | 0.0594352 |
| Loglogistic | 1 | 2.19566 | 0.417062 | 1.51314 | 3.18602 |
| 3-Parameter Weibull | 1 | 1.17165 | 0.736520 | -0.271903 | 2.61520 |
| 3-Parameter Lognormal | 1 | 1.56845 | 0.766190 | 0.0667496 | 3.07016 |
| 2-Parameter Exponential | 1 | 2.99477 | 0.0048366 | 2.98531 | 3.00427 |
| 3-Parameter Loglogistic | 1 | 1.07747 | 0.912922 | -0.711821 | 2.86677 |
| Smallest Extreme Value | 1 | -0.266147 | 1.42508 | -3.05926 | 2.52697 |
| Normal | 1 | 1.52749 | 0.785540 | -0.0121356 | 3.06712 |
| Logistic | 1 | 1.02392 | 0.937272 | -0.813101 | 2.86094 |
| Weibull | 5 | 2.72156 | 0.567960 | 1.80793 | 4.09689 |
| Lognormal | 5 | 3.08982 | 0.360986 | 2.45747 | 3.88490 |
| Exponential | 5 | 0.213590 | 0.0382270 | 0.150397 | 0.303336 |
| Loglogistic | 5 | 3.06770 | 0.434679 | 2.32381 | 4.04971 |
| 3-Parameter Weibull | 5 | 2.58433 | 0.691516 | 1.22898 | 3.93967 |
| 3-Parameter Lognormal | 5 | 2.82584 | 0.613755 | 1.62291 | 4.02878 |
| 2-Parameter Exponential | 5 | 3.09643 | 0.0246842 | 3.04842 | 3.14519 |
| 3-Parameter Loglogistic | 5 | 2.79313 | 0.687380 | 1.44589 | 4.14037 |
| Smallest Extreme Value | 5 | 2.21701 | 0.991990 | 0.272749 | 4.16128 |
| Normal | 5 | 2.81107 | 0.623800 | 1.58844 | 4.03369 |
| Logistic | 5 | 2.77879 | 0.698176 | 1.41039 | 4.14719 |
| Weibull | 10 | 3.36679 | 0.563277 | 2.42553 | 4.67332 |
| Lognormal | 10 | 3.51941 | 0.361988 | 2.87687 | 4.30547 |
| Exponential | 10 | 0.438732 | 0.0785213 | 0.308927 | 0.623077 |
| Loglogistic | 10 | 3.56913 | 0.434655 | 2.81126 | 4.53130 |

| | | | | | |
|---|---|---|---|---|---|
| 3-Parameter Weibull | 10 | 3.36243 | 0.639084 | 2.10985 | 4.61501 |
| 3-Parameter Lognormal | 10 | 3.50010 | 0.541021 | 2.43972 | 4.56048 |
| 2-Parameter Exponential | 10 | 3.22969 | 0.0507032 | 3.13183 | 3.33062 |
| 3-Parameter Loglogistic | 10 | 3.57580 | 0.595175 | 2.40928 | 4.74232 |
| Smallest Extreme Value | 10 | 3.31364 | 0.806594 | 1.73274 | 4.89453 |
| Normal | 10 | 3.49533 | 0.547338 | 2.42257 | 4.56810 |
| Logistic | 10 | 3.57317 | 0.601650 | 2.39396 | 4.75238 |
| Weibull | 50 | 5.87533 | 0.440696 | 5.07207 | 6.80579 |
| Lognormal | 50 | 5.57060 | 0.425565 | 4.79595 | 6.47038 |
| Exponential | 50 | 2.88633 | 0.516577 | 2.03238 | 4.09910 |
| Loglogistic | 50 | 5.57060 | 0.453028 | 4.74983 | 6.53320 |
| 3-Parameter Weibull | 50 | 5.98495 | 0.421489 | 5.15885 | 6.81105 |
| 3-Parameter Lognormal | 50 | 5.90065 | 0.402354 | 5.11205 | 6.68925 |
| 2-Parameter Exponential | 50 | 4.67848 | 0.333567 | 4.06832 | 5.38014 |
| 3-Parameter Loglogistic | 50 | 5.89934 | 0.424059 | 5.06820 | 6.73048 |
| Smallest Extreme Value | 50 | 6.18361 | 0.389331 | 5.42053 | 6.94668 |
| Normal | 50 | 5.90909 | 0.401556 | 5.12206 | 6.69613 |
| Logistic | 50 | 5.90909 | 0.423249 | 5.07954 | 6.73864 |

Table of MTTF

| | | Standard | 95% Normal CI | |
|---|---|---|---|---|
| Distribution | Mean | Error | Lower | Upper |
| Weibull | 5.88070 | 0.409023 | 5.13128 | 6.73959 |
| Lognormal | 5.93995 | 0.467974 | 5.09005 | 6.93177 |
| Exponential | 4.16410 | 0.745263 | 2.93210 | 5.91376 |
| Loglogistic | 5.96534 | 0.471706 | 5.10889 | 6.96536 |
| 3-Parameter Weibull | 5.87506 | 0.405114 | 5.08105 | 6.66907 |
| 3-Parameter Lognormal | 5.91125 | 0.402295 | 5.12276 | 6.69973 |
| 2-Parameter Exponential | 5.43481 | 0.481236 | 4.56892 | 6.46481 |
| 3-Parameter Loglogistic | 5.91068 | 0.423589 | 5.08046 | 6.74090 |
| Smallest Extreme Value | 5.86261 | 0.424896 | 5.02983 | 6.69539 |
| Normal | 5.90909 | 0.401556 | 5.12206 | 6.69613 |
| Logistic | 5.90909 | 0.423249 | 5.07954 | 6.73864 |

Post OSHA Standard (1980-1987)

## Distribution ID Plot: Post OSHA (Year)

Using frequencies in Failures_Post

Goodness-of-Fit

| | Anderson-Darling | Correlation |
|---|---|---|
| Distribution | (adj) | Coefficient |
| Weibull | 1.032 | 0.975 |
| Lognormal | 1.195 | 0.951 |
| Exponential | 6.661 | * |
| Loglogistic | 1.172 | 0.957 |
| 3-Parameter Weibull | 1.083 | 0.978 |
| 3-Parameter Lognormal | 0.994 | 0.979 |
| 2-Parameter Exponential | 4.292 | * |
| 3-Parameter Loglogistic | 0.971 | 0.983 |
| Smallest Extreme Value | 2.119 | 0.940 |
| Normal | 1.049 | 0.973 |
| Logistic | 0.992 | 0.977 |

Table of Percentiles

| Distribution | Percent | Percentile | Standard Error | 95% Normal CI Lower | Upper |
|---|---|---|---|---|---|
| Weibull | 1 | 0.755502 | 0.274315 | 0.370829 | 1.53921 |
| Lognormal | 1 | 1.22743 | 0.256207 | 0.815304 | 1.84787 |
| Exponential | 1 | 0.0310432 | 0.0060998 | 0.0211208 | 0.0456270 |
| Loglogistic | 1 | 1.05364 | 0.314455 | 0.587019 | 1.89116 |
| 3-Parameter Weibull | 1 | 0.550943 | 2.62315 | -0.702802 | 5.69222 |
| 3-Parameter Lognormal | 1 | 0.664213 | 0.530357 | -0.375267 | 1.70369 |
| 2-Parameter Exponential | 1 | 1.01530 | 0.0051733 | 1.00521 | 1.02549 |
| 3-Parameter Loglogistic | 1 | 0.316043 | 0.630685 | -0.920076 | 1.55216 |
| Smallest Extreme Value | 1 | -1.27672 | 0.842964 | -2.92890 | 0.375454 |
| Normal | 1 | 0.121780 | 0.762681 | -1.37305 | 1.61661 |
| Logistic | 1 | -0.410128 | 0.944640 | -2.26159 | 1.44133 |
| Weibull | 5 | 1.42332 | 0.358726 | 0.868497 | 2.33257 |
| Lognormal | 5 | 1.68948 | 0.279035 | 1.22228 | 2.33528 |
| Exponential | 5 | 0.158433 | 0.0311311 | 0.107793 | 0.232864 |
| Loglogistic | 5 | 1.64688 | 0.349334 | 1.08669 | 2.49584 |
| 3-Parameter Weibull | 5 | 1.37822 | 1.33695 | -0.702802 | 3.99859 |
| 3-Parameter Lognormal | 5 | 1.49098 | 0.463182 | 0.583159 | 2.39880 |
| 2-Parameter Exponential | 5 | 1.11912 | 0.0264025 | 1.06855 | 1.17208 |
| 3-Parameter Loglogistic | 5 | 1.43088 | 0.515943 | 0.419652 | 2.44211 |
| Smallest Extreme Value | 5 | 0.843952 | 0.640907 | -0.412203 | 2.10011 |
| Normal | 5 | 1.25789 | 0.600239 | 0.0814417 | 2.43434 |
| Logistic | 5 | 1.17410 | 0.659290 | -0.118086 | 2.46628 |
| Weibull | 10 | 1.88268 | 0.385549 | 1.26027 | 2.81250 |
| Lognormal | 10 | 2.00321 | 0.289443 | 1.50916 | 2.65898 |
| Exponential | 10 | 0.325435 | 0.0639458 | 0.221416 | 0.478321 |
| Loglogistic | 10 | 2.01589 | 0.354452 | 1.42824 | 2.84533 |
| 3-Parameter Weibull | 10 | 1.90014 | 0.805693 | 0.321009 | 3.47927 |
| 3-Parameter Lognormal | 10 | 1.96872 | 0.426243 | 1.13330 | 2.80414 |
| 2-Parameter Exponential | 10 | 1.25522 | 0.0542329 | 1.15330 | 1.36614 |
| 3-Parameter Loglogistic | 10 | 1.99296 | 0.457363 | 1.09655 | 2.88938 |
| Smallest Extreme Value | 10 | 1.78049 | 0.554703 | 0.693298 | 2.86769 |
| Normal | 10 | 1.86354 | 0.522794 | 0.838886 | 2.88820 |
| Logistic | 10 | 1.89123 | 0.543962 | 0.825086 | 2.95738 |
| Weibull | 50 | 3.91463 | 0.398114 | 3.20719 | 4.77812 |
| Lognormal | 50 | 3.65310 | 0.382966 | 2.97459 | 4.48638 |
| Exponential | 50 | 2.14098 | 0.420688 | 1.45665 | 3.14679 |
| Loglogistic | 50 | 3.65310 | 0.378327 | 2.98201 | 4.47523 |
| 3-Parameter Weibull | 50 | 3.97253 | 0.533363 | 2.92716 | 5.01790 |
| 3-Parameter Lognormal | 50 | 3.88584 | 0.368806 | 3.16300 | 4.60869 |
| 2-Parameter Exponential | 50 | 2.73481 | 0.356788 | 2.11776 | 3.53164 |
| 3-Parameter Loglogistic | 50 | 3.88413 | 0.362828 | 3.17300 | 4.59526 |
| Smallest Extreme Value | 50 | 4.23151 | 0.350784 | 3.54399 | 4.91904 |
| Normal | 50 | 4 | 0.372772 | 3.26938 | 4.73062 |
| Logistic | 50 | 4 | 0.367224 | 3.28025 | 4.71975 |

Table of MTTF

| Distribution | Mean | Standard Error | 95% Normal CI Lower | Upper |
|---|---|---|---|---|
| Weibull | 4.00801 | 0.373070 | 3.33963 | 4.81016 |
| Lognormal | 4.07747 | 0.452456 | 3.28048 | 5.06809 |
| Exponential | 3.08877 | 0.606924 | 2.10151 | 4.53985 |
| Loglogistic | 4.13318 | 0.447815 | 3.34241 | 5.11103 |
| 3-Parameter Weibull | 3.99124 | 0.360436 | 3.28479 | 4.69768 |
| 3-Parameter Lognormal | 4.01437 | 0.375941 | 3.27754 | 4.75120 |
| 2-Parameter Exponential | 3.50723 | 0.514737 | 2.63050 | 4.67617 |
| 3-Parameter Loglogistic | 4.02677 | 0.372038 | 3.29759 | 4.75596 |
| Smallest Extreme Value | 3.95737 | 0.370926 | 3.23037 | 4.68438 |

| | | | | |
|---|---|---|---|---|
| Normal | 4.00000 | 0.372772 | 3.26938 | 4.73062 |
| Logistic | 4.00000 | 0.367224 | 3.28025 | 4.71975 |

Unknown rims accident data

Pre OSHA Standard (1972-1979)

### Distribution ID Plot: Pre OSHA (Years)

Using frequencies in Failures_Pre

Goodness-of-Fit

| Distribution | Anderson-Darling (adj) | Correlation Coefficient |
|---|---|---|
| Weibull | 7.806 | 0.944 |
| Lognormal | 11.645 | 0.911 |
| Exponential | 40.024 | * |
| Loglogistic | 13.698 | 0.896 |
| 3-Parameter Weibull | 7.804 | 0.945 |
| 3-Parameter Lognormal | 8.503 | 0.935 |
| 2-Parameter Exponential | 27.601 | * |
| 3-Parameter Loglogistic | 11.350 | 0.914 |
| Smallest Extreme Value | 9.344 | 0.926 |
| Normal | 8.418 | 0.936 |
| Logistic | 11.264 | 0.914 |

Table of Percentiles

| | | | Standard | 95% Normal CI | |
|---|---|---|---|---|---|
| Distribution | Percent | Percentile | Error | Lower | Upper |
| Weibull | 1 | 0.566422 | 0.110008 | 0.387101 | 0.828812 |
| Lognormal | 1 | 1.02449 | 0.0906152 | 0.861433 | 1.21842 |
| Exponential | 1 | 0.0364006 | 0.0024884 | 0.0318361 | 0.0416197 |
| Loglogistic | 1 | 0.909027 | 0.107313 | 0.721257 | 1.14568 |
| 3-Parameter Weibull | 1 | 0.686747 | 0.0901321 | 0.530984 | 0.888204 |
| 3-Parameter Lognormal | 1 | -0.299864 | 0.337472 | -0.961298 | 0.361569 |
| 2-Parameter Exponential | 1 | 1.02125 | 0.0022052 | 1.01694 | 1.02558 |
| 3-Parameter Loglogistic | 1 | -0.691519 | 0.386886 | -1.44980 | 0.0667627 |
| Smallest Extreme Value | 1 | -2.30617 | 0.602690 | -3.48742 | -1.12492 |
| Normal | 1 | -0.384327 | 0.348794 | -1.06795 | 0.299298 |
| Logistic | 1 | -0.799592 | 0.405099 | -1.59357 | -0.0056135 |
| Weibull | 5 | 1.28256 | 0.170922 | 0.987732 | 1.66538 |
| Lognormal | 5 | 1.55656 | 0.111708 | 1.35231 | 1.79164 |
| Exponential | 5 | 0.185776 | 0.0127000 | 0.162480 | 0.212412 |
| Loglogistic | 5 | 1.58485 | 0.142530 | 1.32873 | 1.89033 |
| 3-Parameter Weibull | 5 | 1.29310 | 0.153927 | 1.02402 | 1.63289 |
| 3-Parameter Lognormal | 5 | 1.25011 | 0.274501 | 0.712095 | 1.78812 |
| 2-Parameter Exponential | 5 | 1.14950 | 0.0112544 | 1.12765 | 1.17177 |
| 3-Parameter Loglogistic | 5 | 1.34538 | 0.302206 | 0.753063 | 1.93769 |
| Smallest Extreme Value | 5 | 0.689099 | 0.428208 | -0.150173 | 1.52837 |
| Normal | 5 | 1.22190 | 0.281240 | 0.670680 | 1.77312 |
| Logistic | 5 | 1.31921 | 0.310567 | 0.710515 | 1.92791 |
| Weibull | 10 | 1.84003 | 0.197094 | 1.49159 | 2.26987 |
| Lognormal | 10 | 1.94538 | 0.124571 | 1.71593 | 2.20552 |

| | | | | | |
|---|---|---|---|---|---|
| Exponential | 10 | 0.381598 | 0.0260867 | 0.333746 | 0.436311 |
| Loglogistic | 10 | 2.03829 | 0.159651 | 1.74822 | 2.37650 |
| 3-Parameter Weibull | 10 | 1.79716 | 0.184764 | 1.46918 | 2.19836 |
| 3-Parameter Lognormal | 10 | 2.08479 | 0.244957 | 1.60469 | 2.56490 |
| 2-Parameter Exponential | 10 | 1.31762 | 0.0231174 | 1.27308 | 1.36372 |
| 3-Parameter Loglogistic | 10 | 2.27998 | 0.267958 | 1.75479 | 2.80517 |
| Smallest Extreme Value | 10 | 2.01188 | 0.353456 | 1.31912 | 2.70464 |
| Normal | 10 | 2.07817 | 0.249751 | 1.58867 | 2.56768 |
| Logistic | 10 | 2.27834 | 0.273097 | 1.74308 | 2.81360 |
| Weibull | 50 | 4.73206 | 0.229492 | 4.30298 | 5.20392 |
| Lognormal | 50 | 4.27177 | 0.212661 | 3.87465 | 4.70959 |
| Exponential | 50 | 2.51046 | 0.171620 | 2.19565 | 2.87041 |
| Loglogistic | 50 | 4.27177 | 0.230007 | 3.84394 | 4.74722 |
| 3-Parameter Weibull | 50 | 4.65006 | 0.236799 | 4.20836 | 5.13813 |
| 3-Parameter Lognormal | 50 | 5.07654 | 0.191742 | 4.70073 | 5.45235 |
| 2-Parameter Exponential | 50 | 3.14534 | 0.152085 | 2.86094 | 3.45800 |
| 3-Parameter Loglogistic | 50 | 5.07439 | 0.205386 | 4.67184 | 5.47694 |
| Smallest Extreme Value | 50 | 5.47373 | 0.181449 | 5.11809 | 5.82936 |
| Normal | 50 | 5.09868 | 0.191171 | 4.72400 | 5.47337 |
| Logistic | 50 | 5.09868 | 0.204661 | 4.69756 | 5.49981 |

Table of MTTF

| | | Standard | 95% Normal CI | |
|---|---|---|---|---|
| Distribution | Mean | Error | Lower | Upper |
| Weibull | 5.03998 | 0.212458 | 4.64031 | 5.47408 |
| Lognormal | 5.15714 | 0.275334 | 4.64477 | 5.72603 |
| Exponential | 3.62183 | 0.247595 | 3.16766 | 4.14112 |
| Loglogistic | 5.18653 | 0.270093 | 4.68327 | 5.74386 |
| 3-Parameter Weibull | 5.05801 | 0.223246 | 4.63885 | 5.51505 |
| 3-Parameter Lognormal | 5.09944 | 0.191768 | 4.72359 | 5.47530 |
| 2-Parameter Exponential | 4.09949 | 0.219413 | 3.69124 | 4.55290 |
| 3-Parameter Loglogistic | 5.09832 | 0.205055 | 4.69642 | 5.50022 |
| Smallest Extreme Value | 5.08653 | 0.197070 | 4.70028 | 5.47278 |
| Normal | 5.09868 | 0.191171 | 4.72400 | 5.47337 |
| Logistic | 5.09868 | 0.204661 | 4.69756 | 5.49981 |

Post OSHA Standard (1980-1987)

## Distribution ID Plot: Post OSHA (Years)

Using frequencies in Failures_Post

Goodness-of-Fit

| | Anderson-Darling | Correlation |
|---|---|---|
| Distribution | (adj) | Coefficient |
| Weibull | 5.702 | 0.938 |
| Lognormal | 5.589 | 0.954 |
| Exponential | 25.011 | * |
| Loglogistic | 7.127 | 0.937 |
| 3-Parameter Weibull | 5.017 | 0.940 |
| 3-Parameter Lognormal | 4.377 | 0.964 |
| 2-Parameter Exponential | 17.401 | * |
| 3-Parameter Loglogistic | 6.193 | 0.948 |
| Smallest Extreme Value | 13.926 | 0.895 |

| | | |
|---|---|---|
| Normal | 4.576 | 0.961 |
| Logistic | 6.170 | 0.946 |

Table of Percentiles

| Distribution | Percent | Percentile | Standard Error | 95% Normal CI Lower | Upper |
|---|---|---|---|---|---|
| Weibull | 1 | 0.414904 | 0.0639976 | 0.306657 | 0.561361 |
| Lognormal | 1 | 0.685525 | 0.0652661 | 0.568832 | 0.826157 |
| Exponential | 1 | 0.0280446 | 0.0020160 | 0.0243591 | 0.0322877 |
| Loglogistic | 1 | 0.607725 | 0.0676976 | 0.488526 | 0.756009 |
| 3-Parameter Weibull | 1 | 0.632781 | 0.0414631 | 0.556517 | 0.719496 |
| 3-Parameter Lognormal | 1 | -0.121138 | 0.296160 | -0.701600 | 0.459325 |
| 2-Parameter Exponential | 1 | 1.01289 | 0.0017486 | 1.00947 | 1.01633 |
| 3-Parameter Loglogistic | 1 | -0.577042 | 0.241101 | -1.04959 | -0.104492 |
| Smallest Extreme Value | 1 | -2.22653 | 0.357879 | -2.92796 | -1.52510 |
| Normal | 1 | -0.989346 | 0.299460 | -1.57628 | -0.402415 |
| Logistic | 1 | -1.37644 | 0.318580 | -2.00085 | -0.752036 |
| Weibull | 5 | 0.918824 | 0.101145 | 0.740511 | 1.14007 |
| Lognormal | 5 | 1.05245 | 0.0804412 | 0.906031 | 1.22253 |
| Exponential | 5 | 0.143129 | 0.0102888 | 0.124320 | 0.164785 |
| Loglogistic | 5 | 1.07350 | 0.0897909 | 0.911182 | 1.26473 |
| 3-Parameter Weibull | 5 | 0.981114 | 0.0792592 | 0.837443 | 1.14943 |
| 3-Parameter Lognormal | 5 | 0.722732 | 0.196603 | 0.337397 | 1.10807 |
| 2-Parameter Exponential | 5 | 1.10685 | 0.0089243 | 1.08949 | 1.12448 |
| 3-Parameter Loglogistic | 5 | 0.680852 | 0.191813 | 0.304905 | 1.05680 |
| Smallest Extreme Value | 5 | 0.120638 | 0.271669 | -0.411824 | 0.653100 |
| Normal | 5 | 0.348100 | 0.239972 | -0.122237 | 0.818437 |
| Logistic | 5 | 0.402656 | 0.235464 | -0.0588443 | 0.864156 |
| Weibull | 10 | 1.30532 | 0.119043 | 1.09167 | 1.56080 |
| Lognormal | 10 | 1.32268 | 0.0894741 | 1.15844 | 1.51020 |
| Exponential | 10 | 0.293999 | 0.0211341 | 0.255363 | 0.338482 |
| Loglogistic | 10 | 1.38885 | 0.100784 | 1.20472 | 1.60112 |
| 3-Parameter Weibull | 10 | 1.28643 | 0.101118 | 1.10276 | 1.50070 |
| 3-Parameter Lognormal | 10 | 1.22634 | 0.164154 | 0.904600 | 1.54807 |
| 2-Parameter Exponential | 10 | 1.23001 | 0.0183311 | 1.19460 | 1.26647 |
| 3-Parameter Loglogistic | 10 | 1.31142 | 0.173387 | 0.971585 | 1.65125 |
| Smallest Extreme Value | 10 | 1.15721 | 0.234638 | 0.697325 | 1.61709 |
| Normal | 10 | 1.06109 | 0.212086 | 0.645407 | 1.47677 |
| Logistic | 10 | 1.20800 | 0.204212 | 0.807753 | 1.60825 |
| Weibull | 50 | 3.27182 | 0.156883 | 2.97834 | 3.59421 |
| Lognormal | 50 | 2.96185 | 0.151621 | 2.67910 | 3.27444 |
| Exponential | 50 | 1.93417 | 0.139037 | 1.67999 | 2.22681 |
| Loglogistic | 50 | 2.96185 | 0.156095 | 2.67118 | 3.28415 |
| 3-Parameter Weibull | 50 | 3.14244 | 0.162176 | 2.84013 | 3.47694 |
| 3-Parameter Lognormal | 50 | 3.35668 | 0.170388 | 3.02272 | 3.69063 |
| 2-Parameter Exponential | 50 | 2.56898 | 0.120597 | 2.34316 | 2.81656 |
| 3-Parameter Loglogistic | 50 | 3.41752 | 0.160852 | 3.10226 | 3.73279 |
| Smallest Extreme Value | 50 | 3.87000 | 0.145332 | 3.58515 | 4.15485 |
| Normal | 50 | 3.57616 | 0.159708 | 3.26314 | 3.88918 |
| Logistic | 50 | 3.57616 | 0.164166 | 3.25440 | 3.89792 |

Table of MTTF

| Distribution | Mean | Standard Error | 95% Normal CI Lower | Upper |
|---|---|---|---|---|
| Weibull | 3.46587 | 0.145488 | 3.19213 | 3.76308 |
| Lognormal | 3.60985 | 0.200718 | 3.23712 | 4.02548 |
| Exponential | 2.79041 | 0.200588 | 2.42371 | 3.21260 |
| Loglogistic | 3.63098 | 0.201545 | 3.25669 | 4.04829 |
| 3-Parameter Weibull | 3.46723 | 0.154205 | 3.17779 | 3.78303 |

| | | | | |
|---|---|---|---|---|
| 3-Parameter Lognormal | 3.56602 | 0.160503 | 3.25144 | 3.88060 |
| 2-Parameter Exponential | 3.26799 | 0.173985 | 2.94417 | 3.62742 |
| 3-Parameter Loglogistic | 3.56691 | 0.164545 | 3.24441 | 3.88941 |
| Smallest Extreme Value | 3.56658 | 0.154367 | 3.26403 | 3.86914 |
| Normal | 3.57616 | 0.159708 | 3.26314 | 3.88918 |
| Logistic | 3.57616 | 0.164166 | 3.25440 | 3.89792 |

**APPENDIX B**

Figure B.1: Tire rim assembly

Figure B.2: Dislocation along a portion of the rim circumference.

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# VITA

## Date and Place of Birth

- February 7, 1981 at Guntur, Andhra Pradesh, INDIA.

## Education

- Bachelor of Technology (B.Tech) in Mechanical Engineering, JNTU College of Engineering, Jawaharlal Nehru Technological University, Hyderabad, INDIA.

## Work Experience

- Teaching Assistant, Department of Mechanical Engineering, University of Kentucky, Lexington, KY. (August 2002- May 2004).