August 2017

Optimal Warranty Period for Free-replacement Policy of Agm Batteries

Jennifer Paola Garantiva Poveda
University of Wisconsin-Milwaukee

OPTIMAL WARRANTY PERIOD FOR FREE-REPLACEMENT POLICY OF AGM BATTERIES

by

Jennifer Paola Garantiva Poveda

A Thesis Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Master of Science

in Engineering

at

The University of Wisconsin-Milwaukee

August 2017

ABSTRACT

OPTIMAL WARRANTY PERIOD FOR FREE-REPLACEMENT POLICY OF AGM BATTERIES

by

Jennifer Paola Garantiva Poveda

The University of Wisconsin-Milwaukee, 2017
Under the Supervision of Professor Wilkistar Otieno

The objective of this study is to analyze the suitability of the age-based warranty model and a millage based warranty model for absorbent glass mat batteries (AGM) for the automobile industry. The battery life expectancy can be assessed and described by a combination of different terms such as: state of health (SOH), deep of discharge (DOD), state of energy (SOE) and state of charge (SOC). However, using actual data from the field, the implementation of reliability engineering and statistical modeling we aim to calculate optimal limits for warranty policies that minimize warranty costs. The outcomes of this research will enable battery manufacturers, motor companies and warranty managers in decisions making strategies for cost savings in warranty projects without negatively affecting customer satisfaction.

To

Captain Sean W. Thomas, my partner in life and best friend,

for his love, support and encouragement.

Who patiently endured my ups and downs during this research and report period.

For always being there to cheer me up and stand by me through the good and bad times.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

I would like to express my deep and sincere gratitude to my advisor Dr. Wilkistar Otieno. Her support and guidance throughout this research made this work possible. She has taught me innumerable lessons during my time at the University of Wisconsin-Milwaukee.

I would also like to thank my committee members, Dr. Naira Campbell-Kyureghyan Professor and Department Chair of the Industrial Engineering department and Dr. Benjamin Church Professor in the Materials Science department for their involvement, valuable suggestions and kind acceptance to be part of the committee.

Last but most specially, I want to thank my parents Gloria Poveda and Javier Garantiva for believing in me, to all my friends and family for their encouragement support.

CHAPTER 1: MOTIVATION

In this Thesis, we examine the life cycle of lead acid batteries, specifically AGM (Absorbent Glass Mat) lead acid batteries. There are three phases in the life of any lead acid battery: formatting, peak and decline as shown in Figure 1. (Battery University , 2016).

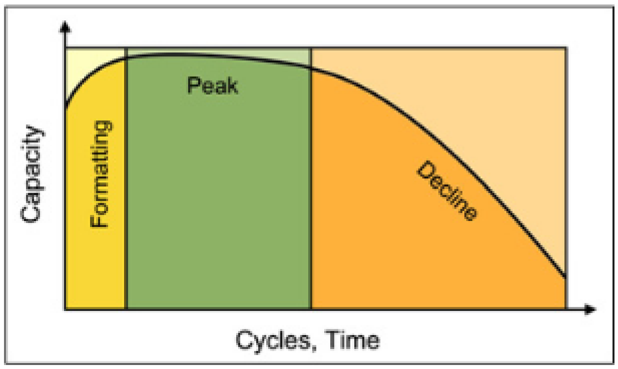

Figure 1. Three main phases of the lifespan of a lead acid battery.
Retrieved from (Battery University , 2016)

The aging process of lead acid batteries is directly affected by the gradually decreasing discharge that occurs over time. As time goes by, battery voltage progressively declines affecting the life expectancy of the battery. There are several known factors that also impact the life on a battery, these include the loss of active material, corrosion or abusive usage like, extreme discharge of the battery, overload and operating temperature of the battery (Glaize & Genies, 2012). Temperature plays a crucial role in the depth of discharge. When usage temperatures of a battery are high, internal chemical reactions occur that cause a “step down”, meaning that discharge of the battery will be greater as the temperature rises. For AGM batteries, the standard is that the battery service life decreases by 50% for every 8- 10°C (14-18°F) increase in average ambient temperature (Avelar &

Zacho, 2016). These thermal reactions occur when the ambient temperature is around 77 degrees Fahrenheit i.e. 25 degrees Celsius (Alber & Nispel). For this reason, manufacturers warn customers about maintaining the batteries at specific ambient temperatures recommendations, the rule of thumb for AGM batteries is that for every 8°C (14.4°F) increase in temperature above optimum 25°C (77 °F) there is a 50% reduction in expected life of the battery (McCluer, 2011). Figure 2 shows the correlation between life of a battery and temperature.

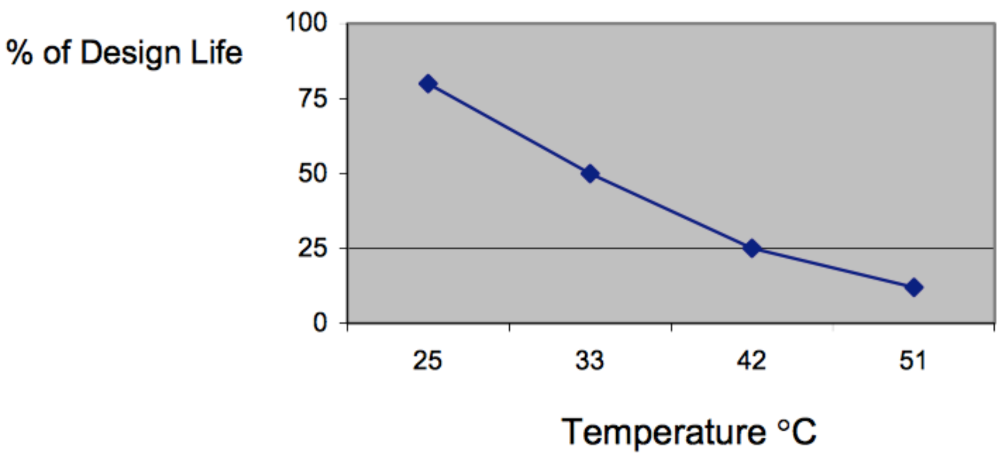

Figure 2. Battery design life vs. environment temperature
Retrieved from (McCluer, 2011)

Subsequently, battery manufacturers specify and describe their product warranty or design life in terms of years at particular operating temperature (McCluer, 2011). These predictions are usually made when variables such a temperature are controlled. This Thesis therefore uses real data of automobile battery warranty failure that had the influence of temperature and the usually overlooked factor – customer care.

There are three main objectives presented in this Thesis:

Objective 1: Descriptively and quantitatively analyze warranty field claims data that was provided for this research, with the aim of understanding the trends within and for further modeling analysis. The data used in this research involves claims under the free renewal warranty policy. In this type of policy, a battery is tested when it is brought to the dealership and consequently the dealer files a claim. In the case that the battery fails the test a new item will be given to the costumer for free.

Objective 2: to develop a usage-based warranty model that best fits the data provided.

Objective 3: Calculate the optimal time t*, that minimizes the cost that manufactures pay for warranty claims.

CHAPTER 2: INTRODUCTION

Battery technology has been well known for over a hundred years. They are the most common and accessible type of energy storage and are considered to be one of the main sources of electricity for industrial applications. Batteries can simply be described as fuel cells inside of which different types of chemicals (fuels) are stored. The most used examples of these fuels include lead, nickel, lithium-ion, Lithium-Sulphur and Sodium-Sulphur.

Historically, fuel cells are known to be the first controlled source of electricity. This technology is attributed to Sir William Robert Grove, who built the first wet cell battery in 1838 (Rayment & Sherwin, 2003). Grove developed a hydrogen and oxygen fuel cell (Sørensen, 2007). This wet cell combined hydrogen and oxygen to which chemical reactions produce electricity. Subsequently, battery technology development timeline and specific energy comparison for every battery over time is presented in Figure 3.

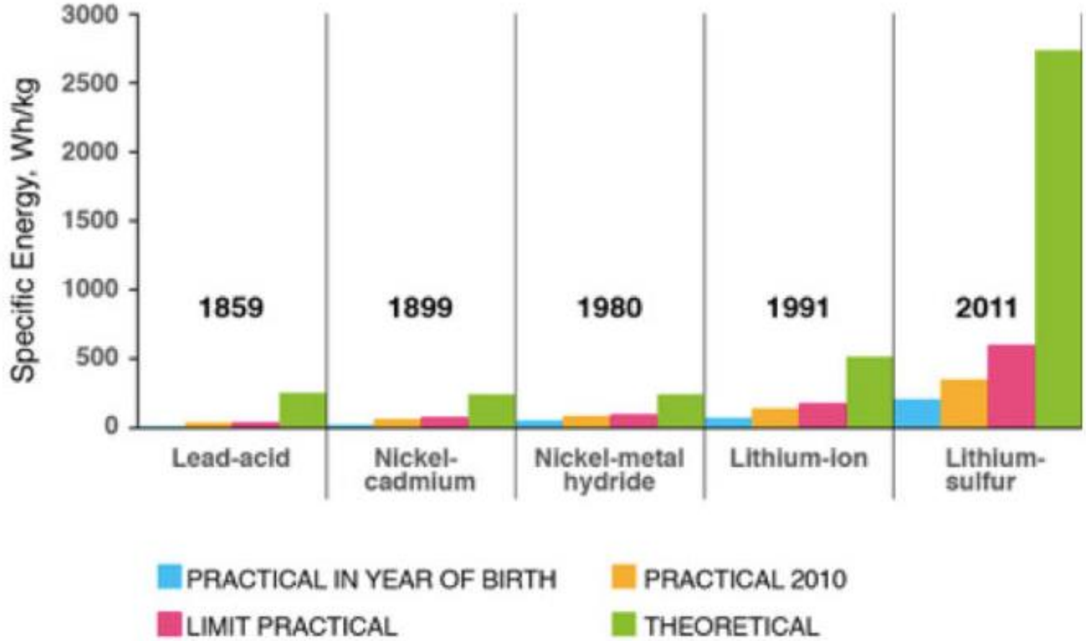

Figure 3. History of battery technology development.
Retrieved from (Cobb, 2013)

Batteries as a type of wet cells can be divided into two broader categories, for example, primary and secondary batteries. Primary batteries cannot be electrically recharged but they have high energy density and good storage characteristics. Secondary batteries, on the other hand can be electrically recharged and they therefore can offer savings in costs and resources (Nishio & Furukawa, 2007). Secondary batteries were developed, in the middle of the 19th century (Glaize & Genies, 2012). One crucial modification between the primary and the later secondary type of batteries is the ability to have a complete discharge-recharge cycle.

This recharge process in secondary types of batteries is therefore a very important aspect to be considered in industrial applications. Some of the most prevalent secondary batteries are nickel-based, lead-acid and lithium-ion batteries. Since, the types of batteries that have most application in the industry are naturally the ones that can be rechargeable;

we will focus on these secondary batteries in this Thesis, particularly the lead acid battery. The lead acid battery type has the largest portion market share, especially in the automobiles, industrial batteries, electronic market base and is the one whose data was provided for this research.

The growing demand of hybrid and fully electric vehicles is creating huge growth opportunities for the battery industry. Lead acid batteries especially AGM batteries are commonly referred to as the SLI battery (starting-lighting-ignition) in the automobile industry. According to Frost & Sullivan's report in 2009, lead acid batteries contributed toward 32% of the total battery revenue. This percentage subsumes starter and stationary lead acid batteries. Figure 4 shows the revenue contribution of different batteries positioning lead acid batteries as the number one (the combined revenue from the starter, stationary and deep cycle).

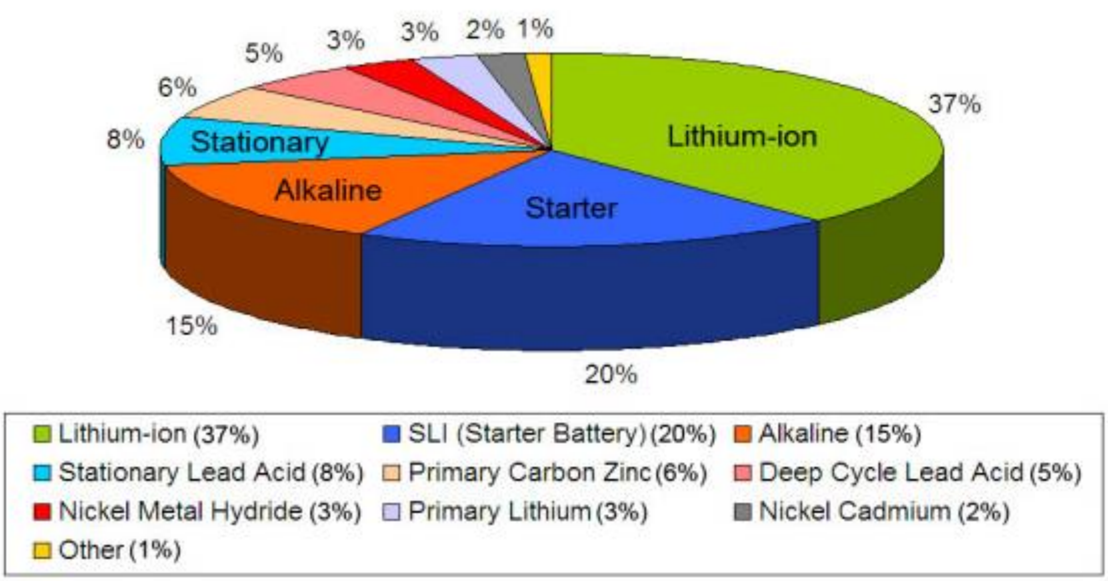

Figure 4. Revenue contribution by different battery chemistries.
Adapted from (BU_103: Global Battery Markets , 2016)

Moreover, the partner company carries a two-year free-replacement warranty policy for the vehicle with a few parts exemptions. The partner company is fully responsible for the cost of repairing or replacing products that fail under warranty free of charge. Free-replacement is the most common approach for the one-dimensional warranty policy.

Warranty policies are mainly divided in two groups. On one hand, is the one-dimensional policy, which is characterized by one variable as the defining attribute of the warranty limit such as miles or months. On the other hand, is the two-dimensional warranty policy, which limit is defined by a combination of two variables and/or their combination.

After analyzing warranty claim return data for all parts, and seeing and increased number of claims for AGM batteries the partner company determined to review warranty for this part. Moreover, process and product continuous improvement projects were implemented within the company and among suppliers and dealers to ensure quality and reliability of batteries. These changes would positively impact the expected number of batteries' warranty claim. The partner company expects to have a 60 % claims reduction over the next five years. This expected reduction in addition to the need to analyze the current warranty claims status necessitated the need for this study.

2.1. Background on Batteries

2.1.1. General Terminology

Before we go into technical detail about batteries, this section provides basic understanding of the main characteristics of the batteries that are discussed later in the paper.

Table 1. General Terminology of Batteries
Source retrieved from: (DOE Handbook: Primer on Lead-Acid Storage Batteries, 1995)

Term	Definition
Active material	Constituents of a cell that participate in the electrochemical charge/discharge reaction.
Battery	Two or more cells electrically connected to form a unit. Under common usage, the term "battery" also applies to a single cell.
Capacity	Number of ampere-hours (Ah) a fully charged cell or battery can deliver under specified conditions of discharge.
Cell	Basic electrochemical unit used to store electrical energy
Current	Flow of electrons equal to one coulomb of charge per second, usually expressed in amperes (A).
Cutoff voltage	Cell or battery voltage at which the discharge is terminated. The cutoff voltage is specified by the manufacturer and is a function of discharge rate and temperature.
Cycle	The discharge and subsequent charge of a secondary battery such that it is restored to its fully charged state.
Duty cycle	Operating parameters of a cell or battery including factors such as charge and discharge rates, depth of discharge, cycle length, and length of time in the standby mode.
Electrode	Electrical conductor and the associated active materials at which an electrochemical reaction occurs. Also referred to as the positive and negative plates in a secondary cell.
Electrolysis	Chemical dissociation of water into hydrogen and oxygen gas caused by passage of an electrical current.
Electrolyte	Medium which provides the ion transport function between the positive and negative electrodes of a cell.
Equalizing charge	Charge applied to a battery which is greater than the normal float

	charge and is used to completely restore the active materials in the cell, bringing the cell float voltage and the specific gravity of the individual cells back to "equal" values.
Float charge	Method of charging in which a secondary cell is continuously connected to a constant-voltage supply that maintains the cell in a fully charged condition.
Gassing	Evolution of gas from one or more electrodes resulting from electrolysis of water during charge or from self-discharge. Significant gassing occurs when the battery is nearing the fully charged state while recharging or when the battery is on equalizing charge.
Potential difference	Work which must be done against electrical forces to move a unit charge from one point to the other, also known as electromotive force (EMF).
Primary cell or battery	Cell or battery which is not intended to be recharged and is discarded when the cell or battery has delivered its useful capacity.
Secondary battery	A battery that after discharge may be restored to its charged state by passage of an electrical current through the cell in the opposite direction to that of discharge. (Also called storage or rechargeable.)
Separator	Electrically insulating layer of material which physically separates electrodes of opposite polarity. Separators must be permeable to ions in the electrolyte and may also have the function of storing or immobilizing the electrolyte.
Specific gravity	Ratio of the weight of a solution to an equal volume of water at a specified temperature. Used as an indicator of the state of charge of a cell or battery.
Sulfation	Formation of lead sulfate crystals on the plates of a lead-acid battery.
Terminal	External electric connections of a cell or battery, also referred to as "terminal post" or "post."
Thermal runaway	A condition that occurs in a battery (especially valve-regulated types) when charging energy results in heat generation within the battery greater than the heat dissipated, causing an uncontrolled rise in battery temperature. This can cause failure through cell dry-out, shortened life, and/or melting of the battery.

2.1.2. Battery Parameters

Battery parameters are often used as indicators of the health of a battery. Some of these parameters include voltage, energy, cold cracking amperes (CCA), capacity and efficiency. Since the goal of this Thesis is to model battery warranty, which is dependent on its life, the following section will provide some of the main battery states, most of which give an accurate representation of the life of batteries.

2.1.2.1. Depth of Discharge

The depth of discharge (DOD) is a measurement of the amount of electricity already extracted from a battery compared to its initial capacity (Glaize & Genies, 2012). The depth of discharge is described as a percentage of the remaining electricity storage in the battery's cells Equation (1). Where i_{dis} is the discharge current.

$$DOD = \frac{\int_0^t i_{dis}(t)\ dt}{\text{Capacity}} \tag{1}$$

The amount of watts drawn from the battery in a specific length of time can be calculated using the above equation to determine the DOD of the battery (McCluer, 2011).

2.1.2.2. State of Charge

The state of charge (SOC) is a measurement that represents the stored available energy in a battery at a given time and therefore is an indispensable characteristic of secondary batteries. Since secondary batteries are rechargeable, they are seen as a reservoir of energy, where the amount of energy stored changes continuously (Glaize & Genies, 2012).

The state of charge of a battery is essential in the automobile industry where automobiles' starting, lighting, and ignition (SLI) require batteries to deliver a significant amount of high power in short periods of time for example when an engine is started (Zhang, Grube, Shin, Salam, & Conell, 2010).

The SOC is a dimensionless quantity that can be expressed as a percentage of the quantity of "charge" still available in the battery in relation to its practical capacity (Glaize & Genies, 2012). Equations (2 &3) are used to calculate the SOC of a battery.

$$SOC = \frac{\text{quanity of charge remaing}}{\text{"practical" capacity of the battery}} \tag{2}$$

The SOC (Glaize & Genies, 2012) can also be evaluated in relationship to the DOD of the battery: $SOC = 1 - DOD\ or\ DOD = 1 - SOC$.

$$SOC = \frac{Capacity - \int_0^t i_{dis}\,(t)dt}{Capacity} \tag{3}$$

2.1.2.3. State of Energy

The state of energy (SOE) is defined as the amount of energy that is still stored in the battery in relation to its practical stored energy (Glaize & Genies, 2012). SOE is also a dimensionless quantity and can be calculated in an identical way to SOC using energy units instead of charge units.

2.1.2.4. State of Health

The state of health (SOH) is directly proportional to the capacity of the cells inside the battery. The knowledge of SOH is useful for battery replacement and optimal utilization

(Shen, 2013). SOH is commonly used by battery testers to estimate when a battery should be replaced, SOH is used as an indication of wear and tear on a battery (Glaize & Genies, 2012).

Nowadays, the above mention parameters and states are used among others by battery testers to diagnose battery's life. Hence, the importance of understanding these stages in warranty management and decision-making.

2.1.3. Types of Batteries

2.1.3.1. Nickel-Based Batteries

There are different electrochemical solutions for the nickel based batteries such as NiCd, NiFe, NiZn, and NiMH. Since all these types of batteries have nickel hydroxide (NiOOH) as a common material into their chemical reactions they are given the standard name of Nickel-based Batteries (Glaize & Genies, 2012). Nickel hydroxides are the most known component in the active material of the positive electrodes. However, the most common is NiCd and much more recently NiMH.

2.1.3.1.1. Nickel-Cadmium Batteries (NiCd)

The first nickel-cadmium battery (NiCd) was developed by the Swedish engineer Waldemar Jungner in 1899 (Bard, 1973). In 1902 in the United States, Thomas A. Edison developed a nickel or cobalt cadmium (International Cadmium Association).

The nickel-cadmium battery has a positive electrode made of nickel hydroxide, a negative electrode in which a cadmium compound is used as the active material and potassium hydroxide is used as the electrolyte (Glaize & Genies, 2012). During charge and discharge, the following reactions occur:

Positive electrode reaction:

$$2NiOOH + 2H_2O + 2e^- \underset{charge}{\overset{Discharge}{\rightleftarrows}} 2Ni(OH)_2 + 2OH^- \tag{4}$$

Negative electrode reaction:

$$Cd + 2OH^- \underset{charge}{\overset{Discharge}{\rightleftarrows}} Cd(OH)_2 + 2e^- \tag{5}$$

Overall battery reaction:

$$2NiOOH + Cd + \ 2H_2O \underset{charge}{\overset{Discharge}{\rightleftarrows}} 2Ni(OH)_2 + Cd(OH)_2 \tag{6}$$

The Stoichiometric Equations 4, 5 & 6 represent and define the electrochemical reactions that happen in a nickel cadmium battery when it is being discharged or charged (Fan & White, Mathematical Modeling of a Nickel-Cadmium Battery, 1991). The overall reaction produces a nominal functional electromotive force of 1.2 volts per cell (International Cadmium Association). The above equations are illustrated in Figure 5:

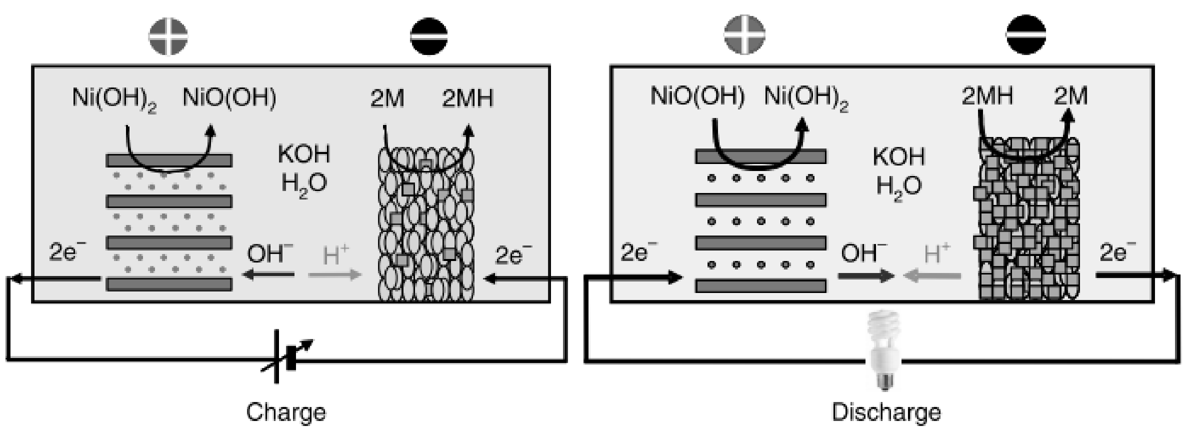

Figure 5. Electrochemical operations principle of nickel-cadmium batteries
Retrieved from (Glaize & Genies, 2012)

Some of the uses for NiCd batteries include portable and industrial applications. For instance, for portable and general applications nickel cadmium batteries are used in toys, personal audio equipment, cameras and cordless phones. Figure 6 shows the typical structural design of a cylindrical portable nickel-cadmium battery.

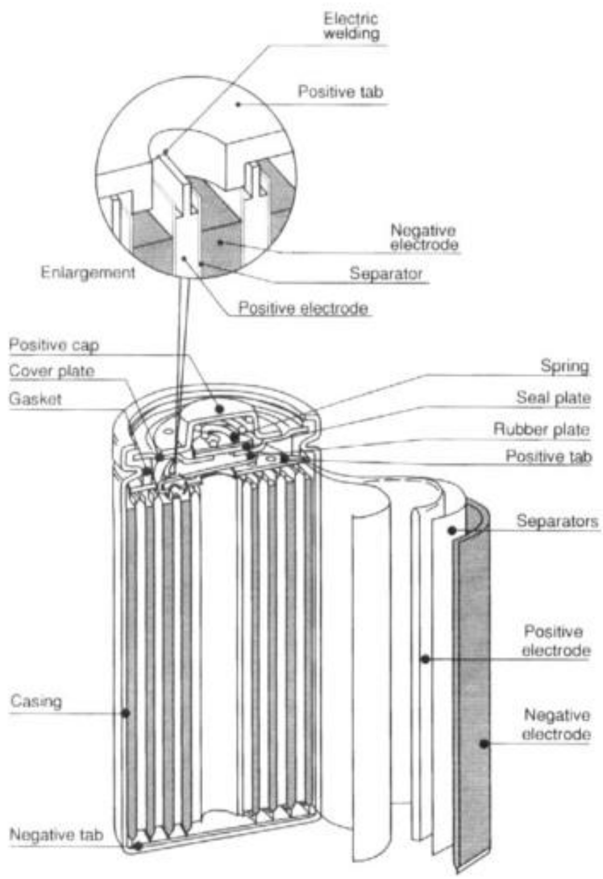

Figure 6. Structural design of a cylindrical portable nickel-cadmium
Retrieved from (Nishio & Furukawa, 2007)

NiCd batteries have also found application in the aerospace industry, particularly for their high energy, power densities and cycling capabilities (Macdonald & Challingsworth, 1993). **Table 2** summarizes the main advantages and disadvantages of NiCd batteries.

Table 2. Advantages and Disadvantages of Nickel Cadmium Batteries
Source retrieved from (Linden & Reddy, 2001)

Advantages	Disadvantages
Batteries are sealed; no maintenance required	Voltage depression or memory effect in certain application s
Long cycle life	Higher cost than sealed lead-acid battery
Good low-temperature and high-rate performance capability	Poor charge retention
Long shelf life in any state of charge	Environmental concern with the use of cadmium
Rapid recharge capability	Lower capacity than other competitive batteries

One of the biggest disadvantages of NiCd batteries is the high level of toxicity of cadmium. This disadvantage is worsened by communities' apathy towards recycling batteries. Thus, NiCd batteries are considered environmentally unfriendly. Environmental objections to NiCd batteries and the possibility of increasing the capacity of nickel oxide based rechargeable batteries by using metal hydrides as anodes led to the rapid development of NiMeHi or NiMH batteries in the early 1990s (Kordesch & Ivad, 1999).

2.1.3.1.2. Nickel-Hydride battery (NIHM)

Nickel hydride and nickel-cadmium batteries both use nickel in their positive electrode and a hydrogen-absorbing alloy for the negative electrode (Nishio & Furukawa, 2007). This is shown in the electrochemical reactions 7, 8 & 9, where M= hydrogen-absorbing alloy and MH= metal hydride.

Positive electrode reaction:

$$NiOOH + H_2O + e^- \underset{charge}{\overset{Discharge}{\rightleftarrows}} Ni(OH)_2 + OH^- \tag{7}$$

Negative electrode reaction:

$$MH + OH^- \underset{charge}{\overset{Discharge}{\rightleftarrows}} M + H_2O + e^- \tag{8}$$

Overall battery reaction:

$$NiOOH + MH \underset{charge}{\overset{Discharge}{\rightleftarrows}} Ni(OH)_2 + M \tag{9}$$

It is well known that nickel based battery high performance is attributed to the hydroxide electrode. NiMH based batteries were first introduced by Bouet and Richard at the Electrochemical Society. Bouet and Richard presented a model for the charging and discharging chemical reactions of the nickel hydroxide electrode (Fan & White, 1991). The chemical reactions that occur at the electrodes are identified in Figure 7.

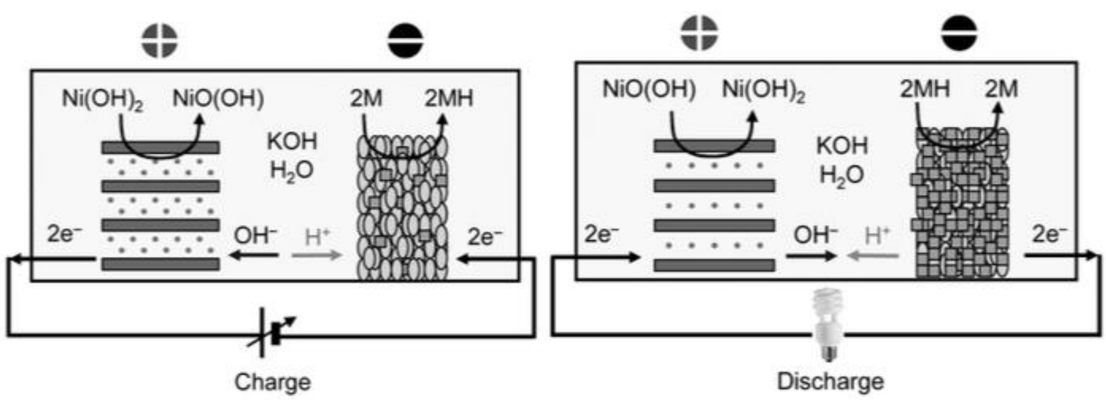

Figure 7. Reaction principles of NiMH batteries
Retrieved from (Glaize & Genies, 2012)

The main characteristics of NiMH batteries are that they are commercialized only in the form of sealed cells and the nominal voltage of a cell is 1.2 V. Today, rechargeable battery like AAA, AA and others still use NiMH mainly because their nominal voltage is close enough to that of the alkaline battery packs that they replaced (1.2 V instead of 1.5 V) (Glaize, C. 2012). Figure 8 shows the typical structural design of a cylindrical portable NiMH battery.

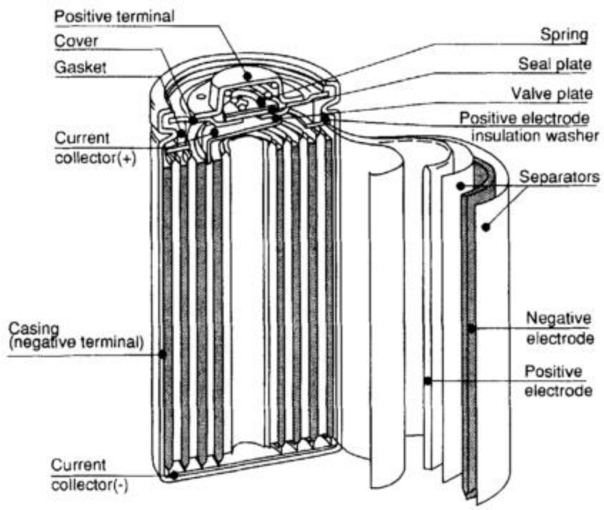

Figure 8. Structure of a cylindrical NiMH battery
Retrieved from (Nishio & Furukawa, 2007)

The advantages and disadvantages of the NiMH batteries are summarized below in **Table 3.** The main advantage that the NiMH has over the NiCd battery is the higher capacity, meaning that NiMH has a higher specific energy and energy density (Linden & Reddy, 2001).

Table 3. Advantages and Disadvantages of the NiMH Batteries
Source retrieved from (Linden & Reddy, 2001)

Advantages	**Disadvantages**
Higher capacity than nickel-cadmium batteries	High-rate performance not as good as with nickel –cadmium batteries
Sealed construction, no maintenance	Poor charge retention
Cadmium-free, minimal environmental problems	Moderate memory effect
Rapid recharge capability	
Long cycle life	
Long Shelf life in any state of charge	

2.1.3.2. Lithium-Ion Battery

The lithium-ion batteries were first used in specific military applications in 1970 (Linden & Reddy, 2001) and first commercialized by Sony in 1991 (Wu, Yuan, Zhao, & Ree, 2015). Li-ion batteries are categorized as secondary type of batteries, meaning that they have charge and discharge electrochemical reactions. In this type of batteries, lithium ion moves from one electrode to the other during every charge and discharge episode (Dey, 2015). This charging and discharging principle of operation can be shown in Equations (10, 11 & 12)

Positive electrode reaction:

$$LiCoO_2 \underset{Discharge}{\overset{Ch\,arge}{\rightleftarrows}} Li_{1-x}CoO_2 + xLi^+xe^- \tag{10}$$

Negative electrode reaction:

$$6C + xLi^+ + xe^- \underset{Discharge}{\overset{Ch\,arge}{\rightleftarrows}} Li_xC_6 \tag{11}$$

Overall battery reaction:

$$6C + LiCoO_2 \underset{charge}{\overset{Discharge}{\rightleftarrows}} Li_xC_6 + Li_{1-x}CoO_2 \tag{12}$$

Li-Ion batteries use LiCoO2 and graphite as the electro materials. During the charging and discharging process lithium in ion state moves back and forth between the positive electrode and the negative electrode (Dey, 2015 and Wu, Yuan, Zhao, & Ree, 2015). This movement of Li-ion is shown in Figure 9:

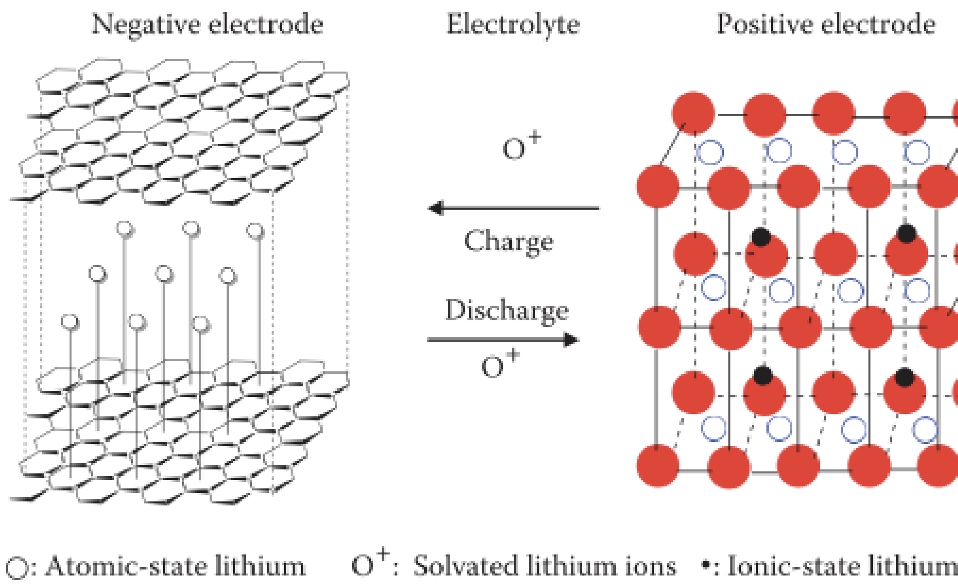

Figure 9. Principle of operation of the lithium-ion battery
Adapted from: (Wu, Yuan, Zhao, & Ree, 2015)

Lithium ion batteries have distinctive characteristics such as a large number of electrode potential and low weight compared to other battery technologies. Li-ion batteries are one of the most advanced power and energy storage. Main advantages of lithium ion batteries are their specific energy and their low self-discharge rate. On the other hand, some of the disadvantages of Li-ion include their high cost and low safety. The advantages and disadvantages of Li-Ion batteries are summarized on **Table 4Table 4. Advantages and Disadvantages of Li-ion Batteries**

Source retrieved from (Linden & Reddy, 2001)

Advantages	**Disadvantages**
Sealed cells; no maintenance required	Moderate initial cost
Long cycle life	Degrades at high temperature
Broad temperature range of operation	Need for protective circuitry
Long Shelf life	Capacity loss or thermal runaway when over-charged
Low self-discharge rate	Venting and possible thermal runaway when crushed
Rapid charge capability	Cylindrical designs typically offer lower power density than NiCd or NiMH
High rate and high power discharge capability	
High coulombic and energy efficiency	
High specific energy and energy density	
No memory effect	

2.1.3.3. Lead Acid Batteries

Invented in 1859 by French physicist Gaston plane, lead-acid batteries are the oldest secondary (rechargeable) battery type (Wu, Yuan, Zhao, & Ree, 2015). Since then, they have become one of the most popular batteries. Lead acid batteries account for half the demand of secondary batteries, primarily due to their low cost (Golam Kibria, Amin, & Rifat, 2014). The principal reactions in a battery are those that allow electrons to be exchanged, stored and then released electrical energy. These electrochemical charge (storage)–discharge (release) reactions are reversible. At the end of a full charge–discharge cycle, the initial components (active material) are once again present at the electrodes (Glaize & Genies, 2012).

Positive electrode reaction:

$$PbO_2 + HSO_4^- + 3H^+ + 2e^- \underset{Charge}{\overset{Discharge}{\rightleftarrows}} PbSO_4 + 2H_2O \tag{13}$$

Negative electrode reaction:

$$Pb + SO_4^{2-} \underset{Charge}{\overset{Discharge}{\rightleftarrows}} PbSO_4 + 2e^- \tag{14}$$

Overall battery reaction:

$$PbO_2 + 2H_2SO_4 + Pb \underset{charge}{\overset{Discharge}{\rightleftarrows}} 2PbSO_4 + 2H_2O \tag{15}$$

The overall battery reaction in lead acid batteries described in Equation 14 is also known as the double sulfation reaction. It illustrates that sulfates generation is a process tightly related to the positive reaction and negative reaction in order for the lead acid battery to storage and release energy (Glaize & Genies, 2012). Figure 10 illustrates how equations 13, 14 & 15 to generate energy in a lead acid battery.

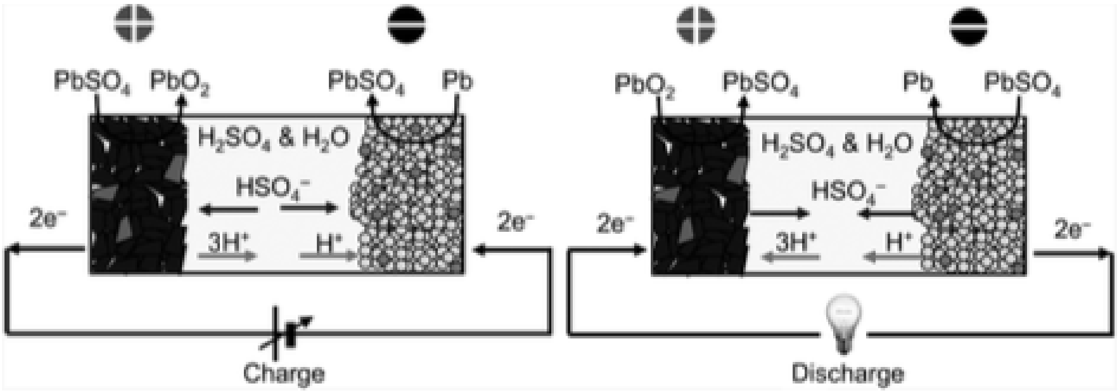

Figure 10. Principles of operation of a lead-acid battery
Retrieved from (Glaize & Genies, 2012)

The technology behind the manufacture and recycling of lead acid is well documented and can be found in (Glaize & Genies, 2012). Lead acid is one of the metals with higher recycling rate. The recycling rate of a lead acid battery is more than 95% in the U.S. and Europe (International Lead Associaton , 2013). One of the advantages of lead acid batteries is their low cost, since a big portion of a common battery contains up to 80% of recycled materials from previous batteries (International Lead Association). Since, lead acid is a hazard and toxic material the high recycling rates of these metals has been a tremendous advantage to the industry and society. Some advantages and disadvantages of lead acid batteries are summarized below in **Table 5.**

Table 5. Advantages and disadvantages of lead-acid batteries
*Note: Up to 2000 cycles can be attained with special designs.
Source retrieved from (Linden & Reddy, 2001)

Advantages	Disadvantages
Popular low-cost secondary battery—capable of manufacture on a local basis, worldwide, from low to high rates of production	Relatively low cycle life (50–500 cycles)*
Available in large quantities and in a variety of sizes and designs—manufactured in sizes from smaller than 1 Ah to several thousand Ampere-hours	Limited energy density—typically 30–40 Wh/kg

Good high-rate performance—suitable for engine starting (but outperformed by some nickel-cadmium and nickel metal-hydride batteries)	Long-term storage in a discharged condition can lead to irreversible polarization of electrodes (sulfation)
Moderately good low- and high-temperature performance Electrically	Difficult to manufacture in very small sizes (it is easier to make nickel-cadmium button cells in the smaller than 500-mAh size)
Electrically efficient—turnaround efficiency of over 70%, comparing discharge energy out with charge energy in	Hydrogen evolution in some designs can be an explosion hazard (flame arrestors are installed to prevent this hazard)
High cell voltage—open-circuit voltage of >2.0 V is the highest of all aqueous-electrolyte battery systems	Stibene and arsine evolution in designs with antimony and arsenic in grid alloys can be a health hazard
Good float service	Thermal runaway in improperly designed batteries or charging equipment
Good charge retention for intermittent charge applications (if grids are made with high- overvoltage alloys)	Positive post blister corrosion with some designs
Available in maintenance-free designs	
Low cost compared with other secondary batteries	
Cell components are easily recycled	

2.1.3.3.1. Absorbent Glass Mat Lead Acid Batteries

Absorbent Glass Mat Lead acid batteries, often referred simply as AGM batteries, were developed initially for military aircraft applications (DC battery specialists). AGM batteries differ from flooded lead acid batteries in that AGM batteries contain only a limited amount of electrolyte in the glass matt (Linden & Reddy, 2001). The sulfuric acid that is inside the AGM battery is absorbed by fine fiberglass mat. AGM batteries are called spill proof batteries due to the small amount of acid store in the fiberglass mat (Battery University , 2016).

AGM batteries are a type of valve-regulated battery (VRLA) because they are sealed and they also have pressure relief valves (Weissler, 2012). The AGM battery technology provides high power at low costs compared to other valve regulated batteries (McCluer, 2011). Even though the manufacturing process and design of the flooded lead acid battery is different from that of VRLA battery the electrochemical reactions are similar (Linden & Reddy, 2001). The electrochemical reactions are shown below in equations 16, 17 & 18.

Positive electrode reaction:

$$PbO_2 + 3H^+ + HSO_4^- + 2e \underset{Charge}{\overset{Discharge}{\rightleftarrows}} 2H_2O + PbSO_4 \tag{16}$$

Negative electrode reaction:

$$Pb + HSO_4^- + \underset{Charge}{\overset{Discharge}{\rightleftarrows}} PbSO_4 + H^+ + 2e \tag{17}$$

Overall battery reaction:

$$PbO_2 + Pb + 2H_2SO_4 \underset{charge}{\overset{Discharge}{\rightleftarrows}} 2PbSO_4 + 2H_2O \tag{18}$$

The electrochemical reactions of AGM batteries and lead acid batteries are very much similar. Nevertheless, there is one aspect of the reactions that differ from one to another. In the charging reaction of the lead acid batteries, hydrogen is liberated; whereas in vented batteries, the hydrogen escapes to the atmosphere through the valve. (McCluer, 2011).

One of the advantages of all lead acid batteries, including AGM batteries over other batteries is their low cost in the market. Lead acid batteries prices are much less expensive than the nickel-metal and Lithium-ion types of batteries. This is the main reason why AGM batteries are preferred by hybrid and stop-go car industry (International Lead Association). **Table 6** summarizes some advantages and disadvantages of valve regulated lead acid (VRLA) batteries.

Table 6. Advantages and disadvantages of VRLA batteries
Source retrieved from (Linden & Reddy, 2001)

Advantages	Disadvantages
Maintenance-free	Should not be stored in discharged

	condition
Moderate life on float service	Relatively low energy density
High-rate capability	Lower cycle life than sealed nickel-cadmium battery
No "memory" effect (compared to nickel-cadmium battery)	Thermal runaway can occur with incorrect charging or improper thermal management
'State of charge" can usually be determined by measuring voltage	More sensitive to higher temperature environment than conventional lead-acid batteries
Relatively low cost	
Available from small single-cell units (2 V) to large 48 V batteries	

In this Thesis, we will focus on the service life expectancy and warranties for AGM batteries. AGM batteries or technically referred as Advance Lead-Acid batteries are going trough a shift in the automobile industry. Figure 11 shows how over a 5 years period AGM battery gained over 50% of the automobile battery market share.

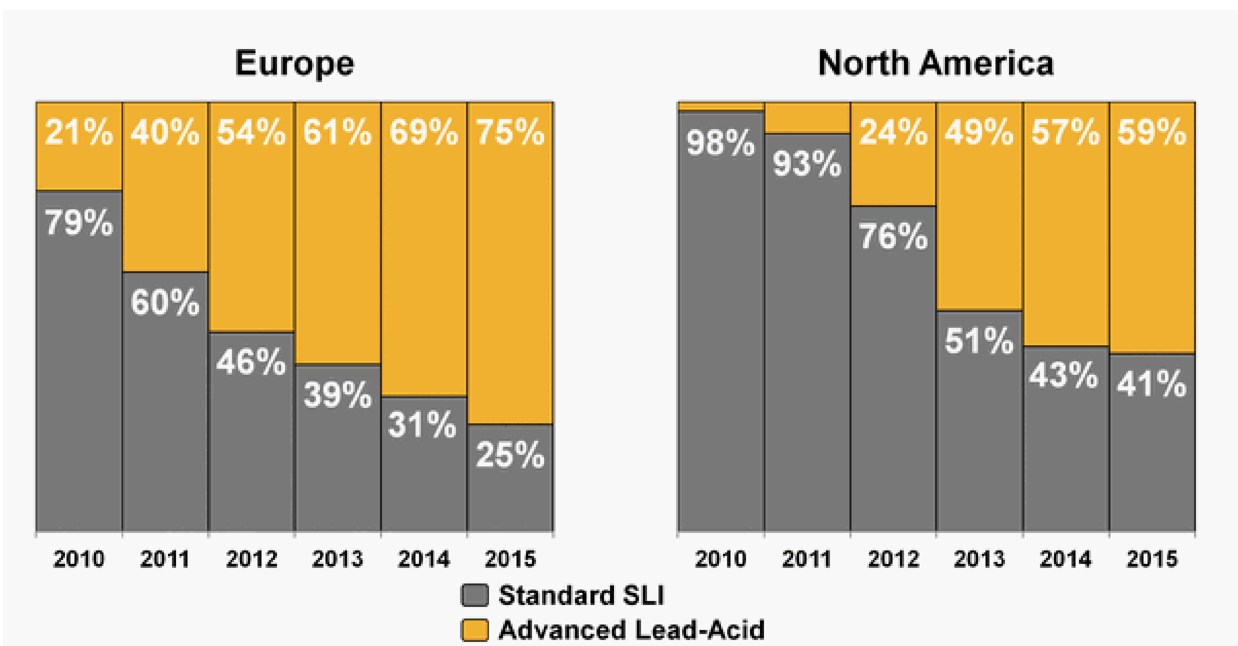

Figure 11. Shifting battery requirements.
Adapted from (Johnson Controls, Inc., 2011)

As a consequence of this shift of battery requirements in the automobile industry, the forecasts of advance battery lead acid battery market value shows a critical increment over the next years. As shown in Figure 12, from 2017 to 2020 the advance lead acid battery market value would increase from $11,000 to $18,000 ($ millions). More importantly, the transportation market would gain about 80% of the market share over the next 4 years. The forecast market of advance lead acid batteries in 2020 would be around $18 billion, of which 58% of those sales will be from the transportation sector, historically one of the most of important industries for lead-acid batteries (Gibson & Adamson, 2012).

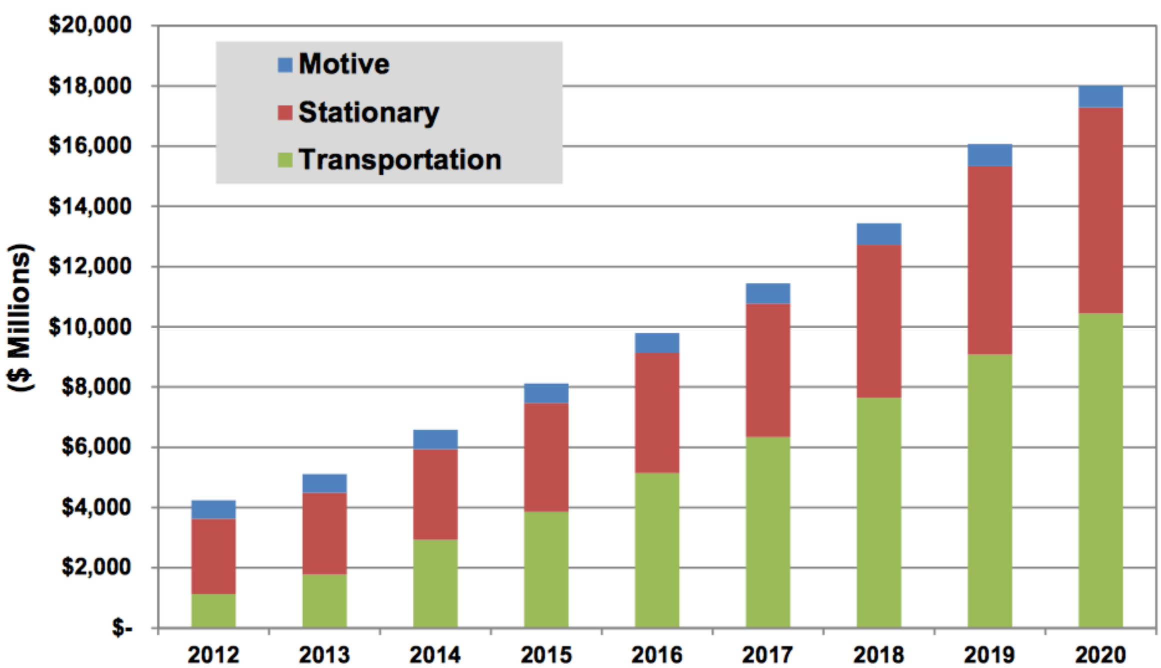

Figure 12. Advanced lead-acid battery market value by application, world markets: 2012–2020
Retrieved from (Gibson & Adamson, 2012)

Thus, the importance and need of analyzing warranty policies for AGM batteries especially in the automobile industry. In this Thesis, we will analyze free-replacement warranty policies exclusively for AGM batteries by defining two different warranty policies that can be applied to this product. Subsequently, we will model the respective warranty cost for each policy to determinate the policy that fits most, given real data from a partner company.

2.2. Warranty

Trustworthiness, quality and therefore warranty of products are important due to the strong competition in the market. The warranty that a product manufacturer offers is associated with the decision that the customer makes when buying a new product. One way that manufacturers have for differentiating their products from others in the market is by offering warranty as a special characteristic of their product.

Nevertheless, some companies see warranty as high quality expenses and fail to recognize the importance of warranty in product reliability. Some organizations however, consider warranty as a service product, separated from the product, thus turning warranty assurance into a new way of earning and maximizing profit, especially by offering extended warranty policies. (Murthy & Blischke, 2000).

In this Thesis, the appropriate warranty models are analyzed and compared to find the one that meets the manufacturer expectations. Moreover, customer expectations of the product and life expectancy would be taken into consideration as well as the design of charging mechanisms for the mileage warranty policies for batteries; the more an automobile is driven the better the life of a battery would be. This is due to the charging mechanisms that are installed in the vehicle.

The next section of the background information reviews warranty basic concepts, terminology and taxonomy, and warranty policies.

2.2.1. Types of Warranty Point of View:

A warranty is a contract between the manufacturer or seller and a customer (Park, 2010). This contract is for the benefit of the two parties since it assures the customer that the product is reliable. Thus, warranties can be used as a marketing strategy for the manufacturer.

2.2.1.1. Customer Point of View

Warranty plays a protecting role because it ensures that the product will work within specific usage limits, such as time and cycles, these are set by the manufacturers. Warranty is also considered a factor in purchasing decisions. When a customer has to make a decision about a purchase, warranty coverage plays an important part. Certain warranty policies include labor and/or parts costs, while some offer extended warranty for an extra cost. In these situations where the customer has different alternatives of warranties, a buyer would more likely prefer the ones that are more cost effective depending on the products' intended use (Blischke & Murthy, 1994).

Hence, the main role of a warranty from a customer point of view is protective (assuring that the product, when properly used and fails in the field will be replaced). This gives the customer a sense of redress. Warranties can also be informative i.e. offers statistical life expectancy for the customer to make decisions (Murthy & Djamaludin, 2002 and Rahman & Chattopadhyay, 2006).

2.2.1.2. Manufacturer Point of View

Manufacturing companies target is the maximization of profit. However, by offering warranty with their products, manufacturers incur in additional costs. For the manufacturers, warranties are a way of limiting their liability to theirs customer (Rahman & Chattopadhyay, 2006). Manufactures use this limitation of their obligations to customer to avoid warranty claims due to factors other than design, manufacturing, environment or life expectancy.

Moreover, warranty also plays a protective role for manufacturers. Warranty policies do often specify the appropriate manner of using their product, conditions and environment (humidity, temperature and light to name a few) of use for which the product was designed (Murthy & Djamaludin, 2002). It is also a marketing instrument to differentiate themselves from their competition.

2.2.2. Taxonomy of Warranty Policies

Warranty policies are promises that the manufactures make to their customers regarding the reliability of their products. Different studies categorized the different types of warranty policies as shown in Figure 13 on next page. (Blischke & Murthy, 1994).

The first two branches are warranties that involve product development or the ones that do not involve product development. The later is additionally divided in single items (type A) and group Items (type B). This simply means that the type A group is for single items sales and type B group is for more than one item sale (block sales). This Thesis analyzes group A warranty policies for single product claims for AGM batteries in the automobile industry.

Further, the group A type of warranty can be subdivided into two subcategories: non-renewing and renewing policies. In the renewing policy, when a single product fails under warranty, the old product is exchanged for a new one with a new separate warranty. The new product gets a new warranty substituting the old warranty of the product that failed in the field. To the contrary, in the non-renewing policy, the new product does not get a new warranty. Instead, new items keep the remaining warranty period of the initial product.

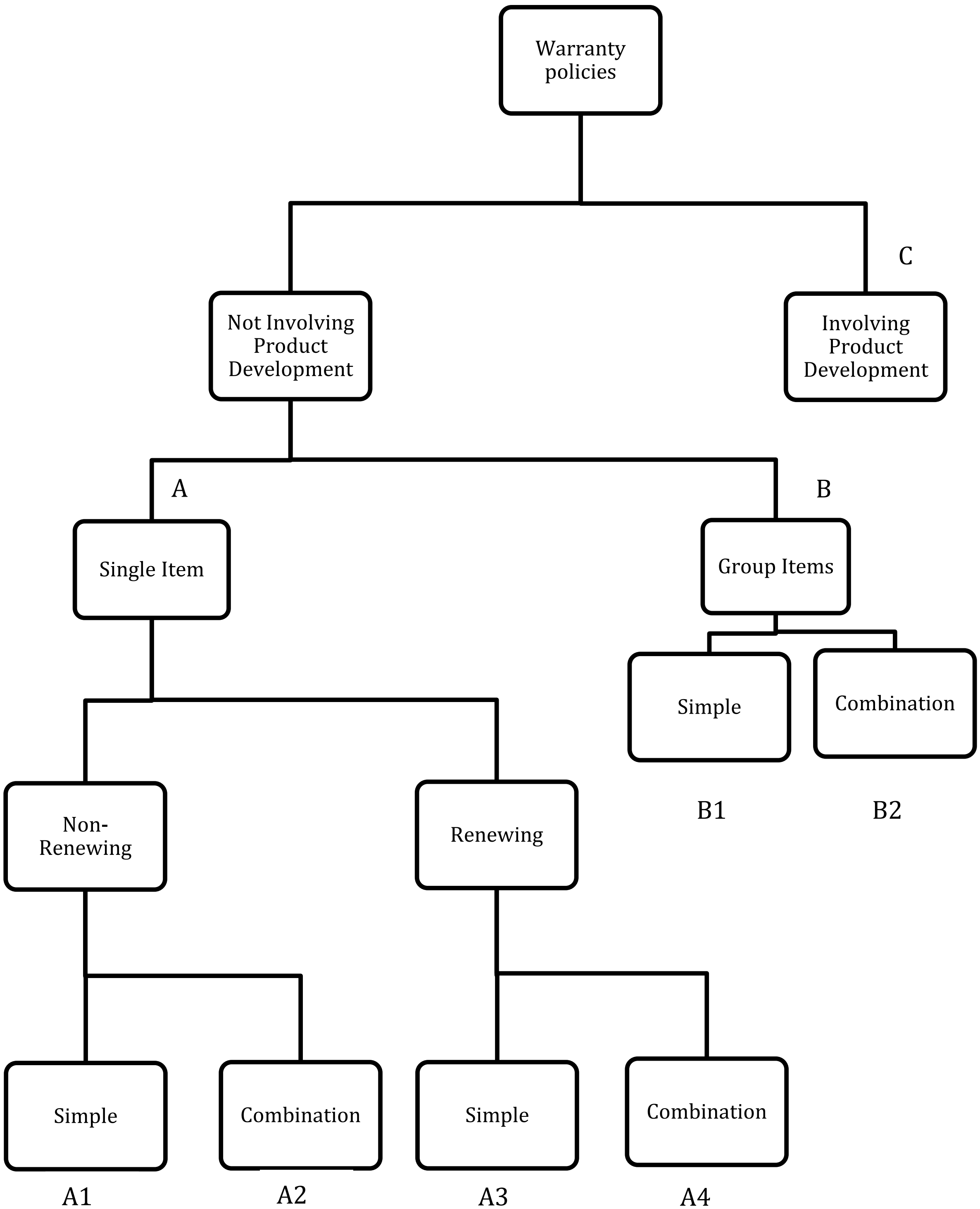

Figure 13. Taxonomy for warranty policies
Source retrieved from (Blischke & Murthy, 1994)

Next, an additional subdivision classifies warranty policies into simple and complex for every category as shown in Figure 13. Consequently, the final classifications of single items or group A warranty policies ends up with 4 different categories from A1 to A4. Single and complex polices can be further subdivided as one-dimensional or two-dimensional policies. In a warranty policy the dimensions simply denote the number of variables that are taken into consideration to limit the warranty (Blischke & Murthy, 1994). For one-dimensional warranty only one variable, such as time delimits the warranty. For batteries, more likely the one-dimensional warranties are either time or mileage of the vehicle. In the two-dimensional warranties, a combination of two variables and their interaction defines the limits of the policy, for instance, a given duration (time) or length of usage (miles) whichever that comes first.

2.2.3. Types of Warranty

In this Section, precise details about different warranty policies are discussed. Some of the characteristics include warranty dimensions and different compensation methods. The two most frequently used warranties for consumer products are the free replacement warranty (FRW) and pro-rata warranty (PRW).

Free Replacement Warranty Policy (FRW)

Under this warranty the manufacturer is fully responsible for the cost of repairing or replacing the products that fail free of charge. The manufacturer is accountable for all the costs up to a time W. This time W, also referred to as the warranty period goes from the moment the product is sold until its failure (Blischke & Murthy, 1994). For free replacement warranties, the most common one is the non-renewing policy. In this case, failure has to occur at age $X_1(< W)$; hence, the remaining duration would be equivalent to the remaining period of the original warranty period $(W - X_1)$.

Pro-Rata Warranty Policy (PRW)

When a product under warranty fails within the limits of the pro-rate policies such as period and failure coverage, the product is repaired or replaced under a pro-rate cost by the manufacturer and a fraction of the repair cost is paid by the customer (Yang, 2007). This type of policy is most usually used for products that fail by wear-out such as cars and batteries (Murthy & Blischke, 2000). The coverage of this policy depends mainly in the age of the product at failure (X_1) and for $X_1 < W$. Thus, linear and nonlinear functions are used to define the pro-rata policy (Blischke & Murthy, 1994).

Three of the functions that are widely used in PRW are:

- The first one is a linear function given by $[W - X_1/W]c_b$, where c_b is the price that the customer paid for the product.
- The second linear function is given by $[\alpha(W - X_1/W)]c_b$, where α is define by the manufacturer this number goes from 0 to 1.
- The third one is a nonlinear function given by $[W - X_1/W]^2 c_b$.

For all three functions, the longer a product has been used (higher X_1) the more the customer has to pay for the replacement of the item (Yang, 2007).

CHAPTER 3: LITERATURE REVIEW

Nowadays, warranty management plays a strategic role in business. For instance, when there are a lot of similarities among different products is hard for the customer to make a decision. Then factors like warranty add on the customer preference for products. Blischke and Murthy developed an approach to warranty management where different factors related to warranty decisions are placed in a decision framework (Murthy & Blischke, 2000). Figure 14 shows the prelaunch, launch, and postlaunch decision frameworks analyzed by Murthy and Blischke.

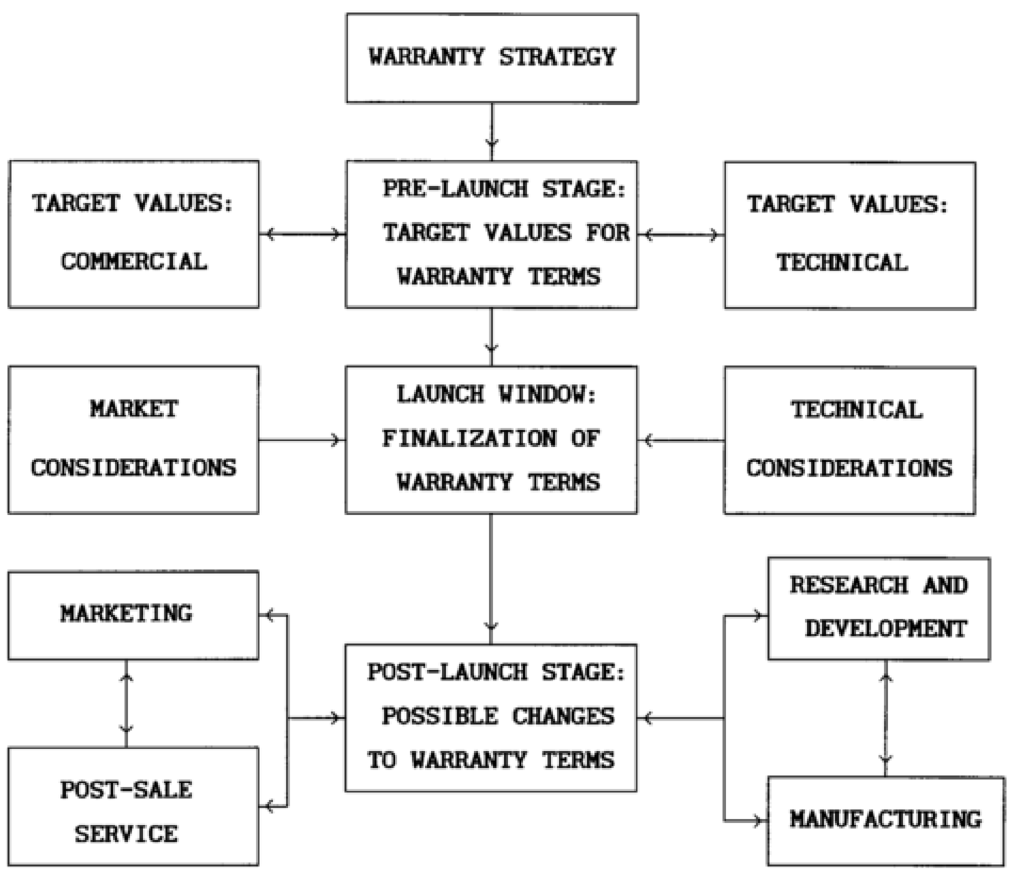

Figure 14. Warranty management. Prelaunch, launch, and postlaunch stages
Source retrieved from (Murthy & Blischke, 2000)

Similarly, Lele and Karmarkar consider product support or warranty as a "smart marketing" strategy. They define product support as warranty programs, service contracts, parts depots, and equipment replacement (Lele & Karmarkar, 1983). Warranty as one of these smart marketing factors, increases customer awareness and expectations about products. Using warranty to increase the ability of perceiving product differentiation through more fitting warranties for every customer is considered a successful marketing tool for companies (Lele & Karmarkar, 1983).

3.1. Warranty Analysis

An immense literature review can be found on warranty data analysis in Wu's research article on warranty data analysis focusing on mathematical models, methods and applications (Wu S. , 2012). In 1995, one of the biggest compilations of warranty articles was done by Djamaludin et al. (Djamaludin I, Murthy, & Blischke, 1995). It contains more than 1,000 records of publications about warranty policies and analysis. A more recent review article done by the same authors, Murthy and Djamaludin, reviews around 190 articles only focusing on new products warranty policies cost analysis, relationships between warranty and engineering, warranty and marketing, warranty and logistics and lastly warranty management (Murthy & Djamaludin, 2002).

Mathematical models for different warranty polices can be found in (Blischke W. R., 1990). Blischke developed different decision models to obtain expected warranty costs from buyer and seller's perspective. Blischke considered models for free replacement warranty, pro-rata warranty and the reliability improvement warranty. The latter is what we usually call extended warranty for free replacement warranty. Additionally, warranty analysis and review articles for long-term and extended warranty policies can be found in (Rahman & Chattopadhyay, 2006). Rahman and Chattopadhyay also review different mathematical models for estimation of warranty costs such as the ordinary renewal funtion, delayed renewal or point process, and non-homogeneous poisson process for renewal.

Zhoua, Li and Tang discuss special warranty policies for products with fixed lifetime such as high-tech products (Zhoua, Li, & Tang, 2009). For example, products like smart-phones, where every year manufactures come out with a new and updated products making old versions obsoluete are consider products with fixed-lifetime.

3.1.1. Warranty Analysis for Free Replacement Policies

Studies about different modeling and cost analysis for free replacement warranty has been done by several scholars. For instance, Blischke and Murthy contributions to warranty modeling and analysis are crucial to this Thesis. They described costs analysis for free replacement warranty policy of non-repairable products from a manufacturer's point of view (Blischke & Murthy, 1994). Batteries are considered a nonrepairable item because once the battery is deeply discharge or one manufacturing component is damaged, the battery must be replaced. Thus, we use the work done by Blischke and Murthy's work as a guide for our modeling. Furthermore, Blischke and Murthy developed models for renewing (repairable) products FRW from the manufacturers' and customers' point of view, also modeling for unit cost or life cycle cost for FRW products again form the manufacturer's point of view (Blischke & Murthy, 1994). In all these models, the one-dimensional and two-dimensional warranty approaches have been addressed, and we will briefly explain the differences in the following sections.

3.1.2. One dimensional Approach

One dimensional warranty policy is characterized by one variable as the defining attribute of the warranty limit such as age or usage. Most warranties in the market are one-dimensional warranties. In the automobile industry for instance, the two most common types of one-dimensional warranties are mileage and time-based. For this Thesis, we consider miles as the warranty metric of usage-based warranty and months as the metric for age-based warranty.

A detailed review of one-dimensional warranty policies can be found in (Blischke & Murthy, 1994). Blischke et al. studied different methodologies for one-dimensional warranty policies, discussed different modeling aspects and analytical approaches to calculate warranty cost. Moreover, they determined first failure calculations for one-dimensional policies. They extended their work to analyze complex one-dimensional polices such as extensions for free replacement warranties. Extensive information about extended warranty policies can be found in (Rahman & Chattopadhyay, 2006 and Blischke W. R., 1990).

3.1.3. Usage-Based Approach

For usage-based warranty policies the estimation of expected number of returns is more complex than that of the age-based policies. First of all, usage-based warranty claim data requires complete information of usage intensity of all products including censored and claimed data (Wu S. , 2012). Most of the time the data collected is only claimed data. Claimed data is collected after a product fails in the field and a claim is filed. To have complete censored data for usage-based warranty analysis, data from products for which warranty claims have not be filed (herein referred to as censored products) have to be collected as well. Frequently, the one-dimensional usage-based type of warranty analysis presents problems whenever there are censored times or usage for those products that have not failed in the field. Therefore, products that are still in good condition are going to have different life distributions than of the failed products (Wu S. , 2012).

There are numerous studies that have been done for incomplete or uncensored data analysis. Suzuki estimated lifetime parameters from incomplete field data for the automobile industry (Suzuki, 1985). Suzuki proposed random follow up surveys to automobiles that had "no record of failures". Once this random censored data was collected the Weibull and exponential distributions were assumed in order to generate lifetime parameters that fit the uncensored warranty data. Further analysis on incomplete data can be found in (Sankaran & Antony, 2009). Sankaran and Antony proposed an extension to the commonly use non- parametric estimator estimation for missing or incomplete data.

3.1.4. Age-Based Approach

Methodologies for estimating the lifetime distribution for age-based warranty policies have been widely reviewed. Age-based approaches include estimating mixed distributions and fitting the frequently use Weibull distribution for warranty claims data (Wu S. , 2012). For instance, Chein presented an optimal age-replacement policy under imperfect free replacement warranty using Weibull distribution (Chein, 2008). The imperfect warranty is when a product that failed is replaced for free by a repaired product. Chein investigated optimal age-replacement policies when the lifetime of new and repairable products both happen to follow weibull distributions. Chein proposed optimal replacement age for products that minimizes the expected warranty cost under the imperfect free replacement warranty strategy. Most recently, Chein proposed a complex optimal age replacement policy (Chien, 2012). In this policy the product should be replace at time N or at failure, whichever occurs first.

Furthermore, Wu, Chou and Huang developed an optimal price, age and production rate from a manufacturer's perspective (Wu, Chou, & Huang, 2009). The expected number of claims from the optimal warranty length was calculated parametrically by fitting a Weibull distribution to real failure data. The study by Wu et al. also considered two different market scenarios, one in which discounts rate are applied and the second one where there is not discount rate.

CHAPTER 4: RESEARCH OBJECTIVES

Due to the to the increased number of claims that AGM batteries presented over the last years warranty performance of these batteries was reviewed by the partner company.

Recent studies done on AGM batteries concluded that batteries that are operated at 77 Fahrenheit typically exhibit faster discharge rates. Moreover, their service life decreases by 50% for every 14-18°F increase in the average ambient temperature (Avelar & Zacho, 2016). Thus, analysis of field warranty claims needed to be performed to determine ways of minimizing warranty costs.

In this Thesis, we analyze warranty claims of AGM batteries that failed in the field and had warranty claims recorded.

In this Thesis, we sought to accomplish three objectives as follows:

Objective 1: Provide a detailed quantitative descriptive summary of the warranty claims data (Chapter 5). Our approach is to first introduce our data and present a statistical data description of the warranty claims to understand the trends within followed by further statistical analysis. The data used in this research is for AGM batteries warranty claims under the free renewal warranty policy. The data contains claims from 2015 and 2016.

Objective 2: Present a usage-based warranty model that optimized the warranty cost and apply it to the warranty claims data.

Objective 3: Present a time-based warranty model that optimized the warranty cost and apply it to the warranty claims data.

Following objectives 2 and 3, a sensibility analysis is performed to determine the expected number of claims for the age and time-based models. In both cases, the warranty models are used to forecast the reduction in the expected number of warranty claims given the expected company strategies to mitigate against early failure modes as well as supplier quality improvements.

Finally, this study includes a discussion of the modeling results followed by conclusions and proposed extensions or possible improvements to the models developed, data collection as part of future research.

CHAPTER 5: WARRANTY MODELING

5.1. Data description

Warranty data is used by manufacturers for many purposes, for instance in predicting future warranty costs. The data used in this Thesis was collected from different automobile dealers in the USA. For proprietary reasons, we are unable to divulge the company name as well as the model of automotive. Every time a customer returns their vehicle to the dealership and a warranty claim was filed, a warrant claim is recorded in the OEM's database. Hence, months to failure was calculated from the date of the sale (to the dealers) until date the claim was filed by the dealer or the end customer. Information such as mileage, sales dates, failure date, model year and the type of vehicle is collected. However, at this point, the data is normally incomplete because failures that occur after the end of the warranty period may not be collected. Another difficulty for this research is that no indication of the environment in which the vehicles were operated or stored is available.

In this chapter, we provide data descriptive analyses of the warranty claims. Warranty claims data from 2015 to 2016 was collected to have 24 months of claims for the analysis. A total of over 25,000 data points were collected for the 24 months of the study. Every data point represents a battery warranty claim. Figure 15 shows the distribution of the number of claims by months, with returns less than a month removed (early failures).

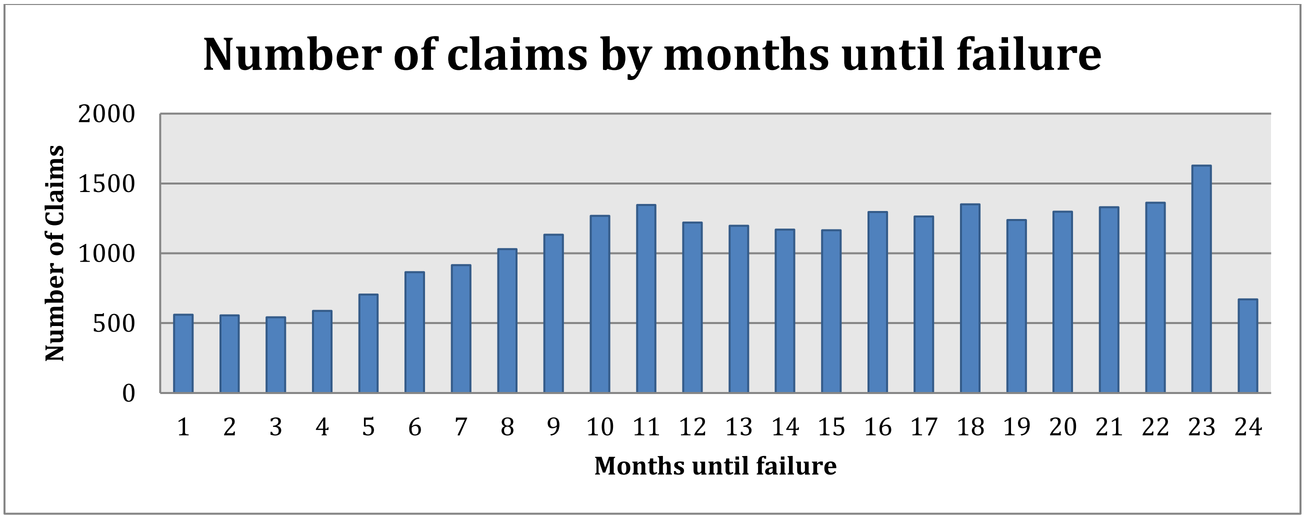

Figure 15. Number of claims by months until failure

Figure 16 presents the percentage of the manufacturer's warranty cost spent by months until failure. We can see that the highest pikes are month 11, 18 and 23 follow by a considerably decrease in claims in month 24.

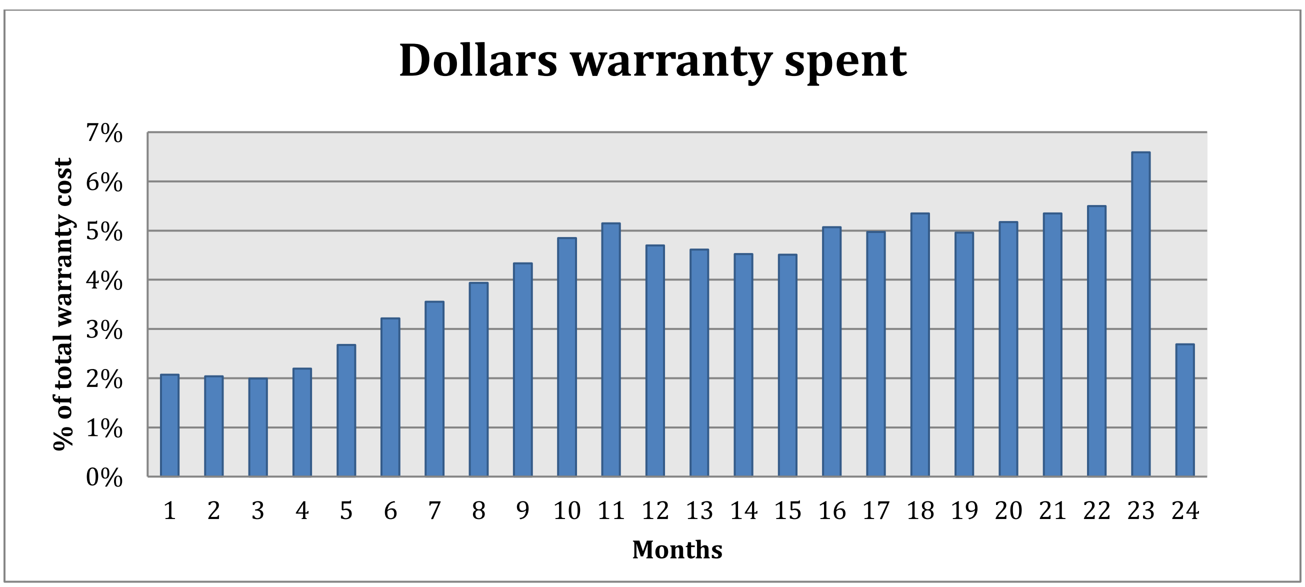

Figure 16. Warranty total cost by months until failure

Since the warranty cost and the number of claims are correlated, we can say that the numbers of claims are higher in the first months of the warranty than the later ones.

Figure 17 shows the number of claims difference from the first year to the second year. In the pie chart, around 42% of the total claims occurred within the 12 months of the warranty and 58% occurred from months 13 to 24.

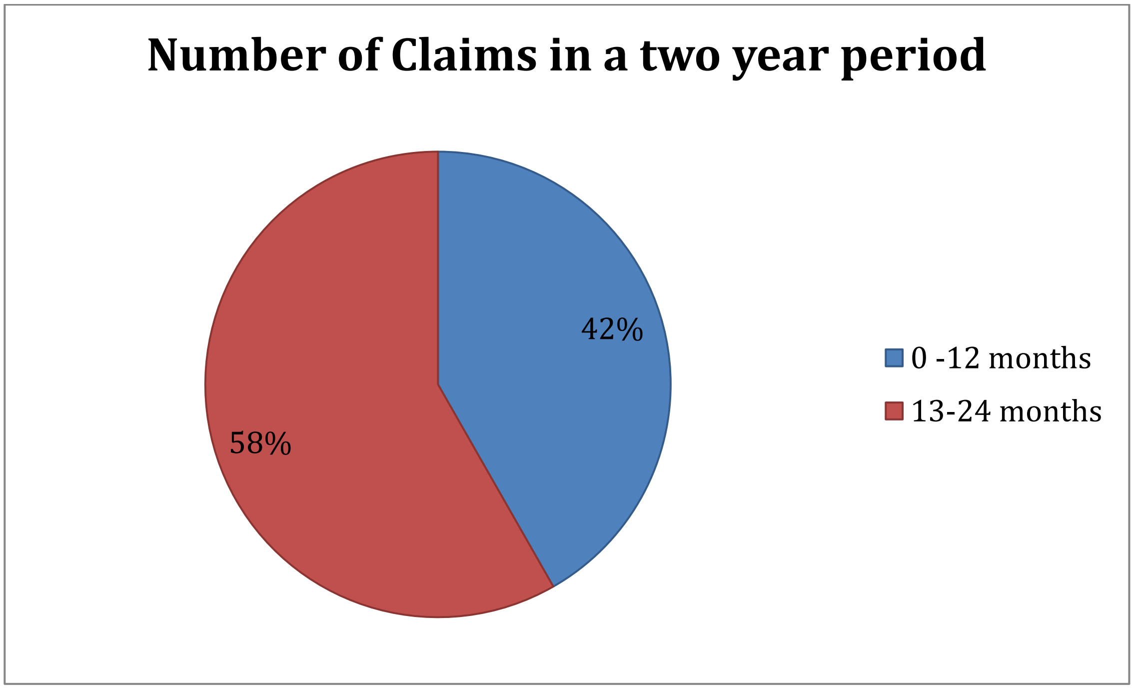

Figure 17. Pie chart of the number of claims in a two years period

Moreover, Figure 18 presents usage in miles at the time of warranty claim was filed. The data recorded was measured as the total distance traveled (in miles) from the time of sale until failure. Figure 18 shows than more than 80% of the battery claims occurred within the first 10,000 miles of usage, which implies that a large percentage of battery failure is as a result of user's negligence.

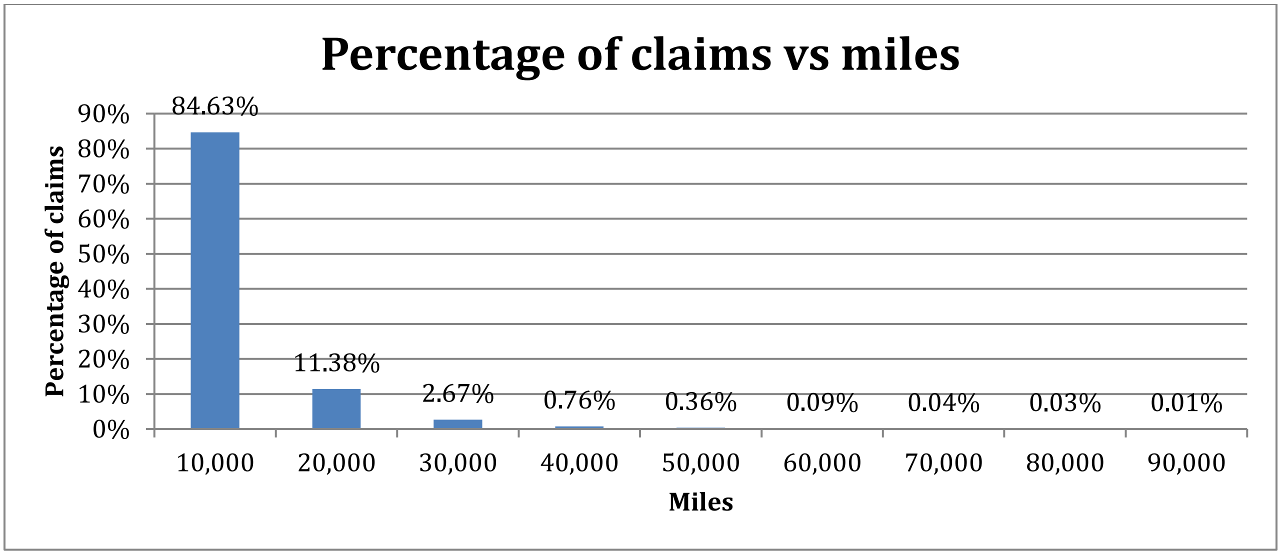

Figure 18. Percentage of claims versus miles until failure

The warranty claim data collected also includes failure mode. As shown in Figure 19, most of the failures are relatively minor problems as is evident from the warranty claim data. The three highest percentages for failure modes are weak/dead battery at 79%, engine will not turn over at 12% and engine turns over, but slow/hard start at 2% of the total of claims.

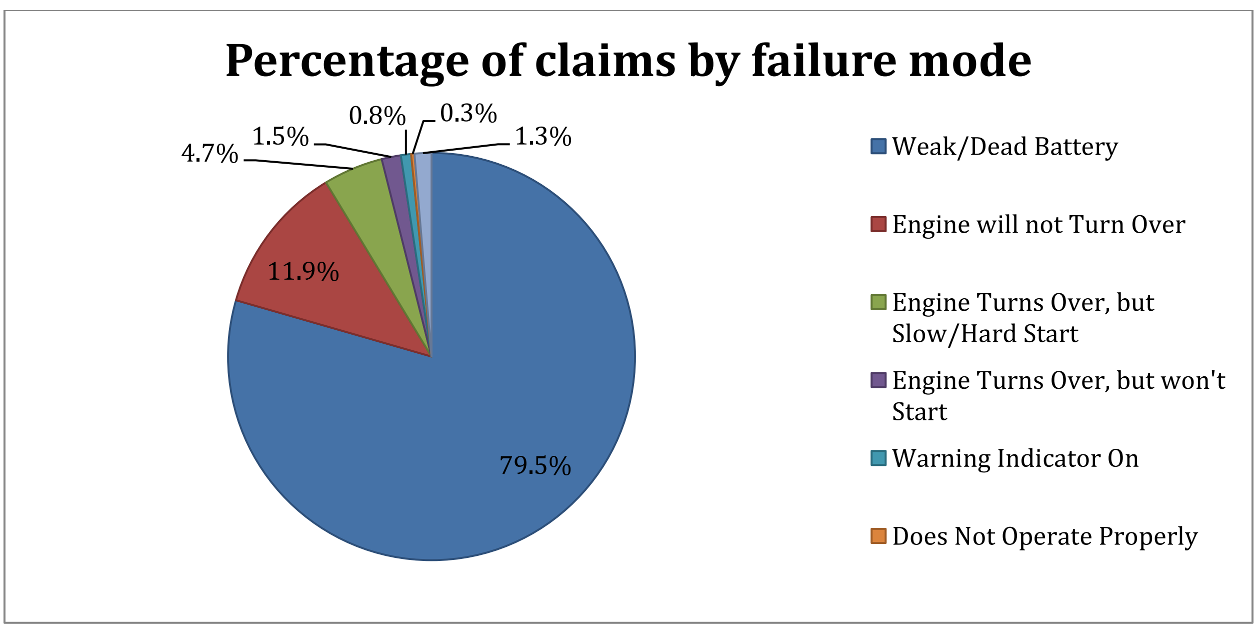

Figure 19. Pie Chart of failure mode for a 24-month period of warranty claims for AGM batteries

Further descriptive analysis in Figure 20 shows the percentage of claims by failure mode for the first 12 months of the warranty policy. Once again, the number one failure mode is "weak/dead battery", with 80% of the total claims, which reaffirms our claim that most failures are largely due to user-related battery maintenance practices.

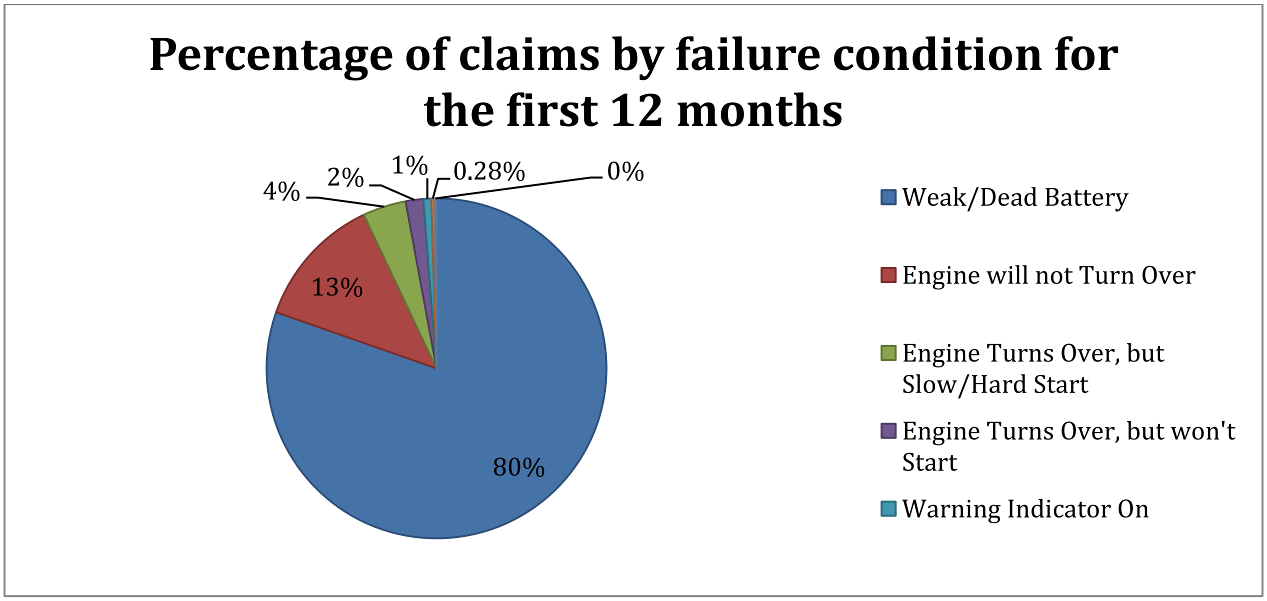

Figure 20. Pie chart of failure mode for the first 12 months of warranty claims for AGM batteries

Next, Figure 21 illustrates the percentage of claims by failure mode for the second year of the warranty policy (month 13 to 24). Similar to Figure 20, the three main failure modes for the second year of the warranty were "weak/dead battery" at 83.2%, "engine will not turn over" at 11.3% and "engine turns over, but slow/hard start" at 3.1% of the total of claims. As shown above, the failure mode does not change for the first year, to the second year of warranty.

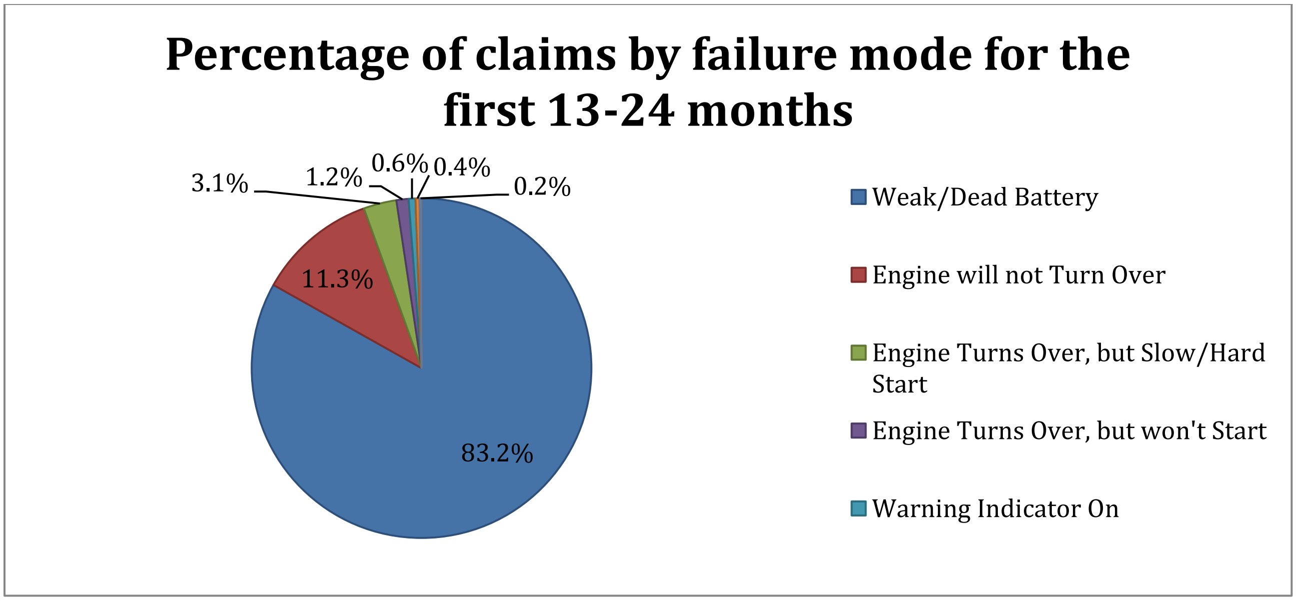

Figure 21 Pie chart of failure mode for months 13 through 24 of warranty claims for AGM batteries

5.2. Probability Distribution Selection

The first step in the mathematical modeling is to identify the right distribution model for the data. A distribution ID plot for right censoring analysis is performed in Minitab to the failure data gets the best-fit distribution. This analysis compares and creates a probability plot for every distribution. The results of this comparison for mileage are shown in Figure 22.

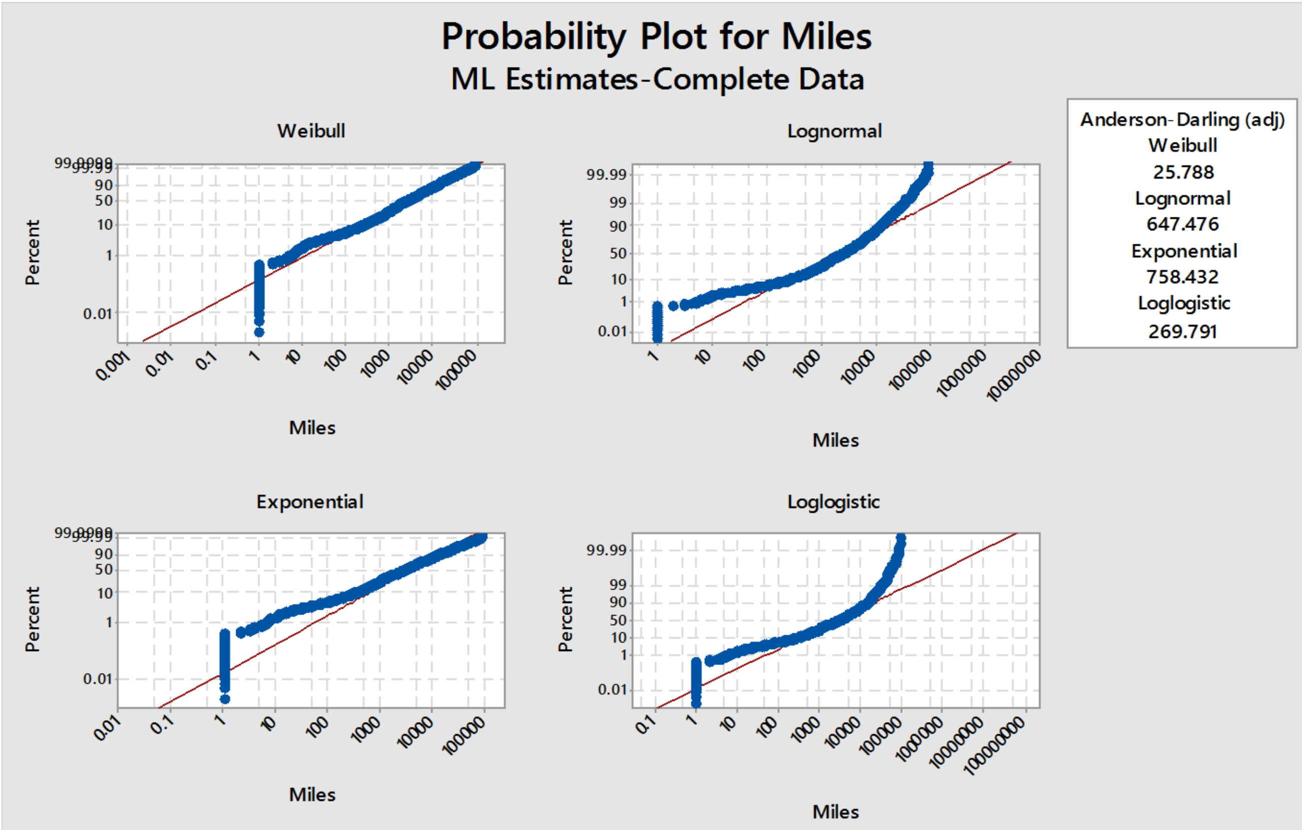

Figure 22. Probability plot for Weibull, Exponential, Lognormal and Loglogistic distributions for mileage failure data

In order to identify the best-fit distribution for the mileage failure data we can simply look at the probability plots. It is pretty noticeable that the Log-logistic distribution plot hardly fits the data points so we discard that distribution. However, it is sometimes difficult to tell which distribution is the best fit for out data. Therefore we need an exact method to choose the right distribution. The probability ID function in Minitab provides the Anderson-Darling test and the exact test value for every distribution. The Anderson Darling is one of the goodness-of-fit tests that can be performed on any failure data. The smaller the Anderson-Darling test value, the better the distribution fits the data (Martz, 2013). The best-fit life distribution for the failure data is the Weibull distribution with the lowest Anderson Darling Value of 27.788.

Subsequently, now we proceed to do the same probability ID analysis for the months to failure data of AGM batteries to identify the best distribution fit. The results are shown below:

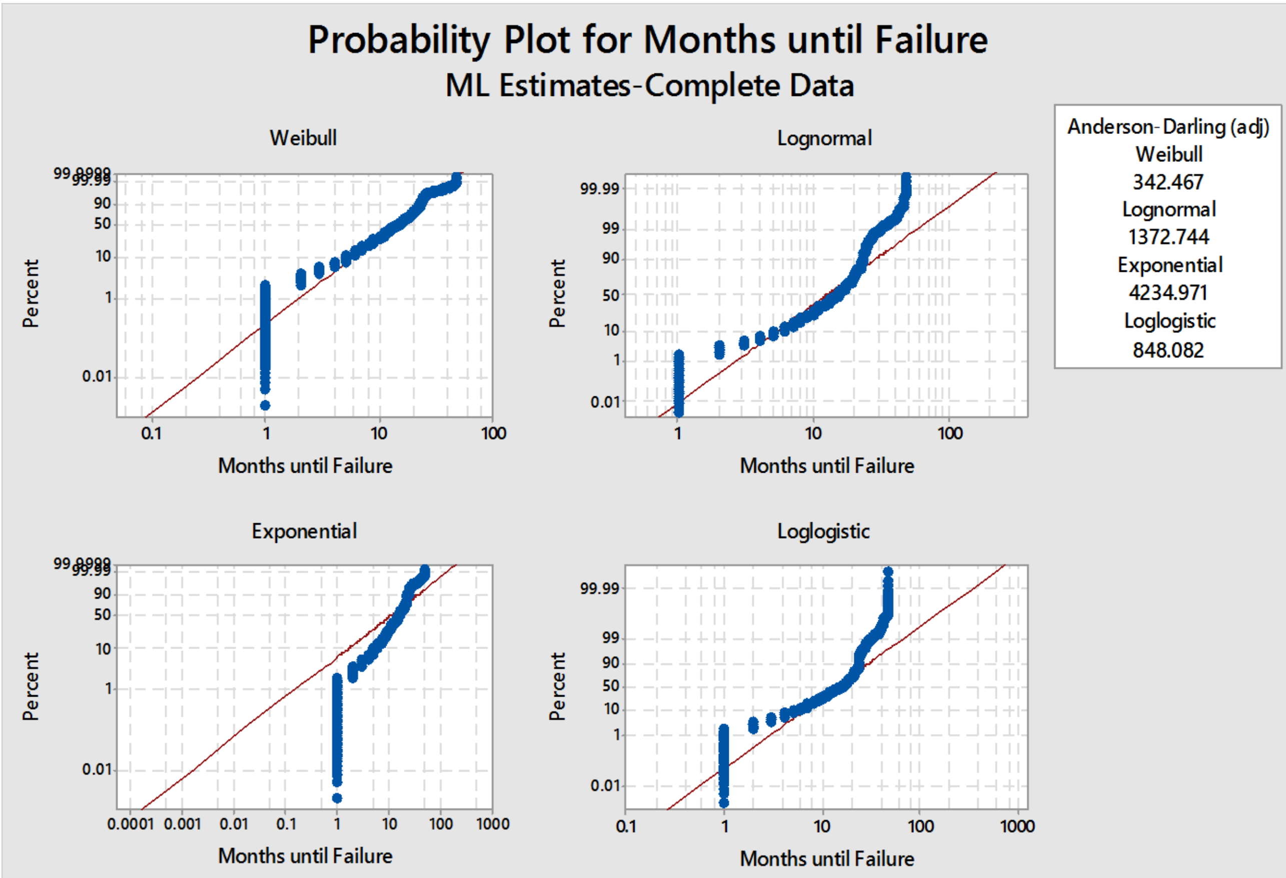

Figure 23. Probability plot for Weibull, Exponential, Lognormal and Loglogistic distributions for months until failure data

Once more, the Weibull distribution is selected as the best fit distribution for the months to failure data with and Anderson Darling value of 342.467 the lowest value of the comparison.

5.3. Product Life Distribution

Following the preceding goodness-of-fit test, we present some probability functions of the Weibull distribution in the following section.

5.3.1. Weibull Distribution

The following reliability metrics differentiate the Weibull distribution from the others. One of the Weibull distribution's main characteristics is that failure rate is time dependent compared for instance with the exponential distribution that has a constant failure rate. This feature is of big interest for this study because we aim to find the optimal mileage and age limits for warranty in order to minimize warranty cost.

In this section the most common metrics to measure reliability are shown. In real life, appropriate metrics depending on the product uniqueness have to be determined. These metrics ideally should be sensitive to time and consider manufacturers and customers (Yang, 2007). As we know, reliability is a function of time. Therefore, the time related metric chosen by a manufacturer as the design life metric should reflect the customer expectations of the product.

5.3.2. Weibull Distribution Functions

Probability Density Function (pdf): this function is denoted as $f(t)$ and it indicates the failure distribution for the entire time range and it denotes the absolute failure speed. (Yang, 2007). The pdf is basically calculated by the usages to failure of all the data range of products.

$$f(t) = \frac{\beta}{\alpha^{\beta}} t^{\beta-1} \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \qquad t > 0 \qquad (19)$$

Cumulative Distribution Function (cdf): this function is denoted as $F(t)$ and it indicates the probability that a product is going to fail in a given time t.

$$F(t) = 1 - exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \qquad t > 0 \qquad (20)$$

Reliability Function: this function is denoted $R(t)$. This function is also known as the survival function (Yang, 2007). The reliability function specifies the fraction of the population that survived given a time t.

Hazard Function: is denoted $h(t)$ and it is also known as failure rate. This measures probability's rate change in given time intervals. (Yang, 2007). The hazard function can be expressed in terms of failure per unit time or length, for instance, number of failures per hour, failures per month or failures per mile.

$$h(t) = \frac{\beta}{\alpha} \left(\frac{t}{\alpha}\right)^{\beta} \qquad t > 0 \qquad (21)$$

There are three types of hazard rates:

- Decreasing hazard rate (DFR) or early failures.
- Constant hazard rate (CFR) or random failures.
- Increasing hazard rate (IFR) or wear-our failures.

Cumulative Hazard Function: it is denoted $H(t)$. This is a non-decreasing function that is linked to DFR, CFR and IFR.

$$H(t) = \frac{t^{\beta-1}}{\alpha} \qquad t > 0 \qquad (22)$$

Percentile: denoted t_p , is defined as the time by which a given fraction of the population fails.

$$t_p = \alpha[-In\ (1-p)]^{1/\beta} \qquad (23)$$

Mean Time to Failure (MTTF): it is the expected life of a non-repairable product. MTTF is denoted E(T),

$$MTTF = \alpha\Gamma\left(1 - \frac{1}{\beta}\right) \qquad (24)$$

and the variance if expressed as follows:

$$Var(T) = \alpha^2 \left[\Gamma\left(1 + \frac{2}{\beta}\right) - \left(\Gamma\left(1 - \frac{1}{\beta}\right)\right)^2\right] \tag{25}$$

Where:

- β is the shape parameter and gives the rate of decay; therefore, it is of great use in engineering and management as a tool to provide insight of the physics of the systems failure (Abernethy, 2000). The shape parameter is also the slope of the line of a Weibull distribution plot.
- α is the scale parameter and it represents the typical time to failure in Weibull analysis i.e. the time at which 63% of the products would have failed. This parameter is related to the MTTF of the system (Abernethy, 2000).

5.3.3. Failure Modeling

The parameter β (the slope of the plot) of the Weibull distribution determines what type of Weibull failure best describes the data (Abernethy, 2000). There are three types of failures families in the Weibull distribution:

- $\beta < 1$ indicates a decreasing failure profile, representing early failures (infant mortality).
- $\beta = 1$ indicates a constant failure rate, which represents random failures (normal life).
- $\beta > 1$ indicates an increasing failure rate, representing wear-out and fatigue failures (end of life).

5.4. Usage Based Modeling

In this section we analyze the mileage warranty data. Using Minitab we generate a distribution overview plot for the warranty data. As shown in Figure 24, we calculate and graph the probability density function (pdf), the probability plot, the survival and hazard function graphs for mileage. From the hazard (failure) function graph we can conclude that the rate of failure decreases significantly within the first 5,000 miles. In the same way, the survival function shows that after 5,000 miles the rate decreased almost by 50%. Moreover, the table of statistics shown in Figure 24 gives the mean time to failure for mileage data. In this case the MTTF is 5435.67 miles with a shape parameter of 0.789077 and a scale parameter of 4749.64.

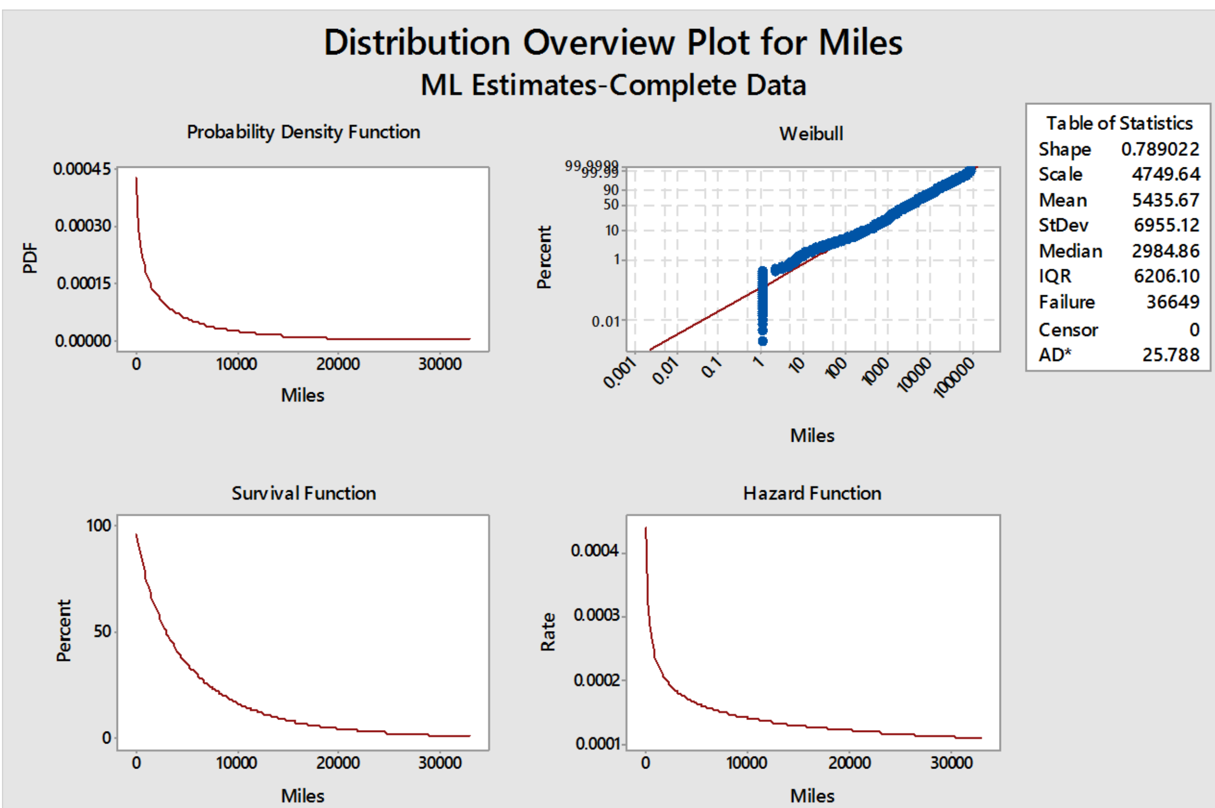

Figure 24. Distribution Overview plots for mileage warranty data

For the usage-based modeling, a policy with MTTF of 5435.67 is relatively low given that most customers drive every day and would be out of warranty pretty quickly. One of the objectives for this warranty policy is to find a policy that minimizes costs for the company without affecting customer expectations.

Moreover, the data collected for usage-based warranty claimed data and was not complete which might affect the warranty analysis. As we mention before, complete censored data requires information from products that have not filed warranty claims. Another factor that can be influencing the warranty data is that nowadays most vehicles have charging systems connected to the battery. These charging systems begin to charge the battery once the vehicle is being driven. Essentially, the state of charge of a battery is indirectly proportional to the vehicle mileage.

5.5. Age-Based Modeling

Now we consider an age-based warranty model for AGM batteries. We first analyze the warranty data and calculate the months until failure for every claim (from retail date to failure date). After we have the months until failure for each claim we generate a distribution overview plot in Minitab shown in Figure 25. This distribution overview plot contains the probability density function graph, probability plot, and survival function and hazard function graphs.

The probability density function graph shows a continuous increment until month 15 and then it begins to decrease, which is related to the scale parameter of 16.69 for the months to failure warranty data and the shape parameter of 2.18. The survival and hazard functions are indirectly proportional which is expected

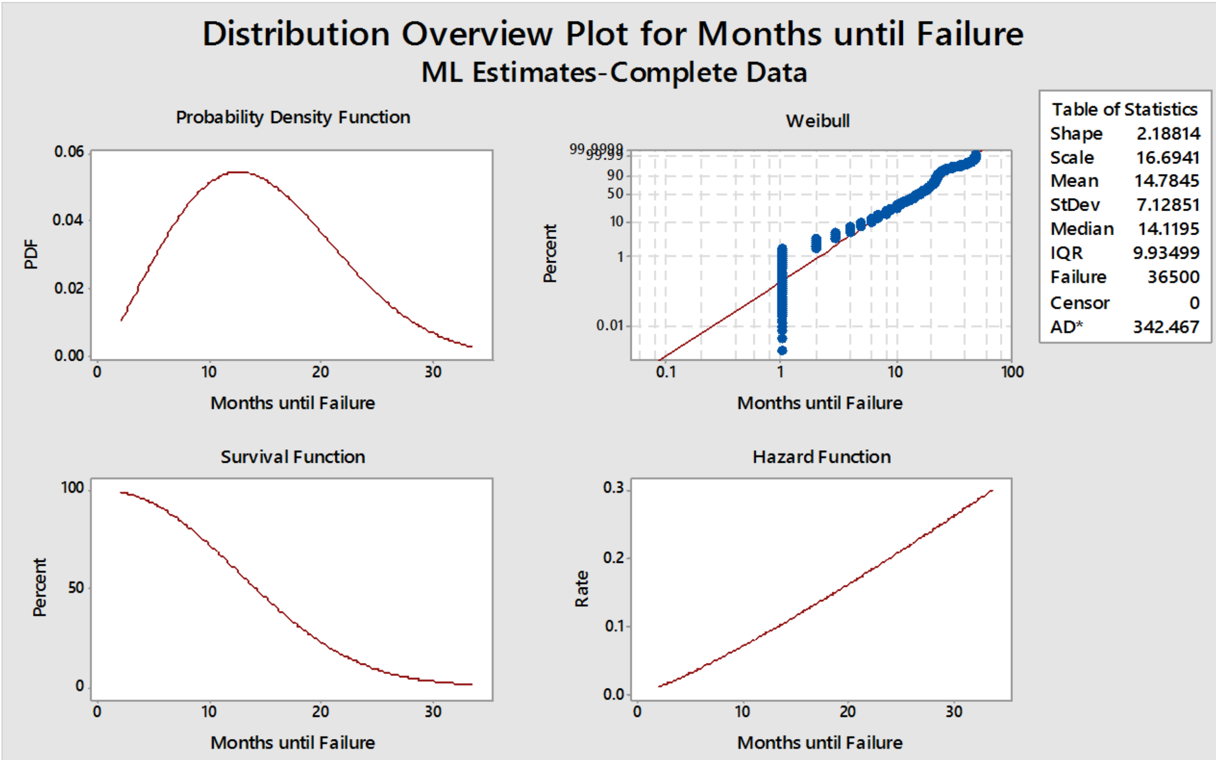

Figure 25. Distribution Overview Plot for Months until Failure

Table 7 below shows the lower and upper limits and the estimated parameters for the actual data. We want to take into considerations best and worst case scenarios, Hence the lower and upper limits.

Table 7. Weibull Parameter Estimate, Lower and Upper limit for Age Warranty Analysis

		Shape	Scale
Actual data	Lower	2.289	15.562
	Estimate	2.313	15.648
	Upper	2.337	15.735

Subsequently, after calculating the shape, scale, and the probability distribution function, the next step is to calculate the expected number of returns or renewals for the warranty cost analysis.

5.6. Expected Number of Renewals for a Good-as-New Repair

In this Thesis, we use the free replacement warranty policy of "good as new repair". This means that the new items will follow the same distribution as the ones that failed. Since this research focuses on the free replacement warranty policy, the good-as-new repair modeling explain by (Yang, 2007) is considered in the paper in order to calculate the expected number of failures.

5.6.1. Renewal Theory

In the good-as-new repair the manufacturer is in the obligation of return the product that failed to the new original condition. Basically, in this type of 'repair" the manufacturer replace the failed product with a new one. Yang uses the renewal theory to calculate the number of renewal item in a period of time because every time a product is "repair as new" can be also interpreted as ordinary renewal process (Yang, 2007). Equation 26 shows the expected number of renewals adapted to the nomenclature that this Thesis uses.

$$M(t_0) = F(t_0) + \int_0^{t_0} M(t_0 - x)\, f(x)dx \tag{26}$$

Where,

$M(t_0)$ is the expected number of renewals within t_0

$F(t_0)$ is the cdf of the product

$f(x)$ is the pdf of the product

Substituting Equations 19 and 20 in Equation 26 leads to the expected number of failures in the case of the Weibull distribution as shown in Equation 27.

$$M(t_0) = \frac{\beta}{\alpha^{\beta}} t^{\beta-1} \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] + \int_0^{t_0} W(t_0 - x) 1 - exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] dx \tag{27}$$

However, the mathematical solution for the renewal function for the Weibull distribution is challenging and cannot express in a closed form (McCool, 2012). Some papers have computed tables for the values of M(t) such as Blischke and Murthy (Blischke & Murthy, 1994) and White (White, 1964). Jiang proposed a simple approximation of the Weibull renewal function (Jiang, 2009). Jiang approximation can be express as:

$$M(t) \approx p\, F(t) + \int_0^{t} q \wedge (t) dx \tag{28}$$

$$M(t) \approx p\left[1 - exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]\right] + q\left(\frac{t}{\alpha}\right)^{\beta} \tag{29}$$

Unfortunately, the renewal function for the Weibull distribution cannot be solved analytically. Therefore, we seek a different approach. The renewal function can also be express as:

$$M(t) \approx \frac{t}{\mu} + \frac{\delta}{\mu^2} \tag{30}$$

Where δ is the variance and μ is the mean of the variable t.

First, we set fixed renewal times of 6, 12, 18 and 24 months for the warranty periods because they are the most commonly time limits in warranty policies. Next, we calculate the mean and variance of the every variable T using equations 24 and 25 respectively.

$$MTTF(T) = 15.648\Gamma\left(1 - \frac{1}{2.313}\right) = 13.86$$

$$Var(T) = 15.648^2 \left[\Gamma\left(1+\frac{2}{2.313}\right) - \left(\Gamma\left(1-\frac{1}{2.313}\right)\right)^2\right] = 40.45$$

Next, after calculating the mean and variance for the variable T we determine the expected number of returns M(T) using Equation 30 As mention before values for T are 6, 12, 18 and 24 months. For example, below we determine M(6):

$$M(6) \approx \frac{6}{13.86} + \frac{40.45}{13.86^2} = 0.49$$

The results for the expected number of returns for the fixed t values using the parameter estimates, lower and upper limits of the estimates are shown below in Table 8.

Table 8. Expected Number of Renewal Calculations For Age-Based Warranty Policy

	Shape β	Scale α	Mean	Variance	M(t)			
					6	12	18	24
Lower	2.289	15.562	13.79	40.74	0.489	0.924	1.359	1.794
Estimate	2.313	15.648	13.86	40.45	0.485	0.918	1.351	1.783
Upper	2.337	15.735	13.94	40.16	0.481	0.912	1.342	1.772

5.7. Sensitivity Analysis

Due to some improvements in the distribution portion of the supply chain for AGM batteries, now the company guarantees that 100 % of the batteries voltage requirements are meet when the customer buys a vehicle. This change is expected to have a positive impact by minimizing the expected number of early returns. Additionally, while the vehicles are being transport to the customers or store in the warehouse a "top-off" charge is applied to the battery to ensure that the battery meets the customer expectations.

Moreover, recent developments in the manufacturing processes of AGM batteries can result in plates that are more resistant to the charging and discharging reactions. This change is expected to give a longer life expectancy of the product. Hence, a sensitivity analysis is performed to the data for the various expected warranty claims percentage reductions. The percentages of claims reductions are 20%, 30%, 40%, 50% and 60% of the actual data as shown in Figure 26

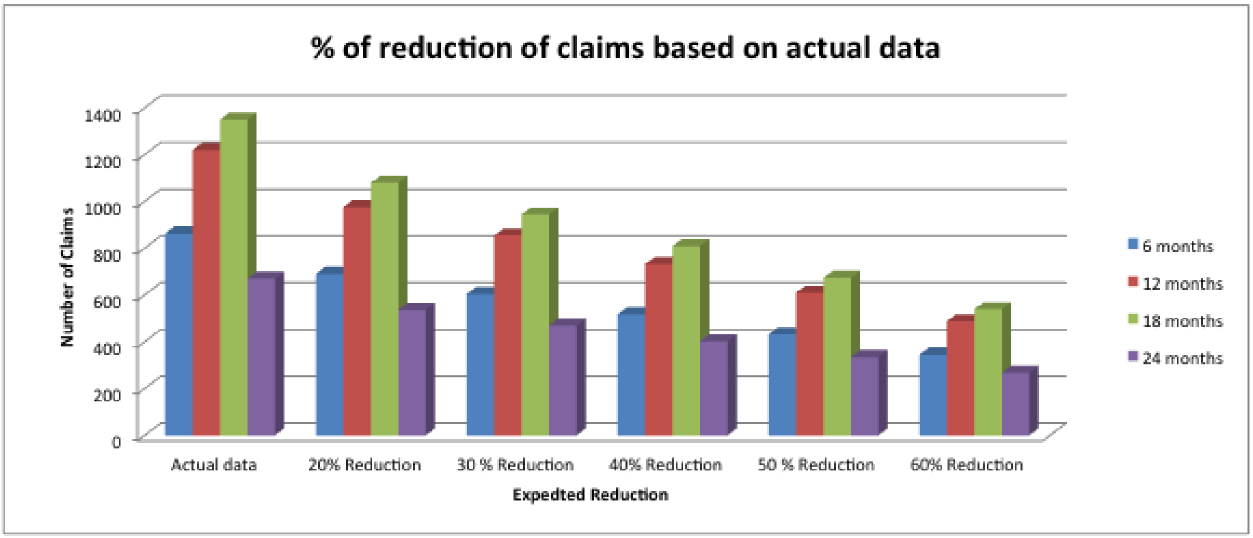

Figure 26. Percentage of reduction of claims based on actual data

Next, the shape and scale parameters for every reduction data set were calculated as well as the lower and upper limit estimates. Then, the mean and variance of every sample was computed in order to calculate the M(t) values. In Table 9 we present the results of the sensitivity analysis for various the times (T), and their respective shape and scale parameters.

Table 9. Sensitivity of Expected Number of Returns M(t)

Data sets		Shape β	Scale α	Mean	Variance	M(t) 6	12	18	24
Actual data	Lower	2.289	15.562	13.79	40.74	0.489	0.924	1.359	1.794
	Estimate	2.313	15.648	13.86	40.45	0.485	0.918	1.350	1.784
	Upper	2.337	15.735	13.94	40.16	0.482	0.912	1.343	1.773
20%	Lower	2.287	15.553	13.78	40.76	0.489	0.925	1.360	1.7968
	Estimate	2.314	15.649	13.86	40.44	0.485	0.918	1.351	1.784
	Upper	2.340	15.746	13.95	40.11	0.481	0.911	1.342	1.772
30%	Lower	2.285	15.546	13.77	40.78	0.489	0.925	1.361	1.796
	Estimate	2.314	15.649	13.86	40.43	0.485	0.918	1.351	1.784
	Upper	2.343	15.753	13.96	40.09	0.481	0.911	1.341	1.771
40%	Lower	2.283	15.538	13.76	40.82	0.489	0.926	1.362	1.798
	Estimate	2.314	15.649	13.86	40.44	0.485	0.918	1.351	1.784
	Upper	2.345	15.761	13.97	40.07	0.481	0.911	1.340	1.770
50%	Lower	2.280	15.528	13.76	40.85	0.491	0.926	1.363	1.799
	Estimate	2.314	15.649	13.87	40.43	0.485	0.918	1.351	1.784
	Upper	2.348	15.772	13.98	40.03	0.481	0.910	1.339	1.769
60%	Lower	2.276	15.513	13.74	40.91	0.491	0.927	1.364	1.801
	Estimate	2.313	15.649	13.86	40.44	0.485	0.918	1.351	1.784
	Upper	2.352	15.786	13.99	39.99	0.480	0.909	1.338	1.767

It is expected that the relative return ratios increase with time, since age is a determining factor in the life of an AGM battery. Moreover, the ratios within the fixed times (i.e. 6, 12, 18, 24 months) are quite similar. For instance, for a 6-month policy the relative return ratio is approximately 0.48 for all the data sets in the analysis, same for the 12, 18 and 24-month policy. Hence, the sensitivity analysis validates the warranty model and the ratios of returns.

The expected warranty returns that were calculated using the M(t) values, the selected percentage warranty return reduction and the actual, lower and upper limits of the Weibull parameters are shown in Figure 27, Figure 28 and Figure 29.

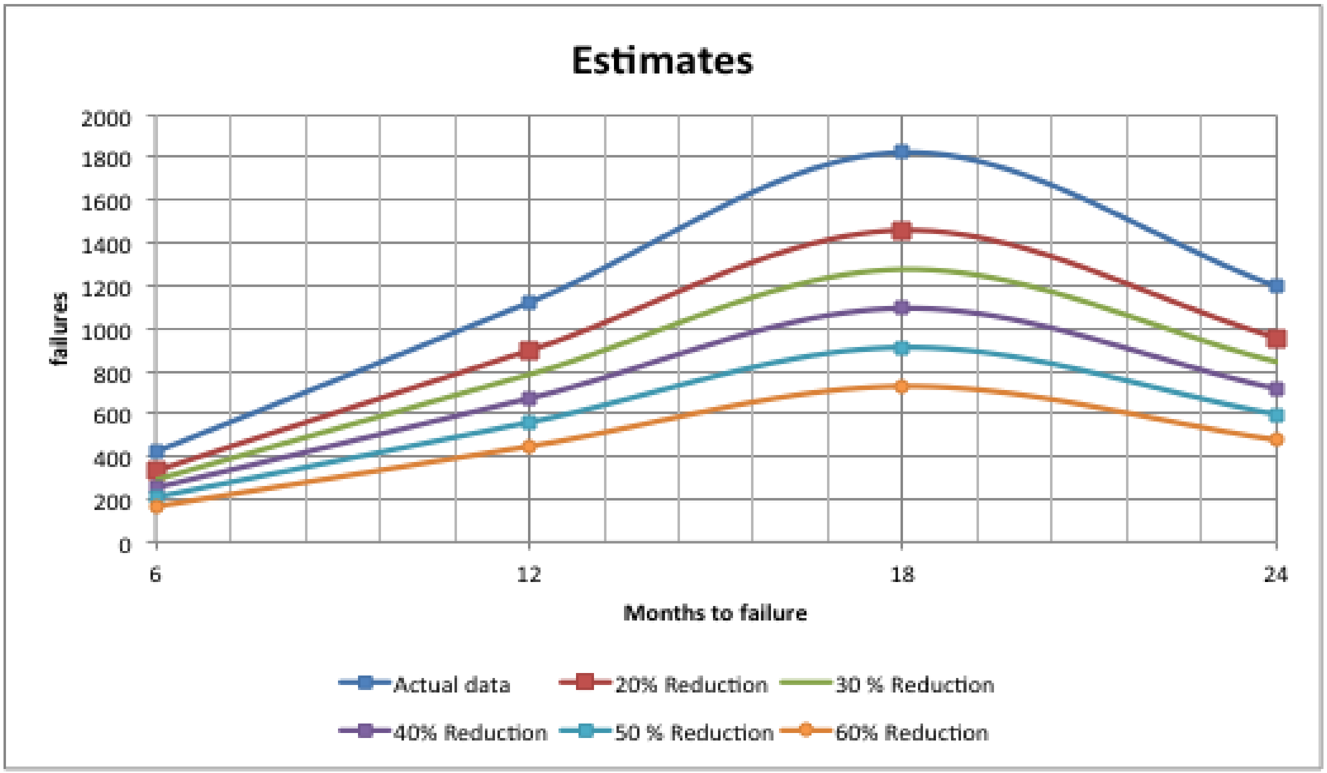

Figure 27. Expected number of returns using the estimates parameters

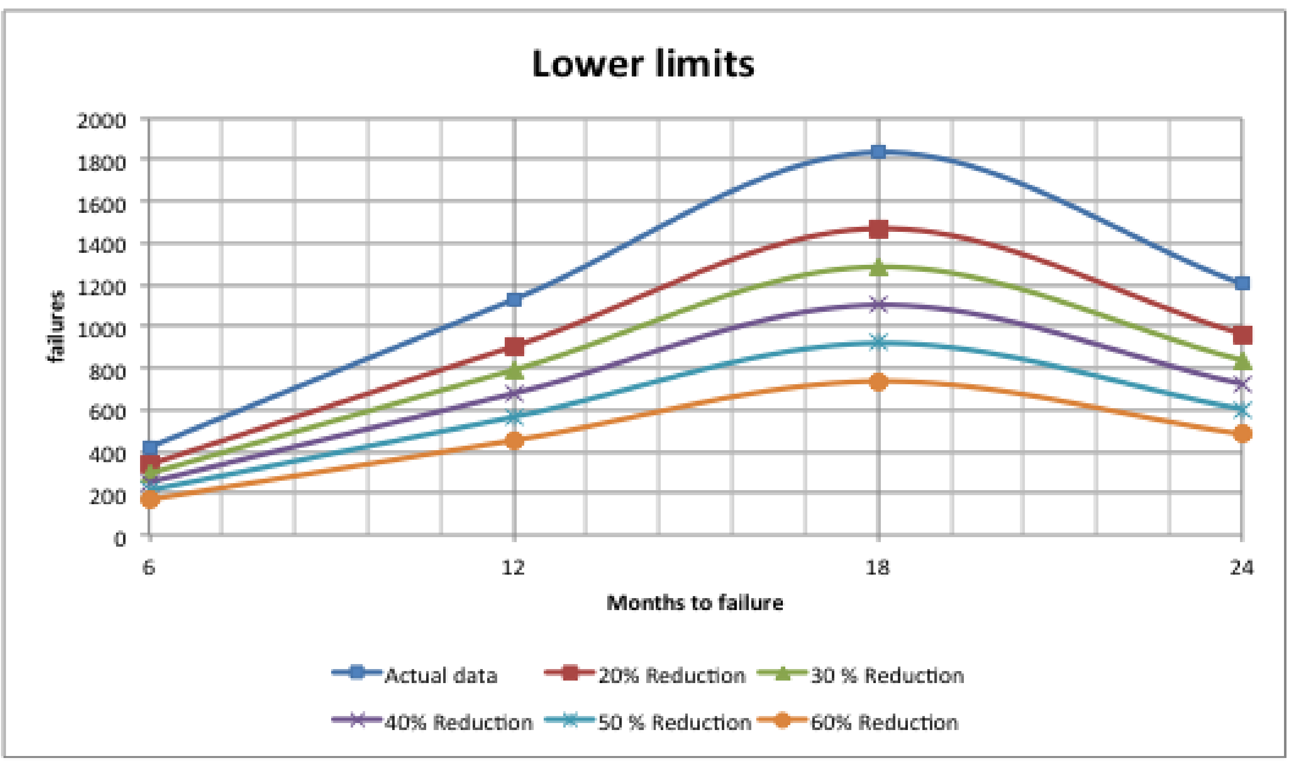

Figure 28. Expected number of returns using the lower limits of the estimates

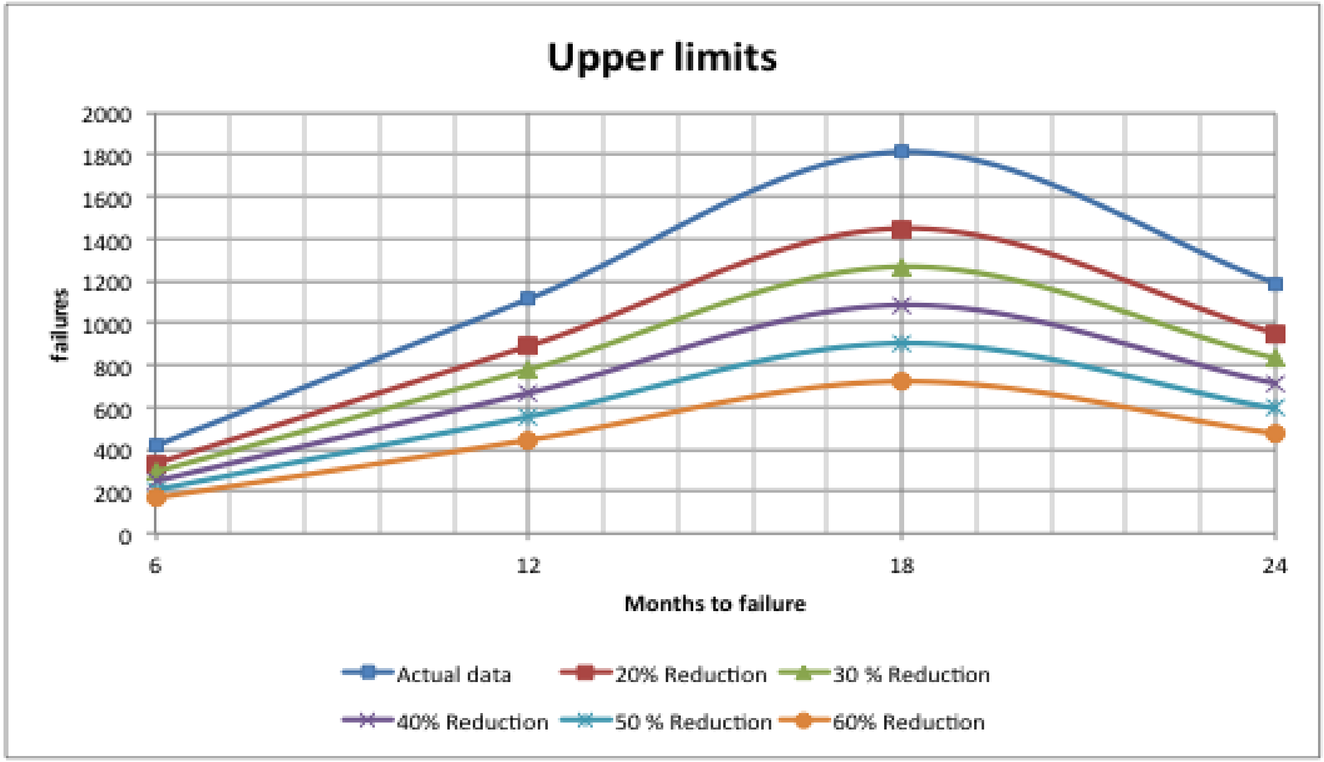

Figure 29. Expected number of returns using the upper limits of the estimates

The three figures indicate a very negligible difference between the actual, lower and upper limit results. Hence, the remaining discussion will be based on Figure 27 (using actual Weibull parameter estimates).

If we take a look at the trends over time (from Figure 27), we can see that there is a steady (almost linear) growth in the expected returns from months 6 to 18 as expected. However, the sudden drop from month 18 to 24 is explained by a reduction in the return in the real data, given that by month 24, the battery warranty has run out and most customers would instead buy a new replacement battery. For instance, the expected number claims for an 18-month policy would be 18,000 compared to a 24-month policy at 12,000. In the 60% claims reduction scenario, an 18-month policy would result in approximately 730 claims compared to a 24-month policy with 480 claims. Moreover, Figure 30 shows the number of claims from the original data set. It is quite visible that the high peaks in the data collected occurred at months 11, 18 and 23 being the highest. This highest peak is explicable by the fact that most customers will want to take advantage of the free replacement warranty policy before the 24 months elapse.

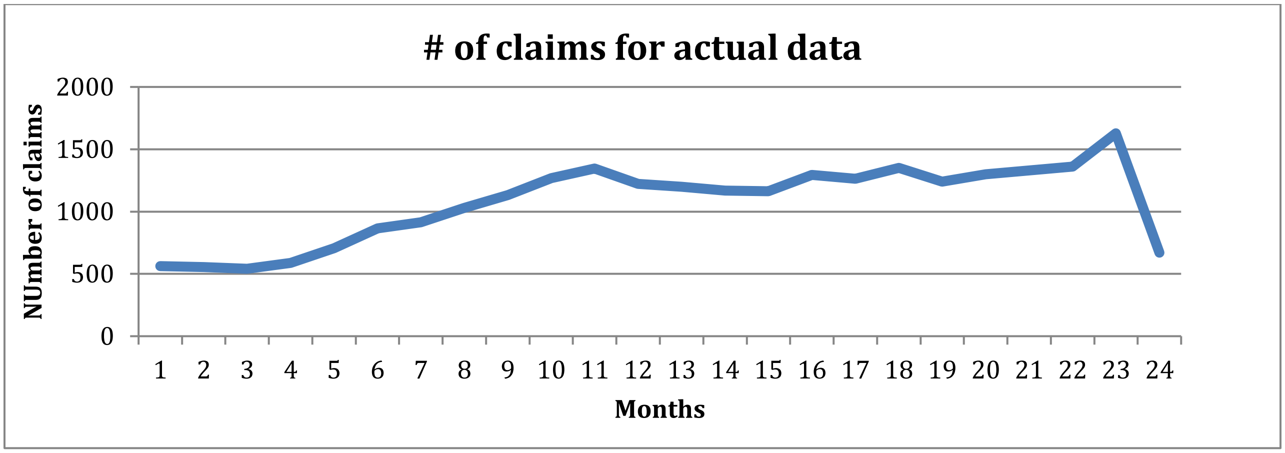

Figure 30. Actual number of claims for a two-year period

A further consideration of a 23-month warranty policy for the 60% returns reduction scenario results in an M(23) of:

$$M(23) \approx \frac{23}{13.86} + \frac{40.44}{13.86^2} = 1.711$$

Next, we calculate the actual expected number of returns by multiplying the M(23) ratio by the number of claims for month 23 for the 60% reduction data set. Figure 31 shows how the peak of the expected returns at month 23 for all the return percentage reduction scenarios.

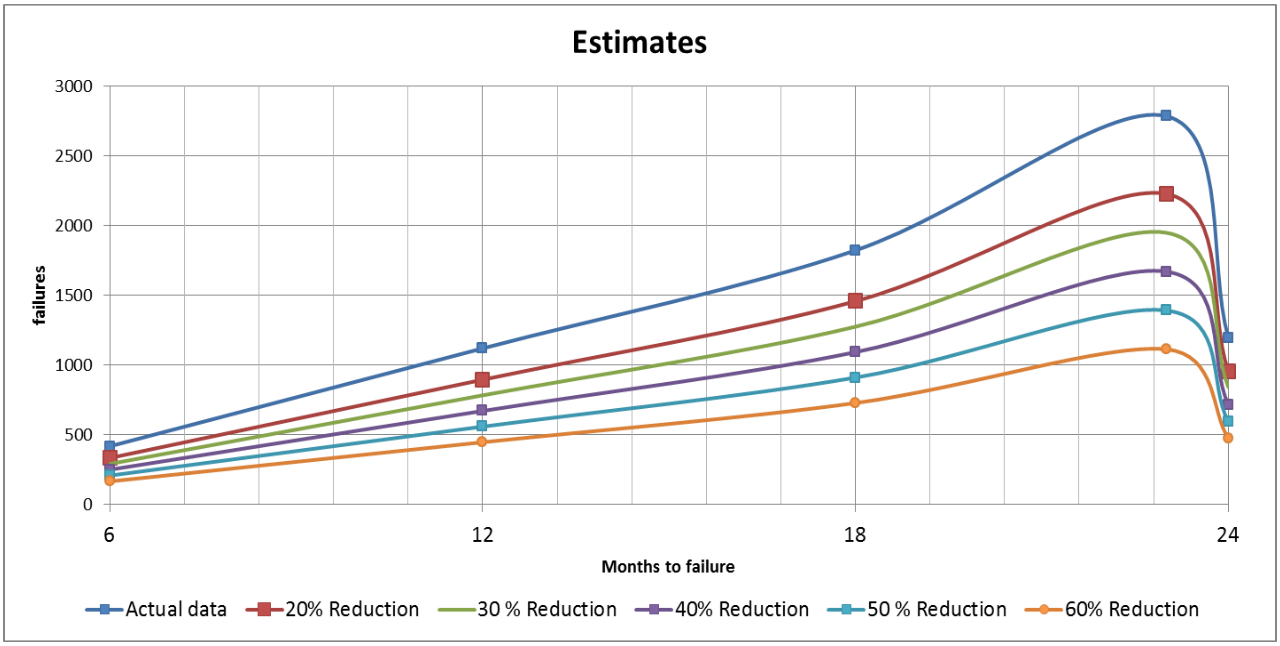

Figure 31. Expected number of returns using the estimates parameters including month 23

CHAPTER 6: WARRANTY COST ESTIMATION

In this chapter we analyze the warranty cost under a free replacement policy, where each battery replacement carries a new warranty identical to the original purchase. Therefore, under this warranty policy, the expected cost of warranty is directly proportional to the expected number of returns. This is why it is important to estimate the optimal warranty period that reduces warranty cost.

In chapter 6 we calculated the expected number of returns ratios. Equation 31 estimates the total cost of failures occurring a t period limit.

$$C_w = c_0 W(t_0) \tag{31}$$

Where

C_w is cost of the duration of the warranty.

c_0 is the unit cost of the product.

$W(t_0)$ is the expected number of returns at t.

Let us consider the unit cost for an AGM battery fixed at $115 arbitrarily and for the purpose of calculation. Using the results from the expected number of returns and the warranty claim data multiplied by the unit cost, we are able to obtain the expected cost estimates. The total warranty cost from the manufacturer's point of view was calculated for four different warranty times. In addition, six data sets were extracted from the actual data to represent the tested percent reduction in returns as a result of product and process continuous improvements.

The results are presented in Table 10 (using actual parameter estimates), Table 11 (using the lower limits of the parameter estimates) and Table 12 (using the upper limits of the parameter estimates). For instance, for the actual parameter estimates, the expected warranty cost using for a 6, 12, 18, and 24-month policies are $48,228, $128,924, $209,773, and $137,641 respectively. In addition, the difference between the costs of 6-month warranty calculated using the actual parameter estimates is only a few hundred dollars. Hence the rest of the discussion will only consider the cost estimates using the actual parameters. Once more, just like it was determined from the warranty returns estimates, the expected cost is higher at 18 months, then drops to 24 months which is as a result of the increase in returns in the real data. It is also expected that the 23-month warranty cost would be highest due to the fact that most customers will want to return their batteries before the free replacement warranty elapses.

Table 10. Warranty Cost Estimation for Free-Replacement Warranty Policy Using the Actual Parameter Estimates

	Warranty Cost Using the Estimates Parameters			
	6 months	12 months	18 months	24 months
Actual data	$48,228	$128,924	$209,733	$137,641
20% Reduction	$38,579	$103,132	$167,776	$110,106
30 % Reduction	$33,756	$90,238	$146,801	$97,060
40% Reduction	$28,934	$77,349	$125,832	$82,579
50 % Reduction	$24,111	$64,455	$104,857	$68,814
60% Reduction	$19,289	$51,565	$83,887	$55,052

Table 11. Warranty Cost Estimation for Free-Replacement Warranty Policy Using the Lower Limits of the Estimate Parameters

	Warranty Cost Using the Lower Limits of the Estimates Parameters			
	6 months	12 months	18 months	24 months
Actual data	$48,568	$129,748	$211,025	$138,471
20% Reduction	$38,884	$103,870	$168,932	$110,849
30 % Reduction	$34,041	$90,928	$147,882	$96,370
40% Reduction	$29,198	$77,988	$126,833	$83,223
50 % Reduction	$24,352	$65,039	$105,771	$69,402
60% Reduction	$19,505	$52,088	$84,705	$55,578

Table 12. Warranty Cost Estimation for Free-Replacement Warranty Policy Using the Upper Limits of the Estimate Parameters

	Warranty Cost Using the Upper Limits of the Estimates Parameters			
	6 months	12 months	18 months	24 months
Actual data	$47,890	$128,103	$208,448	$136,813
20% Reduction	$38,277	$102,399	$166,627	$109,366
30 % Reduction	$33,473	$89,552	$145,725	$95,680
40% Reduction	$28,673	$76,714	$124,837	$81,939
50 % Reduction	$23,872	$63,876	$103,949	$68,230
60% Reduction	$19,076	$51,047	$83,075	$54,529

CHAPTER 7: RESULTS, CONCLUSSIONS AND FUTURE RESEARCH

7.1. Result Discussion

In Chapter 5, we studied a one-dimensional warranty model using both time and usage dimensions of warranty data. We have presented the free replacement warranty models and the renewal function from which the expected number of returns was calculated. In addition, the expected number of returns was used to calculate the expected cost of warranty. Given the partner company current focus on product improvement, a sensitivity analysis was also incorporated in Table 9, where data was randomly extracted from the real data to mimic 20%, 30%, 40%, 50% and 60% reduction. Table 9 shows that the Weibull parameter estimates were not considerably different for the actual, 20%, 30%, 40%, 50% and 60% reduction in the returns. This is an important statistical finding, which indicates that the failure distribution parameters (hence the failure mode) do not change markedly, hence are robust to the data.

In reality, to validate these findings, the sensitivity analysis results should be compared with real data from the field once the newly improved products enter the market. In addition, in comparing Tables 10, 11 and 12, there are no meaningful differences between of each result of the actual, lower and upper limit parameter estimates. For instance the data set of 60% reduction with a warranty time limit of t=6 months has an expected cost of $19,289 for the actual estimate (Table 10), $19,505 for the lower limit (Table 11) of the estimate and $19,076 for the upper limit (Table 12). We wish to remark here that the slight increase in the cost for the lower limit compared to the actual estimate is due to the multiplicity effect, in that for instance, the mean time to failure equation has the shape parameter in the numerator and the scale parameter in the denominator. In addition the multiplication of the M(T) value has the mean time to failure in the denominator and the standard deviation in the numerator.

The results also shows that the ratio for the warranty time limits (i.e. 6, 12, 18, 24 months) are relatively similar, indicating that the sensitivity analysis validates the warranty model and the ratios of returns. The results also show that the variation in costs from a 12 months period to a 24 months period warranty policy is not considerable. The increase of the expected warranty returns can be explained by the trends that raw data exhibited. For instance, the abrupt decrease from month 18 to 24 is explained by the reduction in the claims that occur in the real data during those months. Customer patterns suggest that batteries would be brought to the dealership to be replaced before the warranty policy terminates.

The partner company currently offers a two-year free-replacement warranty policy for their AGM batteries. The results derived in this chapter show that a 6 months free-replacement warranty policy has the lower expected cost for every scenario of the sensitivity analysis. However, if the company has a planned reduction of 60% in total returns, using the parameter estimates to calculate the expected cost calculations, the expected warranty cost for a 12 months policy is lower for than a 24 months policy by only 6%. In cases like this, marketing strategies play a crucial role. If the company decided to have a 12 months warranty policy instead of the current 24 months policy, the savings would be up by about 6%. On the other hand, this information can be used in marketing for instance, to offer extended warranty for batteries, or to offer a tiered warranty policy strategy that encompasses both 1 and 2 years depending on the volume of sale, geographical location of usage (since it is expected the high temperatures lead to faster battery degradation) as well as amount of usage (high usage lead to better health due to the increased charge discharge cycles). The results derived indicate that the company can use different marketing techniques, product pricing, and sales strategies based on the warranty cost estimates and expected number of returns.

7.2. Conclusions and Future Research

In this study, we've presented a one-dimensional warranty for AGM batteries, a non-repairable product, under free-replacement policy. The models proposed were usage-based and age-based models characterized by mileage and time respectively as the metrics of warranty limits.

In chapter 5 we fit different lifetime distribution to mileage and time data. The two variables follow a Weibull distribution. However, a mileage-based warranty policy is not adequate given the nature of the product (increased usage leads to higher charge discharge cycle hence better battery health). We also discussed the disadvantages of the usage-modeling approach due to incomplete data. The age-based model is also presented where we show the Weibull distribution to have the best fit for the warranty claim data provided.

We analyzed a warranty policy with fixed product failure times (6, 12, 18 and 24 months) that minimize the manufacturers cost for products a under non-renewing policy. There were significant challenges associated in obtaining the expected number of returns for the Weibull distribution. To compute it, we applied an approximation of the function that uses the shape, scale, MTTF and variance values from the data. We presented the numerical results of M(t) for the age-based approach for all the fixed times and estimators. The upper and lower estimators are substantially close, which means that the data do not have outliers driving the estimators. This is an important statistical finding, which indicates that the failure distribution parameters (hence potentially the failure modes) do not vary with time.

In the age-based model presented we have used the real dataset to mimic the company expected reduction in claims as a result of planned improvement such as modernizing the AGM battery manufacturing processes and improvements in the supply chain distribution centers. In this study, we considered a 20%, 30%, 40%, 50% and 60%. These sets of data were used in the sensitivity analysis which was performed to assess the changes in the model parameters. In addition, we varied the warranty time limits such as 6, 12, 18 and 24 months to assess the changes in the model parameters estimates.

Overall, we found that considering the current returns status, the lower the warranty time limit, the lower the warranty cost that a 6-month warranty policy for free-replacement had the lower expected cost for every scenario of percentage claims reductions. However, we determined that it is economical to provide a 24-month warranty at $137,000 cost to the manufacturer. Once we considered the expected reductions in claims are realized, then the difference in manufacturers' cost between the 12-month and 24-month warranty limits was 6%. This means therefore that the manufacturer could choose either, or go for a tiered warranty policy depending on the order volume, customer needs or environment of usage. The partner company can use these results in product pricing and developing new services strategies.

Several future research paths can be undertaken following the results if this Thesis. For instance, as a marketing strategy companies now sell extended warranties. A mathematical study about extended length to the warranty policy for AGM batteries can be performed, to analyze the economic impact on profit and service pricing of this strategy.

Moreover, some of the limitations of this research included incomplete data sets. In order to develop more fitting model better data collection techniques should be implemented, such as surveys to randomly selected customers. Surveys will provide complete and censored data of products that failed and the ones that survived after the warranty expired. With this in mind, after complete data collection is accomplished, the next warranty policy to analyze should be the pro-rata policies for AGM batteries, which highly depends on the extent of both time and usage at the time of failure.

Lastly, with the emergence of Internet of things (IoT) and new advances in technology, current battery-testing machines are able to give better reading results. For instance instead of giving just a fail or pass reading, testing machines can give digital evaluations of the precise tests that the battery failed. Other pertinent information that would be needed in the warranty analysis include geographical location of usage, ambient temperature, internal temperature of the battery, voltage and CCA. To obtain this information, new frontiers should be considered to place state of health readers in the vehicles, these devices are available in the market and they take constant readings of the voltage, CCA and amperes of the battery and calculate the state of the battery. These devices would then alert the customer when the battery needs to be charged. This approach would give real time data of the product and would enable the company to develop a more versatile warranty allocation structure.

REFERENCES

A simple history of batteries: Panasonic . (n.d.). Retrieved February 16, 2017, from Panasonic : https://www.panasonic.com/global/consumer/battery/academy/rekisi.html

Abernethy, R. B. (2000). *The New Weibull Handbook* (Fourth ed.), Robert B. Abernethy, North Palm Beach, Florida, USA, (1994).

Alber, G., & Nispel, M. (n.d.). *Tech Note: Thermal Runaway in Flooded Lead Calcium Batteries.* Retrieved February, 12, 2017, from http://www.alber.com/docs/thermalrunawaypaperfinal073107.pdf

Avelar, V., & Zacho, M. (2016). *Battery Technology for Data Centers: VRLA vs. Li-ion.* Retrieved February 17, 2017, from Schneider Electric: http://www.schneider-electric.com

Bard, A. J. (1973). *Encyclopedia of electrochemistry of the elements.* New York: M. Dekker.

Battery University . (2016, 07 12). Retrieved February 27, 2017, from BU-201a Absorbernt Glass Mat : http://batteryuniversity.com

Blischke, W. R. (1990). *Mathematical models for analysis of warranty policies*. Mathematical and Computer Modelling. Page 1 – 16. https://doi.org/10.1016/0895-7177(90)90124-6.

Blischke, W. R., & Murthy, P. D. (1994). *Warranty cost analysis.* New York : M Dekker.

BU_103: Global Battery Markets . (2016, 04 11). Retrieved April 11, 2017, from Battery University : http://batteryuniversity.com/learn/article/global_battery_markets

Chien, Y. H. (2008). *Optimal age-replacement policy under an imperfect renewing free-replacement warranty*. IEEE Transactions on Reliability. https://doi.org/10.1109/TR.2007.909769

Chien, Yu Hung. 2012. "The Effects of a Renewing Free-Replacement Warranty on the Discrete Age Replacement Policy." *IEEE Transactions on Reliability*.

Cobb, J. (2013, July @#). *OXIS Jump-Starts First Commercialization Of Lithium-Sulfur Batteries.* Retrieved 06 20, 2017, from hybridcars.com: http://www.hybridcars.com/oxis-jump-starts-first-commercialization-of-lithium-sulfur-batteries/

DC battery specialists . (n.d.). Retrieved February 27, 2017, from dcbattery.com: https://www.dcbattery.com/agmtech.html

Dey, S. (2015). *Estimation and diagnostics of lithium-ion batteries.* A Dissertation Presented to the Graduate School of Clemson University In Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy Automotive Engineering by Satadru Dey August 2015 Acce. (2015), (August).

Djamaludin I, M., Murthy, D., & Blischke, W. (1995). *Bibliography on warranties*. In W. Bischke, Product Warranty Handbook (pp. 839-916). New York: Marcel Dekker.

DOE Handbook: Primer on Lead-Acid Storage Batteries. (1995, 09). Retrieved 02 14, 2017, from Department of Energy of the United States of America: https://energy.gov/sites/prod/files/2013/06/f2/hdbk1084.pdf

Fan, D., & White, R. E. (1991). *A Mathematical Model of a Sealed Nickel-Cadmium Battery*. Journal of The Electrochemical Society, 138(1), 17–25. https://doi.org/10.1149/1.2085532

Fan, D. (1991). *Mathematical Modeling of a Nickel-Cadmium Battery*. Journal of The Electrochemical Society, 138(10), 2952. https://doi.org/10.1149/1.2085347

Christian Glaize and Sylvie Genies. (2012). *Universal Characteristics of Batteries Definitions and Methods of Measurement*. Lead and Nickel Electrochemical Batteries. Editorial Wiley.

Gibson, B. E., & Adamson, K.-A. (2012). *Executive Summary : Advanced Lead-Acid Batteries Applications : Global Market Analysis and Forecasts.* Retrieved 07 20, 2017, from Pike Research: http://www.navigantresearch.com/wp-content/uploads/2012/12/ALAB-12-Executive-Summary.pdf

Golam Kibria, M., Amin, A., & Rifat, U. A. (n.d.). *Application of Porter's Five Forces Model in Battery Manufacturing Industries of Bangladesh*.

How to Prolong Lead-acid Batteries. (2016, March). Retrieved February 13, 2017, from http://batteryuniversity.com.

International Cadmium Association. (n.d.). Retrieved November 16, 2016, from International Cadmium Association: http://www.cadmium.org

International Lead Association. (n.d.). Retrieved February 27, 2017, from Environmental and social responsibility for the 21st Century: http://www.ila-lead.org/UserFiles/File/FS_Recycling.pdf

Jiang, R. (2009). *A simple approximation of the Weibull renewal function*. In IEEM 2009 - IEEE International Conference on Industrial Engineering and Engineering Management. https://doi.org/10.1109/IEEM.2009.5372970

Johnson Controls, Inc. (2011, October 12). *Strategic Review and 2012 Outlook.* Retrieved 07 20, 2017, from U.S. Securities and Exchange Commission: https://www.sec.gov/Archives/edgar/data/53669/000095012311089573/c66320exv99w2.htm

Kordesch, K. and Ivad, J. D. (1998) Global Competition of Primary and Secondary Batteries, in Handbook of Battery Materials (ed J. O. Besenhard), Wiley-VCH Verlag GmbH, Weinheim, Germany. doi: 10.1002/9783527611676.ch3

Lele, M. M., & Karmarkar, U. (1983, 11). *Good Product Support Is Smart Marketing*. Retrieved from Harvard Business Review: https://hbr.org/1983/11/good-product-support-is-smart-marketing

Reddy, T. B., & Linden, D. (2011). *Linden's handbook of batteries*. New York: McGraw-Hill.

Macdonald, D. D., & Challingsworth, M. L. (1993). *Thermodynamics of Nickel-Cadmium and Nickel-Hydrogen Batteries*, *140*(2), 606–609.

Martz, E. (2013, January 03). *Choosing the Right Distribution Model for Reliability Data.* Retrieved from The Minitab Blog: http://blog.minitab.com/blog/understanding-statistics/choosing-the-right-distribution-model-for-reliability-data

McCluer, S. (2011). *Battery Technology for Data Centers and Network Rooms: VRLA Reliability and Safety.* Retrieved 2 17, 2017, from Schneider Electric: http://www.apc.com/salestools/SADE-5TNRJR/SADE-5TNRJR_R2_EN.pdf

McCool, J. I. (2012). Weibull Probability Models. In J. I. McCool, *Using the Weibull Distribution: Reliability, Modeling, and Inference* (First Edition ed., pp. 97-129). John Wiley & Sons, Inc. doi:10.1002/9781118351994.ch4

Murthy, D. N. P., & Blischke, W. R. (2000). *Strategic Warranty Management: A Life-Cycle Approach*. IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT, 47(1).

Murthy, D. N. P., & Djamaludin, I. (2002). *New product warranty: A literature review*. International Journal of Production Economics, 79(3), 231–260. https://doi.org/10.1016/S0925-5273(02)00153-6

Nishio, K., & Furukawa, N. (2007). *Handbook of Battery Materials .* Weinheim : Jurgen 0. Besenhard.

Written, S. E., & Pham, H. (2010). C*ost analyses on warranty policies for systems*. A dissertation submitted to the Graduate School-New Brunswick Rutgers , the State

University of New Jersey In partial fulfillment of the requirements For the degree of Doctor of Philosophy Grad.

Rahman, A., & Chattopadhyay, G. (n.d.). R*eview of long-term warranty policies*.

Rayment, C. and S. S. (2003). *Introduction to Fuel Cell Technology*. University of Notre Dame, 156. https://doi.org/10.1.1.129.3231&rep=rep1&type=pdf

P.G.Sankaran and Ansa Alphonsa Antony. *Non parametric estimation of life time distribution of competing risks models when censoring times are missing*, Statistical Papers, 50, 339-361, 2009

Shen, Z. (2013). *Control-Oriented Modeling, State-of-Charge, State-of-Health, and Parameter Estimation of Batteries*, (August), 73.

Sørensen, B. (2007). *Renewable Energy Conversion, Transmission and Storage.* Burlington, MA, USA : Elsevier Inc. Retrieved from https://www.elsevier.com

Suzuki, K. (1985b): *Estimation of lifetime parameters from incomplete field data*. Technometrics, 27, 263-271.

The Advanced Lead Acid Battery Consortium. (n.d.). Retrieved 02 27, 2017, from alabc.org: http://www.alabc.org/press-releases/ILA_Battery_study_release_102413.pdf

U.S. Department of Energy. (n.d.). Retrieved 2 2, 2017, from U.S. Department of Energy: http://www.afdc.energy.gov

US patents . (1902, Feb 02). *Patents.* Retrieved 01 15, 2017, from United States Patemt and Traemark Office: https://www.uspto.gov/

Weissler, P. (2012, 02 14). Society of Automotive Engineers. Retrieved 02 27, 2017, from *AGM battery takes primary role for idle stop-start in microhybrids*: http://articles.sae.org/10667/

White, J. S. (1964, January 1). *Weibull Renewal Analysis.* Research Laboratories, General Motors Corp. SAE International. doi:10.4271/640624

Wu, C.-C., Chou, C.-Y., & Huang, C. (2009). *Optimal Price, Warranty Lenght and Production Rate for Free Replacement Policy in the Static Demand Market*. Omega, The intermational Journal of Management , 37, 29-39.

Wu, S. (2012). *Warranty data analysis: A review. Quality and Reliability Engineering International*. https://doi.org/10.1002/qre.1282

Wu, Y., Yuan, X., Zhao, S., & van Ree, T. (2015). Introduction. In *Lithium-Ion Batteries* (pp. 1–18). CRC Press. https://doi.org/doi:10.1201/b18427-2

Yang, G. (2007). *Life Cycle Reliability Engineering*. In G. Yang. John Wiley & Sons, Inc. doi:10.1002/9780470117880

Zhang, X., Grube, R., Shin, K.-K., Salam, M., & Conell, R. (2010, june). *Parity-relation-based state-of-health monitoring of lead acid batteries for automotive applications*. (Elsevier, Ed.) *Control Engineering Practice, 19*(6), 555-563.

Zhoua, Z., Li, Y., & Tang, K. (2009). *Dynamic pricing and warranty policies for products with fixed lifetime*. European Journal of Operational Research*, 196*(3), 940-948.