Use of the Modular Design and Wearout Parameters to Improve High Mileage Reliability of Wiper Motors

by

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Submitted to the Department of Aeronautics and Astronautics Engineering in Partial Fulfillment of the Requirements for the Degree of

Master of Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September, 1996

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August 9, 1996

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Abstract

Ford Motor Company has set an objective of 10 years/150,000 miles useful life for all the components in Ford vehicles. Ford's Electrical and Fuel Handling Division, the manufacturer of windshield wiper motors for Ford vehicles, needed a method to meet the Company's objective. The current generation wiper motors were designed based on modules in order to take advantage of flexibility without altering modules, or sub-assemblies, extensively for various applications. This provided opportunity for flexibility to cover a range of product line. However, there are overall metrics such as High Mileage and Useful Life which must be maximized across the whole platform. With a module based design, improvements can be made in the area of High Mileage and Useful Life reliability and performance across the entire platform of wiper motors when changes need to be made on a module because the same module is shared in all wiper motors. In this thesis, a methodology is developed and tested for ensuring High Mileage and Useful Life metric across the platform while providing flexibility required by the different needs of the members on the platform.

The first step is to identify each module's function. Then certain high mileage parameters were selected that show wearout characteristics. By linking those parameters back to functions which can be related to modules, improvements that need to be made in modules can be identified. The end result is improvement in modules which in turn can have overall impact on entire platform of wiper motors. Because High Mileage and Useful Life plays important roles in various parts of Product Development Process (PDP) at Ford Motor Company, such information can then flow into PDP to make improvements on current and future designs and to enhance the process itself as well.

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Chapter 1

Introduction

Product architecture is an important characteristic of any given product. It has major impact on product's flexibility, serviceability, manufacturability, and many more. It could be a constraint, but it could also be an advantage that can be utilized to make improvements. The focus of this thesis is on utilizing wiper motor product architecture to improve high mileage and useful life. This chapter gives a brief description of product architecture and background information on the High Mileage and Useful Life requirements set by Ford Motor Company.

1.1 Product Architecture

Product architecture is defined as "the arrangement of the functional elements of a product into physical blocks."[1] Determining product architecture is a very important process in all design activities because it is a description of what a product is made of and how components are organized or arranged. This process takes place at system level where decomposition and integration decisions are made, and these decisions directly effect product architecture.

One of the most important part of product architecture is in modularity of a product. A designer always has a choice in making a product more modular or more integrated. There is a tradeoff between the two in areas of flexibility and performance. Modular product architecture tends to create more flexibility where a product can be easily modified to meet different needs and requirements. Platform design used in automobiles and other products are good examples of how modularity is utilized. From

[1] Ulrich, Karl T., and Steven D. Eppinger, "Product Design and Development," McGraw-Hill, Inc., New York, 1995.

the same platform of Taurus, other vehicles such as Windstar and Continental can be produced using the same chassis and other components. However, by making a product highly modular and flexible, it often leads to sub-optimal performance. This is because in many cases, when one is trying to satisfy many different needs, he or she cannot meet each need fully. On the other hand, in a highly integrated product, the goal is to produce the most optimal design for a single need, and thus, it tends to be inflexible toward other needs. Depending on the designer's intent on modularity of a product, its architecture is determined. The product architecture of Ford's wiper motor will be discussed in details in Chapter 3.

1.2 Parameters

In any given platform, or module-based product, I define two types of parameters that can be used to measure its performance and characteristics. The first type are platform-wide parameters which are shared by all the members of the platform. The second type are product-specific parameters, and these parameters are different from one member of the platform to the other. In the case of wiper motors, the useful life of wiper motor is the first type of parameter, and it is a measure of how long the current generation wiper motors last in vehicles. Torque and speed of wiper motors are the second type of parameters because depending on the applications, these parameters are different. The current platform of wiper motors is designed to meet various torque and speed requirements depending on the wiper system, and thus they vary from one type of wiper motor to another.

1.3 High Mileage and Useful Life

High Mileage and Useful Life refers to reliability of a product during the time prior to wearout. Improving high mileage and useful life of a product is not a new concept, nor is it something Ford Motor Company has come up with on its own. Any product development company would try to improve the life of their products and their performance and reliability during its useful life. In 1993, Ford Motor

Company set the high mileage reliability target stating that "Products are to meet a useful life of 10 years/150,000 miles, whichever is tougher, when subjected to the duty cycle of the 90th percentile customer." It basically means that for 90 percent of customers, the product should last 10 years or 150,000 miles. "Whichever is tougher" means if a car is used for 10 years before it reaches 150,000 miles, then the 150,000 miles become the target because it is the tougher case. In other cases where 150,000 miles are reached before 10 years of usage, then 10 years become the target. This applies to all components in vehicles, including wiper motors.

1.3.1 95 Percent Reliability for 95th Percentile Customers

When the company's high mileage and useful life objective of 100 percent reliability for 90 percent of customers was established, it was left up to each division to come up with a way to verify the reliability level of components it is manufacturing. Electrical and Fuel Handling Division which designs and manufactures windshield wiper motors faced that issue, and the Quality Office of the division interpreted that requirement to be equivalent to 95 percent reliability for 95 percentile customers. The main reason behind that interpretation is that it is almost impossible to prove 100 percent reliability through any testing. It would require an enormous sample size. From a statistics point of view, it is possible to interpret 100 percent reliability for 90th percentile customer into 95 percent reliability for 95th percentile customers. Figure 1-1 shows a graph explaining 95th percentile reliability for 95th percentile customers.

In Figure 1-1, Stress Distribution refers to stress seen by a component. Component Strength Distribution refers to strength a component is capable of withstanding. 0.05 shown on the left side represents the 5 percent of customers who may experience higher stress on a component than a component can handle because that is where the strength distribution is actually lower than stress distribution.

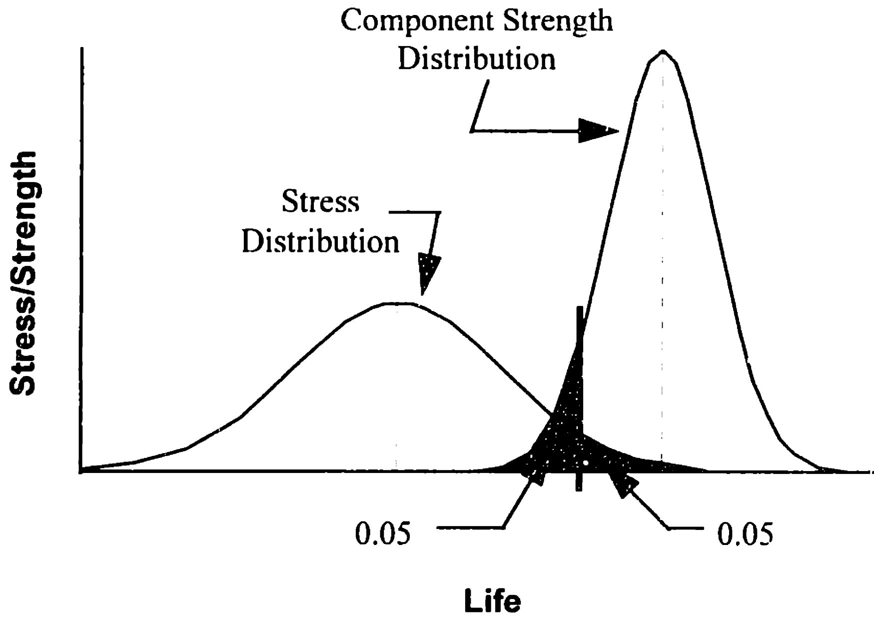

Figure 1-1: 95th Percent Reliability for 95th Percentile Customer

What Figure 1-1 shows is that if a component is 95 percent reliable for 95 percent of customers, then it is equivalent to 100 percent reliable for 90 percent of customers. Therefore, identifying the 95th percentile customer and his/her driving condition becomes very important. It is the customer who operates a component at a condition where 95 percent of other customers operate at less severe condition, and the rest, or 5 percent, of customers operate at more severe condition. What this assumes is that if a component is tested at this 95th percentile customer's conditions and passes the test, it should not fail when it is tested under less severe conditions, or the conditions experienced by 95 percent of customers. One important point is that this condition is different for each component. For some component, cold temperature is what makes condition severe, while for others, it is the hot temperature condition. For example, many of the failed alternators are seen in high temperature and dry regions such as Nevada and Arizona. For wiper motors, however, the highest number of failures is seen in heavy snow areas, especially in New England region, because it is the frozen condition that causes most failures (See Section 6.3 for more information).

1.3.2 Ford Vehicles' Time in Service and Mileage Information

To illustrate the 95th percentile customer concept, here is an example of how it is used. For Ford vehicles, there was a study done to determine the relationship between mileage and time in service. This was done by collecting data on the amount of time one owns a Ford vehicle and how much mileage it has accumulated. Figure 1-2 is a collection of data from wiper motors that were returned on warranty. The straight line is a line fit of all data points. R-squared value for the line fit is 0.644, and this was done based on nearly 1,000 Ford vehicles.

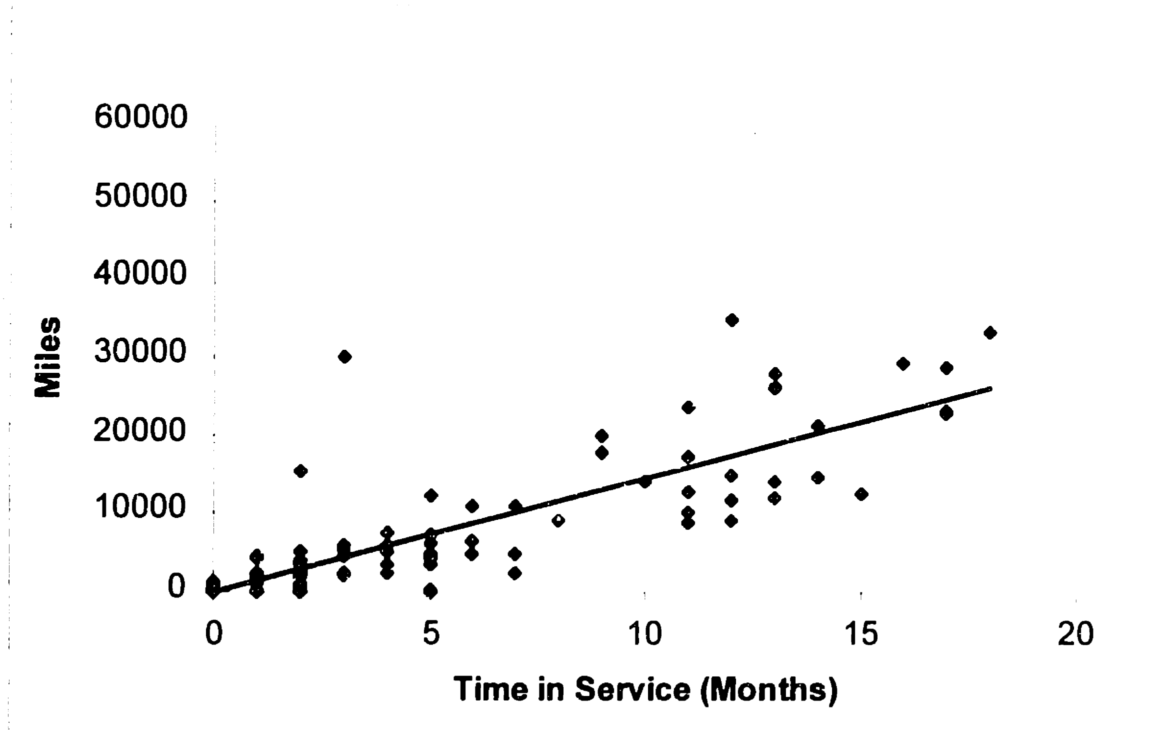

Figure 1-2: Miles vs. Time in Service in Months

What the graph shows is that on average, 10 years in service is projected to be equivalent of roughly 168,000 miles driven on the road. When it is analyzed for the top 5% of the customers, they are projected to drive 250,000 miles or more. In either case, 10 years in service is tougher case because it means over 150,000 miles of usage, and that becomes the target. Such correlation may vary from a vehicle line to another vehicle line when analyzed separately, so for components that are used in one vehicle line only, such as engine, the study needs to be done for the relevant vehicle line only. However, for wiper motors, 10 years in service is the target they need to meet because they are used in all Ford vehicles supported by the data shown in Figure 1-2.

1.3.3 Relationship Between High Mileage and Useful Life Parameters and Company's Objective

In order to improve high mileage and useful life reliability and performance of its products, Electrical ıd Fuel Handling Division at Ford Motor Company established a 7-step process. This incorporates not only the high mileage and useful life requirement, but also any other reliability issues that could occur during any point in useful life of a wiper motor. The major distinction between high mileage and useful life requirement and other types of reliability issues is that high mileage and useful life reliability refers mostly with wearout issues that do not lead to failure until the very end phase of a product life. It is different from any other special cause failures due to design or manufacturing defects that could occur at any time during the life of a product. Wearout type of failures takes a long time to develop and become any problems. The detailed description of 7-step process is taken from an EFHD document, and it is shown in Appendix A.

Two critical steps for high mileage and useful life are determining real world usage profile and developing key life test. Real world usage is a way to determine under what conditions a wiper motor operates for the 95th percentile customer. Then, a key life test needs to be developed to simulate those conditions in a lab. Obviously, it is not practical to test components such as wiper motors in those real conditions for 10 years to see whether it can last that long or not. The goal is to develop an accelerated life test to determine high mileage and useful life of a wiper motor in a short period of time. That is why it is so important to correlate a lab test stand with the real world. Currently, the wiper motor department has a durability test to validate life of wiper motors, but there is no correlation data between the number of cycles on the test stand and real world mileage.

There are two ways to correlate the number of cycles on a test stand and real world mileage that can be used.

- One way is to gather wiper motors from vehicles with various mileages. Then, they are put on a test stand and run until they fail. A plot showing the number of cycles a motor lasted on the test versus the mileage of the vehicle each wiper motor is taken from can be generated. It shows the overall correlation between the number of cycles and mileage. One problem with this method is that it takes a long time to run a number of wiper motors to failure. And that is the main reason why this thesis does not have any data on this type of test. In the time frame of this paper, this type of tests could not be completed.
- The second way is to choose a parameter that measures high mileage and useful life wearout, and that parameter should be relatively easy to measure. The next step is to gather wiper motors from vehicles with various mileages, and plot the measurement of the parameter versus mileage of the vehicle each wiper motor came from. Then wiper motors were run on test stand and they are measured how the same parameter changes as the number of cycles on the test stand increases. In this case, wiper motors do not need to be tested to failure, and in fact, they can be stopped after a sufficient number of cycles have accumulated. Then by comparing the rate at which that parameter changes, the correlation between the number of cycles on the test stand and mileage can be determined for that parameter.

1.4 Purpose of Thesis

The purpose of this thesis is to develop a methodology that can be used to improve platform-wide performance metric, such as High Mileage and Useful Life, utilizing module-based design and platform-wide parameters. The general methodology is described in Chapter 2, and the body of this thesis will be on how the methodology is implemented for improving High Mileage and Useful Life of wiper motors. The difficulty is in selecting right parameters that are shared among all the different types of wiper motors that have major impact on platform-wide parameter that needs to be improved.

The major portion of the analysis section in this thesis will discuss various parameters that were selected and how they are used to improve high mileage and useful life of wiper motors. It will discuss how they are used not only to correlate mileage to the number of cycles on test stand (brush wear example), but also how they can be used as metrics to determine whether a wiper motor can function and perform as intended or not. Also, by understanding how these parameters are effected by various sub-assemblies and components of a wiper motor, design changes can be suggested to improve platform-wide metric. Therefore, the selected parameters play critical role in improving high mileage and useful life reliability and performance of wiper motors at Ford's Electrical and Fuel Handling Division.

Chapter 2

Methodology

As mentioned in Chapter 1, this chapter describes the methodology of utilizing modular-based product architecture to improve overall platform-wide metric. It will describe general procedure to follow and how it applies to wiper motors specifically. The detailed application of the procedure on wiper motor is shown in Chapter 3 and 4.

2.1 Procedure

The table below shows the 6-step procedure. These steps are general so that they can be used in various applications. Step 3 is specific for useful life type of analysis, but the rest of steps can be followed for improving a product using its product architecture and certain parameters. Examples will be given for wiper motor, which is the focus of this thesis.

1. Understand Product Architecture
2. FMEA to Identify Parameters
3. Gather Products at Various Points of Useful Life
4. Map Parameters to Product Architecture
5. Map Parameters to Platform-wide Metric That Needs to be Optimized
6. Make Necessary Changes in Product

Figure 2-1: Procedure to Improve Product Utilizing Product Architecture and Parameters

2.1.1 Understand Product Architecture

This step involves understanding the product architecture of a product. The type of questions that need to be asked are:

- What are the components of a product?
- How are they connected physically? Functionally?
- Is the product modular? Integrated?
- What are common in all members of the platform? What are different?

This step is the foundation of the methodology shown above. Functional flow or interface diagrams are useful tools that can be used in this step.

2.1.2 FMEA to Identify Parameters

FMEA (Failure Modes and Effects Analysis) is a well-known and well-adopted methodology to identify possible failure modes of a product. The purpose is to use that information to make improvements in quality and robustness. The same FMEA can be used to identify parameters that can effect platform-wide metric that needs to be improved. For example, in the case of wiper motors, the overall platform-wide metric we are trying to improve is high mileage and useful life. We want wiper motors to last at least 10 years and 150,000 miles in vehicles. The FMEA for wiper motor shows that high mileage and useful life is effected by wears on various parts, such as thrust plug, armature, and brush. From this, we selected wearout parameters like end play, axial play, radial play, angular play, and brush wear that measure wear on the parts mentioned. These wearout parameters then can be used to measure how long wiper motors last. See Chapter 4 for FMEA and parameters for wiper motors.

2.1.3 Gather Parts at Various Points of Useful Life

In order to understand how the parameters selected in Step 2 change over the course of product's life, we need to gather products at various points of useful life. This is especially crucial in a product like wiper motors because the wearout pattern or characteristic is not well known. The product has been in the market for a little over 2 years, and there is not much knowledge on how components will wear out over the course of 5 or 10 years. The idea here is to gather parts and take measurements of the selected parameters. The end result we are interested in is how the parameter changes over a course of time or usage. Then projection can be made on how these parameters change over the course of product's useful life.

2.1.4 Map Parameters to Product Architecture

The next step is to understand how each parameter is linked to the product itself The goal is to identify which part of the product effects each parameter. Fishbone diagram is an effective way to illustrate this step. Some of the questions that need to be asked are:

- Which component effects each parameter? The answer can be more than one component, and one component can effect more than one parameter.
- If one component effects more than one parameter, is there tradeoff between different parameters? In other words, can improving one parameter lead to adversely effecting the other parameter?
- Is the component product-specific or platform-wide? In other words, can it be changed across the platform easily?

2.1.5 Map Parameters to Platform-wide Metric That Needs to be Optimized

In this step, we are trying to establish a relationship between parameters selected in Step 2 to the platform-wide metric we are trying to maximize. In the case of wiper motors, it is determining the relationship between End Play, Axial Play, Radial Play, Angular Play (Parameters) and High Mileage and Useful Life (platform-wide metric). This will help us to understand which parameter has the most impact on high mileage and useful life and thus give us a focal point to work on.

2.1.6 Make Necessary Changes in Product

And lastly, all the analysis done so far needs to produce improvement in the product. Once we understand the relationship between the parameter and platform-wide metric that needs to be improved, we know what parameter is important in improving the metric. Also, we know how that parameter is effected in the product. Then by making necessary changes in components that effect that parameter, we can in fact effect the platform-wide metric. In case of module-based design, changes made in one module can effect all members if it is a common module for all members. Then the improvement leads to better overall product.

Chapter 3

"F" Generation Windshield Wiper Motor

Electrical and Fuel Handling Division (EFHD) at Ford Motor Company has been producing critical automotive components such as alternators, starter motors, fuel pumps, fuel injectors, throttle bodies, ignition products and windshield wiper motors for most of Ford vehicles. With plants and technical centers all over the world, EFHD has design and manufacturing capabilities for all of these products, and its goal is to be a world leader in the area of automotive components. As one of its main product line, EFHD has been producing wiper motors for over 30 years. It went through 5 generations up to now (A, B, C, E, and F), and currently it is working on the next generation of wiper motors. The "F" generation wiper motor was introduced for 1994 model year vehicles, and most of today's and future Ford vehicles have "F" generation wiper motors in them.

3.1 Description

"F" generation wiper motors were designed based on modules, and they utilize many common sub-assemblies for different types of wiper motors. The goal was to have the same or similar outside packaging, while maintaining the ability to switch some of the sub-assemblies to meet various torque and speed requirements of different vehicles. Another advantage of having such similarities among the same product line is that one assembly line can be used to manufacture all different types of wiper motors. Other key features of "F" generation wiper motors are:

- Low Noise, Low Vibration
- Internal Circuit Breaker
- Radio Frequency Interference (RFI) Suppression Capability
- Water Resistant

- Corrosion Protection

The advantages of utilizing platform design were mentioned earlier. However, there are few disadvantages as well. For example, it is very difficult to alter or change any one of the sub-assemblies significantly for one specific application because that usually means changing or creating new assembly line(s). Compatibility with existing assembly line is always an important issue because of all the costs associated with changing or creating new line(s). Another disadvantage is that it may not be the most optimal or efficient design for each application. There is a tradeoff between optimal performance and flexibility in modular design.

3.2 Modules/Sub-Assemblies/Component

A "F" generation wiper motor consists of basically 8 main sub-assemblies, or modules, and small components. They are "assemblies" in a sense that they are made up of a few other components. Figure 3-1 shows the major sub-assemblies and other components of a wiper motor.

3.2.1 Housing Assembly

Housing assembly is an aluminum die-cast part with machined holes and bearings in it. There are six different types of housing assembly.

- 2 Types of Long
- 3 Types of Short
- 1 Type of Stub

The description of long, short, or stub refers to the length of cylinder where output shaft goes through. Different lengths are required due to packaging constraints in vehicles. Long housing assembly has two short bearings for output shaft, and short and stub housing assemblies have one long output shaft bearing.

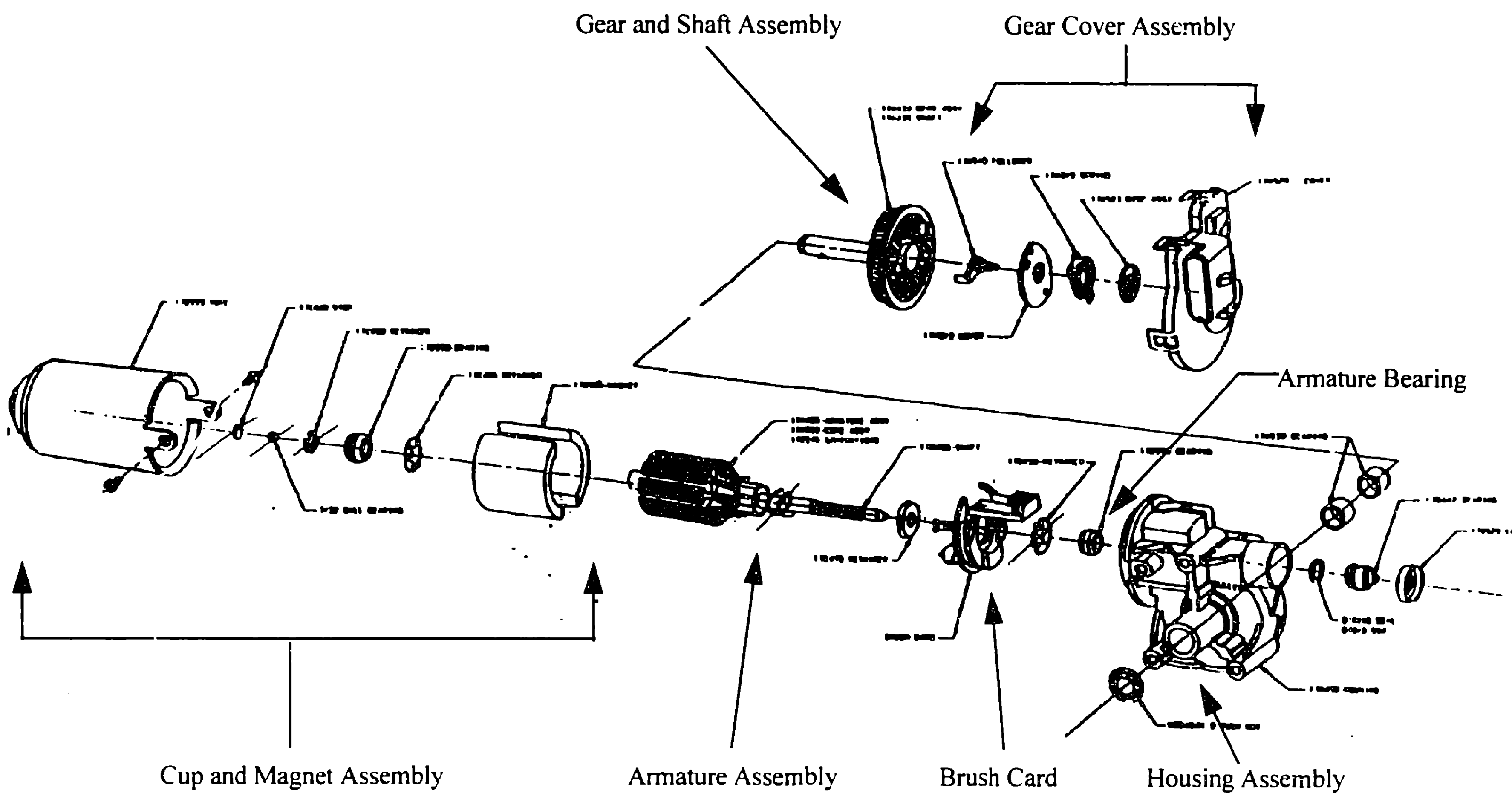

Figure 3-1: Ford "F" Generation Wiper Motor

3.2.2 Gear and Shaft Assembly

Gear and Shaft assembly is made up of a plastic gear and aluminum output shaft which is attached to the middle part of the gear. There are 8 types of gear and shaft assembly.

- White Long
- White Short
- Orange Short
- Red Short
- Blue Short
- Yellow WIN88
- Brown WIN88
- Green Stub

The color refers to the color of the gear, and they are color coded in order to minimize confusion at the assembly line. The description of long, short, or stub refers to the length of the output shaft, and they are matched with housing assemblies. In other words, long gear and shaft assembly goes only with long housing assembly, and the same is true for short and stub gear and shaft assembly and housing assembly.

3.2.3 Armature Bearing

Armature Bearing is a component which controls the torque level of a wiper motors. There are basically three types of armature bearing:

- Ball Bearing (High Torque)
- Vespel (Mid Torque)
- Bronze (Low Torque)

3.2.4 Gear Cover Assembly

Gear Cover Assembly consists of an electric connector which interfaces with wiring harness, follower mechanism that controls where a wiper motor "parks", or stops, when it is turned off. It is set at a specific angle to ensure that when wiper motor is turned off, the wiper blades always return to the same position, which is at the lower portion of the windshield near the hood. There are three types of gear cover assembly:

- 5-Pin
- 6-Pin
- 7-Pin

The number of pins refer to the number of terminals on the electric connector. The electric connector is designed as waterproof.

3.2.5 Armature Assembly

Armature assembly consists of shaft, wound armature core (lamination around which wires are wound), wires, and commutator. There are three types of armature assembly:

- 2 Types of Prog.
- 1 Type of Retro.

Different types refer to different thickness and different number of turns of wire around the wound armature core. They effect the speed at which armature turns.

3.2.6 Brush Card

Brush card is made up of many electronic components (coils, resistors, capacitors), and three brushes. Currently, there are two types of brush card used in "F" generation wiper motor. They are:

- RFI
- Non-RFI

RFI means that it suppresses RFI (Radio Frequency Interference), and Non-RFI lacks that suppression. In many applications today, the trend is going toward RFI, and thus in the future it is very likely that all brush cards will be protected against RFI.

3.2.7 Cup and Magnet Assembly

Cup is the housing for armature, and it is also where magnets are located. Cup and magnet assembly also includes back end components, such as bearing, stop plate, and retainer that holds the armature shaft in place. There are two types of magnets that are used today:

- Non-Tapered
- Tapered

These refer to the type of magnets that are in cup and magnet assembly, and tapered magnets were introduced recently in order to reduce whine noise of wiper motor.

3.2.8 Water Cap

Water cap is a black plastic piece that can be placed on the output shaft. It is used in vehicles where wiper motor getss exposed to excessive amount of water. This is an optional component.

3.2.9 Miscellaneous

Then there are minor components that are in all wiper motors. They are:

- RTV - Black glue-like adhesive which is applied around gear cover assembly, housing assembly, and cup/magnet assembly to hold them together.
- Thrust Plug - White plastic cap that is located at the tip of the armature.
- Push Nut - It fits around the output shaft against housing assembly to hold output shaft in place.
- Screws - Two are used between housing assembly and cup and magnet assembly to secure them together.

3.3 Function and Interface

In order to understand any relationship among sub-assemblies and components, it is very important to identify functions of each sub-assembly and interface with other sub-assemblies. Later in this paper, once certain parameters are selected as metrics, it will be shown that any recommended changes will flow back into sub-assemblies and components based on their functions, interfaces with other sub-assemblies and components, and their effect of parameters. The overall function and interface diagram[2] of "F" generation wiper motor is shown in Figure 3-2.

3.3.1 Housing Assembly

The basic function of housing assembly is to provide protection or cover of the wiper motor. Its main interface is with armature assembly and output shaft and gear assembly; also, it is connected with gear cover assembly and cup and magnet assembly to form outside packaging of a wiper motor.

3.3.2 Gear and Shaft Assembly

Gear interacts with armature and it carries torque and rpm generated from the armature. The torque is relayed to output shaft which provides torque and speed for wiper linkage and arm. Gear also interacts with gear cover assembly through a follower, and that is how park angle/position is determined for each wiper motor.

3.3.3 Armature Bearing

The armature bearing sets the torque level at which a wiper motor operates. Different wiper systems require different torques, and the wiper system dictates which bearing is to be used. Sometimes, the systems group requests a specific torque level, while other times, it is up to EFHD's wiper motor group to determine what torque level is appropriate for a given system. There is additional cost associated with going with high torque wiper motor versus mid torque, and thus, the wiper motor with lowest possible

[2] Otto, Kevin N, "Optimal Product Redesign, Lecture 3: Functional Teardown," Massachusetts Institute of Technology, Cambridge, MA, 1995.

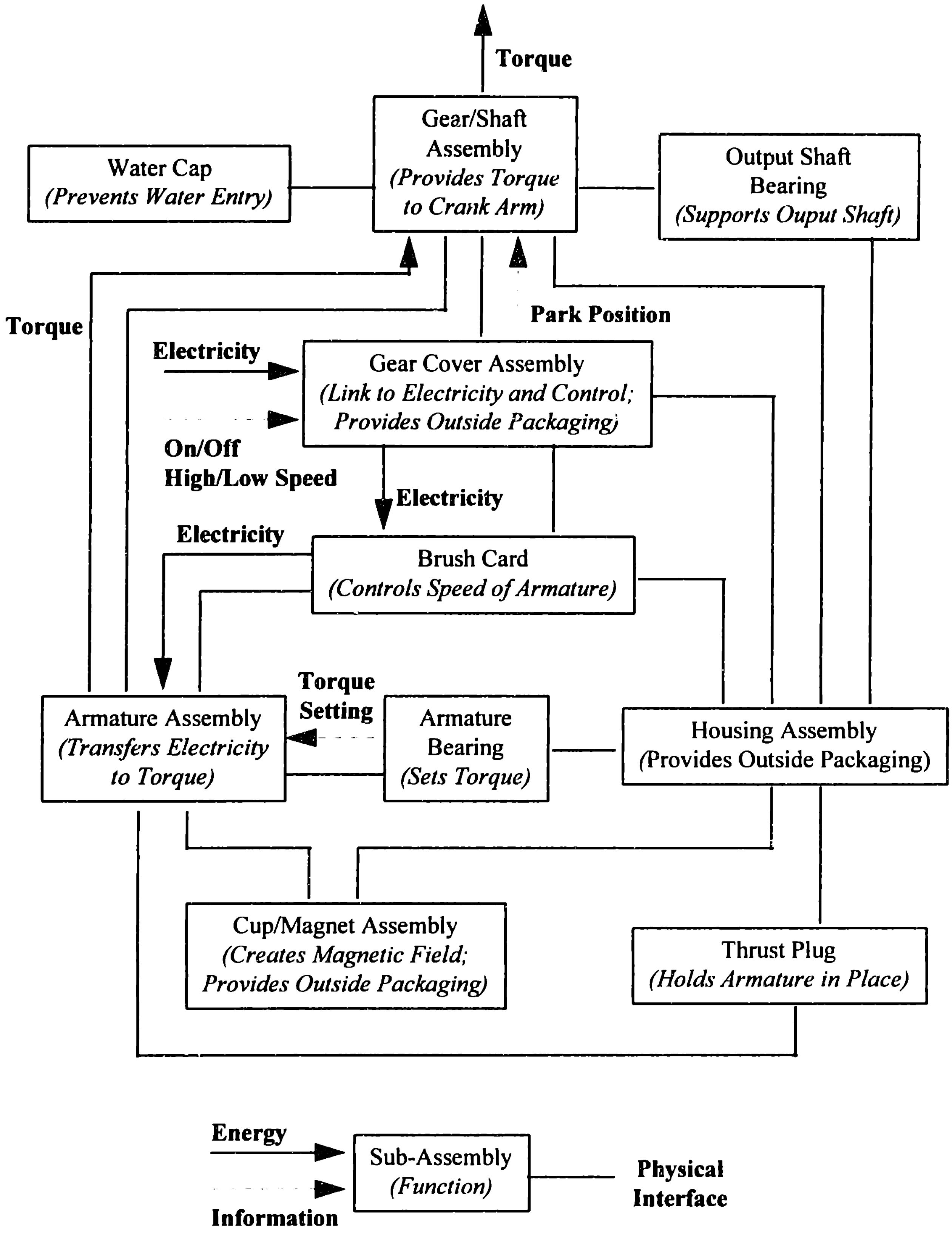

Figure 3-2: "F" Generation Wiper Motor Main Function and Interface Diagram

torque that satisfies the wiper system's requirements is used in each application. Because armature bearing is an internal component, it is possible to produce wiper motors that are identical outside and yet have different torque levels.

3.3.4 Gear Cover Assembly

The gear cover assembly is one of the most critical sub-assembly in a wiper motor. It has three basic functions.

- To provide outside covering/packaging of the wiper motor along with housing assembly and cup and magnet assembly.
- To serve as an interface between power source and control logic in the vehicle and wiper motor.
- To set park position of wiper motor.

5-pin and 6-pin gear cover assemblies have electric connectors with 5 and 6 terminals respectively. They are for what is called Non-Depressed Park wiper motors. They are the ones seen in most vehicles where wiper blades stop at the lower portion of the windshield, with wiper blades exposed. 7-pin gear cover has an electrical connector with 7 terminals, and it is for wiper motors with Depressed Park feature, which allows the wiper blades to go below the hood once it is turned off. It is usually for more expensive vehicles because the cost is higher for Depressed Park wiper motors. 5-pin and 6-pin gear cover assemblies are identical except that in 6-pin electric connector, there are separate terminals for "ground" and "common", while in 5-pin, they are combined into one terminal. Thus, 5-pin connector is smaller, requires less space, has one less connector, and costs less to manufacture. The cost difference small, but when there are millions of units to each year, any reduction in cost becomes quite significant. The main interface of gear cover is with brush card in transporting power, current, and voltage to brush card. It also interacts with gear and shaft assembly through follower which determines park position, and it is connected with housing assembly to provide outside packaging for a wiper motor.

3.3.5 Armature Assembly

Just like any other electric motor, wiper motor has an armature assembly which interfaces with brush card via commutator and brush contacts. The speed and current draw are determined by wires wrapped around the wound armature core. This is where the electric energy is translated into rotational energy, which provides necessary torque and speed for wiper motors. Its main interfaces are with brush card, magnets in cup and magnet assembly, and gear and shaft assembly.

3.3.6 Brush Card

Brush card transports electrical voltage and current to armature. There are three brushes, one for common, one for high speed, and one for low speed. They need to maintain contact with armature's commutator, or wiper motor would not turn. When a brush does not make contact with commutator, it is identified as "hung brush". Brush Card interfaces with armature assembly, gear cover assembly and housing assembly.

3.3.7 Cup and Magnet Assembly

This sub-assembly's main function is to provide housing or cover for armature's main body. It is where magnets are located as well as what is called back-end plate where armature's one tip rests on. Its main interface is with armature and with housing assembly to provide outside packaging or cover for a wiper motor.

3.3.8 Water Cap

The function of water cap is to prevent water from entering inside wiper motor through the small opening gap between housing nose and output shaft is located. Therefore, its main interface is with output shaft and housing assembly.

3.3.9 Miscellaneous

Miscellaneous items are common in all wiper motors, and they have different functions and interfaces.

- RTV - The function is to act as glue to hold housing assembly, gear cover assembly, and cup and magnet assembly together tightly. It also acts as a seal to prevent water from entering a wiper motor.
- Thrust Plug - The function is to prevent armature from having too much movement along the line of its shaft. Thrust plug is fixed on housing assembly.
- Push Nut - Push Nut is a thin metal place with a hole in the middle. It has jagged edges around the hole in the middle. The function is to keep output shaft in place.
- Screws - Two screws are used to attach housing assembly and cup and magnet assembly.

3.4 Permutation and Applications

Based on the number of different types available for each sub-assembly and component, it is relatively easy to determine the number of possible different types of wiper motors that can be generated from current modules of wiper motors. There are:

- 6 Types of Housing Assembly
- 8 Types of Gear and Shaft Assembly
- 3 Types of Armature Bearing
- 3 Types of Gear Cover Assembly
- 3 Types of Armature
- 2 Types of Brush Card
- 2 Types of Cup and Magnet Assembly,
- And Whether to Have a Water Cap or Not

The possible permutation is equal to 6*8*3*3*3*2*2*2 = 10368, which means there are 10368 different wiper motors that can be produced with existing sub-assemblies and components. However, this is not entirely true. The main reason this is not true is that certain housing assembly is not compatible with certain gear and shaft assembly. For example, short housing assembly cannot accommodate long gear and shaft assembly, and long housing assembly cannot accommodate stub gear and shaft assembly. Depending on which type of housing assembly is used, the available option of gear and shaft assembly becomes limited. Thus, the calculation for permutation of the maximum number of different motors that can be produced needs to be adjusted. The following facts are known:

- For one long housing assembly, there is only 1 gear and shaft assembly that is compatible.
- For the other long housing assembly there is only 1 gear and shaft assembly that is compatible.
- For one short housing assembly, there are 2 gear and shaft assemblies that are compatible.
- For the second short housing assembly, there are 3 gear and shaft assemblies that are compatible.
- For the third short housing assembly, there are 3 gear and shaft assemblies that are compatible.
- For the stub housing assembly, there is only 1 gear and shaft assembly that is compatible.

The remaining sub-assemblies and components are interchangeable and compatible with all types of wiper motors. Therefore,

- For one long housing assembly, the number of permutations = 1*1*3*3*3*2*2*2 = 216
- For the other long housing assembly, the number of permutations = 1*1*3*3*3*2*2*2 = 216
- For one short housing assembly, the number of permutations = 1*2*3*3*3*2*2*2 = 432
- For the second short housing assembly, the number of permutations = 1*3*3*3*3*2*2*2 = 648
- For the third short housing assembly, the number of permutations = 1*3*3*3*3*2*2*2 = 648
- For the stub housing assembly, the number of permutations = 1*1*3*3*3*2*2*2 = 216

The total number of permutations that result from this calculation is 216*3 + 648*2 + 432, which is equal to 2376. Thus, due to the fact that certain housing assemblies are compatible with certain gear and shaft assemblies, the number of permutations dropped drastically, from 10368 to 2376, and the result is 23% of the original maximum number of possible permutations.

Currently, EFHD does not manufacture 2376 different types of wiper motors although it can if it chooses to. First of all, there is no need to have so many different types, and the goal is to always keep the number of different types of wiper motors as low as possible so that complexity and confusion at the assembly line can be minimized. Currently, there are 27 different types of wiper motors EFHD is producing, including 3 service parts that were retrofit into vehicles produced before "F" generation wiper motors were introduced. In other words, when these vehicles come in for service to replace wiper motors, instead of putting "E" generation wiper motors that were originally in the vehicle, "F" wiper motor is put in instead. These 27 types of wiper motors are used or scheduled to be used in 29 different current and future vehicles, and this is due to the fact that there are two wiper motors that are used in two different vehicle applications. The list of all the vehicles with "F" generation wiper motors are shown in Appendix B.

Chapter 4

High Mileage and Useful Life Parameters

High mileage and useful life refers to reliability of a product, such as a wiper motor, over its useful life. It typically follows what is known as a bathtub curve, shown below in Figure 4-1, where x-axis represents time of usage and y-axis is failure rate.

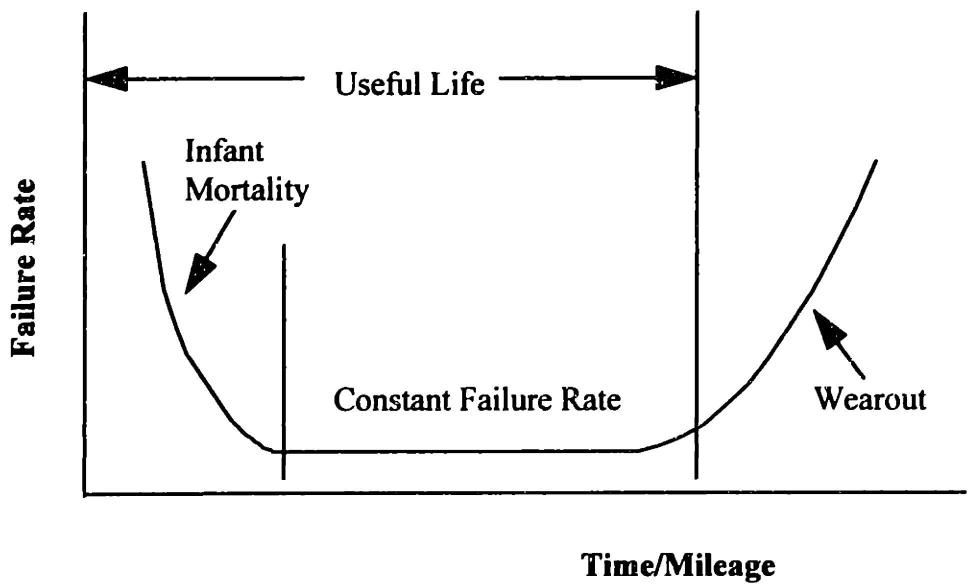

Figure 4-1: Bathtub Curve

In the beginning life of a product, the failure rate is high due to manufacturing issues, and these are known as infant mortalities. Then the failure rate levels off in the middle part until wearout characteristics begin to bring failure rate up again. High mileage and useful life focuses on extending the time at which the wearout characteristics begin to show. Ford Motor Company has an objective to meet for all the vehicles, as mentioned in Chapter 1.

4.1 Description

In order to measure high mileage and useful life of wiper motors, parameters need to be selected that can be physically measured on the products and represent useful life. It is important to identify a parameter to measure and analyze how it changes over a period of time. The basic question to answer is at what the threshold value of the parameter is, and that refers to a value beyond which wiper motor's performance is no longer acceptable. There were many different parameters that could be used, but the following 5 parameters were chosen. These were chosen mainly because 1) they are relatively easy to measure, 2) they represent measurements that are directly related to critical functions of wiper motors, and 3) they represent high mileage wearout characteristics very well. Item 3) means that because high mileage wearout characteristics refers to things that wear out over a long period of time, it does not include any special cause issues that can effect performances at any point in its useful life. High mileage wearout parameter must be something that shows slow decay over a long period of time, and these measurements represent wearouts very well. These parameters also have to be platform-wide parameters that are present in all products across the platform. They cannot be product specific parameters because the goal is to improve platform-wide performance, such as high mileage and useful life, of wiper motor. The parameters chosen are consistent with FMEA (Failure Modes and Effects Analysis) for wiper motors shown in Figure 4-2. These are failure modes that relate to wears.

4.1.1 End Play

End Play is the measurement of how much armature moves back and forth along its axis. This is measured by measuring the movement of thrust plug while turning output shaft. It is an important measure because if a wiper motor has too great of end play measurement, it will lead to "clunk" sound, which a user will hear and complain about. As components that hold armature in place wear out, they lead to larger and larger end play measurement, until the noise level becomes unacceptable for users.

Failure Mode	Effect	Causes
Excessive brush wear	1. Reduced motor life 2. Excessive noise	1. Worn armature shaft 2. Light bearing retention spring
Premature wear of armature shaft ball bearing	Excessive noise	Excessive bearing retention spring force
Excessive backlash between output gear and armature or a milled gear	1. Excessive noise 2. Inoperative wiper system	1. Excessive wear of thrust plug 2. Excessive end play 3. Thrust plug material is too soft
Increase in sweep radius	1. Noise at blade reversal 2. Wiper pattern growth	1. High loading at elevated temperature 2. Inadequate hardness of shaft
Premature brush wear	Erratic or inoperative wiper system	1. Incorrect brushbox angles 2. Excessive clearance between the brush and brushbox
Premature wear of the armature shaft bearing in the yoke	Reduced motor performance and motor life	Excessive heat

Figure 4-2: FMEA Table for a Wiper Motor

4.1.2 Axial Play

Axial Play is the measurement of how much the output shaft moves back and forth along its axis. This is measured by recording the how much output shaft can be pulled in and out of the housing assembly. Like end play, it also has an effect on noise. High measurement means it is moving more than it should, and such loose configuration creates noise customers do not desire to hear.

4.1.3 Radial Play

Radial Play is the measurement of how much the output shaft moves side to side. Force is applied perpendicular to the output shaft, and it is measured by how much the shaft can be moved. Radial play has one major impact on the wiper motor. Since the output shaft rotates around one or two bearings, if the output shaft has too much side to side movement, it will rub against the bearing, and too much wearout on bearing will eventually lead to failure.

4.1.4 Angular Play

Angular Play is the measurement of how much output shaft can be rotated. Unlike all the other parameters which are measured in mm, this is measured in degrees since it is dealing with angular movement. This is measured by attaching arm to the end of the output shaft and applying torque to the output shaft and recording how much angular movement the output shaft has. The major impact of angular play is if a wiper motor has too much angular movement, it allows the blades to rotate too much, and it leads to what is called pattern growth on windshield. In cases where angular movement is too much, sometimes blades end up hitting the side of the windshield. Angular Play is related to End Play to a certain degree in that if armature can be moved back and forth, it will make the output shaft to turn; however, there are differences due to the fact that Angular Play is not limited just to armature movement, and it also includes wearout issues of gear and shaft assembly.

4.1.5 Brush Wear

One of the internal components that is critical in maintaining functionality of a wiper motor is brush. Brush tends to wear, especially high speed brush as it rubs against commutator on armature. If the brush gets too short and stops making contact with commutator, the motor basically cannot function. That is why it is so important to understand how much brush wears over a period of time so that enough brush can be added in design to ensure that wear will not exceed to the point where the motor will stop running.

4.2 Analysis of High Mileage Measurement Data

With these high mileage and useful life parameters chosen, the next step is to gather data at various points in its useful life. Typically, since a car is not something that is used continuously, it is not necessarily the time of usage that is important. We often correlate the usage of a component in a car with mileage instead of time in service. A car is clearly in use while it accumulates the mileage, and it is when a car is being driven that a wiper motor is also used due to rain or snow or cleaning windshield. In Chapter 1, it is mentioned that for wiper motors, 10 years is tougher requirement than 150,000 miles. But since tracking mileage is more useful for wiper motors, we will use the mileage the 95th percentile drives in 10 years, which is about 250,000 miles, as the target for high mileage and useful life of wiper motors. Therefore, one of the major efforts in high mileage and useful life project is to keep track of various fleets where mileages are recorded and any issue with wiper motors are being tracked. Ford Motor Company runs many different fleets throughout the year, and we try to get our hands on many fleets and vehicles as they accumulate mileages for wiper motors inside the vehicles. Then those wiper motors are removed and retrieved after various miles so that they can be analyzed to see how wiper motors perform at various points in its useful life.

Appendix C shows a list of 25 high mileage vehicles from which wiper motors were removed for measurements of high mileage and useful life parameters. They ran in fleets for a few months to years in order to accumulate mileages shown in the table. These wiper motors were collected over a period of 4 months, from April of 1996 to July of 1996. Special requests were made to groups within Ford Motor Company that coordinates a number of fleets, and they removed and shipped wiper motors from various vehicles. This is where the platform nature of wiper motor also play a significant role. Because so many of wiper motors are very similar in content due to module-based design, even though wiper motors were removed from different vehicles, they still can be used as a group in analysis because they share many of the same components. If only differences were lengths of shaft or number of electric terminals on the gear cover assembly, and they do not have any significant effect on the parameters we are concerned with.

After these wiper motors were retrieved from various fleets, they were taken to the EFHD's prototype shop for measurements. All the measurements were taken in the prototype shop except the brush wear because in order to get to brushes, wiper motors need to be disassembled. Then, each brush length is measured to see how much it has worn place. As mentioned earlier, high speed brush wears the fastest due to the fact that there is more friction as brush and commutator stay in contact more frequently when armature spins faster. Therefore, we are mostly concerned with high speed brush wear.

Appendix D through H show actual End Play, Axial Play, Radial Play, Angular Play, and Brush Length data taken from the 15 high mileage motors as well as from a few brand new wiper motors that came off the final assembly line of wiper motors. These new motors were important because they provided the initial measurement points at 0 mile of usage. This fixes a beginning point of the general trend we are trying to find. This fact was recognized after plotting angular play versus mileage of wiper motors. Here the trend was going downward as mileage went up. It meant that angular play became less as parts wore out more, which did not make any sense. Thus, 6 brand new wiper motors' measurements were added to the data, and the trend was what we expected, where angular play went up as mileage increased. Brush Length measurements mostly came from warranty returns. As mentioned earlier, these need to be measured after wiper motors are disassembled. Wiper motors returned from dealers through warranty system provides brush wear information because all of them are disassembled for brush wear measurements as well as other measurements and analysis to determine the root cause of the problem. Figure 4-3 through 4-7 show graphs of measurement versus mileage of wiper motors the data was from. The brush wear graph, Figure 4-7, show many more data points than others because there are far more warranty return wiper motors analyzed in the last few years compared to high mileage wiper motors from fleets that are just starting to be collected.

The fitted lines in each graph is linear regression fit determined using Microsoft Excel. For each parameter, an equation is derived to calculate what the parameter is once mileage is known.

- End Play: $E = (3.97 \times 10^{-6})\ M + 0.13$, where E is the end play measurement and M is mileage. End play is measured in mm (Normalized). R-squared value for end play data is 0.7178.

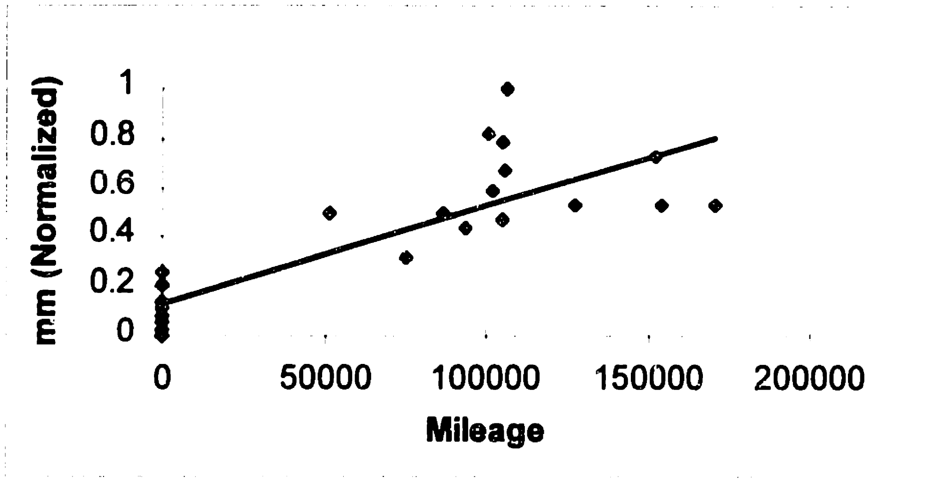

Figure 4-3: End Play

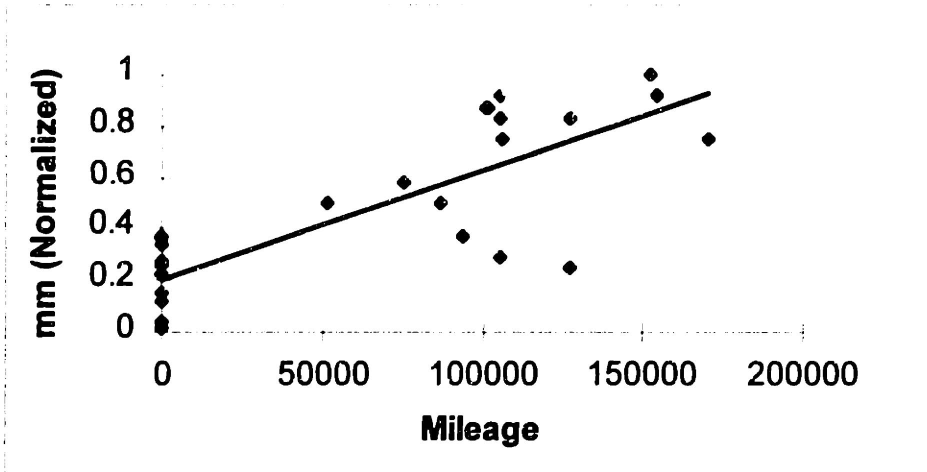

Figure 4-4: Axial Play

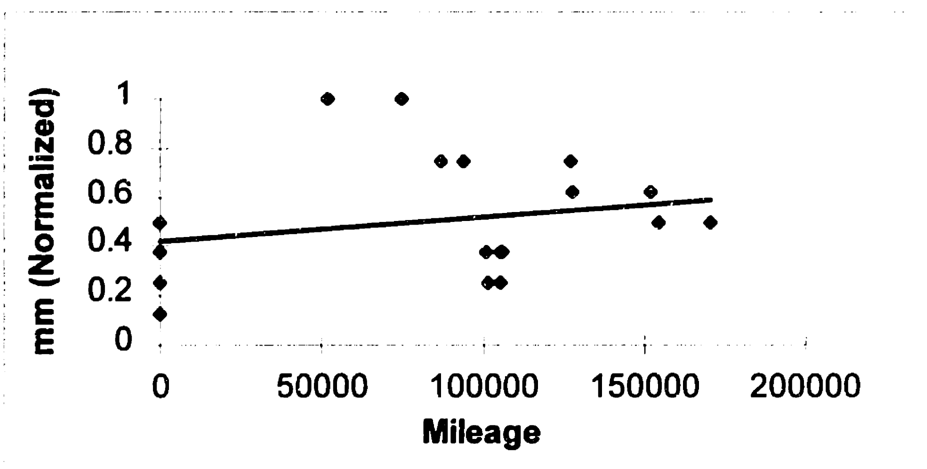

Figure 4-5: Radial Play

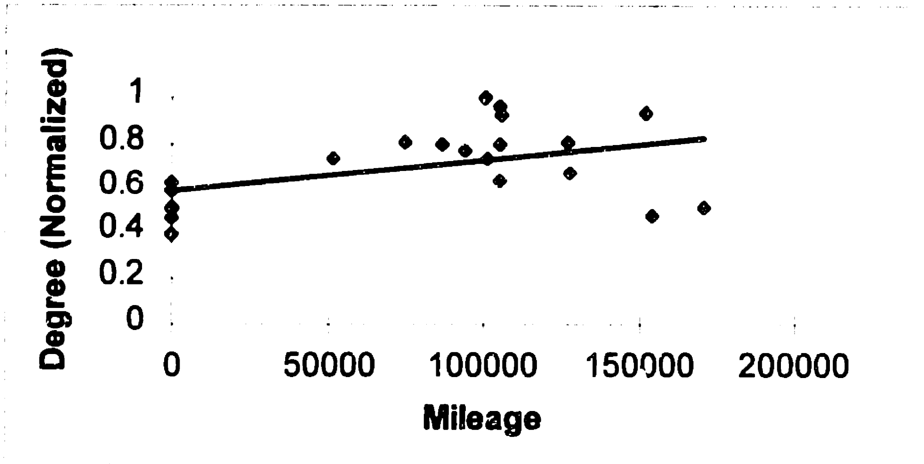

Figure 4-6: Angular Play

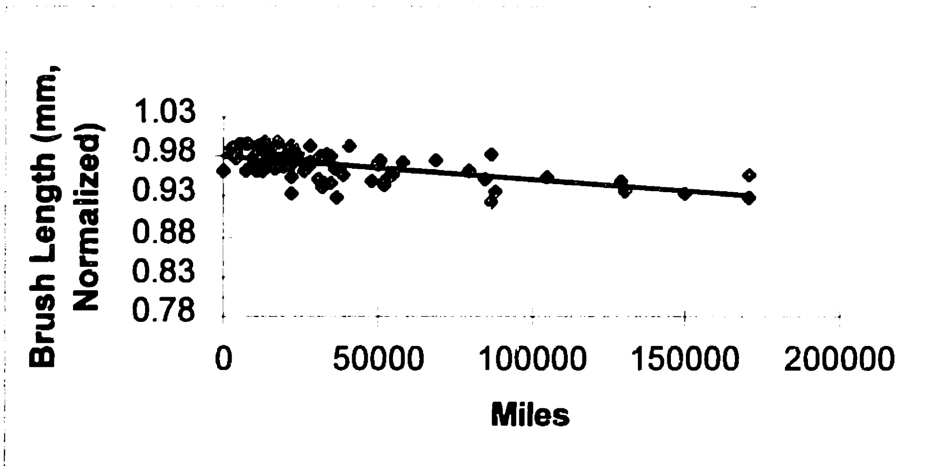

Figure 4-7: Brush Wear

- Axial Play: A = (4.26×10^{-6}) M + 0.20, where A is the axial play measurement and M is mileage. Axial play is measured in mm (Normalized). R-squared value for axial play data is 0.6514.
- Radial Play: R = (9.84×10^{-7}) M + 0.42, where R is the radial play measurement and M is mileage. Radial play is measured in mm (Normalized). R-squared value for radial play data is 0.0735.
- Angular Play: ANG = (1.44×10^{-6}) M + 0.58, where ANG is the angular play measurement and M is mileage. Angular play is measured in degrees. R-squared value for angular play is 0.2165.

- Brush Wear: B = (-2.96×10^{-7}) M + 0.98, where B is the high speed brush length measurement and M is mileage. Here the slope is negative because brush length decreases as mileage increases. Brush length is measured in mm (Normalized). R-squared value for brush wear is 0.3481.

Slopes are rate at which each parameter changes in respect to mileage. Since R-squared value for some data are poor, such as radial play, it seems to suggest that there is no correlation between mileage and radial play. It may be due to the fact that we are dealing with dimensions that are of the order of their tolerances, and in case such as this, it may be more useful to measure the change in parameter from installation to failure than just the value of measurements at various mileages. This may be more difficult because it means the initial radial play needs to be measured, then put in a vehicle, and measured again after certain number of miles to determine the difference. For parameters with low R-squared value, it may be necessary because a line fit does not provide much useful information.

4.3 Application of Results in Design

One way to apply the results shown above is to determine at what measurement of each high mileage and useful life parameter a wiper motor either stops functioning or is no longer acceptable due to too much noise or pattern growth or any other reason. For example, from a study done in the past on brush wear, we know that brush needs to be above 0.51 mm (Normalized) in order to make a wiper motor function. Then we compare whether that limit has been reached at the useful life requirement given for wiper motors. If the measurement is projected to reach the limit before the useful life requirement, then design changes are required to improve the performance of wiper motors to ensure that they still meet all the useful life requirement.

In the example of brush wear, the data in Section 4.2 show that the brush length is projected to be 0.91 mm (Normalized) at 250,000 miles, which is the useful life requirement. Since it is significantly greater than 0.61 mm (Normalized) required, we know that the current brush length is sufficient to meet the useful life requirement. In fact, it may be possible to reduced brush length to save cost.

4.4 Application of Results in Correlation with Test Stand

Another use of the data from high mileage and useful life parameters is in correlating the number of cycles on test stand with real world mileage. This is an important step in developing Key Life Test for wiper motors. A Key Life Test is basically a durability test which measures how long a product would last. Wiper motor engineering specification requires continuos running of 1.5 million cycles on current Programmed Load Test Stand. Programmed Load test procedure is written as follows:

> "..... subject it (the wiper motor) to a programmed load ... starting out on high speed and then alternating between high and low speed every 24 hours until 205 hours of high speed durability hours have been completed. After 205 hours of high speed durability hours have been completed, switch over to low speed for the remainder of the test until 1.5 million cycles have been completed."

The biggest problem, however, is that there is no correlation between 1.5 million cycle requirement and mileage. The basic question we currently cannot answer is: How many cycles on test stand is equivalent of one mile of usage in real vehicle? High mileage and useful life parameter provides useful information in this correlation.

For example, in measuring brush wear, we know the rate at which high speed brush length changes over mileage, which is shown in Figure 4-7. And we also have data on how brush wear changes on our test stand. Figure 4-8 shows the graph of high speed brush wear versus number of cycles on the Programmed Load test stand. Actual data is shown in Appendix I.

- Here the equation is $B(PL) = (-1.09 \times 10^{-7})\ C + 1.03$, where B(PL) is the high speed brush length measurement and C is the number of cycles on the Programmed Load test stand. Again, the brush length is measured in mm (Normalized), and R-squared value is 0.8922.

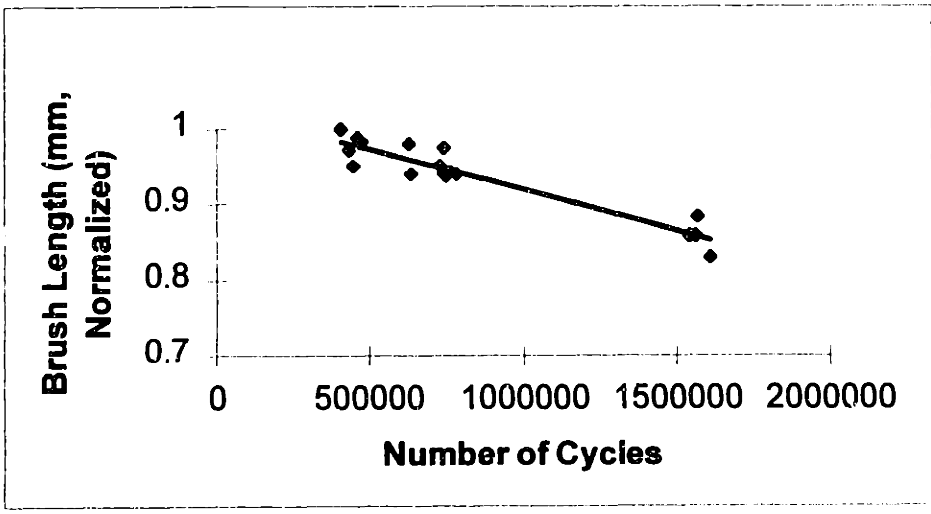

Figure 4-8: Brush Length - Programmed Load Test Stand

This equation shows that for every cycle, the high speed brush wears 1.09×10^{-6} mm (Normalized). In earlier equation on brush length versus mileage, we found out that for every mile, the high speed brush wears 2.96×10^{-7} mm (Normalized). It means that there is 0.296/1.09, or approximately 3.7 to 1 ratio between mileage and the number of cycles, or 3.7 mile is equivalent to 1 cycle on the Programmed Load Test Stand. Therefore, if there is a requirement that a component should not fail for 250,000 miles as mentioned earlier as the target for wiper motors, then, for brush wear, wiper motors need to be tested for at least 250,000 divided by 3.7, or 68,000 cycles, which is about 1/22 of 1.5 million cycles we are currently testing.

It is important to note that this applies only for brush wear, and for any other high mileage and useful life parameter, the same steps need to be taken in order to determine the correlation ratio between mileage and the number of cycles on the Programmed Load test stand. So far, due to constraints on the availability of Programmed Load test stand, the experiments are not completed for other high mileage and useful life parameters. If the correlation factor is not the same for all parameter, which is highly likely, then the highest correlation factor will be chosen to ensure that wiper motors do meet all the useful life requirements. And if the maximum number of cycles for all parameters on the current durability test stand comes out to be quite different from 1.5 million cycles we are currently testing, as was in the case of brush wear, then the test procedure needs to adjusted in order to meet company's high mileage and useful life objective.

4.5 Relationship Between High Mileage and Useful Life Parameters and Sub-Assemblies

The next step in using high mileage and useful life parameters is to link how these parameters are effected by various sub-assemblies and components. The goal here is to understand what changes needed to be made if necessary on which sub-assembly or component so that changes can be implemented most effectively to improve high mileage and useful life. Figure 4-9 through 4-13 show fishbone diagrams which illustrate what component effects each high mileage and useful life parameter.

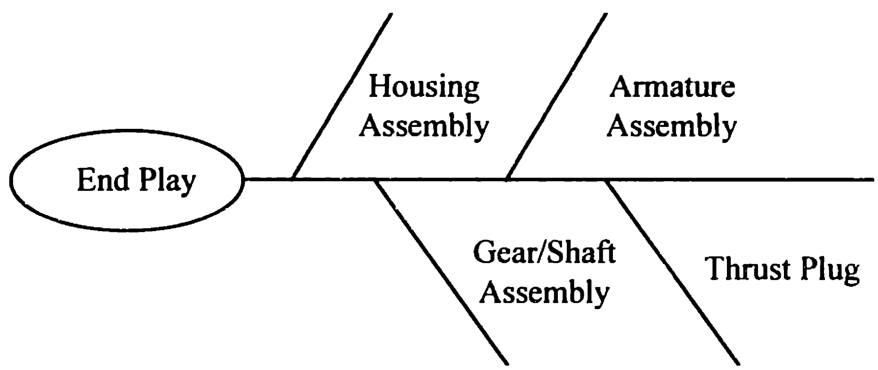

Figure 4-9: End Play

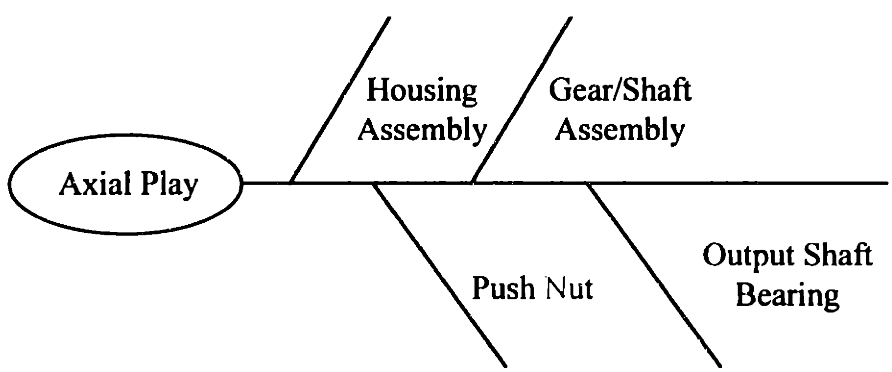

Figure 4-10: Axial Play

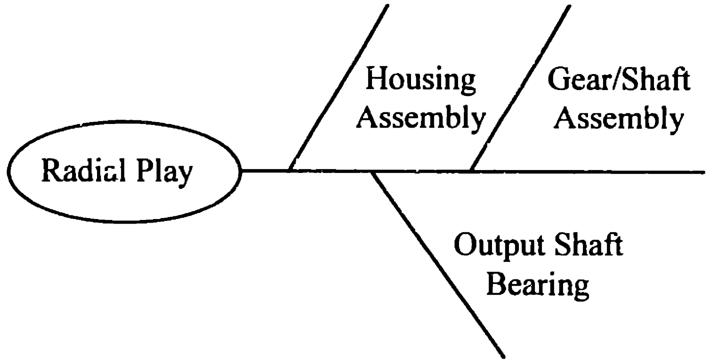

Figure 4-11: Radial Play

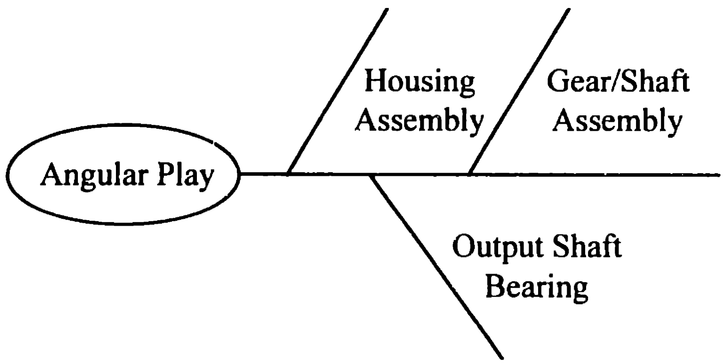

Figure 4-12: Angular Play

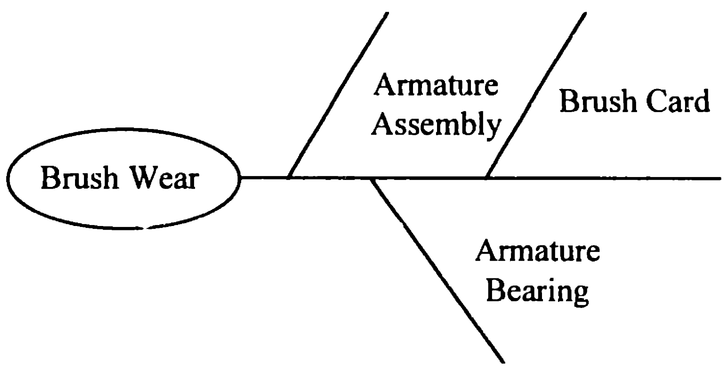

Figure 4-13: Brush Wear

One important thing to note is that a sub-assembly or component shown in most number of high mileage and useful life parameters is the most critical item which effects the most number of high mileage and useful life parameters. Sub-assemblies such as gear and shaft assembly and armature assembly are very important in improving high mileage and useful life of wiper motors because they are related to more than one parameters. These diagrams can be used to determine which sub-assembly needs to be modified to make significant impact on a high mileage and useful life parameter we are interested in.

4.6 Relationship Between High Mileage and Useful Life Parameters and Mileage

In determining the relationship between the selected parameters and mileage, the following assumptions are made:

- The relationship is first order and linear. Mathematically speaking, it is expressed as

  $$\text{Mileage} = C_0 + (C_1 * EP) + (C_2 * AxP) + (C_3 * RP) + (C_4 * AnP),$$

  where EP is End Play measurement, AxP = Axial Play measurement, RP is Radial Play measurement, and AnP is Angular play measurement. Brush wear is not included in this calculation because its measurement came from different wiper motors, and in order to do this analysis all the measurements of each motor must be known. For wiper motors where brush wear came from, the other measurement data (End Play, Axial Play, Radial Play, and Angular Play) were not included in this thesis.
- Coefficients C_1 through C_4 are all positive. This is based on the nature of wearout parameters. As the usage of wiper motors increases, these parameters' measurements tend to increase and never decrease. This is a valid assumption because parts in wiper motors do not "unwear". Wearouts tend to increase as mileage goes up, and when wearouts increase, all the parameters will increase as well because they are measurements of wears.

4.6.1 Determining Coefficients

Two methods were used to determine four coefficients and one constant. One was regression fit and the other was optimization model. They were both done by using Microsoft Excel. The data are taken from wiper motors in Mustang only in order to reduce possibility of variations resulting from different applications.

4.6.1.1 Regression Fit

In this method, Y-values were mileage accumulated on each motor, and X-values were parameter measurements. The table showing the solution from the regression fit is in Appendix J. The summary of results are:

- Data are very scattered. Even though R-squared value is 0.7972, the percentage error ranged from 2% to 89%. For 7 out of 12 wiper motors with significant mileage, the error was within 20%, but there were also 2 wiper motors with error greater than 40%.
- End Play has the biggest impact on mileage. Based on the resulting coefficients, the End Play term in the equation has the highest contribution to mileage calculations. Axial Play and Radial Play have some impact on mileage, but not nearly as much as End Play. Angular Play has minimum impact on mileage.

4.6.1.2 Optimization Model

An optimization model was used to determine coefficients and constant. Microsoft Excel's Solver function was used.

- Decision Variables: 4 coefficients, C_1 through C_4, and 1 constant, C_0
- Objective Function: Minimize the sum of differences in calculated mileage and actual mileage.
- Constraint: C_0 through C_4 are all greater than 0.

The actual mileage is known because of the record where the wiper motors came from. The Solver tries different values of C_0 through C_4, and calculate mileage based on the first order linear function shown above. Then the differences are added and minimized to find optimal solution. The table showing the solution from the optimization model is in Appendix K. The summary of results are:

- Data are very scattered. The percentage error ranged from 0% to 70%. For 7 out of 12 wiper motors with significant mileage, the error was within 20%, but there were also 3 wiper motors with error greater than 40%.

- Axial Play has the biggest impact on mileage. Based on the resulting coefficients, the Axial Play term in the equation has the highest contribution to mileage calculations. End Play and Angular Play have some impact on mileage, but not nearly as much as Axial Play.
- Radial Play has no impact on mileage. The coefficient is 0, and this was expected because the R-squared number for Radial Play vs. Mileage was very low (see Section 4.2), which means that there is no correlation between Radial Play and Mileage.

4.6.2 Result

The common result from both methods is that for a majority of wiper motors, the mileage can be determined fairly accurately once all the measurements of parameters are known. However, there will be wiper motors where the mileage calculations will not be very accurate. The average percent error was better for the optimization model than for the regression fit (22% vs. 26%), but standard deviation was slightly better for the regression fit (22% vs. 23%). Looking at the results, the optimization model generated many 0% error (three compared to none for the regression fit) while the regression fit simply tried to find a relationship that was optimally positioned for all data points.

One major difference is that the regression fit result shows that End Play is the parameter that wears out the "most" or goes through most changes compared to other parameters. In contrast, Angular Play changes very little as wiper motors accumulate mileage. The optimization model, on the other hand, shows that Axial Play is the parameter that impacts the mileage the most.

Based on this result, the recommendation is to make improvements in components that effect End Play and Axial play as shown in Figure 1-9 and 4-10. The components listed are housing assembly, armature assembly, gear and shaft assembly, and thrust plug for End Play and housing assembly, gear and shaft assembly, push nut, and output shaft bearing for Axial Play. A study needs to be done in order to determine how these components effect End Play and Axial Play. The common components, housing assembly and gear and shaft assembly, need to be looked at more carefully because they can effect both parameters, and they may present trade-off cases where improving one parameter may effect the other parameter adversely.

Chapter 5

Product Development Process (PDP)

Ford Electrical and Fuel Handling Division utilizes Product Development Process (PDP), which is a disciplined process to bring a product to market. The major steps in PDP are:

- Voice of Customer
- Sort Design Alternatives
- Analytical Design Alternative; Sort Manufacturing Process Alternatives
- Product Development; Process Development
- Production Launch; Production Ramp-Up
- Ship to Customer

It is an integrated process with cross functional teams, and there is feedback loop for continuos improvement. It involves a number of activities at Ford EFHD, such as Advanced Engineering, Design and Manufacturing Engineering, System Engineering, Technical Specialists, CAD Services, Lab Services, Purchasing, Design and Release Activity, Timing/Program Management, Manufacturing Plan and Logistics, Cost Estimate, Quality Office, and often includes suppliers. It is also viewed in 4 phases:

- Phase I: Plan/Define Program
- Phase II: Product/Process Design
- Phase III: Product/Process Development
- Phase IV: Product/Process Validation

The PDP provides a common process for product development which all activities in EFHD can follow.

5.1 Role of High Mileage and Useful Life in PDP

High mileage and useful life of a product is involved various parts of the PDP at Ford EFHD. It is a requirement all the products need to meet (See Chapter 1 on High Mileage and Useful Life Objective), and therefore it needs to be incorporated into the PDP. It is shown explicitly in certain parts of the PDP, while it is involved in many more parts of the PDP.

5.1.1 Voice of Customer

According to the *EFHD - Product Development Process: Users' Guide Glossary* published in January 31, 1996, the *Voice of Customer* is an early step in the Product Development Process, and it refers to determining the end customers' wants and needs for components, systems, and services. These wants and needs are usually identified by different activities of Ford and its partners. Quality Function Deployment (QFD) is a common and well-known method in this step. One of the items listed under the *Voice of Customer* step is High Mileage Useful Life. For the description of that part, *the Users' Guide Glossary* states:

> "Integrate the appropriate product knowledge from the High Mileage useful Life Process. Prove assurance that previously 'Identified Opportunities For Reliability Improvement' and results from 'Test-The-Best' (Benchmarking) have been included. Utilize appropriate 'Real World Usage Profiles', and 'Key Life Tests'. Consider similar product 'Reliability Targets', and previously 'Demonstrated Reliability' (Useful Life, mean Time/Miles to Failure), 'Value Management' results, and 'Robustness' improvements."

What this statement basically says is that all the results from High Mileage and Useful Life efforts need to flow into determining end customer's wants and needs. This is at a more general level where each component, such as a wiper motor needs to last 10 year/150,000 miles as set by the company.

5.1.2 Develop Useful Life Reliability Plan (Product Engineering)

Another step in the PDP where High Mileage and Useful Life efforts is in Phase II: Product/Process Design, in a step called *Develop Useful Life Reliability Plan*. The *Users' Guide Glossary* says the following in regards to that step.

"The Useful Life Reliability Plan identifies the necessary steps and timing for the Reliability activities, including the Corporate useful Life Reliability Initiatives described below:

1. Useful Life Reliability Mission - Satisfy car and truck customer expectations for reliability throughout a vehicle useful life of 10 years or 150,000 miles.
2. Value Management - Design trade-off analysis and decisions that attempt to maximize Company profits while maximizing customer satisfaction.
3. Useful Life Reliability Targets - Targets established to verify the amount of time (miles, cycles, years) a product can withstand before costs, time, or safety render it not feasible to repair.
4. System Design Specifications - Design discipline intended to capture all known requirements in a controlled document.
5. Product Robustness - The ability of a system/component to function in the presence of uncontrolled variation.
6. Key Life Tests - Customer correlated tests that best simulate operation under extremes of load, usage, and environments, and include the effects of interactions with each other, and with other items.
7. Test-The-Best - A process of evaluating Ford processes and products to those processes and products of recognized Best-In-Class (BIC) companies."

Here, many items such as reliability target and key life test, which were mentioned and discussed earlier are repeated. As a product development enters Phase II, targets become more specific and concrete comapared to Phase I, which is more general. At this level, the statement shown above means the following:

- All the wiper motors that are being developed need to meet requirements set by High Mileage and Useful Life efforts. It has identified the parameters mentioned in Chapter 4, and we need to determine what they need to be in order to ensure that wiper motors meet reliability targets.
- The requirement that end customers want or need, such as lasting 10 years of 150,000 miles, can be expressed in terms of the number of test cycles on key life test developed through High Mileage and Useful Life efforts. It gives us an objective metric that can be used in design and developing products that meet the company's objective.

5.1.3 Complete Design Verification Test

The last major step in the PDP where High Mileage and Useful Life information gets involved is in *Design Verification* step under Phase IV: Product/Process Validation. This is a step where a product is tested to prove that all the requirements are met satisfactorily. All the reliability targets and metrics or parameters mentioned earlier come into play here once again because they are chosen as parameters that will be measured. The key life test will be the method to measure these parameters which will determine whether a product meets all the requirements or not.

5.1.4 Other Steps

The three steps mentioned above are just the ones that mention certain aspects of High Mileage and Useful life explicitly. There are many other steps that also involve High Mileage and Useful Life efforts in a variety of ways. In *Develop Engineering Specification* step in Phase III: Product/Process Development, Key life test becomes a part of engineering specification under durability requirement. Fleet Tests in Phase III and Phase IV are also ways to develop real world usage profiles of a product. It is a way to test a product in real world situation, and it provides information on what type of environment a product operates in, what types of stresses are applied, and this will lead into developing key life test. And there are many more steps where High Mileage and Useful Life efforts get involved in minor ways throughout the PDP.

5.2 Importance of Feedback

The bottom line is that High Mileage and Useful Life is a long process that takes time due to the nature of the data it needs to collect. It needs to gather parts which have accumulated significant miles. And key life test it requires is durability test in nature, which requires placing a product under certain stress for a long period of time. It is not a simple test where one or few measurements can be taken at a given time. Therefore, the feedback will occur continually throughout the PDP. It is not practical to stop or even slow down the PDP in order to gather all the high mileage and useful life information on the product that is being developed. In most cases, the information comes from previous generation products, and often times, changes are made in certain requirements after the product is launched. For "F" generation wiper motors developed at Ford EFHD, all the initial high mileage and useful life reliability targets and methods were carried over from previous "E" generation wiper motors. Now almost 2 years after the product launch, we are starting to get enough information and data to establish what the "F" generation wiper motors' high mileage and useful life reliability and performance are compared to the targets. The PDP has a feedback loop with a focus on continuos improvement. All the efforts shown in this thesis are aimed toward providing this feedback for "F" generation and future wiper motors.

Chapter 6

Recommendations and Further Studies

Based on analysis of high mileage and useful life parameters shown in Chapter 4 and description of company's requirement and process (PDP) in Chapter 5, many recommendations can be made to make improvements. Also, as mentioned earlier, all the parts of high mileage and useful life steps were not completed in the time frame of this thesis due to the nature of tests and data involved. Therefore, recommendations are mostly further studies that need to be done, and I will describe what information and data will come from each recommendation. Some of them were already discussed in various parts of the thesis, and they will not be discussed in too much details.

6.1 Programmed Load Study

This is a study where wiper motors taken from vehicles with various mileages will be tested on the Programmed Load test stand until failure. This test is important because it correlates the number of cycles on the test stand to mileage for the entire wiper motor. In other words, it does not take each parameter separately, and it takes into account wiper motors' high mileage and useful life as a whole. All the interactions and interfaces among sub-assemblies and components are included, and therefore, it is a good way to get overall system effect of wiper motors.

6.2 More Correlations Through Specific Parameter

Although it is the overall correlation we are concerned with between the number of cycles on the test stand and mileage, it is very helpful to find the correlation based on a specific high mileage and useful life parameter. The analysis in Chapter 4 only showed the study of brush wear, but the same type of study needs to be done for End Play, Axial Play, Radial Play, and Angular Play. This is helpful because as mentioned in that chapter, it will lead to the correlation between the number of cycles on the existing durability test (Programmed Load Test) with miles for each parameter. Then by breaking down and analyzing each parameter separately, we can identify what sub-assembly or component needs to be looked at more deeply based on the relationship between each parameter and sub-assembly or components shown in Chapter 4.

6.3 Real World Usage Profiles

Currently, there is no information on who the 95th percentile customer is for wiper motors and under what condition he or she operates his or her vehicles. Based on the warranty returns from real world, it is safe to say that most of problems occur in places with significant snow. Figure 6-1 show the top 10 warranty return states in the United States.

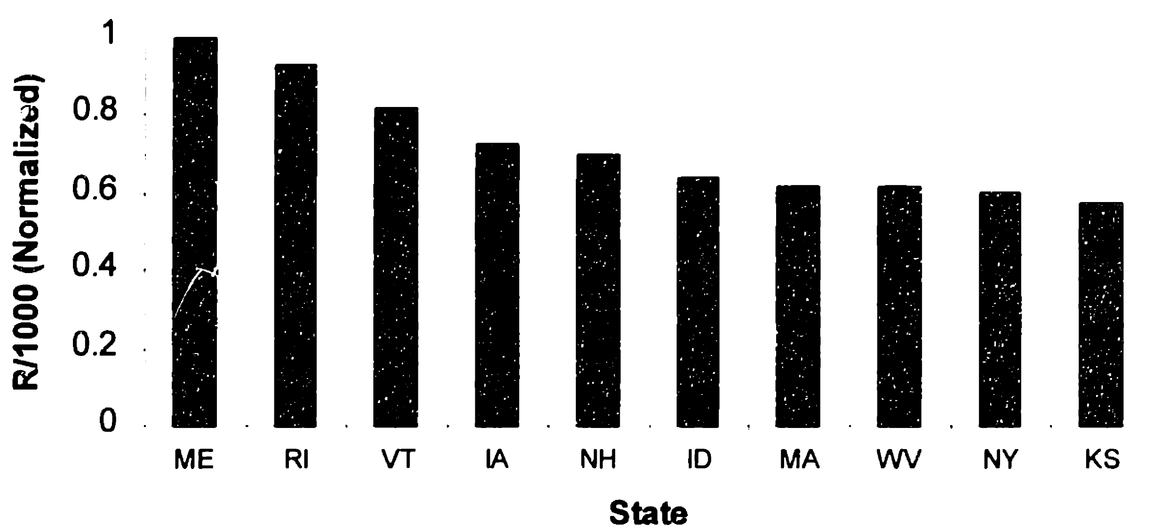

Figure 6-1: Top Ten Warranty Return States

R/1000 stands for repairs made per 1000 vehicles, and it represents the average number of repairs made for every 1000 vehicles. Some repairs might have been from the same vehicle while other vehicles may not have any repairs. All these numbers are for wiper motor warranty only.

One thing to point out is that there is no information on how many times a wiper motor is turned on and off, how long they operate in low speed, high speed, intermittent speed, how many times it is parked, etc. This is important in developing key life test which should accurately simulate the real world environment. High mileage and useful life efforts have not been a major part of our department until recently, and therefore, such information needs to be gathered. One proposal is to install a counter which counts the number of cycles a wiper motor operates in a fleet in New England area. Perhaps this can be done through a dealer or any police, taxi, or carrier fleet Ford Motor Company deals with often. Or, it can be done through recently created Ford's Global Test Fleet, which is an internal test organization that coordinates various fleets around the world. The information will be used to determine who the 95th percentile customer is, what conditions he or she operates a wiper motor, and how much it is used.

6.4 Determining Threshold Value of High Mileage and Useful Life Parameters

As mentioned earlier, there is no information on what the measurement of each parameter needs to be in order to be certain that it meets all the performance requirement. For example, currently, we do not know at what measurement of end play, the wiper motor will fail to perform. Same is true for axial play, radial play, and angular play. Therefore, it is important to determine that threshold value. It can be used to see whether current "F" generation wiper motors do meet the high mileage and useful life reliability requirement set by Ford Motor Company based on the measurement versus mileage data of each parameter shown in Chapter 4. These limits can be found by conducting various performance tests with wiper motors that have different measurement values for each parameter. It could be speed or torque test because those requirements are known. Or it could be noise test that needs to be rated by experienced jury that are familiar with wiper motor sound inside a vehicle. Whichever tests are selected, the important point is to have a good understanding of what the each parameter needs to be to ensure that a wiper motor still meets all the performance requirements. Currently, such information does not exist for wiper motors.

6.5 Accelerated Life Test Development

It is important and necessary to correlate the current existing Programmed Load test to real world usage. But ideally, key life test should be highly accelerated so that test time, which effects development time in Product Validation phase, can be reduced. Control factors of the test stand such as torque, duration at each torque level, temperature, etc. can be varied to see whether test can be accelerated or not. Here, Taguchi's Design of Experiment method will be highly appropriate. The trade-off will be between time of test and how well results match with non-accelerated and more accurate (in terms of simulating real world condition) test. The most optimal set-up for control factors can be determined for new accelerated test.

6.6 Other High Mileage Issues

Besides all the parameters and measurements mentioned above, there are other high mileage and useful life issues for wiper motors. One prime example is in Depressed Park mechanism. This is one of the highest warranty return items, and that means it is costing the Ford Motor Company in terms of money to replace parts and reputation for having unhappy customers. One major problem with this issue is that in our test stand, we cannot seem to repeat the wearout failures that are seen real world. Thus, it is very difficult to analyze the root cause of that issue. In order to avoid such issues in the further, it is very important to develop a key life test that will show the failure that are seen in real world. That way, for the next generation of wiper motors, we can test those motors and determine whether that issue has been resolved or not through testing. This is where experts in depressed park mechanism need to get together and come up with a test that can repeat the failure. This has no clear solution at this point, but it is necessary. There are other such separate high mileage and useful life issues that need to be addressed.

Chapter 7

Summary

High Mileage and Useful Life is an important part of Product Development Process here at Ford Electrical and Fuel Handling Division. It provides reliability targets, metrics or parameters that can be used to measure reliability, and key life test which is a way to test wiper motors for reliability. In high mileage and useful life study shown in this paper, certain parameters are selected to measure wearout characteristics of "F" generations wiper motors developed at EFHD. I have looked at how they change as motors accumulate miles in vehicles, and how they can be used to correlate the number of cycles on the test stand and mileage, which in turn will lead into key life test development. By linking these parameters to functions and sub-assemblies and utilizing module-based design of the "F" generation wiper motors, improvements and changes in the area of high mileage and useful life performance can be made rather easily for the whole platform. This is because we confined the redesign to the platform-wide parameters. Due to important role of high mileage and useful life study in PDP, improvement in high mileage and useful life reliability and performance of wiper motors will lead to better products and will enhance PDP.

Appendix A: EFHD Seven Step High Mileage and Useful Life Process (Page 1)

A. Identify Opportunities For Reliability Improvements
- Estimate current high mileage useful life performance in terms of B_5.
- Estimate current MTTF/MMTF (Mean Time to Failure/Mean Mile to Failure).
- Evaluate data base of past model year quality performance using ESP, CQIS, 5/50, Emissions, Warranty, and Bumper to Bumper Warranty data.
- Determine where improvements are needed (i.e. infant, chance, wearout).
  - Perform teardown analysis, and Pareto failure modes. Sources for parts could be Warranty, High Mileage Fleets, Test Fleets, Bench Tests, etc.
  - Identify failure modes that are mileage/time dependent.
  - Evaluate the effects of rework.
- Identify critical characteristics contributing to wearout.
  - Compare performance to carline/engine family.
  - Understand effects of environmental differences.

B. Determine Real World Usage Profiles
- Conduct QFD analysis.
- Analyze marketing data for 95th percentile customer usage: driving patterns, conditions, environment.
- Identify 95th percentile environmental conditions: climate (mapping of vehicle temperature and vibration), corrosion, packaging, etc.)

C. Establish Reliability Targets
- Based on product history, technology assessment, and BIC benchmarking.
- Consider customer expectations, competition, and cost using SDS and Value Management.
- Allocate reliability targets in terms of MTTF/MMTF from TGR, and warranty requirements.
- Establish useful life objectives in terms of B_5 for the 95th percentile customer.

D. Develop Key Life Tests
- Correlate electrical/mechanical measurements over time to better relate parametric trends versus failure modes.
- If current test standards do not provide data with confidence, develop new accelerated test methods that correlate with field failure data.
- Perform accelerated tests to failure that duplicate field failure modes.
- Develop simulation models where appropriate to make testing more containable/affordable.
- Identify 95th percentile duty cycles accounting for load magnitude and duration/frequency profiles using information from QFD studies, DTS, prior product history, and other pertinent studies.

Appendix A: EFHD Seven Step High Mileage and Useful Life Process (Page 2)

E. Test the Best
- Conduct competitive analysis of design and manufacturing process.
- Evaluate using key life testing and determine if significant durability life difference exist.
    - If better than EFHD component, determine significant design differences.
    - If worse than EFHD component, determine significant system (including environmental) differences.

F. Demonstrate Reliability
- Perform key life test.
- Perform Weibull analysis relative to target failure rate.
- Perform accelerated fleet durability testing.
- Reliability growth: Useful life, MTTF, MMTF
- Number of design iterations, Number of CR's

G. Implement Design/Process Changes
- Assure compliance to SDS, TGR, TGW, R/1000, F/1000.
- Apply Value Management
- Employ Robustness Methods in design and manufacturing.
- Develop Reliability Plan.
- Make prediction based on significant characteristics (Model).
- Consider environmental effects and differences.
- Conduct Quality of Event (QOE) assessment of Reliability Plan.

Appendix B: "F" Generation Wiper Motor Applications

Current and Future Vehicles (Model Year Followed by Vehicle Line)

- 94' T-Bird/Cougar, 95' Econoline/Club Wagon
- 94' Mark VIII
- 94' Taurus/Sable
- 94.75' Contour/Mystique
- 95' Mustang
- 95' Windstar
- 95' Crown Victoria/Grand Marquis/Town Car
- 95' Escort/Tracer
- 95' F-Series/Bronco
- 95' Heavy Truck
- 95.25' Continental
- 96' Taurus/Sable, 98' Continental
- 96.25' Light Truck
- 96' Heavy Truck
- 96' Windstar
- 96.5 Escort/Tracer
- 97' Econoline/Club Wagon
- 97' Windstar
- 97.25' Contour/Mystique
- 97' Explorer
- 98' Explorer
- 98.25' Town Car, 98.5' F-Series
- 98.25' Thunderbird/Cougar
- 99' Mustang

Service Vehicles

- L-Series Heavy Truck
- Probe
- Windstar

Appendix C: High Mileage Wiper Motors

Model Year	Vehicle	Mileage
1993	Mustang	58402
1994	Mustang	130493
1994	Mustang	33537
1995	Windstar	85175
1994	Thunderbird	86933
1991	Mustang	51552
1991	Mustang	93929
1994	Mustang	127623
1991	Mustang	75076
1994	Mustang	152282
1995	Cougar	52895
1995	Grand Marquis	53873
1993	Mustang	88000
1994	Mustang	127184
1995	Windstar	154314
1995	Windstar	170663
1994	Camaro	104248
1995	Continental	53992
1994	Camaro	100312
1994	Mustang	100815
1994	Mustang	105405
1994	Mustang	105497
1994	Mustang	105229
1994	Mustang	106183
1994	Mustang	101651

Appendix D: End Play Data

Mileage	Measurement (mm, Normalized)
0	0.00
0	0.03
0	0.03
0	0.06
0	0.06
0	0.09
0	0.09
0	0.12
0	0.12
0	0.12
0	0.15
0	0.15
0	0.21
0	0.26
51552	0.50
75076	0.32
86933	0.50
93929	0.44
100815	0.82
101651	0.59
105229	0.79
105405	0.47
105497	0.68
106183	1.00
127184	0.53
127623	0.53
152282	0.74
154314	0.53
170663	0.53

Appendix E: Axial Play Data

Mileage	Measurement (mm, Normalized)
0	0.017
0	0.042
0	0.042
0	0.042
0	0.042
0	0.125
0	0.150
0	0.225
0	0.258
0	0.275
0	0.342
0	0.367
0	0.375
0	0.375
51552	0.500
75076	0.583
86933	0.500
93929	0.375
100815	0.875
101651	0.875
105229	0.833
105405	0.292
105497	0.917
106183	0.750
127184	0.833
127623	0.250
152282	1.000
154314	0.917
170663	0.750

Appendix F: Radial Play Data

Mileage	Measurement (mm, Normalized)
0	0.13
0	0.25
0	0.25
0	0.25
0	0.25
0	0.38
0	0.38
0	0.50
0	0.50
0	0.50
0	0.50
0	0.50
0	0.50
0	0.50
51552	1.00
75076	1.00
86933	0.75
93929	0.75
100815	0.38
101651	0.25
105229	0.38
105405	0.25
105497	0.25
106183	0.38
127184	0.75
127623	0.63
152282	0.63
154314	0.50
170663	0.50

Appendix G: Angular Play Data

Mileage	Measurement (Degree, Normalized)
0	0.39
0	0.47
0	0.51
0	0.52
0	0.58
0	0.62
51552	0.73
75076	0.81
86933	0.80
93929	0.77
100815	1.00
101651	0.73
105229	0.96
105405	0.80
105497	0.63
106183	0.92
127184	0.81
127623	0.67
152282	0.93
154314	0.48
170663	0.52

Appendix H: Brush Length Data

Miles	High Speed Brush Length (mm, Normalized)	Miles	High Speed Brush Length (mm, Normalized)
0	0.96	22200	0.95
2647	0.98	22378	0.99
2900	0.99	23785	0.98
3500	0.99	25785	0.96
3900	0.99	26670	0.97
3915	0.98	27986	0.97
4011	0.98	28001	0.99
5132	1.00	28214	0.97
5277	1.00	30734	0.95
7500	0.96	31573	0.98
7678	1.00	31994	0.94
7805	1.00	33039	0.95
9500	0.97	33537	0.98
9755	0.97	34510	0.98
10204	0.98	34700	0.95
10523	0.96	35870	0.97
11680	0.99	36807	0.93
11798	0.97	38630	0.96
11898	0.99	41113	0.99
12127	0.99	47855	0.95
12131	0.97	50138	0.97
12387	0.96	50224	0.97
13458	1.00	50854	0.97
15609	0.98	52500	0.95
15615	0.97	52895	0.95
15693	0.99	55000	0.96
16325	0.98	58402	0.97
16582	0.97	69225	0.98
17101	0.98	79659	0.96
17480	1.00	85175	0.95
17698	1.00	86933	0.98
18843	0.97	86995	0.92
19462	0.97	88209	0.94
19866	0.97	104838	0.96
20240	0.98	129354	0.95
20848	0.98	130493	0.94
21400	0.99	150130	0.93
21805	0.98	170663	0.93
22053	0.93	170782	0.96
22100	0.97		

Appendix I: Brush Length Data from Programmed Load Test Stand

Number of Cycles	High Speed Brush Length (mm, Normalized)
400695	1.00
434000	0.97
445756	0.95
456684	0.99
474383	0.98
628262	0.98
634495	0.94
724981	0.95
740816	0.94
741108	0.98
747624	0.94
760833	0.94
781145	0.94
1540000	0.86
1560000	0.86
1570000	0.88
1610000	0.83

Appendix J: Relationship Between Parameters and Mileage (Regression Fit)

C	C_1	C_2	C_3	C_4
-12728	322018	2663700	8728498	4399

Motor Number	End Play	Axial Play	Radial Play	Angular Play	Mileage	Calculated Mileage	Difference	Percent
1	0	0.002	0.001	0.62	0	4055.278	4055.278	
2	0.01	0.0005	0.001	0.68	0	3543.848	3543.848	
3	0.02	0.0005	0.001	0.52	0	6060.188	6060.188	
4	0.02	0.0005	0.0015	0.77	0	11524.187	11524.187	
5	0.03	0.0015	0.0005	0.82	0	8899.519	8899.519	
6	0.04	0.0005	0.001	0.67	0	13160.398	13160.398	
7	0.17	0.006	0.004	0.97	51552	97178.282	45626.282	89%
8	0.11	0.007	0.004	1.07	75076	80960.802	5884.802	8%
9	0.15	0.0045	0.003	1.02	93929	78233.824	15695.176	17%
10	0.28	0.0105	0.0015	1.32	100815	124305.317	23490.317	23%
11	0.2	0.0105	0.001	0.97	101651	92639.978	9011.022	9%
12	0.27	0.01	0.0015	1.27	105229	119533.337	14304.337	14%
13	0.16	0.0035	0.001	1.05	105405	61465.278	43939.722	42%
14	0.23	0.011	0.001	0.83	105497	103016.508	2480.492	2%
15	0.34	0.009	0.0015	1.22	106183	139190.947	33007.947	31%
16	0.18	0.01	0.003	1.07	127184	102764.664	24419.336	19%
17	0.18	0.003	0.0025	0.88	127623	78918.705	48704.295	38%
18	0.25	0.012	0.0025	1.23	152282	126972.915	25309.085	17%
							Sum	**Average**
							339116.23	26%
							Std. Dev.	**Std. Dev.**
							14715.315	22%

Appendix K: Relationship Between Parameters and Mileage (Optimization Model)

C	C_1	C_2	C_3	C_4
-17298	86478	7991619	0	18290

Motor Number	End Play	Axial Play	Radial Play	Angular Play	Mileage	Calculated Mileage	Difference	Percent
1	0	0.002	0.001	0.62	0	10025.038	10025.038	
2	0.01	0.0005	0.001	0.68	0	-0.2105	0.2105	
3	0.02	0.0005	0.001	0.52	0	-2061.8305	2061.8305	
4	0.02	0.0005	0.0015	0.77	0	2510.6695	2510.6695	
5	0.03	0.0015	0.0005	0.82	0	12281.5685	12281.5685	
6	0.04	0.0005	0.001	0.67	0	2411.2295	2411.2295	
7	0.17	0.006	0.004	0.97	51552	63094.274	11542.274	22%
8	0.11	0.007	0.004	1.07	75076	67726.213	7349.787	10%
9	0.15	0.0045	0.003	1.02	93929	50291.7855	43637.2145	46%
10	0.28	0.0105	0.0015	1.32	100815	114970.64	14155.6395	14%
11	0.2	0.0105	0.001	0.97	101651	101650.9	0.1005	0%
12	0.27	0.01	0.0015	1.27	105229	109195.55	3966.55	4%
13	0.16	0.0035	0.001	1.05	105405	43713.6465	61691.3535	59%
14	0.23	0.011	0.001	0.83	105497	105680.449	183.449	0%
15	0.34	0.009	0.0015	1.22	106183	106342.891	159.891	0%
16	0.18	0.01	0.003	1.07	127184	97754.53	29429.47	23%
17	0.18	0.003	0.0025	0.88	127623	38338.097	89284.903	70%
18	0.25	0.012	0.0025	1.23	152282	122717.628	29564.372	19%
							Sum	**Average**
							320255.551	22%
							Std. Dev.	**Std. Dev.**
							24031.364	23%