ABSTRACT

Title of Document: AUTOMOTIVE DESIGN-TO LIFE-CYCLE CRITERIA FOR LOWERING WARRANTY COSTS AND IMPROVING OWNERSHIP EXPERIENCE THROUGH THE USE OF A NEW "BINARY DECISION MODEL" AND APPLICATION OF A "WARRANTY INDEX"

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Financial challenges facing the automotive sector require identification of new opportunities for quality improvement. A new *Design-To Life-Cycle-Cost* strategy is introduced that applies a unique "***Binary Decision Logic Model"*** that classifies corrective action opportunity into Life-Cycle categories. The intended result is to lower a manufacture's warranty costs and improve ownership experience. This is done by setting Design-To goals in a Life-Cycle way for Reliability and Serviceability.

The sample space for data to drive this change of process is found in an existing warranty system with data elements consisting of failure occurrence, failure symptom, mileage, part cost, and labor cost. One can investigate new factors, such as the "***Warranty Index,"*** that parses the corrective action in favor of lowering part costs or labor costs found in a typical service event. The data considers opportunities over mileage and time domains to improve vehicle quality over the Life-Cycle.

AUTOMOTIVE DESIGN-TO LIFE-CYCLE CRITERIA FOR LOWERING WARRANTY COSTS AND IMPROVING OWNERSHIP EXPERIENCE THROUGH THE USE OF A NEW "BINARY DECISION MODEL" AND APPLICATION OF A "WARRANTY INDEX"

by

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Preface

Many business models are not as effective in today's marketplace. There exist a need for a more effective quality improvement implementation strategy from the design cues that come from a wide range of product usage and warranty data. In the automotive sector, a new approach to evaluate "Design for Maintainability" or "Design for Service" or more broadly "Design-To Life-Cycle Cost" is needed to improve product quality over traditional design objectives. There is a larger need to understand vehicle usage and maintenance after the sale in contrast to a focus upon design functionality and efficient assembly. Design for Assembly or just DFA, is a methodology that does not sufficiently address the service needs or the full spectrum of a customer's needs over the product's Life-Cycle.

The object of the this study is to build upon a logic definition used in the aircraft industry known as Reliability Centered Maintenance and apply a new set of binary decision rules with a unique use of a Warranty Index to help guide the Design to a more effective Life-Cycle alternative. This should improve quality by reducing warranty costs and improve the ownership experience of the customer.

Foreword

A better design strategy is one that considers the full Life-Cycle of a product. Often the techniques to develop product requirements fall short of this intended purpose. The methods in product development are largely incongruent with the more important goal found in a Life-Cycle approach. Proposed in this study is a binary decision algorithm that is hierarchical and able to be integrated into a product development cycle. When to apply these techniques to maximize the benefits in the design process has not been apparent and can and should impact the very architecture of given design theme.

This presentation is intended to be read with a point of view that will focus upon the nature of automotive design processes embracing the serviceability aspects of systems created so that more control over warranty costs and the customer's ownership experience can be employed. The outcome can then be realized in a way that will lead to improved customer satisfaction.

The unique approach offered is intended to differentiate on part and labor costs that have not been addressed satisfactorily as a design criterion. Those development programs that are looking more narrowly at costs per unit or repairs per thousand vehicles have not been able to identify these additional quality improvement opportunities. In order to improve upon this work it is hopeful that suggestions will be made and brought to the attention of the author.

Dedication

This thesis is dedicated to the hard working team at Ford Motor Company, family and friends that have sacrificed to help provide the continuation of my dream to pursue this advanced degree. It has taken a long time to accomplish and even survive the various ups and downs at Ford and at home. At times it just did not seem possible. A special thank you is in order:

First, a special thanks to Debby, a spouse whom freely asks the hard questions that helps to drive a better understanding of the technical ideas in a business-wise way.

Second, a thank you for those that helped support a distance learner whose efforts were required to see me through – the help was so appreciated!

It has been my pleasure to participate in the program. Please count on me to express the benefits of continuous education with the University of Maryland that does make a difference in so many ways where the least of those ways are experienced in the improved quality products and services we enjoy that so many graduates have a part. Assurance technologies bring into our lives better products services and in a small but exiting role I have had the privilege to participate.

Acknowledgements

The writing of this document was with the help of the Brighton Public Library where their facility was made available with its various resources. Access to the internet, reference materials, and facilities made it an excellent environment for study while offering an isolated space needed to ponder the subject and develop a relevant body of work. Being a distance learner did not afford me the usual scholastic environment of a university nor provide access to those facilities. However, this gap was bridged effectively by use of the local library.

It is hoped that this work will meet a need in design, one that differentiates on Life-Cycle design strategies in a practical way. Within existing data structures there is a means to re-visit the data and emerge with new and actionable information offering Life-Cycle design alternatives. These opportunities include advances in vehicle longevity and ownership experience with a window towards a wider impact in new vehicle architectures.

It is further hoped that these unique concepts presented will be built upon in the next generation factory to fully integrate the concept of design for the Life-Cycle and a means to utilize concepts of maintainability with personality. A natural outgrowth of the Life-Cycle design development may find an expression in an “i-car.” This truly will yield a means to balance reduction in plant complexity in favor of rational personalization offered by the local dealer.

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Chapter One:

Introduction

One goal of most business models is to provide a quality product or service at an affordable price that meets the need of the consumer bringing satisfaction over the expected use of that product or service and in return receive a fair profit to continue such provision of services or products in the market place. However straight forward this may seem, the objective is not easily accomplished in today's fierce competitive and difficult economic climate. There is therefore a need to consider more intently what improvements can be offered the customer to assure his satisfaction and to manage and minimize quality costs effectively.

Design cues that come from a wide range of product usage and warranty data may hold a key to continuous improvement over a wider range of customer expectation not realized, specifically in the automotive sector. In particular, one significant item is the high cost of commercial warranty and low customer satisfaction facing businesses, as addressed by Roush and Webb (2001), including high value properties (p. 529). This is certainly true in the automobile industry. One observation includes the high warranty costs that still could amount to over $27.5 billion spent per year world wide, according to the Newsletter Subscription Service, Warranty Week, (2006) and costs per car per year over $500 dollars. It should be clear that these costs can be associated directly to the high cost of repair as a factor of labor and part costs.

The high service costs affects each the manufacturer and customer. From a customer and Life-Cycle cost of ownership view, the effects of product failure directly impacts customer satisfaction with the possible loss of vehicle use and the high cost of repair out side of warranty and to the manufacturer, the in-warranty costs as noted. Opportunity therefore exists in current business and design processes to minimize these warranty and ownership costs.

This needed improvement should be a natural evolution in design processes building on the value of being “best-in-class” that has focused strictly on a “find-and-fix” approach to product failure and reducing “things-gone-wrong.” A Design-To Life-Cycle cost approach may offer a more proactive design improvement methodology.

Statement of the Problem

Design teams are facing the law of diminishing returns with current improvement programs. Quality has been improved and warranty has been reduced but more opportunity is not being identified effectively, in part do to certain business practices that do not address the two driving factors, part cost and labor cost. The motivation should be clear that new ways to address improvement are needed in a design approach that is recommended by this study where the concept of Design-To Life-Cycle cost is being explored. Related approaches have been successful that have in part been adopted by military programs and the commercial airline industry.

Definition of Terms

The key terms identified herein represent those concepts and engineering practices needed to successfully understand and develop the Design-To Life-Cycle Cost (DTLCC) quality improvement methodology. A practical application is provided utilizing fundamental practices of Design Assurance and using a Binary Decision Logical

Model (BDLM) similar to Reliability Centered Maintenance, (RCM). Of concern within product development teams are the needed requisite skills for practicing Design Assurance including Maintainability engineering. Secondarily, an organization will have to possess the aptitude to address organizational inertia to bring new players to the design responsibility.

Design Assurance – Includes the engineering disciplines of Reliability and Maintainability. These technical fields require certain skill sets to be effectively deployed in a product cycle for a durable good, such as an automobile.

Life-Cycle Cost - an acquisition strategy that considers concept, development, production, service, and disposal costs of a product. These concepts have been used since the early 70's in Military programs partially due to the high cost of service and poor reliability of fielded equipment.

PAF – A practice to manage quality costs or the cost of quality (COQ) The primary attention of a COQ method is the PAF model which is defined by the three terms:

(P) Prevention: Actions taken to ensure that a "process" provides quality products and services.
(A) Appraisal: Actions measuring the level of quality in the given process.
(F) Failure: Actions to correct quality issues internal - prior to the customer and after the sale or external feedback.

Reliability – A characteristic of design. The probability that a product will perform its intended functions and under specific operating conditions. Expressed another way, reliability is the percent of vehicles, which meet customer requirements (without failure) at a specified time/mileage objective. As a statistical measure or a probability of survival. As an engineering discipline, Reliability includes those engineering activities that assure designs adequately address product duty cycle, the stress and strength of materials, and follow and recommend design practices that avoid, reduce and eliminate failure modes.

Maintainability – A characteristic of design and installation which is expressed as the probability that an item will conform to specified conditions within a given period of time, when maintenance action is performed in accordance with prescribed procedures and resources. Also, the measure of the ability of an item to be retained in or restored to specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair. As an engineering discipline it is those engineering activities that assure designs adequately consider human factors, the level of repair, the activities to minimize the time to repair through proper maintenance practices and logistic concerns and strategies.

Design of Assembly – a practice to build features and characteristics into a design to enhance the build and assembly of products in an effective manner that minimizes costs of assemble and considers human factors in process to minimize variation.

Reliability Centered Maintenance, RCM - developed as a flight line to depot level response strategy for assuring a repair time can be scheduled with little interference to an operational mission. A logical decision approach that identifies a proper maintenance strategy using product reliability and safety features that assure critical mission factors with a goal to optimize the maintenance effectiveness and assure mission success throughout a logistic and service concept of a fleet maintenance program.

Part Costs - Costs that include parts in the repair.

Labor Costs - Costs that include labor in repair – Divide by rate to get time.

Assumptions

The study methodology to be developed assumes there is a data structure in an automotive manufacturing environment that possesses certain records (and fields) typical of such warranty systems. This data must have both part and labor costs identified in a repair event and some level of codification as to the function and causal component part. By causal, it is understood that it is knowledge of failure and service activities that one can investigate that is or can be defined down to the root cause of failure if necessary. Further, that there is a service organization that supports the warranty system and certain design skills for design assurance are present. This may not be the case when the design area of maintainability is discussed for which there is a gap in the automotive sector in product development.

Significance of the Study

The introduction and development a new methodology that identifies specific weaknesses in design, previously hidden from most product teams, is a welcome idea given that there is an extremely high cost in warranty still being reported and born by the automotive manufacturer during an economically challenging time. The study purpose is to show how an application of a sound BDLM and the use of a "Warranty Index" can improve the design in a Life-Cycle manner.

Study Proposal

In this study, the development of a new Design-To Life-Cycle methodology and the benefits of its application will be shown to establish a unique discriminating criterion or Warranty Index that can be used to identify Life-Cycle-cost related weaknesses in design and related business practices. The result will be to lower repair costs and/or improve vehicle reliability by addressing vehicle design issues including vehicle architecture. In so doing, there will be a positive impact on residual value, customer loyalty and create an attraction for new customers.

The process to identify Life-Cycle design requirements is to consider not just corrective related measures towards unreliability but to include goals of serviceability and address related cost drivers that can be interpreted in terms of change opportunities required to improve the design to a more robust Life-Cycle design. This should have benefit to the Original Equipment Manufacturers (OEM) and customers. The new practice would improve a customer's broader perception of vehicle quality while lowering warranty liability. Implementation of a new Design-To targeting method can be most successful if it can be used early in a cycle plan where change opportunity can be effectively implemented. By reducing costs of ownership for the customer and yielding higher margins through reduced warranty costs to the company a long term benefit is secured.

The ability to select components that have a high impact, ones that threaten customer satisfaction in service, will position or leverage a design team to take advantage of the ability to differentiate and prioritize the magnitude of cost savings on a Life-Cycle basis and in an informed manner.

Limitations of the study

This study is limited in its application as it only observed trends in several car lines within a warranty system from a domestic automaker. Further analysis could be applied to functional component groupings where a "measures of importance" as discussed by Modarres et al. (1999) in combination with a "level of effort" similar to that applied by Roush and Webb (2001) to help allocate or prioritize the opportunity. A cost related allocation that optimizes on the desired change opportunity. Although the BDLM methodology shown is applied to automobiles, there is a broader application to any fielded product that may have a warranty such as any durable goods product.

Organization of the Study

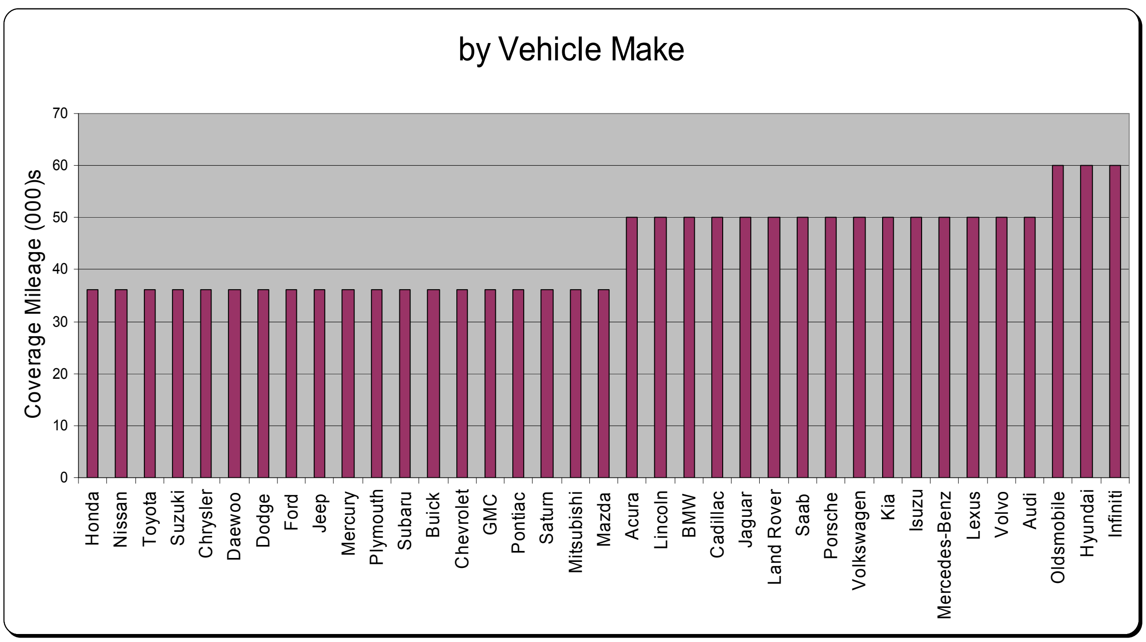
- Chapter One will provide the introduction, statement of the problem, offer the definition of key terms, provide study assumptions, significance, limitations and organization.

- Chapter Two will present and discuss the relevant literature related to the Design-To Life-Cycle Cost methods and quality improvement strategies by using a Warranty Data System. The concept of a binary logic decision model is explored and how it might be modified for use as a Design-To Life-Cycle strategy for automotive use to improve quality.
- Chapter Three will detail the methodology of the study and its purpose with a discussion on the part pricing issues as it relates to the study
- Chapter Four will present an application of the methodology, the findings of the study, including statistical analysis of the data obtained.
- Chapter Five will comprise a summary of the implications of the study and a discussion of the recommendations for future research.

Chapter Two

Current quality measurements between the major manufacturers have tightened in the race for quality. There are new performers that are offering 100,000 mile warranties where three years (or 36,000 miles) used to be a standard,

Figure 1. Basic Warranty Comparison - Miles (thousands).



* data compiled from: url: http://www.carsmart.com.

The ownership experience that is influenced by what can be called the touch points - involves the service experience including the frequency and costs. Further, the extension of a warranty or life limit has been explored by Ireland (1984) where he points out that there is a need to have a statistical approach (p. 72).

In addition, it is the author's point of view that there has been a trend developed in divesting technical competency and if it is continued there will likely be an inability to respond to the challenge in the Life-Cycle quality improvement arena. Recent actions of OEMs to disassemble the technical competency in product teams in favor of program management based activities to manage programs has been considered by some to be a practice that constrains the design community in a way that threatens a proper integration of components and systems. There is a lack of interest in engineering competency in the US as reported by Downey and Luccena, (2007) (p. 4).

The importance of this competency can be viewed from a dealer experience and how this touch point to the customer may enhance or hurt loyalty and satisfaction. Then it must be reconciled if an OEM is going to differentiate itself on something of substance. The OEM will have to do it through the combined efforts of design for service and likely through the dealer network. Therefore, a service focused Life-Cycle design strategy is a new gateway to customer satisfaction and customer purchasing decisions as O'Connor (2002) points out the need for design rules for maintainability (p.285). The buying experience through resale and repurchase – are all elements to be treated by design and are required to wage the war to gain a customer's trust.

Financial challenges facing the domestic automotive sector (now more than ever) reveal an economic crisis. It is also a design crisis requiring the identification of new opportunities for quality improvement and lower cost of ownership for the customer. How OEMs do business structurally must be evaluated. Interestingly, by using the typical data found in an existing warranty system that routinely records failure occurrence, failure symptom, mileage, part cost, and labor cost one can investigate such factors over mileage and time to observe trends with the purpose of learning from that data against the backdrop of business operations. This data has not been unused with respect to find-and-fix approaches to quality problems. However, additional "critical to quality" service related weaknesses have not been properly identified or effectively improved upon. One can make this observation simply by organizational deployment having engineering and service parts organizations separate.

Related Research

Life-Cycle Design

The study subject matter is most closely related to this paper presentation on the subject of Life-Cycle design methodologies that have been identified and discussed and for which there is a computer model approach used in beta at General Motors as reported by Byran et al., (1992).

The entire research and application of the Life-Cycle design methodology considered attributes of design respecting the typical functional requirements but also producability, assembly, testability, serviceability, transportability and disposability.

A significant weakness was apparent in this model as to its reliance on the design aid methodology that assists producability - Design for Assembly (DFA). It seems incompatible if one applies a DFA methodology that involves sequential building of a complex system in contrast to the required access needed to isolate, remove, repair or replace a component at the site of failure. DFA respects sequence in production as a convenience. Using DFA as a means to provide cost savings as if it was a significant contributor to a successful approach for Design for Serviceability or Life-Cycle just would not work well. This weakness is only touched on lightly by the authors. Most importantly there were findings that there is a lack of a systematic means to apply serviceability or maintainability guidelines. This study's methodology takes this into account and solves this exact weakness in the product design effort.

Cost of Quality

A meta-study conducted by Schiffauerova and Thomas (2006) considered the literature about measuring systems to help improve quality by a costing approach identified as CoQ or Cost-of-Quality. In the research there was evidence presented to show that companies that provide a formal approach to CoQ are successful in reducing quality costs and improving quality to the customer. Of particular interest has been the most common model used - the prevention-appraisal-failure model or PAF.

Understanding PAF in terms of the study approach considers the Life-Cycle and might be interpreted as follows:

(P) Prevention:

Actions taken to ensure that a "process" provides quality products and services.

a) <u>From the customer's point of view</u> he is purchasing, with a vehicle, a product and service that extends after the warranty period if one continues holding a vehicle beyond the warranty period. Here the owner holds for residual value and some time with no *payments! The study Life-Cycle approach supports understanding the service experience extending the notion of prevention into the full Life-Cycle-ownership experience.*

b) <u>From the company's point of view</u> both elements as a business process and as a customer focus goal the trend has been to look at the ownership experience and service side of ownership as a profit from the sale, financing, and resale of parts if a vehicle owner is surviving the warranty period.

This has not fostered satisfaction or loyalty. In contrast, a system of design rules for Design for Life-Cycle cost would naturally bring a customer focus to extend beyond the showroom and purchase event and into the dealer and personal service arena where a customer-manufacturer-service quality event occurs instead of a dreaded customer service event.

(A) Appraisal:

Actions measuring the level of quality in the given process

a) <u>From the customer point of view</u>, there is the voting with his wallet – where he makes his initial purchase of a product or service resulting from a given business process. Then there is the feedback after the sale as to customer satisfaction from its use, its repair if repairable and finally its disposal and re-purchase cycle. This can be communicated by a web blog or through warranty event comments and ultimately by his next purchase but seldom beyond warranty. Again, the study Life-Cycle approach supports improving quality and ownership experience in service.

b) From the company point of view, management of warranty data, internal measuring, external measuring, and paid for services that assess quality and customer sentiment or marketing buzz to associate product or service to market share achieved. How that data is used is not clear in the PAF model – as to its effective use.

(F) Failure:

Actions to correct quality issues internal - prior to the customer and after the sale or external feedback

a) From the customer point of view, he hopes that manufacturing defects are minimized so he does not buy a car made on Monday or Friday or a new model out in its first year. As to external there is a warranty system when new and residual upon sale. His service experience will determine over a longer exposure than an advertisement campaign his buying decisions. If unsuccessful, a lemon law can recoup his purchase price. If no service can be economical, then it makes the next buying decision less favorable and should be no surprise. So PAF supports having an excellent service network – less interested in profit but understood that there must be some – just and reasonable business case supported. The study Life-Cycle approach supports and is uniquely able to focus on service, a missing element only referred to for future study in the research for the soft targets. This makes this study all the more meaningful looking back at PAF systems.

b) From the company's point of view – it is more interested in how it is competing against others to the oversight of the customer. Service has been generally ignored. Resale values have been, according to the domestic automakers, compromised by lease fleets sales mix diluting the value and resale.

Intangibles on failure costs are often hard to resolve according to the research. However, it is fully resolved in successive buying decisions. This study does not relate loss of market share and demand modeling but the shift or loss of share has a dollar value that can be calculated and projected over the Life-Cycle behaviors and aftermarket service experiences where there is likely a critical mass that is hard to over come and regain customer confidence if lost.

Further it was noted in the report that the PAF model was "supported by Modarres and Ansari (1987)" where they expand the dimensions of the PAF model to include cost of inefficient resource utilization and quality design cost. This observation is a good fit for alignment to the process using the study Life-Cycle approach presented in this study where quality is broad in scope over the Life-Cycle.

In this, the concepts of maintainability are either creating a good impression or a bad one to a customer inside and outside of warranty. The modularity or serviceability (a design attribute to facilitate ease of service) in vehicle design today does not take advantage of the power of this design philosophy when compared to the life-limit-sustainability mind set that has established today's themes of vehicle architecture. Life-Cycle design strategy has the power to open up architecture not found in most cycle plans. It would be a new field of work if automakers would be willing to address this area of design.

Consider vehicle durability; aging and purchase decisions that have been studied by Lanoy (2005). Basically, the service cost that equals the leasing cost is near the point of decision. Service costs are fully developed by industry research companies to the extent that the government applies this research when developing and fixing reimbursement rates of automobile usage considering the costs of ownership in various markets.

Related to the cost of ownership and cost of quality are the extended warranties that may sweeten the pot towards extended ownership but it is also viewed as a profit model for OEMs and hence may detract from the fostering of future sales due to Life-Cycle issues experienced by the customer.

Design-To Life-Cycle and Congruence to Quality Measures

In the development and application of the Binary Decision Logic Model and Warranty Index approach created in this study it will be shown that by common warranty tools a design may be leveraged against specific component knowledge to achieve the desired quality improvement.

These issues have been hidden in the automotive industry due to a profit focus from service and segregation of business practices that effect labor and material or part costs. Understanding the stubbornness of parts and labor costs can help in developing strategies to overcoming these items. Flexibility needed to change these cost drivers is seldom achieved due to how entrenched systems are that burden them. Flexibility to apply and develop criteria to effectively identify and control these cost drivers can be accomplished by the use of the Life-Cycle approach. However significant the opportunity to truly adopt this approach it is evident that a dramatic wake up call is in the market place demanding companies find new objective methodologies that can "find and fix" to new levels the various structural issues and failure modes in a design. There is but little chance to survive without engaging changing of practices that have hindered higher quality achievement. The confidence to proceed is coming from economic conditions that pressures loss of market share or even OEM viability.

Finally, there are then two keys to know to define new design goals for service and Life-Cycle cost favorable to both warranty cost reduction and a lowering of the cost of ownership. The first key is that of the price of parts in service. Often, price is dismissed as a warranty cost factor that cannot be adjusted downward. It has been considered unmovable as a contractual value with supply that is governed by various state and federal laws to some extent as reported by Zenz, (1981). The pricing structure must be confronted as there is room to change to improve quality and profitability. Price driven warranty cost in warranty parts distribution is not to be viewed from archaic monopolistic offering given by the dominant controlling interests in the manufacture as reported by Hamilton and Macauley (2008). This pushing of the monopolistic price to service parts is what it termed "succumbing to the Coase temptation (p.4)." Under these circumstances such a market share pricing model can rarely develop customer satisfaction. A gain in sales should offset any losses from trying to extract high aftermarket sales.

The second key is realizing that a maintainability design solution for better serviceability has largely been overlooked as a design strategy in the ownership of a new vehicle design. Here the principals of maintainability can be exploited to reduce labor costs in service.

Chapter Three

Robustness and Reliability of Study Data

To bring advancement in the design process there must be a win-win outcome to maintain business practice viability while attempting to cross company lines while lowering costs of ownership. At the same time an increase a vehicle's value within the ownership experience is expected through this process of the study. This is where satisfaction and loyalty are fostered in an increasingly difficult and fiercely competitive market.

With the goal in sight and an environment of data overload from every type of information available today it is important to use caution on reliance or belief in the new data emporium that the web offers. More importantly, when considering the factors that support a sustained change from a data systems usage one should meet certain system robustness criteria as a requirement.. These criteria have been evaluated by Henley and Hiromitsu (1981) discussing stability and integrity over time for a change process to work. If the new process demonstrates robustness for the elements in the data structures and the data itself validated as in an existing tested database then re-mining of that data for formerly hidden value could offer a lasting solution.

A company's warranty system has just those properties of integrity and has been stable in terms of assessing frequency and quality of event (inside a warranty period). The information includes cost, event description, date and various items traceable to the service event and its resolution. As much as a root-cause determination is lacking in such symptom based systems the ability to trigger deeper investigations to get at cause exists.

This is required to achieve what is herein called "actionality." It is the subject of most problem solving methodologies where one must address a primitive mechanism or root cause to assure failure recurrence is prevented and that a problem is understood beyond the symptom level. This is presented by DRM Technologies in their R & M Primer (not dated) assuring the use of a failure review and corrective action system or FRACAS.

Business Processes Affected by the Study

It is not always clear how business practices may hinder improvement strategy. However, there is a divide between the cost factors that can be controlled and the engineering needed to fix a problem. Inspection of cost factors is hardly novel in a warranty system as it is first a financial reimbursement system for the dealer network and secondarily a tool to understand reported repair events for the company within the time or usage domains assisting the find-and-fix process.

With this in mind, engineering's "find and fix" approach to the data does not have impact on the direct cost elements only on the reliability or occurrence rate of a failure factor. This improvement methodology had worked and is behind the reliability growth models expressed by Crow (1974). Frequency and time rates of occurrence are able to be studied to understand if such specific component failure rates within a population of vehicles is increasing or decreasing over time allowing a means to statistically estimate future or total cost of warranty. In this application, one must consider if there are failure-modes that increase over time (See the Appendix "Reliability Bath Tub Curve, Targets and Tasks)." There are some such as Sonza and Carvalho , (2005) who have evaluated fault tolerant and fault avoidance activities to improve reliability and service. This assessment can be enhanced by various design approaches and the use of probability analysis of the failure data. One can prioritize by the total cost of improvement to repair costs against the volume in the market.

In this view, the Cost-per-Unit or CPU (a typical quality measure of performance) that indexes the warranty expenditure of a specific problem across the number of vehicles produced to get a liability per vehicle over a period of say 3 or 12 months. The CPU, if used as a design target, is difficult to manage for engineering groups. What is not addressed in these assessments are the part and labor costs as segregated factors since engineering in general has considered those factors unchangeable cost factors and reliability as the item to change in a design.

The notion that price items cannot change is from the belief that the price is established by a financial business practice where a component being serviced is the result of a contractual agreement determined by a commercial business unit negotiation. Yet even the labor rate can be affected by the application of maintainability if less complexity or skill level would be required. The next question is what can be controlled in engineering effecting cost? The ownership of the time to repair has not been identified as an engineering effort but relegated to service organizations to address almost as an after thought devising how something is repaired or replaced. Engineering all but ignores the time-to-repair as a design parameter.

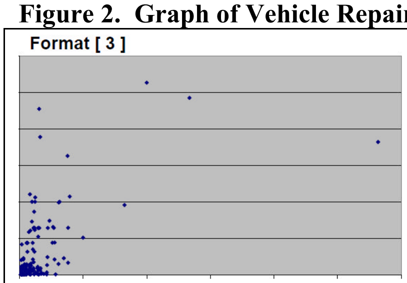
The segregated responsibility is a fox guarding the chicken coop where service is interested in making money from that service event and work package. At most, goals are reactive only when not deemed competitive to other vehicles. This is a very rough granularity to lack actionality unlike other quality measures and performance targets.

When comparing military contracting to automotive programs for maintainability requirements, military programs are highly defined. However, this focus also concerns itself with service needs being driven by poor reliability Gryna et al., (1960) with alignment to the formation of the AGREE report, 1957 (p. 25) yet lessons blend the needs of Reliability and Maintainability.

Within a company it is not unusual to find an organizational chimney exacerbating the situation that could identify and treat service issues aggressively by being responsible to competitive analysis in terms of serviceability but only if it is in the design requirements definition phase of a program. Instead of having this presence in a program serviceability has been addressed only through a series of checklists for reporting against the competitive benchmarks - it has never been a requirement of design with any teeth. One personal example is the 2.5 hours to replace a headlight on a Mustang which is a high impact component subject to replacement frequencies due to accidents and life limit characteristics.

Although this additional insight has been available in the data it has rarely been considered methodically and proactively. If addressed in more detail, these elements of warranty and ownership costs reveal relevant actionable opportunity. Here is the new leverage point that is the foundation for this study to offer a new “find and fix” to a Life-Cycle design approach.

Figure 2. Graph of Vehicle Repair Cost Labor vs. Part.



Y-axis: Part Costs
X-axis: Labor Costs

Finding: Data clustering in part and labor near the origin, meaning well behaved repair in general. However, Significant higher Part variable needs to be understood.

Investigating the part and labor elements of a repair event (i), one finds that these costs are mapped into a function and to related hardware that needed to be repaired or replaced (Part Cost (i) to Labor Cost (i) for a given repair) . The Warranty Index, as a ratio of these two values is used to relate characteristics of the design requirements in relation to serviceability. In an absolute sense, each term is a measure of its complexity. A high Part Cost (i) should be designed to be easy to service if there is a concern of frequent repair or make it so reliable and durable that it does not need service.

If the ratio of Labor Cost (i) is much greater than Part Cost (i) then the resultant ratio is a number that can be as large as 10 or even 20, reference Figure 2. "Graph of Vehicle Repair Cost Labor vs. Part," A full scale assessment of a design is needed to develop and classify formerly unrealized improvement opportunities from specific threats discovered in the warranty data base. The cost and frequency of repair from failure or high incident accidents are inherit in the design and have resulted in unnecessary warranty and costs of ownership largely unresolved. The chart above shows the relationship of labor costs estimated from the knowledge of the material costs in an average repair. Knowing the labor and dividing by the labor rate would yield an understanding of the time involved or allowed for that repair, a characteristic of the design.

The development of the Warranty Index from the type of data shown above in Figure 2. "Graph of Vehicle Repair Cost Labor vs. Part," will be shown to provide guidance for an improved "Life-Cycle design" methodology. By using the BDLM and the “Warranty Index,” design teams can readily identify commodities that need improvement in reliability and durability over the Life-Cycle and if needed, provision for effective service. A review of current means to assess serviceability requirements is found to be largely ineffective at identifying and correcting these formerly hidden design defects in part addressed by Grzanowski et al., (2002). Therefore, the use of the BDLM and Warranty Index will overcome today’s vehicle design practices that deny any significant need for Maintainability as a “Design-To“ parameter and where it has been sufficient in the past to settle for answering serviceability in a general competitive sense.

Warranty, Price and Design Dilemmas

The Warranty Dilemma:

A company doing business to offer its goods or services for profit will have an interest in their customer’s resulting satisfaction. To continue viable, those goods and services offered by the company then must meet or exceed customer expectations with a fair price to value realized as mentioned by Grzanowski and Long (2002) quoting Henry Ford. Revenues must also meet investor expectations creating a dual edged sword.

In the marketplace, the manufacturer bears a risk as does the consumer. Buyers beware, caveat emptor, and from biblical perspective, the seller says it is everything while the buyer is saying it is nothing when negotiating price to value (Proverbs 20:14, KJV) and so it seems little has changed. In current market applications a seller or manufacturer and buyer do not walk away after the sale but there is a continuing obligation of service and maintenance with respect to the products purchased. When the product is a motor vehicle purchased for business or personal use the risks are significant.

The purchase of warranty contracts considers many elements of specific and implied liability that spans fitness for use, merchantability, product defect and remedies when things go wrong.

Today, a warranty will be offered to offset the belief the consumer may have as to his financial risk from the selection and use of a product that may not meet expectations. A warranty may be offered as part of a product to just be competitive in the value offered in its goods or services and to some extent as part of the reputation of the company to stand behind its product, refer back to Figure 1. Basic Warranty Comparison – Miles (thousands). With the adoption of the various local lemon laws, a risk expands the liability of the manufacturer up to the purchase price rather than a lesser specific repair.

Figure 3. Buyback Due to Lemon Law Data.

A typical data collection set for an OEM Buy Back under lemon laws offers another stream of data to understand the impact of serviceability as a design criterion. Data can be evaluated for chronic symptoms and service issues to reveal weakness in designing for serviceability which can be a combination of design inadequate fault isolation and skill level of service personnel.

Year	Make	Mileage	Disposition	Buyback Rationale	Buyback Concern

When a lot of time is spent, the Labor content to Part content can be multiple times part content.

A manufacturer is cognoscente of the fact that the concept of cost-of-ownership broadens the scope of customer satisfaction well beyond that of acquisition costs and value received or perceived at purchase. An inducement on its face to offer an extended warranty from the grantor's perspective looks at it as an additional service agreement that can be an additional profit center against the risk of failure outside of a basic warranty.

On the service side, an extended warranty brings some peace of mind and control to the buying relationship as a marketing tool and revenue stream to the company and as a means to assure proper care is given to a vehicle requiring maintenance to operational specifications to maximizing operating life and performance. Under these arrangements then there is customer value and peace of mind for a covered repair as the customer does not want to pay aftermarket prices for major items. The preventive nature to assure service is performed under an extended warranty is a means to reduce variability in service and encourage proper maintenance of a vehicle at the expense of losing coverage in warranty.

The Price Dilemma:

It is apparent that a minimization of the costs of ownership and warranty will improve the long term operating results of both the company and the consumer. One significant conflicting approach to the aftermarket comes from the OEM sales goals. A balance needs to be struck between warranty costs when the manufacturer pays within warranty and when the customer pays outside of warranty. The conflicted element is when the company considers the sale of service parts as a major profit making arm of the company. This practice may not always be a proper business model in today's economy and buyer choices. With pressure to push the price up and costs down this model cannot continue to work when there is limited resources to owners.

The Design Dilemma:

There are pressures in design to define a level of effort to improve quality by various attributes. By improving the component reliability the frequency factor in the failure event reduces the cost of warranty for that type of repair within the time and cycle domain in the population of impacted vehicles.

However, it is felt in the dealer network when there is success in improving reliability it also decreases the dealer's ability to service vehicles on a volume repair basis weather paid by the company or the customer. Lowering the cost of the part that is replaced lowers warranty and the sense of dealer profit if outside of warranty. This is a factor in the Dealer Business Model where this concern is voiced by MacNamara, (1998). These pressures have continued the last ten years with continuous warranty events shrinking with improved reliability as reported in the Detroit News by Hoffman (2008).

Looking further into the service support of the OEM-Dealer network the service-parts-for-profit model includes technical service to dealer networks and fleets. High frequency items of service consumables and normal wear and high failure components require many parts to fill the pipeline to assure effective service. In this case, central depots or dealers are on hand.

It is a normal process to prepare the service industry through past program analysis that identifies most common replacement parts. Yet, it is uncommon to have a maintainability model as an automotive vehicle characteristic of design. On the other hand, it is common place to have a maintainability plan for military systems. There are many who develop this concept to the automobile community but it has not taken hold as it continues to be offered in the research as a new methodology for the auto industry as by Vacante (2001) and Klyatis and Klyatis (2006) to mention just two. Klyatis proposes that the four elements of quality, Reliability, Durability, and Maintainability offers the right but complex solutions requiring accelerated testing strategies. The weakness seems to be centered in the complexity of the approach.

A detailed review of certain warranty and aftermarket part sales can help structure the costs in service, under warranty or outside of warranty. The costs may be accumulated in a warranty model as a cost of repair that includes the two elements of total part and total labor costs on an average basis. Seldom is this detail actually considered as part of design alternatives with prices that are typically fixed due to commercial agreements discussed. Over a life time, the individual knowledge of repairing a certain problem for a certain cost can be understood by the frequency of the repair event per a useful life or other measurement. At best, serviceability efforts currently will look at labor as a comparative benchmark that says we are as good as the other guy rather than managing improvement potential through a customer vehicle market driver.

Looking Closer at a Warranty System

When looking at the costs of service under warranty from the manufacture's point of view one can disassemble the costs into its constituent parts. Fundamentally, total warranty costs are the sum of part and labor cost for a covered repair. The frequency or rate of occurrence of such unscheduled repair can be understood by a particular component failure rate. Then the product of the cost and frequency of that repair during a coverage period would be the cost of warranty for all such warranty repairs. Distribute this across all failures and their repairs would collectively sum to total warranty.

The rate of occurrence of component failure or failure rate is tabulated by summation of repairs expressed as Repairs per Thousand Vehicles in Service (Rs/1000) as an index of quality of a particular vehicle over a given service period to serve as an index of quality and even a design target for improvement. This data that is gathered from a warranty system database is managed by the OEM for just this purpose. Similarly, the data can be looked at from a Cost Per Unit (CPU) basis which is the vehicle's cost for service on a per vehicle basis removing the total number of units of scale from the calculation – again over an equal time in service as the Rs/1000. The cut-off service periods used typically include 0 months (pre-sale issues), 1, 3, and 12 months in service. The feedback from this system of warranty reporting brings to light the need to identify specific failure modes as contributors and the development of action plans to eliminate the individual failure modes – this is in part the find-and-fix approach found at the customer's expense rather than in development. The effort to reduce the failure modes is referred to as "failure mode avoidance" and is prioritized by either CPU or Rs/1000 or both.

These modes of failure can be understood by analysis as to the cause of failure with a proper investigation. The macro grouping of issues is often subdivided by vehicle functional groups or by replaceable component tracking – at the warranty serviceable part level. The assignment of responsibility as to being a manufacturing issue is separated from a design controllable issue or even a supplier issue. In all cases, it is still the OEM's issue to consider a possible corrective resolve. The influence on Design towards failure mode avoidance has been to improve the reliability and hence reduced warranty. This approach has reached diminishing returns with most competitors reaching parity.

To distinguish amongst OEMs one can see their marketing plans that include some variation reference, Figure 1. “Basic Warranty Comparison – Miles (thousands),” with respect to warranty offerings. Since there is only symptom level data in warranty data then without a deeper investigation or without a deeper look into specific failures as to root cause in the warranty data base, there is a lack of visibility as to seeing deeper causes of failures against vehicle architecture. Warranty systems do not routinely attempt to address, in a feed-back sense, back into the development cycle plan with respect to serviceability.

The Basic Properties of the “Warranty Index”

The “Warranty Index” as it is developed in this study, is the relation between the Labor Cost and the Material or Part Cost of a given repair. The approach attacks head-on the belief that neither of these items can be changed effectively by design. These factors that are inherent in a warranty system’s database and with some review can be evaluated to a component level and with appropriate assessment. These factors can become primary targets that trigger an investigation into “Design-To” objectives include Maintainability and Serviceability in support of a Life-Cycle design methodology. From these failure events or from analysis proactively where they are triggered by frequency rankings. The frequency rankings are part of the Warranty Index application methodology. These rankings become discriminating characteristics of design and are applied to Life-Cycle cost design principals.

The first tier triggers are frequency of event, as frequency drives the multiplication times the cost of a repair in warranty costs. Breaking down the total cost of repair into the above factors allows one to see that there is a ratio that most repairable parts are contrasted. The Warranty Index can be subject to a lot of manipulation statistically but in this study relevance and simplicity can guide this approach. Then it is the Warranty Index defined by looking at a ratio of Labor Cost to Part Cost - a differentiation that can exist to help prioritize effort to improve design.

Understanding the need for improvement comes to each of us that have sought a repair service. A most interesting human condition goes to the "sense of fairness" one has about a repair. If for instance, a part costs $5 dollars but the labor is $200 dollars – something is wrong! But a light on a corner module or under the dash needing the dash removed just might cost this much.

The failure in design is the lack of access, the need for special tools or the requirement to remove "bonus parts" – ones that must be removed first - adding waste to the formula. This is a touch point that one would hope would be easy to effect as to the degree of dissatisfaction that results when out of warranty.

Since frequency triggers the analysis into serviceability and most systems will compile a list of "high value parts" that are often repaired or break in use then how might one create a hierarchical approach to setting up "Design-To" targets? A proper response to this listing follows the basic principals found in Reliability Centered Maintenance or RCM as analyzed and discussed by Vacante (2001) and described in report ALM-43-7494-C, Chapter 12.

Using the Warranty Index as a relation between cost of labor and parts, there is a logical decision process utilized to guide a design team. As in any use of a logical decision model, an effectiveness criterion should be developed when performance goals are intended. Use of a logical model has been shown to be effective if the following three elements of are used in its design as reported by Kellogg Foundation (2004) where models are constructed from conditions, actions, and rules to follow. The selection of a decision algorithm or logic model helps provide a systematic and visual way to represent and share an understanding of the relationships among the resources defined to operate the system and the activities planned together with the changes or results one hopes to achieve. A prescriptive guide for Design-To Life-Cycle cost and service requires such an orderly device to communicate the process.

The decision model is simplified differentiate which is more, labor or part cost, where one can begins to focus attention on the relations in the data. The ratio between labor and part cost helps focus improvement opportunity. As discussed above, higher labor is a problem if the part is cheap. In a similar fashion, a highly integrated part that has no serviceable parts may mean that a very large part cost is charged and the labor being low, yielding a low ratio of Labor to Part cost. So the model would be consider extremes on either side of unity – very large or very small ratio with respect to unity in the ratio being nominal – labor and part costs being nearly equal where equal opportunity may exist for improvement.

An analysis in quadrants, like the one below, helps bring a three dimensional relationship into focus. Here the cost factors of Parts to Labor relative to frequency (Part - X axis, Labor -Y axis) versus frequency (Z - axis), see Figure 16. Frequency MTBF – Part – Labor: Region I-IV."

Labor - Part Costs - 2 x 2 Box Analysis			
	Low	**High**	
High	II. Alert (labor cost)	IV. Bad	**Labor Cost**
Low	I. Good	III. Alert (part cost)	
	Part Cost		

Table 1. Warranty Claims - Qualitative Analysis.

Warranty and Service Parts Business

"The related service parts business in America is said to be over 7.7 Billion dollars in 2006. Further, manufactures such as Ford Motor Company have indicated a reduction of 1 Billion in warranty costs due to improved quality that has reduced component failure rates. The manufacturers, dealers, and customers all are significant stake holders in this relation" says Hoffman, (2008) in a recent news story.

A Deeper Look into Part and Labor Cost of Repair:

Service from either an independent or a franchised dealer has given rise to a phrase “out-the-door-pricing.” This terminology is supposed to give confidence to the consumer as to the belief that there are no hidden costs associated with that dreaded trip to the dealer or service center for parts needed when not covered by warranty. This will also include service for consumables and items not covered under a warranty agreement such as a tire replacement due to “normal” wear. However, this terminology does not change the cost of any particular service or part needed to restore a vehicle’s operation. It does serve to understand the customer’s real expectation to want fair and complete service for their vehicle. With the evaluation of such consumer focused organizations as JD Powers, Consumer Reports, insurance agencies, and the Federal Government, publishing comparative performance data there is clearly room to improve quality and owner satisfaction.

Historical Serviceability in Prior Vehicle Generations

With an eye on serviceability when quality was lower and reliability poorer, service solutions had to be essentially easy. Today, systems are more complex, less easy to diagnose a problem and service the repair yet they are lasting longer. Increased longevity is realized today to exceed up to 8 years. On an individual repair basis, there is an increase in complexity that has pushed up the cost of repairs where there is less attention to service effectiveness and user serviceable parts. Complexity of diagnosis tools and time to isolate failure causality eludes most service groups reviewed by Ishi et al., (1993). The serviceability effectiveness has suffered even though reliability has improved.

In an analogous way, computer software design in the 80s under the early DOS™ or assembler for embedded systems environment required execution in very limited memory. Applications for desktop and earliest lap tops, such as the Otrona™ to run on floppy disks or 5/14" with storage capacity of 360K bytes and no hard drive storage or at most 10 Mega bytes (IBM Xt). Assembly Language, BASIC, FORTRAN, C, and various languages used to create executable code to manage the task in fewer than 256K bytes of Random Access Memory. Today, that is not the case and where computer instruction is no longer coded in a compact way as there are Millions of Bytes of Code required just to create a structure for programs to initiate. The analogy when comparing the auto designs of today for longer life and longer service intervals gives less attention to service effectiveness increasing fault diagnosis and makes servicing PCs or Cars left to skilled technicians.

For a service center to be competitive to support franchise administration there is a challenge when looking at the time-to-repair costs from the prevailing labor rates within region and adding the additional margins required sustaining a business. A second time element for a service event is design related. Just how long a service event takes is a formidable task to decide by the OEM and how it is handled in the service center. Traditional maintainability time elements are often defined by the allowable time durations to assess against labor codes due to a warranty service event. These times are spelled out in maintenance manuals and through the service system defining warranty service events. In other words, they are contractual time standards to conduct most service events. If on one hand a dealer can perform the task in less time, there is more margin and hence more profit. Alternately, if the tasks cannot be performed to standard there is a network that interacts with the actual field issues and resolution is still possible where the system can update with experience to changing the standard times upwards.

By looking at the interaction of manufacture, dealer, and customer one can expect a successful service event can be obtained because of the risk under the issuance of state lemon laws. Most of the obligations of the interested parties lie within the OEM who must be able to satisfy a repair need within three visits or be subject to the financial penalties of the law. This penalty can be up to the reimbursement for the entire vehicle. The liability that falls to the manufacture is an inducement to maximize elements of service through design. Typical elements like diagnosis and validation methods aid in service care. This is why within an OEM-Dealer network there is a service technician within the OEM to aid a dealer technician to solve problems that are truly design driven and often labor intense.

Within the specified time parameter allowed for any service event there is a complexity in the design with respect to the ease of that maintenance. The accounting of diagnosis, access time and any removal of "bonus parts" explain the costs experienced. Bonus parts are those parts that must be removed to access the causal part needing the actual repair. Again, this drives labor costs higher and if the broken part is inexpensive then there is high dissatisfaction.

Poor diagnosis, lack of modularity, inadequate training, need for specialized tools, ineffective ergonomics are all failure modes of poor maintainability. All this adds to a new area to target reduction potential in warranty cost and poor ownership experience. The adverse effect of any and all of these elements can be addressed by design practices in Maintainability engineering. Again, to a customer under a warranty there is the aggravation of down time opposed to service or part cost. Similarly, high service costs outside of warranty and the expectation for the cost of a repair will influence future purchase decisions and opinions about the product that could take years to correct.

Components that cannot be restored in an adequate time or within adequate costs limits will cause a negative bias. Through application of the BDLM and the "Warranty Index" service related issues between part costs and labor costs can be challenged. The offensive component design practices that are entrenched in a vehicle's design architecture can now be exposed and solutions for effective serviceable parts and part price points can be measured and managed.

Exposing the Price Point for the Aftermarket

Price determination involves both legal and economic considerations for any part that is ultimately sold to a consumer. The OEM selling their product under terms of a warranty has a duality of concerns in which pricing draws a distinct difference between the original part-price built into equipment and that which is differentiated by being a service part or a replacement part, discussed by Zenz, (1981). The cost for service parts being higher than the same part built in producing new product originally. It is commonly known that to build a car out of parts from a service center will cost considerably more than the parts procured that support the OEM production and with good reason. There can be costly logistic considerations of distribution, storage and support coupled with somewhat unpredictable periodic low volume purchases for service parts after production through the service life of the product – support for up to 10 years past last production.

Focusing on general pricing strategies one may include any mix of cost, market conditions, economics, administration, controlled or even psychological strategies.

Monopolistic Pricing

The more the corporate position in the marketplace is monopolistic then the more a price strategy may favor the administrative pricing characterized as having higher profit potential indicated Hamilton and Macauley, (2008). This may be interpreted by the consumer as just adding an unfair weight upon his back – the very consumer the company wants to sell its next product at time of disposal and replacement, a point made by Zenz, (1981).

Further, the notion that selling original equipment manufacturer's (OEM) parts in the aftermarket as a profit center has likely been leveraged to the determinate of the consumer, refer to the fact that Ford's Field Service Division was 350th of 500 of the fortune 500 in 2001 with $2,000,000,000 in profit. Looking at more reasonable price point for aftermarket product is needed to heighten ownership experience and customer satisfaction.

The marketing model that sells administratively low for an OE product can with proprietary required consumables continue to earn through these replacement parts – e.g. ink to printers or software to a computer. Similarly, one could compare gas and oil consumption to the car costs. Sustaining consumables include additional items as insurance, licensing, maintenance scheduled and unscheduled and lastly interest on loans to purchase vehicles. Having the terms of loans equal the life of a vehicle would liken the operational and acquisition costs to a guaranteed flat rate pricing. These facts are explored by Hamilton and Macauley, (2008) when looking at longevity, durability, and operational costs as a price willing to be paid for maintaining a vehicle to be equal to leasing a vehicle.

For an OEM with a resale service part seller there are controls or legal considerations that are regulated by the Fair Trade Laws. Court action has provided for dual pricing strategies but prevents unfair trade where lower priced OEM parts would unfairly compete with resale and therefore it is illegal. For this reason, the differentiation of OEM and resale must be clearly stated on purchase orders.

Where trade within a state may very between states with regards to pricing of a resale item there is a direct impact on cost of ownership. Where all this concerns the cost of ownership is when together, with the cost of warranty, there are clear effects to both seller and buyer. If the buyer experiences a failure of his vehicle there may be a concern if it is covered under warranty. If covered then it becomes only a time liability from the buyer's point of view. To the manufacturer it is a warranty expense. If the selling price for that part, in warranty versus out of warranty is a shock it is required of a service part to be at service pricing and not the lower priced OEM part. Mark ups for the part manufacture, mark up for the dealer sales, and mark up for the OEM distributor is in this chain if the OEM considers the service part sales as a profit center. Having part reliability survive a warranty period pushes the burden to the buyer if useful life equals the warranty period and will adversely affect resale once this weakness in a vehicle is significant. Each a time this liability is a cost liability and in his view it adds to his cost of ownership.

Another design concept is to push reliability with longevity past the “sustainability” life-limit – vehicle end of life as a disposable. Under this condition, the unscheduled maintenance would be minimized and in reality is ultraistic. However, much of this is evaluated in engineering and test demonstrations to understand the end-of-life of components and systems.

Sense of Fairness

It seems everyone considers a sense of fairness when faced with a repair cost. In other words, there is an expected cost for the value of a failed part and its repair. If not deemed fair this goes to customer dissatisfaction. Under warranty, it is the interruption of usage. Outside of warranty the full liability of time and cost is to be born by the consumer and can be a shock as it was subsidized prior under warranty. On the other hand, if the price is believed to be fair then a service experience may be very positive one. Such is the point of view of the chief editor of the Reliability Collaborative Association, Vacante, (2001).

The regional impact of the cost of car ownership provides powerful insight into some of the issues facing car owners. The variance is in large part due to economic and insurance rating factors. The study of cost of ownership differences help to establish rates for reimbursement for car usage for tax purposes, state and company policy. One respected research organization for such data is from Runzheimer International, as reported by a CNN Money staff writer Les Christie, (2008). The lowest yearly cost of

$7,399 is found in Knoxville TN whereas the highest of $11,844 is from Detroit. These costs identified that insurance in Detroit is more than $5,000 annually from a baseline vehicle.

The Maintenance contribution is measured in cents per mile with a low of 4.69 in Bismarck, North Dakota to 7.35 cents per mile in San Francisco as expected for a baseline vehicle being a Ford 500 2006 fully loaded used for 4 years at 15000 miles per year. Many of the factors influencing the costs are also design related including fuel economy, accident repair, and service requirements. Naturally this excludes warranty costs which are a part of the purchase price of a vehicle considering the data.

The element of insurance that is design related is the costs of coverage for comprehensive and collision. Additional studies of such costs are on a vehicle by vehicle basis and the expected frequency is of an actuarial nature. It is not clear what if any cost is factored in for deductible costs but even minor accidents are evaluated by the Insurance institute for 5 mile per hour crash tests presented by Mayes and Wasilak (2004).

Because an incandescent light assembly should be on a high frequency list efforts should be used to drive down labor and material costs. All customer experiences are cumulative as to their relationship to the OEM and purchasing decisions in the future. A simplified interaction viewed by the customer includes relating to the customer from purchase through service, see Figures 4. The OEM-Dealer-Customer Interaction. and Figure 5. The Typical Repair Flow Chart.

Figure 4. The OEM-Dealer-Customer Interaction.

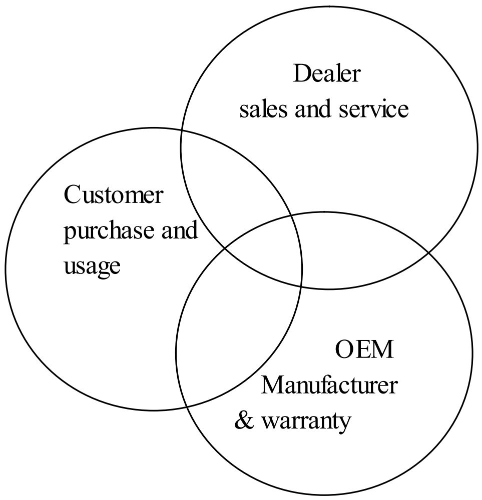
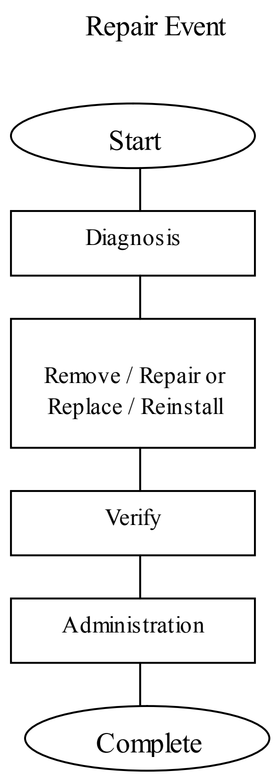


Figure 5. The Typical Repair Flow Chart.



Chapter Four

In this section, the development and application of the study methodology is given together with an organizational deployment of the BDLM and "Warranty Index" process. Guidance is shown as to the meaning of the factors and certain graphical analysis to both qualitatively and quantitatively create an example for a given data structure in warranty.

Required Organizational Structure

In order to conduct the study in a target organization there is a required establishment of policy, procedures and the definition of the roles and responsibilities for the quality improvement processes described.

An organization that meets today's quality standards provides the basis for that responsibility. A new element for the automotive team is to assure there are Design Assurance specialists that can carryout the data driven processes that take the following form:

Basic Design Actions – long term

Reliability Projects

Maintainability Projects

 Parts Cost Reduction in Projects

 Labor Time Requirements in Projects

There are high level organizational objectives that are cascaded to lower levels of indenture of the work breakdown structure of systems produced. The targets that become objectives are developed at four levels of responsibility:

1. Level 1: Organizational – DTLCC goals at the Top Functional Level:
2. Level 2: Vehicle
3. Level 3: High Level Functional Groups.
    a. Engine
    b. Body
    c. Electrical
    d. Chassis
4. Level 4a: Lower Level Functional Level
5. Level 4b: Lower Level Part / Item Level

Project Management Structure

The project management structure defines the team, organizes the tasks and assures the design team carries out the mission to achieve Life-Cycle wise designs. Eighteen tasks have been developed that are summarized in a table. A Walk through those 18 steps are given as the method used to assure this concept can be deployed.

1. Design-To LCC Decision Logic Modeling

Develop the policy, procedures and work instructions to carry out the quality improvement program.

2. Roles and Responsibilities Defined

The program elements agree with procedures and identify CEO – sets policy; Vice Presidents and Directors Carry out the Policy and assure commodities write procedures and work instructions; Program Managers, Chief Engineers Identify the teams; Design Assurance Technologies Staffed; Cost and Service Organization involved early in the program.

3. Establish Design Requirements

Design Requirements are set at four levels. The first considers past program data and sets a tasks to reduce variance in service by the 3rd quartile in part costs and labor in service. Reliability tasks are established based on sufficiency to the improvement goals. Statement of Work, required with suppliers.

4. Data Process

Validate the data systems for each project

5. Generate Frequency Lists

Use the Decision Logic to generate the Frequency Lists

a. Reliability List Generated
b. Maintainability Labor List Generated
c. Maintainability Part Cost List Generated
d. No Project Lists Generated

6. No-Action Lists Published

The No-Action lists are those components that are not high frequency threats.

7. Define Actionable Lists

a. Reliability Project team reviews and makes proposal
b. Maintainability Labor Project team reviews and makes proposal
c. Maintainability Part Project team reviews and makes proposal

8. Undefined Action Lists

Those items that have no planned actions but are on the frequency lists. These become projects if goals are not met by assigned projects.

9. Assign and Track Projects (objectives set in program plan)

Chief Engineer Approves of Project Commitments and obtains budget.

10. Reliability Frequency Projects Conducted
11. Accident Frequency Projects (assigned in the Maintainability projects)
12. Maintainability Projects Conducted
13. Failure Rate Improvement Specialized Reliability Project – Tracked by PM and CE
14. Extended Life Limits Specialized Reliability Project – Tracked by PM and CE
15. Part Cost Projects Specialized Maintainability Project – Tracked by PM and CE
16. Labor Cost Projects – Tracked by PM and CE Specialized Cost Project – Tracked by PM and CE
17. Completed DTLCC
18. Monitor – Executive Level

Process Deployment – Target Setting on New or Existing Programs

Chief Engineer – Product Group or Functional Group
Existing Program Application: (how to get started)

- Using the Statistical 3rd Quartile cost values (sufficiently large sample) as a guide to begin controlling Labor and Part costs.

- Using the manager's *Maintainability Action Sheet*, Identify the action plan benefits by time category for labor factor

- Using the manager's *__Cost Opportunity Action Sheet__*, Identify the Cost / Pricing challenge.

New Program Application: - Ground Zero – uses surrogate data and can apply techniques earlier in a cycle plan for improved effectiveness.

- Using existing program surrogate data develop new targets for Life-Cycle Design.
- In response to the Binary – Decision Logic Assessment:

1. Using the manager's *__Reliability Action Sheet__*,
2. Using the manager's *__Maintainability Action Sheet, and__*
3. Using the manager's *__Cost Action Sheet__*,
4. Using the manager's *__Basic Design Action Sheet__*.

The action plans have the following form for Reliability actions with noted signatures required:

Figure 6. *__Reliability Action Sheet__*

	Other Resurces	Y/N	Reference	Project		
	Decision Logic Used				Project No.	
Program	Maintainability					
System	Cost					
Subsystem	Architecture					
Component	Quadrent Part Threshold					
Requested by:	Quandrent labor Threshold				Date	
Design Relibility Actions	Action Proposed	Current Value	Improvement Percent	How Verified	Validation	Approval
Life Extention						
Safety Factor						
Redundance						
Simplification						
Derating						
Variation Reduction						
Other Robustness Actions Failure Mode Avoidance						

Signatures	Sign below	Date
Chief Engineer		
Commodity Specialist		
Reliability Specialist		
Service Engineer		

Figure 7. *Maintainability Action Sheet*

	Other Resources	Y/N	Reference	Project	Project No.	
	Decision Logic Used					
Program	Reliability					
System	Cost					
Subsystem	Architecture					
Component	Quadrant Part Threshold					
Requested by:	Quadrant Labor Threshold				Date	
Design Maintainability Actions	Action Proposed	Current Maint Time	Improvement Percent	How Verified	Validation	Approval
Fault Isolation & Self Diagnosis						
Parts Standardization						
Modularization						
Accessibility						
Repair vs. Replacement						
Proactive Maintenance Preventive						
Proactive Maintenance Predictive						

Signatures	Sign below	Date
Chief Engineer		
Commodity Specialist		
Maintainability Engineering		
Service Engineer		

Figure 8. *Cost Action Sheet*

	Other Resources	Y/N	Reference	Project	Project No.	
	Decision Logic Used					
Program	Maintainability					
System	Reliability					
Subsystem	Architecture					
Component	Quadrant Part Threshold					
Requested by:	Quadrant Labor Threshold				Date	
Design Cost Actions	Action Proposed	Current Value	Improvement Percent	How Verified	Validation	Approval
Current Logistics Costs (including service strategy)						
Current Production Parts Cost						
Current Service Parts Cost						
Current Quantity in Service						
Warranty Agreements						
Other Cost Factors						
Commercial Issues						

Signatures	Sign below	Date
Chief Engineer		
Commodity Specialist		
Purchasing Specialist		
Service Engineer		

Figure 9. *Basic Design Action Sheet*

	Other Resources	Y/N	Reference	Project		
	Decision Logic Used					
Program	Maintainability				Project No.	
System	Reliability					
Subsystem	Cost					
Component	Quadrant Part Threshold					
Requested by:	Quadrant Labor Threshold				Date	

Design Architecture Actions	Action Proposed	Current Value	Improvement Percent	How Verified	Validation	Approval
Current Targets for Cost						
Current Targets for Reliability						
Current Targets for Maintainability						
Structural Systems that Hinder Change						
Next Available Time						
First Program Opportunity						
Other Design Issues						

Signatures	Sign below	Date
Fundamental Design Cycle Specialist		
Chief Engineer		
Commodity Specialist		
Purchasing Specialist		
Reliability Specialist		
Service Engineer		

Deployment - Warranty Data System Usage

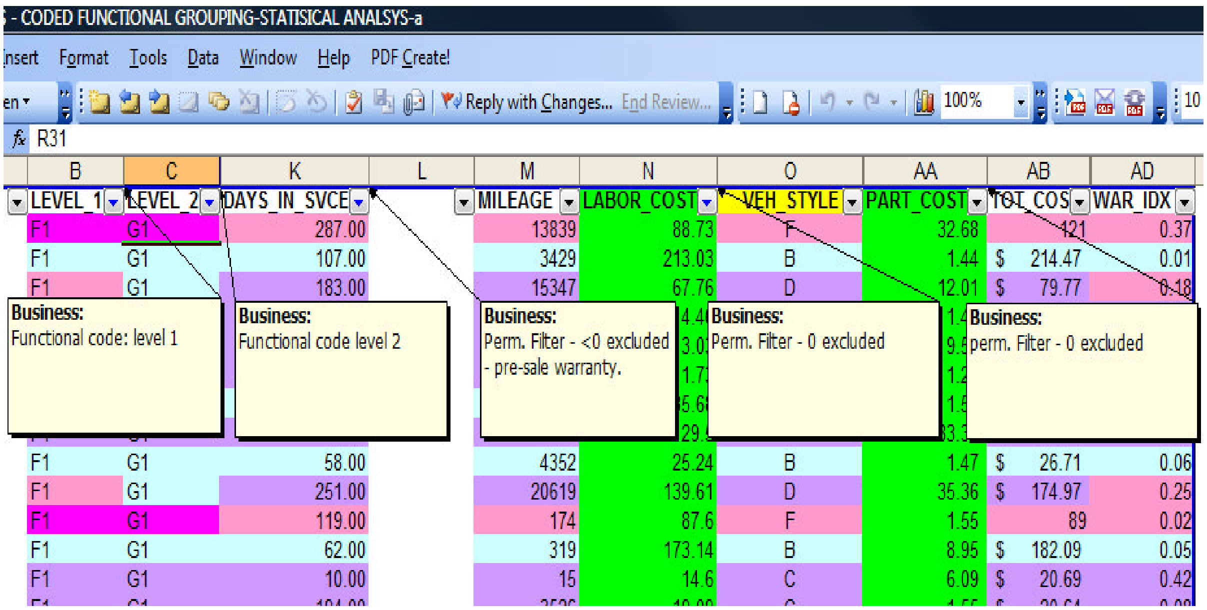
Figure 10. Warranty Database Definition

A Warranty System is a collection of Repair Events and is used in this study as follows:
A Record is a repair Event
A field is a data association within the record.
Fields Used in this study
Time Domain:
Miles,
Days in Service
Qualifiers:
Vehicle Styles
Functional Codes (Symptom Based)
Service Part Codes (Hardware)
Labor Costs
Part Costs
Vehicle Styles
A vehicle line may have major style identifiers such as a convertible or a performance enhanced version, a sedan or a coup and so on. Therefore, each may have a different application that can influence a system's stress e.g. miles driven per unit of time.
Functional Codes (Symptom Based)
Functional codes break the repair down to lowest symptom e.g. Electrical - > Radio - > CD Changer (not working) and is similar to Effect in the Design FMEA.
Service Part Codes (Hardware)
Labor Costs – Time to repair is not in the database directly. Labor costs could be reduced to time by knowing the labor rate.
Part Costs – Includes all materials.

Deployment - Warranty Data Filtering

Removed pre-sale warranty claims by setting filter of view days in service >0.
Part Costs > 0
Labor Costs > 0

Figure 11. Excel Data Feed – Warranty Data Filtering for Study



Deployment – BDLM & Warranty Index Procedure

Rationale

An automotive manufacturer's warranty system forms a wealth of knowledge concerning the quality (or the lack of quality) of a fielded product. The warranty system is a managed business process that provides and aids to a dealer network in response to a repair required. The vehicle owner obtains a needed repair and the dealer obtains reimbursement for covered repairs.

In this report, when costs are noted, unless otherwise stated, it means a retail value as viewed by a customer who pays or as reimbursed amount to the dealer which in general are equivalent costs.

Warranty agreements are part marketing and part competition and part regulation. In addition to a reimbursement system for service providers for warranty covered repairs, the data also includes the ability to make assessments of product quality and as such have been culled to effect quality improvement opportunity. A fresh review of this data has identified a new business process developed to improve quality in design – a design that focuses on the Life-Cycle. This Life-Cycle approach is operationalized and examined in this study.

Fundamental understandings of the key parameters of cost, under warranty, are needed to develop the Life-Cycle design approach. Essentially, the cost elements of a repair process include a claim made by the dealer for the Parts and Labor used to affect a repair. Further, these parameters are fields in the larger data record for that repair with their association within that and other such warranty repair records.

It is important to note that the tracking and assessing of costs of a particular repair or type of repair are the factors collected with a warranty claim record that is required input of the dealer actions. Repair records that allow for symptom level information and hardware level information all of which help assess the warranty claim and assist in understanding the reason for the claim in terms of the product function and the impact of profits due to the dealer visit and as related to the product unreliability in the use of the vehicle.

Warranty Index

A created and measurable parameter is proposed by the ratio of Part Costs divided by Labor Costs. This statistic will be called the "Warranty Index." The index, as Part Cost divided by the Labor Cost, is defined as an independent and random variable associated with a repair event. Similarly, it can be a tabulated value based on the collection of repair events associated by various factors in the warranty repair record. Inquiries into the warranty data base for all similarly defined repair events becomes a sample set of the warranty data, representing members of the sample space of all repairs.

Let's define further a value given as the Total Cost of Repair, or TCR that is simply the sum of the cost items that yield the total part and labor costs for a specific repair.

Total Cost of Repair, TCR

The TCR for any repaired item is a dependent variable with independent variables being the paired cost contributors of Part Cost, given by P(i) and Labor Costs, given by L(i) for part and labor costs respectively of the "ith" repair.

The cost to effect a given repair are entered by a dealer for which there is a warranty agreement that allows certain recoverable dollar and time values in a predefined manner as determined by the manufacturer's service parts organization and dealer assistance function.

The labor charged comes from a detailed compilation of standard repair reimbursement rates that have been developed and authorized by the service organization of the manufacturer. The labor costs are derived from the local labor rates and assessed against the time allotment.

Each P(i) and L(i) are found in the warranty system record and retained on each repair in warranty and possesses certain detail down to the vehicle identification number, odometer reading, days in service, technician and customer comments to name a few. All these elements of the record can aid the warranty data manager to assure that a properly coded, validated repair record exists. For this study we will take a closer look at a data types from the warranty record that will support the design approach for the Life-Cycle.

Deployment - Cost Creep and Maintenance Time Control

Repair data is captured primarily according to documented repair agreements through a set of standards between the OEM and the service network. The warranty system classifies the data by a uniform set of interactions. The system is on line and if a given repair is not resolved at a dealer service center under the warranty cost recovery rules then a resolution process exists to review the standard and the allowable reimbursement.

As to the effect on empirical results for labor costs or parts needed over time, there is a property of "Labor Creep." If a dealer's skill, training and ability assures repairs are completed in less time than the standard then there is no complaint made.

There is more profit per repair in this case. However, if the service cannot be performed in the allotted time, then a complaint system can be used to adjust the time standards upwards – hence labor hours for certain coded failure repair events will grow. While the growth or elevation is correcting a problem, the opposite does not hold where less time is allotted for lack of complaints on allowable time.

Deployment - Quality Assessment

When large numbers of repairs are gathered of a similar nature, then one may graphically observe a trend. One macro trend reveals that overtime labor hours are reduced across all repairs on average. This may be attributable to initial quality in a new model introduction where the bugs have not all been worked out sufficiently or from a lack of experience in the field for the repairs.

To this end, a network of service technical assistants are available to interact/train/and certify regionally dealer service centers. Over time, a maturity results in both product and service costs.

Construct for key variables of the study

Definitions related to labor costs, L(i)

The average and standard deviation for labor costs for the ith repair is given by:

$$L_{avr} = \frac{\sum_{i=1}^{n} L_i}{n} \quad \text{and} \quad s = \sqrt{\frac{\sum_{i=1}^{n} (L_i - L_{avr})^2}{n-1}}$$

Similarly, the average part costs for the ith repair is given by:

$$P_{avr} = \frac{\sum_{i=1}^{n} P_i}{n} \quad \text{and} \quad s = \sqrt{\frac{\sum_{i=1}^{n} (P_i - P_{avr})^2}{n-1}}$$

This is done at the lowest symptom code available in the data structure.

Note that P(i) and L(i) are independent and random variables

Finally, the total cost of the ith repair is given by:

TCR(i) = P(i) + L(i)

Where the average and standard deviation of the costs of a the ith repair are given by:

$$TCR_{avr} = \frac{\sum_{i=1}^{n} TCR_i}{n} \quad \text{and} \quad s = \sqrt{\frac{\sum_{i=1}^{n} (TCR_i - TCR_{avr})^2}{n-1}}$$

Finally, the reciprocal of the Coefficient of Variation (CV) is given by:

1/CV = 1/ (s/X_{avr}) or just

X_{avr} / s.

The CV has been applied as a standard measure related to variation in the data sample. The simple meaning gives objective power in terms of the development of the sample space in the study's measured values. Specifically, CV answers the question of what percent of the mean is consumed by the standard deviation.

If the mean were 20 and the standard deviation 5, then the CV is 5/20 or 25%. One could then say there is a limit to the confounding as to the dispersion of the data about the mean of the given measured value.

If a normal distribution is attributed to the measured values and its variation, then one would know that there is 68% chance that of all values measured they will likely fall within a standard deviation of the mean value – or 68 out of 100 measurements and an estimate of the mean the answer should be between 20 - 5 and 20 + 5 or between 15 and 25. These are central tendencies of the data that analysts may rely from which inference may be made.

The choice to use 1/CV in the study considers that the reciprocal of the CV or 1/CV. We have substituted X_{avr} for mean in the general formula. As used in this study is found by:

$$1/CV = \quad 1 / s/X_{avr} \quad = \quad X_{avr} / s$$

The utility of the valuation and being able makes it easy to differentiate in relative terms about the ratio being unity with respect to the data and its behavior.

In a repair process we observe the following:

If $s = X_{avr}$ then $1/cv = 1$

If $s << X_{avr}$ then $1/cv = X_{avr}$ / s(small) >> Unity

If $s >> X_{avr}$ then $1/cv = X_{avr}$ (small) / s(large) << Unity.

Applying the 1/cv can be a can be used in a macro sense to understand if a measure value is orderly and if it behaves well as an estimator. Note the measure is considered well behaved if s << X_{avr} or if ill behaved when s >> X_{avr}.

When compared to production, one wants to minimize variation so there is a smaller loss function – directly related to quality in manufacturing where it is desirable to have all the parts the same to favor assembly quality. However, in a service or repair process, variability is higher, much higher. In part due to less control operator to operator, or technician to technician.

With the P(i) and L(i) defined a given repair can then be assigned a class of repair to levels that differentiate symptoms and hardware at lower levels of failure mode and cause. Here we have collectively the TCR(ijkl) failure type where a coded repair may follow the following descriptors:

Figure 12. Depth of Warranty Target Data in Service.

I = Design Hierarchy – Body, Chassis, Electrical and so on. Design Responsibility is often defined organizationally along these lines of basic design.
J = Functional Subgroup - such as Brakes – a hardware related descriptor - a subset of Chassis in this example.
K = Symptom Code - such as Noisy, Broken, Wrong Feel, a qualifier similar to a failure symptom.
L = Hardware Code - Part grouping that has been replaced.

These four codifications allow inquiry into the warranty data to allow for effected hardware and symptom basis. This in turn allows an association of miles or days in service to the classified repair. If an actual mechanism of failure is not readily identifiable at the detailed part level where the point of failure occurred then physical parts can be returned to the responsible design engineer or plant personnel for analysis. The descriptor of K and L can be reversed with different outcomes in the search. Any or all of the descriptors can be named for evaluation. One could request all things with the symptom code for noisy. A sense of a quiet vehicle to a customer there has often been an association with a halo effect on quality overall. Noise is also one of those issues related to basic design and separate from lose fastener; it is hard to correct in service.

With this presentation, only the three descriptors are used as noted above. P(ijk) and the associated L(ijk) for any number repairs of the same coded basis, there are statistics of cost generated that will be utilized to show the impact in design terms of well behaved or not and with an respect to the impact on Design-To Life-Cycle.

"Well behaved" means there is lower variability in the repair events of the coded repair. "Ill behaved" means there is a large variation in the repair event as is easily viewed by the 1/CV valuation.

Combining the use of histograms with an investigation of the three cost terms, TRC, P, or L several common observations are made.

1. The histogram is flat over a large range of cost.

   The 1/CV value of the cost item will be much greater than one. The repair cost element(s) do not have a "well behaved" repair event. The large variability for the coded repair becomes an opportunity to understand the variability and determine what if any corrective action may reduce service costs.

2. The histogram is bi-modal.

   When the 1/CV value is approximately unity - there may be a bi-model repair cost for the coded repair. In one case there may be two repair types that are differentiated in the population of coded repairs and in another, there may be improper repair or "bonus" parts – those replaced due to poor diagnosis before the real problem is found. The histogram may appear somewhat Normally distributed.

3. There is good definition in the histogram.

   With the 1/CV value much less than one, a given repair's cost elements that follow this trend is well defined and understood to the consistent part or labor cost of the coded repair.

The following guideline is used to provide individual assessments of a repair's part or labor costs. Based on the "wellness" of the behavior the analyst can recommend the qualitatively within a program team the use of the statistic in managing quality risk within the Life-Cycle methodology based on the 1/CV valuation of the given cost element together with the use of the Warranty Index in the BDLM.

Program Team

A discussion of the responsible organizational entities is needed to realize the benefits of a Design-To Life-Cycle approach. The responsibilities can become more evident if cost factors are also aligned in the design team. The product team is challenged to addresses service cost for parts as an example. Take an exiting vehicle needing brakes serviced. It is classified as a component subject to wear. As brakes are applied to stop a vehicle, frictional forces result in having the brake pads forced upon the rotor where at a micro level grind down the pads at a certain rate based on the applied force, material properties of the contacting parts. The rotor in this case, is a harder material than the pad by design. The rotor allows for the rejection of heat so not to boil the brake fluid or diminish the braking forces needed to slow the vehicle. The braking force can further be linked back through the fluid, booster using engine vacuum to multiply braking advantage, master directing the flow of brake fluid, interacting with the anti-lock brake unit, and driver pedal input that created the chain of energy transfer that would cause deceleration.

In this situation, there are also undesired outcomes such as brake dust – the evidence of wear. This continues to a point where the pad needs replacement. There is provision to make it easy to service the pads due to their limited life. If all goes well, the materials have lasted long enough, but not over a Life-Cycle – so it is by the virtue of the wear-out rate, serviceable – by easy of access and available replacement parts that are inexpensive, say $80 dollars a pair to replace and out the door – a consumable that may not be under warranty.

Variability in the repair may be involved with many repairs. As a process of service in this case we might have the following:

1. document the repair request and estimate
2. logistics time to set up for repair
3. skill level in place
4. tools in Place
5. specific Training / assistance in place
6. scheduling
7. enter the bay
8. hoist the vehicle
9. diagnose complaint to a serviceable repair item
10. access the brakes by removing the tire
11. inspect the pad
12. inspect the rotor
13. grind the rotor if needed
14. replace the rotor if needed
15. repair the caliper if needed
16. replace the caliper if needed
17. remove and install the new pads
18. re-install the tire and wheel
19. remove from the bay
20. verify the repair
21. logistics to document the repair
22. receive payment
23. restore to the customer

Clearly, if the rotors and calipers need replacing, the costs can be variable for the simple symptom of worn brake pads and be $80 dollars or $800 dollars.

When considering all this, from the service items definition, one might suggest full life pads, maybe twice as thick to last twice as long if that takes one through the Life-Cycle and no longer would it have to be made serviceable, take time at the dealer, and so on. When considering the extra secondary damage that results from waiting too long to replace the pads – rotor and caliper replacement, then what is the part cost of these items and could they be made (sold) at a lower price in service.

These types of decisions, on a Life-Cycle basis, are not on the day to day evaluation of a program for a vehicle. The considerations are bounded by the warranty period, if it is a consumable and not under warranty as in the brake replacement and what a Life-Cycle design rule might be in this situation.

To turn this data into actionable design goals and projects to improve the Life-Cycle objectives, one also has to develop a responsive system to prioritize the actions and to set targets for each of the coded repair types. This is done by the generation of frequency lists, the number of repair types are translated into three frequency lists.

Deployment – Descriptive Statistics on Key Factors

It is required to validate the key indicators or factors to understand the BDLM with the Warranty Index and its application. To develop the descriptive statics the related repair event data for part and labor costs are studied:

Vehicle Function Codes

Select Most Detailed Symptom Code

Identifies Major Functional Subsystem in vehicle architecture and then to a specific symptom that can be associated with a Design FMEA effects code or even to the Failure Mode level of description, e.g. CD Changer Inoperable.

Index of measured values in a general way is shown below:

Part, Labor, Warranty Index - using descriptive statistics:

Measured value $= X_i$ Cost data – labor or part costs. They are paired.

$$X_{avr} = \frac{\sum_{i=1}^{n} X_i}{n} \quad \text{and} \quad s = \sqrt{\frac{\sum_{i=1}^{n} (X_i - X_{avr})^2}{n-1}}$$

Indication of strength of the predictor can be given by:

Indexed value: X_{avr} / s or 1 / C.V. Or alternately C.V.(*)

- used as a measure of variance relative to the mean – for expedience - the smaller the better or more well behaved x(i)'s as an indicator. Used in terms of > or < or << or >> than 1. It is the reciprocal of the Coefficient of Variation (C.V.) which expresses what percent of the mean is the standard deviation. As a design rule, one might want a 2 or a 3 which says a given repair is consistent across the service network in terms of part cost or labor. For each Functional Symptom Code – a tally is built for each Labor and Part Cost for the "ith" repair.

Qualitative Analysis Part vs. Labor against Frequency

When the analysis using the binary decision logic drives the flow to consider a need for maintenance then the "Warranty Index" analysis directs that flow to consider part cost or maintainability practices to mitigate the cost on a Life-Cycle basis.

What is depicted in the following 2 x 2 charts is guidance to develop criteria to be used for weighting the service event as "good," to "very very bad," reference Figure 13. Frequency – Labor: Region I-IV. The extremes of the ratings qualitatively, reflect the degrees of impact comparing part to labor costs. Further, the impact to satisfaction has a larger impact when the part costs are somewhat lower in comparison to labor and not just high costs for each alone or together.

One could similarly look at the box with "good" as the low cost part and low cost labor solution with a low frequency occurrence and likely not impact any satisfaction of the user in or out of warranty.

The charts look at increasingly higher rates of occurrence for the single event that the charts represent. The frequency trigger could be unreliability or part failure, accident frequency risk, or life limit issues. The lowest failure rate is of concern if the part and labor cost are both high. Also shown is the guidance provided by the Warranty Index that shows preference to the action that should be recommended given either (P) part cost reduction tasking or (L) labor time reduction.

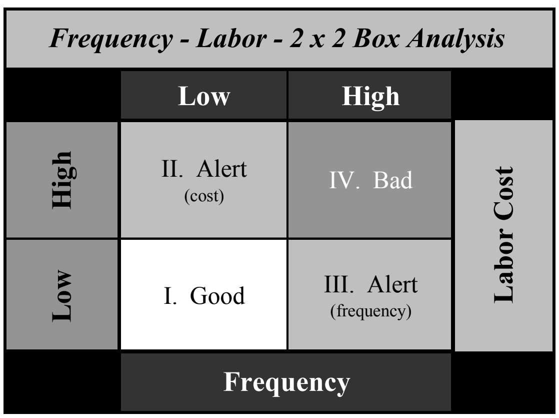


Figure 13. Frequency – Labor: Region I-IV.

Frequency – Labor: Region I. "Good"

Frequency is related directly to service count rate of a given repair type. To fix the service rate generally attributed to failure rate, a reliability improvement may be considered or even a life-limit extension. However, with the frequency low and labor cost low there are no recommended changes due to the assessed factors.

Frequency – Labor: Region II or III "Alert"

When either frequency or cost for labor high alone then it may not generate a need for improvement actions. The threshold of action must be derived by design rules and can be associated with knowledge of best in class competitor or continuous improvement philosophy. However, if the cost of labor is high even with frequency low, it may indicate a need to improve fault identification and verification. There are no part costs being considered in this repair.

Frequency – Labor:. Region IV "Bad"

Claims that have high labor cost and high frequency are typically identified for corrective action. In general, the frequency of repairs per thousand vehicles produced will have a trigger to initiate at least a review of high failure rate events.

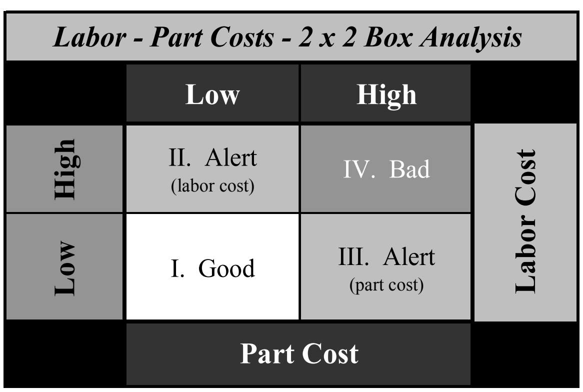


Figure 14. Frequency – Labor-Parts: Region I-IV.

Part – Labor: Region I. "Good"

This is a target area where costs for service meet customer expectations. Design-To goals can be established that focus on part complexity in service

Part – Labor: Region II or III "Alert"

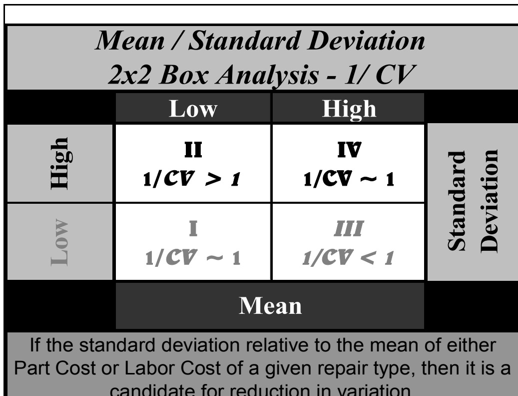
High Part cost is fixed as a service part in or out of warranty and much higher cost than an OEM part for production. Actions are commercial in nature. Pressures under monopoly pricing and a desire to make significant profit in retail drives this cost element. At times, there is a reduction in price but it is unusual.

If labor cost is high, this can equate to time or labor hours per repair rather than labor rate. Design solutions are available but seldom pursued.

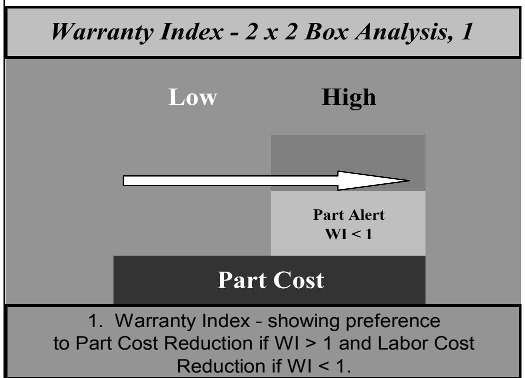
Part – Labor:. Region IV "Bad"

If a service part cost is high and labor cost is high then this is a design risk component if frequency is high. Corrective measures are seldom taken as architecture is fixed. The top service items by frequency can be benchmarked.

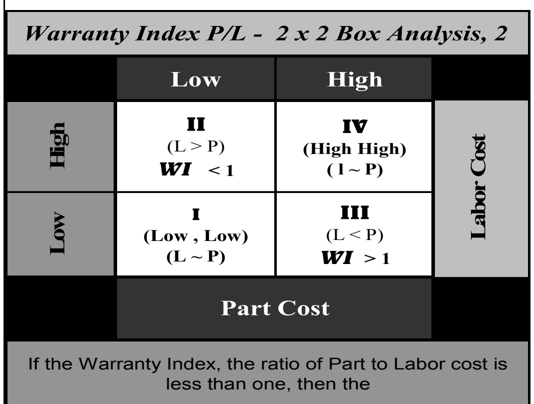
Figure 15. Mean and Standard Deviation and Warranty Index: Region I-IV.



The evaluation of the relation of the mean and standard deviation of a sample is explored in terms of the reciprocal of the CV. Its utility is asking if the number is greater than one or less than one or near one.



Once the statistics for Part Cost and Labor Cost for a give repair are understood, then the application can be recommended for use in the decision algorithm where a warranty index greater than one will favor changing the part cost. The first thing to consider is if the generic goal of reducing part costs by the 3rd quartile will satisfy the goal.



In this chart, all the values of the warranty index are expressed qualitatively.

Figure 16. Frequency MTBF – Part - Labor: Region I-IV.

Frequency Trigger (Reliability, Life-Limit, Accident)
Frequency Low (High MTBF)

Low Frequency - 2x2 Box Analysis

	Low	High	
High	II. Alert *L < P : WI > 1*	*IV. Bad* *L=P : WI=1*	Part Cost
Low	*I. Good* *L=P : WI=1*	*III. Alert* *L > P : W I < 1*	
	Labor Cost		

These three charts show the relationship of the warranty index and the interpretation as an increase in frequency impacts the decision process.

This chart is the lowest failure rate or highest Reliability and given a corporate strategy on the target setting, this chart is indicating that the low likely not be put on a project list, but on the No-Project list if low part cost and low labor cost and lower failure rate. The do not touch list is a powerful tool to resist change for the sake of change.

Frequency Trigger (Reliability, Life-Limit, Accident)
Frequency High (Low MTBF)

High Frequency - 2x2 Box Analysis

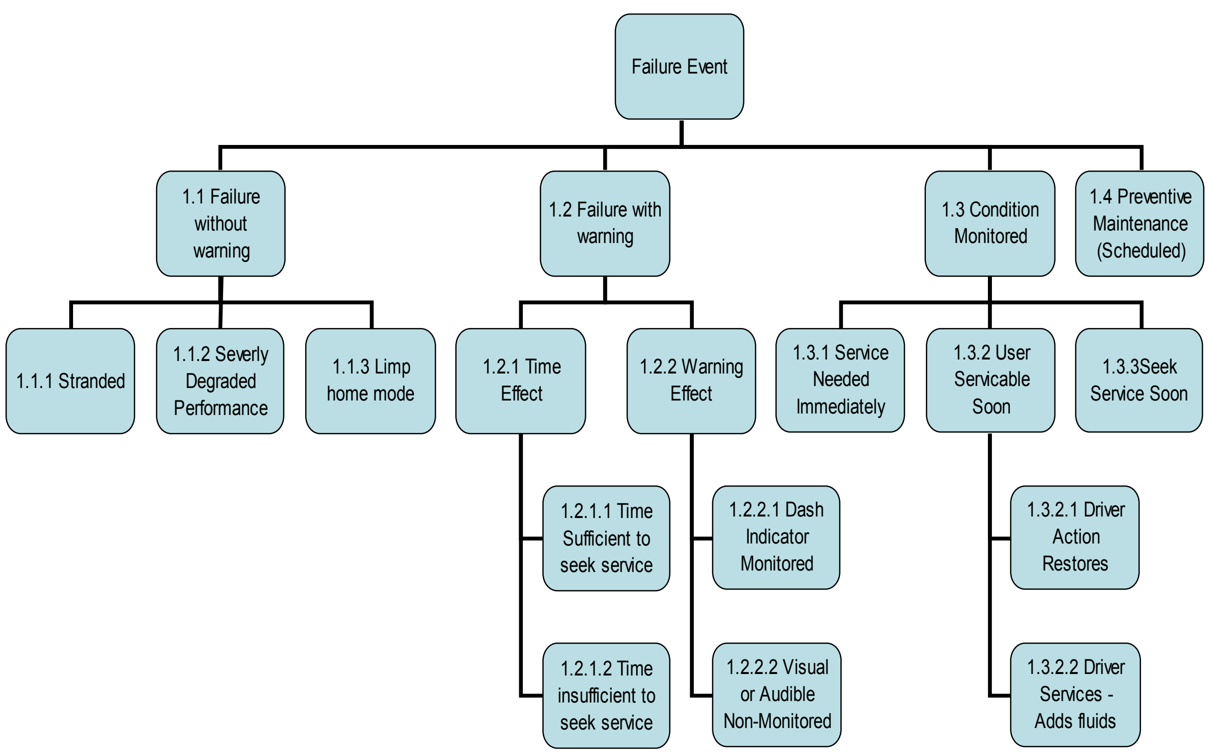
	Low	High	
High	II. Very Bad	**IV. Very Very Bad**	Part Cost
Low	I. Bad	III. Very Bad	
	Labor Cost		

Here the assessment of poor failure rate puts us into a need for change in service if there is no Reliability project to fix this situation.

Binary Decision Logic, Frequency Lists, & Event Landing

The use of binary decision logic is founded in the RCM process discussed prior. The maintenance effectiveness strategy replaces the mission critical view found in the RCM flight – service tool. One omission in this study is the attention in a design Failure Modes Analysis or DFMEA. The ratings collectively or individually can relate the factors of Severity (safety or economic) alone, or Severity times Occurrence (failure rate related) or all three such risk identifiers used in the DFMEA as a product of Severity, Occurrence and Detection (raking with or with out warning or monitoring to the triggering event).

Figure 17. Binary Decision Logic Model – Criteria Defined.



These are techniques that rank failures into various risk associations and are familiar tools in the automotive industry managing design and failure mode avoidance management. These categories are treated without safety called out in the Event Trigger Topology and Driver Interface Leading to Service classifications.

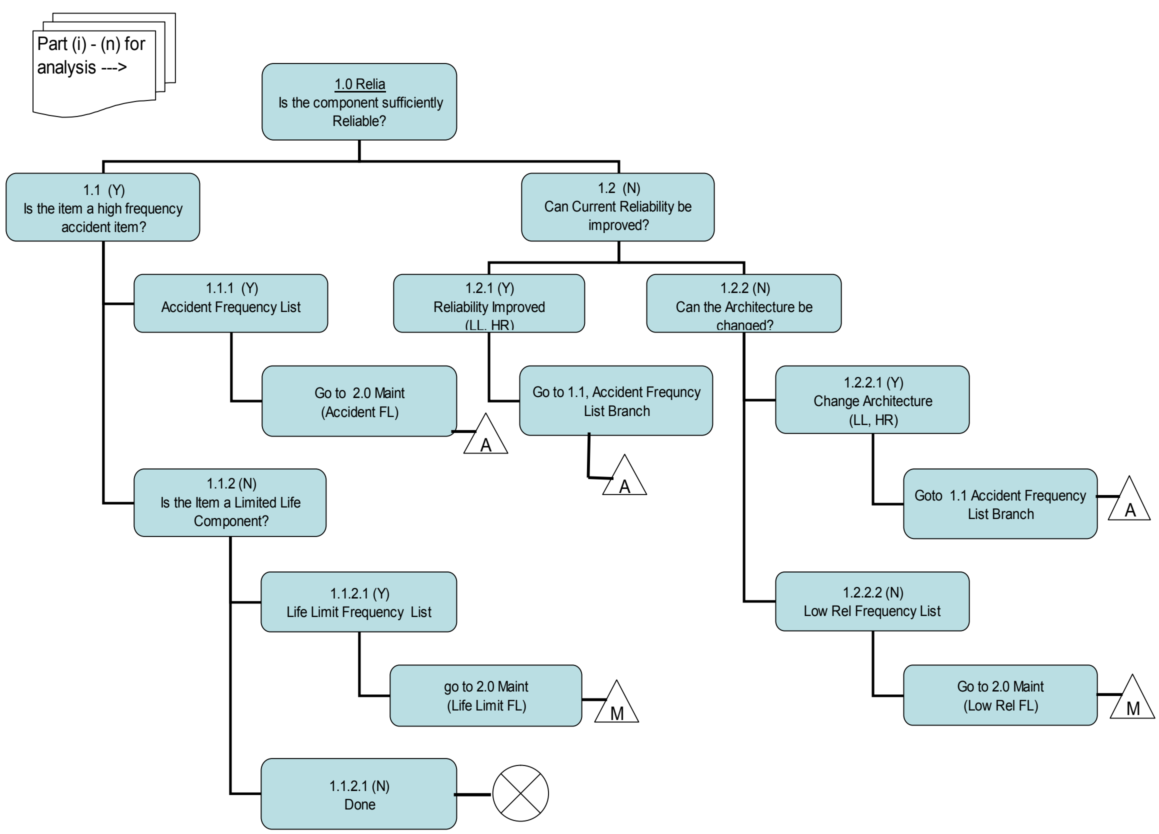
When one has developed the BDLM with clear functional and operational characteristics, as shown in Figure 17 "Binary Decision Logic Model – Criteria Defined" then the concept of designing a fault tolerance could be made that might be called "The Event Landing." The description of the event and the frequency that generates a related service action would then influence the design strategy. The design team when considering a candidate change recommendation can decide which branch to Design to in the topology that so service is arrived at by design in a certain manner. For instance, the designer specifies that he would rather fail with warning and specify that there will be an indicator on the dash (element 1.2.2.1).

The service engineer would then write the "service landing" mode into the service manuals for the vehicle and then Reliability engineer would evaluate the design for the frequency status and would evaluate what rate of failure is to the standard and if maintenance requirements need to be evaluated in a Life-Cycle manner. If acceptable frequencies then the job is done, if not then the cost engineer or the Maintainability engineer would then address the two cost elements in the design for service.

The design in our case is interrogated for 1) Reliability, 2) Life-Limit, and 3) Accident threat wherein the team is asked to evaluate if a measure of frequency is sufficiently low occurrence that there is little need to improve that design element. If insufficient a rate of occurrence that an improvement is recommended, the team is given a priority order as to first ask to improve reliability, then life-limit. If the design is still insufficient or not challenging the reliability then to do to consider the economic issues of cost effective maintenance through a logic transfer to the maintainability interrogation.

If the conclusion is that the interrogation is sufficiently reliable, sufficiently not prone to accident replacement and sufficiently not life-limited wearout and the cost to repair is sufficiently low(not a high risk on its own no matter what the frequency), then the assessment is done. The program receives a list of items from the assessment that essentially directs the traffic through the design requirements definition. The list of times that are historically non-offensive go on a do not touch or no action list.

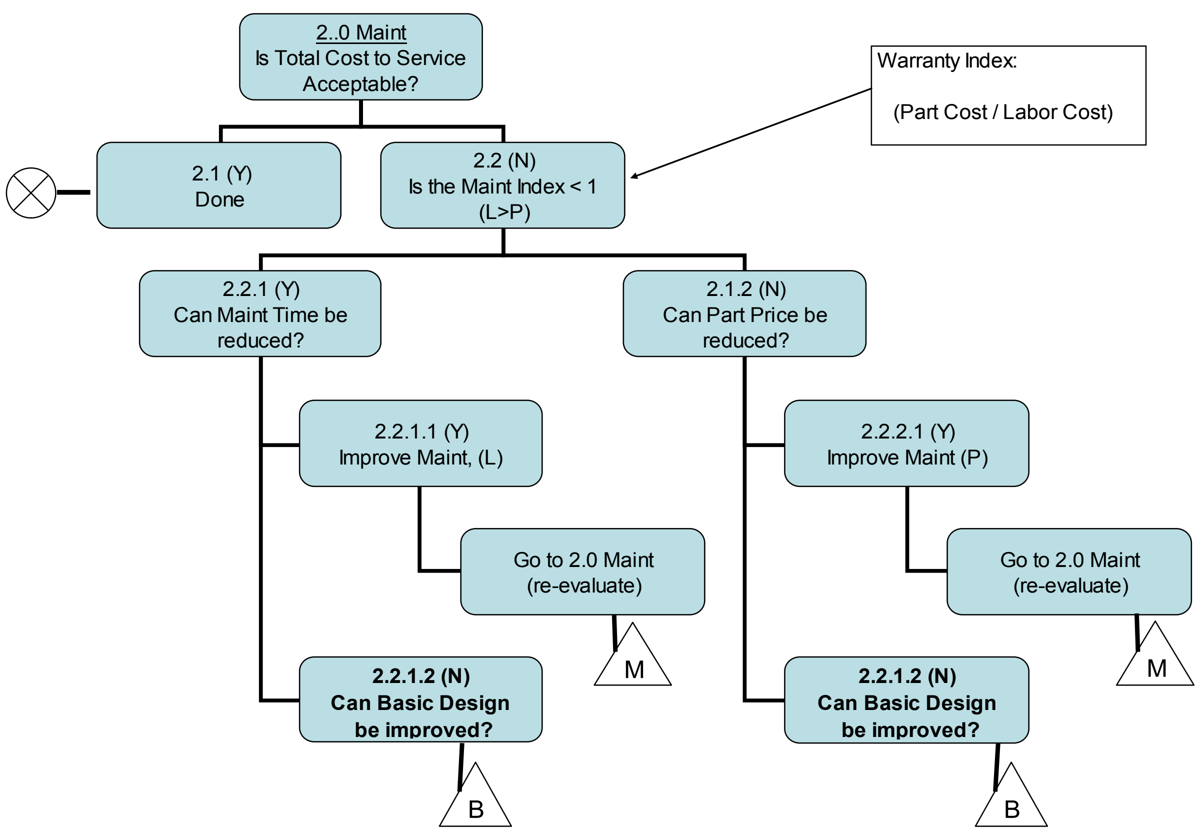
Figure 18. Event Trigger Topology and Driver Interface Leading to Service.



Binary Decision Logic, Maintainability Decision

During this interrogation, the logic model checks effectiveness of the service cost and if effective and sufficient then the component is done, no further action is needed. If not, the maintenance index is used to identify the best opportunity from a cost perspective what should be evaluated. In both Parts I and II architecture of the design is challenged. In each case there is a feedback loop to re-evaluate if needed. Also, the part pricing is challenged if part price is high. This is novel in the industry today. As a practical matter, there would be a need to develop a maintainability skill set in the OEM product development team.

Figure 19. Binary Decision Logic Model, Maintainability Branch.



Decision Rule – Example Candidate for Maintainability

Figure 20. Design Rule Applied to Frequency Listings.

			Frequency List Items						
item	Repair Part	Service Summary	Reliability	Life Limit	Accident	Comment - Accessibility	Part	Labor	Warranty Index
1	Front Pads	Disc pads - front remove and install - remove and replace both sides		X		Wear - must remove tire	Low	Low	=
2	Rear Pads/Shoes	Disc pads/Drum Shoes - rear Remove and Replace, both sides		X		Wear - must remove tire	Low	Med	< 1
3	Front Rotor	Front Rotor Remove, Turn or Replace, Both Sides	X	X		Warp - might have secondary damage - pads	High	Med	> 1
22	Windshield	Remove and Replace Windshield			X	Threat Foreign Object Damage	High	Med	> 1
Note: If exact costs are not known in terms of Part Costs, P(i) and Labor Costs, L(i) their relative values may direct effort through the Warranty indexing noted above.									

In this example, a listing of the frequency driven items become consideration for maintainability actions since they are high impact from Part I of the algorithm for Binary Decision using the “Warranty Index” Method. The three triggers for being on a frequency list is given as reliability, Life-limit and Accident initiated. Event description of the service needed for part and labor are provided. An opinion as to the type of maintainability strategy price strategy is offered. The status of the index is given as a ratio of Part Cost / Labor Cost in relative terms as in the quadrant analysis. More than one trigger could exist and be treated separately for causal impact.

Data Dispersion Part to Labor

The analysis process that helps to create the frequency lists are displayed in a set of five graphs. The detail of the data query selects data based on the filtering discussed and the level of symptom codes - up to four levels deep – referred to as the (ijkl) granularity. One level can be interchanged (k and l) to reveal more hardware or symptom resolution into the data set. Only the (ijk) approach is used. The object is to classify a certain repair data and its variance from historical data and assess the rate of occurrence to be used in the target setting process for quality improvement for the Life-Cycle. The key parameters include Reliability and Service.

Reliability looks at targets for life limited components and basic reliability or failure rate while service considers part cost and labor times (or costs). The five graphs represent a proposed data standard that can help identify visually how the frequency factory is working and the variation of part to labor costs look over time or mileage.

From an introduction to the data on the whole vehicle, a manager can identify the overall relationship or cost of repair for each repair and can be considered a serviceability standard in the historical record of the vehicle. Each design change can ask how this might impact the vehicle as costing more or less with respect to cost of repair over time in and out of warranty.

This value can be compared to other vehicles and selected repair inquiry by the responsible design community to determine existing best practices – ones that cost the least in warranty spending and lowest cost of ownership in the Life-Cycle.

Here, graph 1, there is a rate of usage or miles per day. The graph uses miles driven on the Y-axis and days in service on the X-axis.

Figure 21. Key Graphs Explained – Full Vehicle.

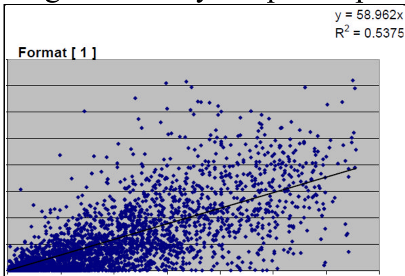
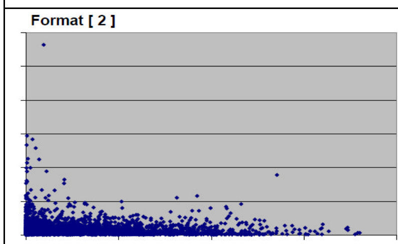
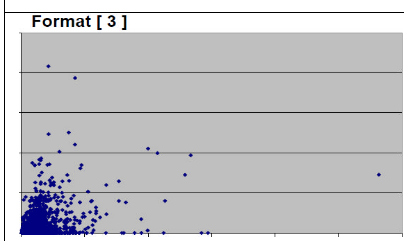
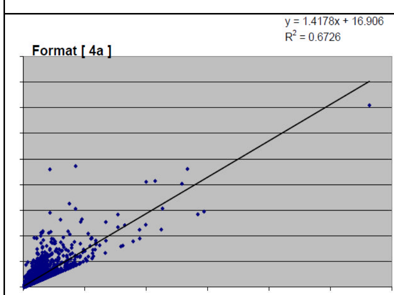
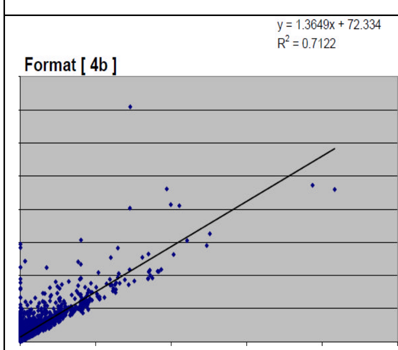
	Y-axis: Mileage Data Ref: Full Vehicle X-axis: Days in Service Purpose: Application gross duty cycle in miles per day. Approximately 60 miles per day. A Life-Cycle estimate of oil changes in a population can be significant costs in oil and dollars by increasing the interval.
	Y-axis: Labor Costs X-axis: Mileage Purpose: Understand the labor costs over time. Service has more variability early in a vehicles service period. Learning may explain reduction over time. Care not to have unequal populations per interval with respect to density.
	Y-axis: Part Costs X-axis: Labor Costs Purpose: Data that demonstrates the density of the average repair is focused in a cluster. There are flyers that have broken away from the pack and represent possible need to understand why.
	Y-axis: Total Cost of Repair (per event) X-axis: Labor Costs Purpose: A relation between labor and total cost of repair. Here there is an estimate that total cost of a repair is 1.4 times the labor content plus ~ $16. This could be used as a cost estimating relationship in planning. It also reveals that there is never a part cost without a labor cost.
	Y-axis: Total Cost of Repair (per event) X-axis: Part Costs Purpose: A relation between part and total cost of repair. Here there is an estimate that total cost of a repair is 1.4 times the part content plus ~$70. dollars. This could be used as a cost estimating relationship in planning. It also reveals that there may be a part costs can be zero indicating a soft fix issue exists on new vehicles.

Figure 22. Key Graphs Explained, Failure Code: i1,j1,k1.

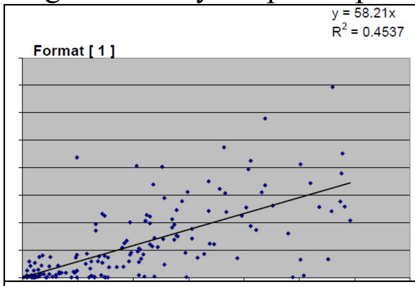
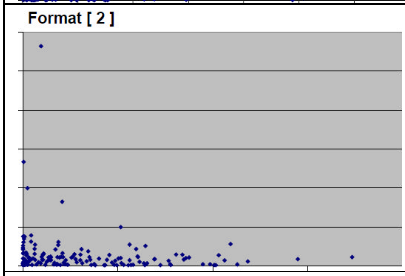
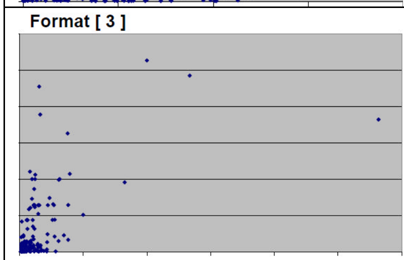
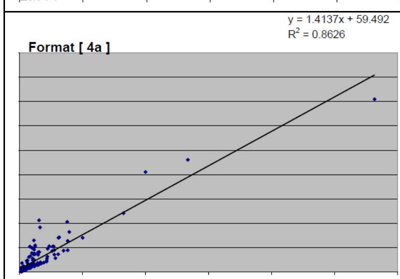
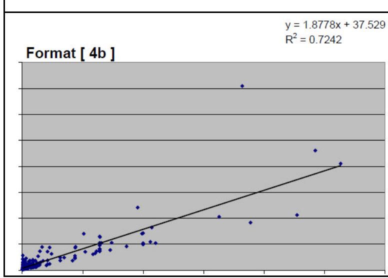
	Y-axis: Mileage Data Ref: (i1,j1,k1) X-axis: Days in Service Finding: Frequent occurrence with many days in service but low miles accumulated at first.
	Y-axis: Labor Costs X-axis: Mileage Finding: There is a spike at first with low mileage and very excessive labor costs. Much lower labor costs with learning. What lessons were learned and how were the problems early solved.
	Y-axis: Part Costs X-axis: Labor Costs Finding: Data clustering in part and labor near the origin, meaning well behaved repair in general. However, Significant higher Part variable needs to be understood.
	Y-axis: Total Cost of Repair (per event) X-axis: Labor Costs Finding: A relation between labor and total cost of repair. Here there is an estimate that total cost of a repair is 1.4 times the labor content plus ~ $16. This could be used as a cost estimating relationship in planning. It also reveals that there is never a part cost without a labor cost.
	Y-axis: Total Cost of Repair (per event) X-axis: Part Costs Finding: The relation between part and total cost of repair indicates there is significant part variability as compared to labor.

Figure 23. Key Graphs Explained – Failure Code i1,j1,k2

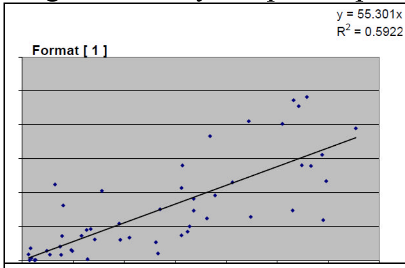
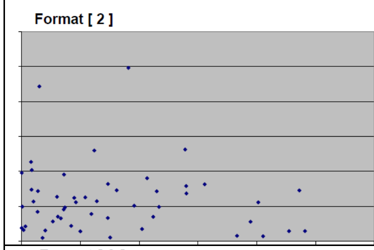
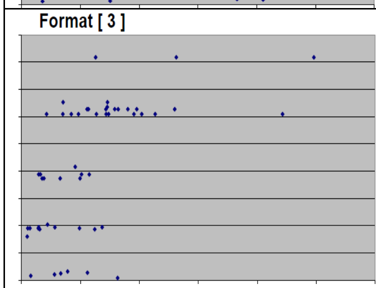
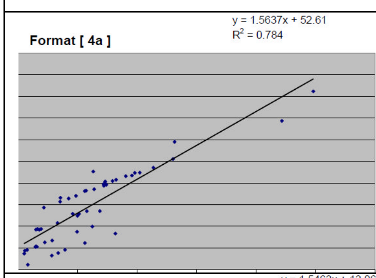
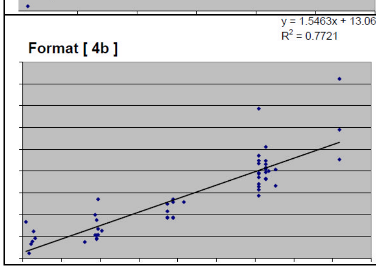
	Y-axis: Mileage Data Ref: (i1,j1,k2) X-axis: Days in Service Finding: Wide spread in the data. Likely to occur at any mileage or days in service, favors neither cycle domain.
	Y-axis: Labor Costs X-axis: Mileage Finding: Weak association labor to mileage with respect to lowering of labor over time.
	Y-axis: Part Costs X-axis: Labor Costs Finding: Highly correlated groupings. 5 discrete part cost levels identified. Higher costs need to be investigated. A lot of labor cost variability within groups. Possible faulty diagnosis that has systematic higher part costs if find that they are all the same issue.
	Y-axis: Total Cost of Repair (per event) X-axis: Labor Costs Finding: no findings with respect to labor, no stratification in the data observed. Labor is about the same cost but shows higher part costs dominate as the component of TRC less Labor.
	Y-axis: Total Cost of Repair (per event) X-axis: Part Costs Finding: Clearly actionable data in part costs.

Figure 24. Excel – Pivot Table that Generates that Category Statistics.

Pivot Table - Showing F1 and G1 level 1 & 2 Symptom Codes, Individual Repair Events, and Summary with Mean and Std dev

BOD_CAB_STL	
LEVEL_1	F1

LEVEL_2		Data	Total
G1		ODOMETER	1424.00
		DAYS IN SVCE	14.00
		1. LABOR_COST	21.60
		2. PART_COST	15.28
		WARRANTY_INDEX	0.71
		ODOMETER	4504.00
		DAYS IN SVCE	147.00
		1. LABOR_COST	75.82
		2. PART_COST	4.50
		WARRANTY_INDEX	0.06
		ODOMETER	11239.00
		DAYS IN SVCE	74.00
		1. LABOR_COST	75.33
		2. PART_COST	27.74
		WARRANTY_INDEX	0.37

G1 Average of MILEAGE	6072.03
G1 Average of DAYS_IN_SVCE	102.75
G1 Average of LABOR_COST	135.59
G1 Average of PART_COST	113.78
G1 Average of WAR_IDX	1.04
G1 StdDev of MILEAGE	6774.51
G1 StdDev of DAYS_IN_SVCE	80.44
G1 StdDev of LABOR_COST	269.65
G1 StdDev of PART_COST	186.02
G1 StdDev of WAR_IDX	1.36

Building Warrant Index Design Guidelines

Figure 25. Warranty Index Design Guidelines.

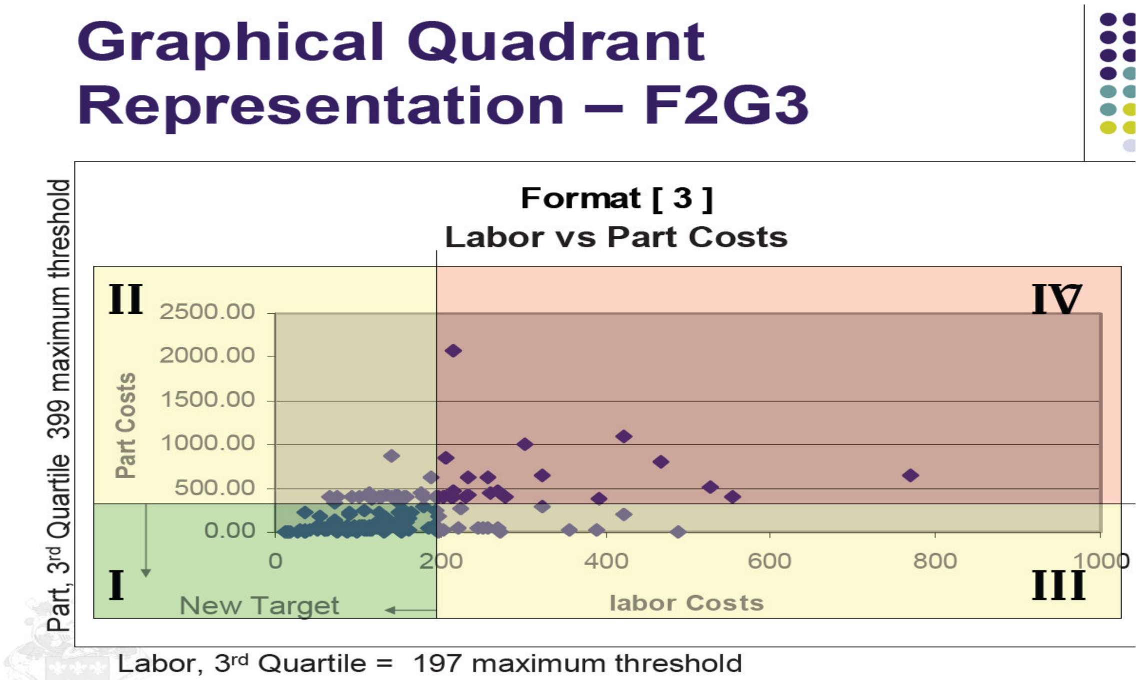
Mean	Relation	Std Dev	Indexed Mean/Std Dev 1/(CV)	Comment
Mean (i)	>>	Std Dev (i)	<<1	Very Good definition
Mean (i)	>	Std Dev (i)	<1	Good definition
Mean (i)	=	Std Dev (i)	1	Poor definition
Mean (i)	<	Std Dev (i)	>1	Bad definition, Variability
Mean (i)	<<	Std Dev (i)	>>1	**Very Bad, Variabilility**

Figure 26. Assessment of Factor Behaviors, Mean and Standard Deviation.

Study Data

Vehicle Line	Level 1 Symptom Code	Level 2 Symptom Code	Part Average	Part Standard Dev	Behavior	Labor Average	Labor Standard Dev	Behavior	Action Direction
All	F1	G1	113	186	1.65	135	269	1.99	Labor: Bad-Needs attention immediately Part: Needs attention immediately
All	F1	G2	85	48	0.56	59	48	0.81	Labor: Needs attention soon/watch Part: Good
All	F2	G3	111	217	1.95	134	99	0.74	Labor: Good Part: Needs attention immediately
All	F2	G4	94	182	1.94	139	97	0.70	Labor: Good Part: Needs attention immediately

Figure 27. Generating Targets for Design-To Life-Cycle, Cost Category Variability.



In the above graph there are four regions defined. They are used to prescribe to the program teams what the improvement targets are in terms of part and labor costs. By identifying variation in the warranty data system, and making an assessment concerning the data scatter for the given repair level for the Part and Labor components then one can set upper limits on the data as an improvement challenge.

By a detailed descriptive statistical study as found in this failure code [F2G3] (refer to Figure 28 and 29 respectively), one can set the new target at the 3rd quartile limit – as a design rule. This has been selected as the targeting threshold for the cost factors in service. Zone II is the part cost "threshold" with Zone III being the labor "threshold" and collectively in Zone IV, the must fix cost area. Program teams are tasked to get the costs under control in this manner.

Figure 28. Target Modeling, Repair Code: P_F2G4, 3rd quartile Target.

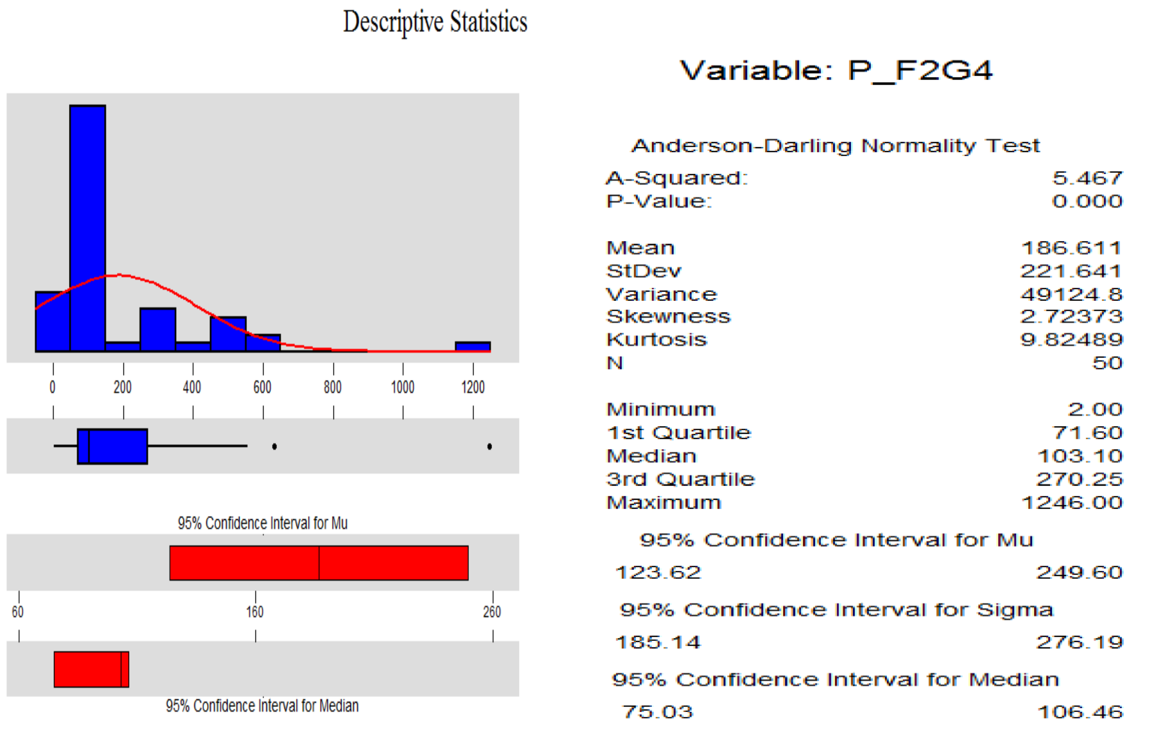
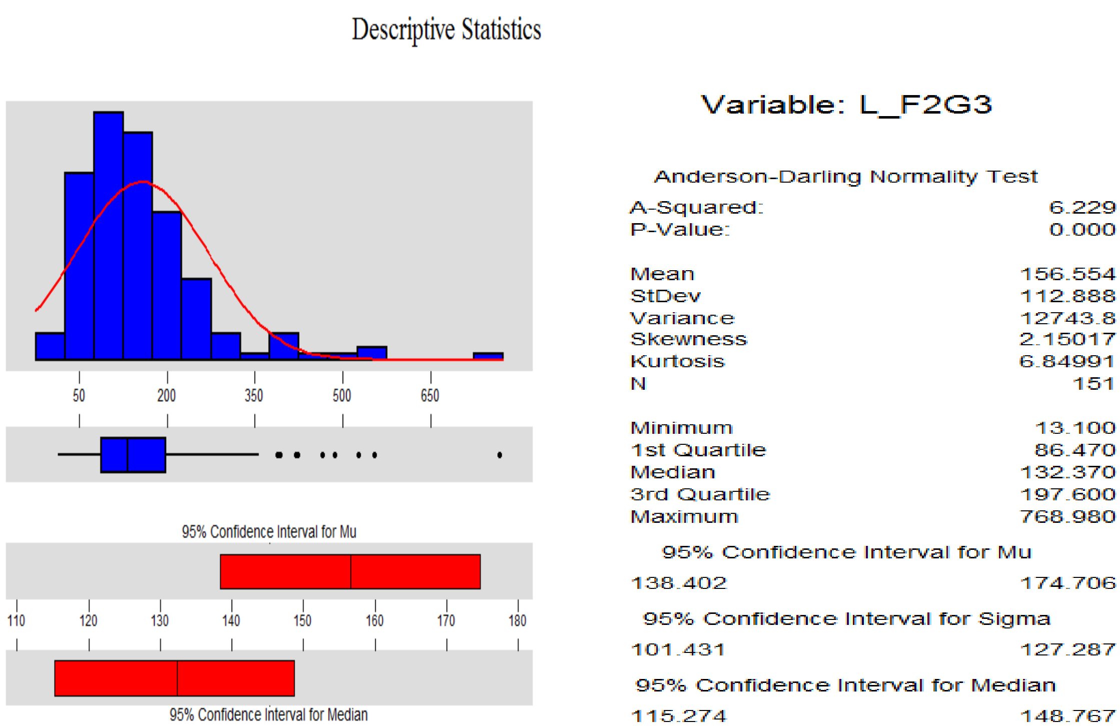


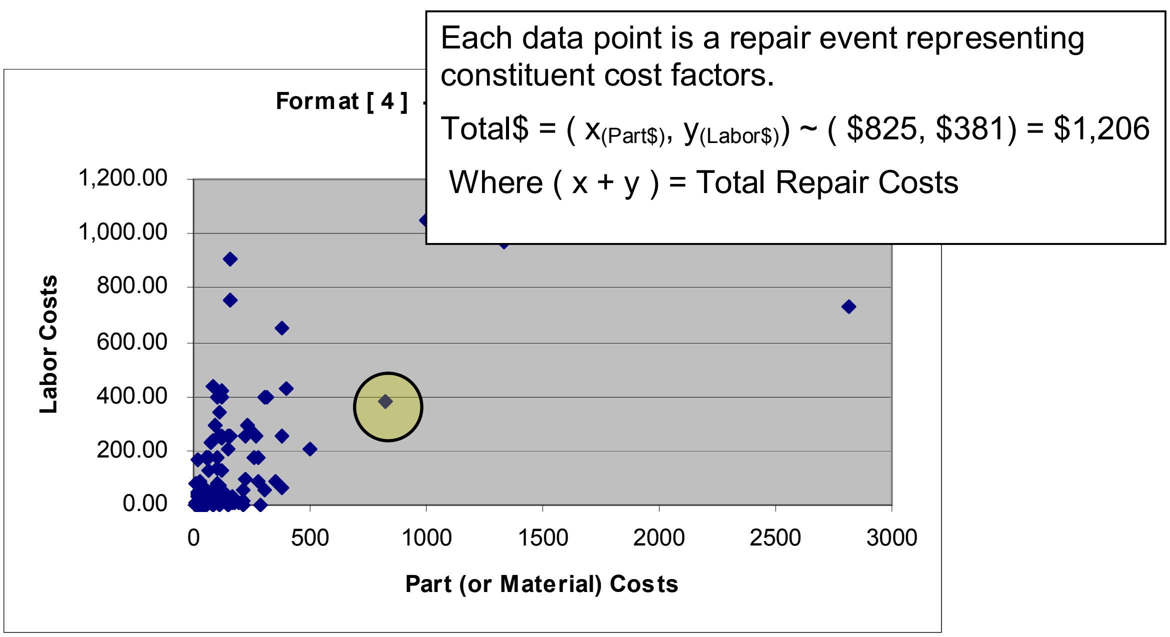
Figure 29. Target Modeling, Repair Code: L_F2G3, 3rd quartile Target.



Recall that the warranty system is primarily a reimbursement system administered through a dealer network to honor the warranty contract with its sale of a vehicle to a customer. The warranty system and network of dealers is like an insurance policy and of course is subject to abuse. Therefore many checks and balances are applied to assure integrity for the most part reveals. A byproduct of this system is the joint opportunity to take system of failure information that initiates the dealer visit under warranty and the associated information that is captured to correct the subject defect and those repair actions that restore vehicle function.

Understanding a Single Data Point

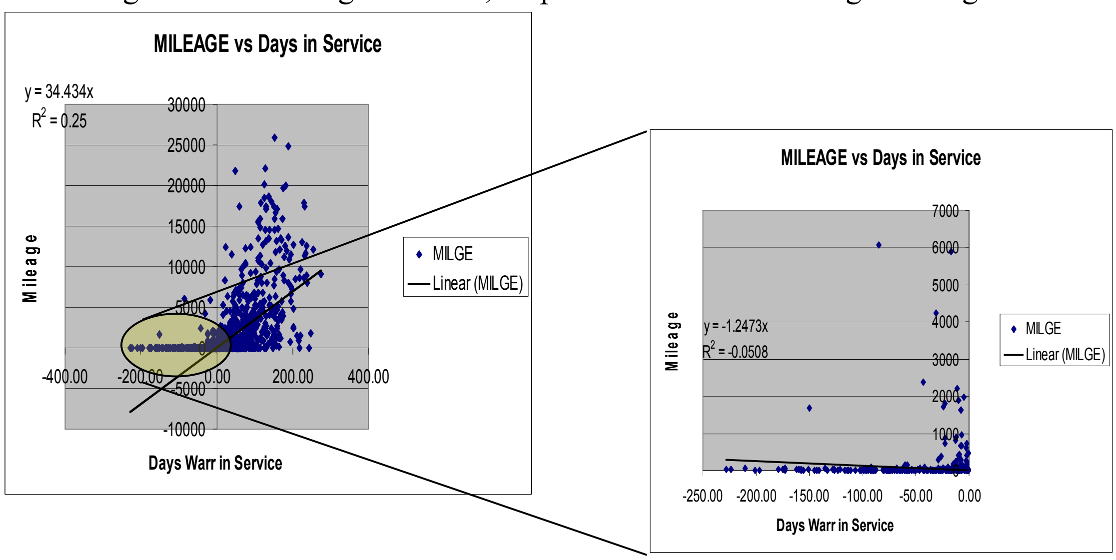
Figure 30. Data Point of a specific repair cost elements, Part and Labor.



This data is based on a selection of a certain functional code and a certain vehicle. Permanent filters are on, excluding specific data.

Data that shows warranty claims from a Pre-Service or sale date is excluded from the study. The specific case refers to the number of repair or claims events prior to the introduction into service. This occurs when a vehicle goes to a third party for a major modification as in a performance vehicle. This is an interesting area to study the effects of such delay and function while under warranty rules in the pre-sale condition, as vehicle would not start, battery too low – battery replaced. It does not seem reasonable to have these warranty claims under this usage.

Figure 31. Filtering Rationale, no presale data used for target setting.



From this, one can learn through detailed analysis and physical review of part returns the root cause of most failures. This data and frequency data come together to prioritize "find and fix" approaches to quality improvement and warranty improvement programs. Year on year the domestic automotive companies have gained ground on quality and are now reported to be equal to the imports through these efforts. There are two related lists I have gathered from my experience showing ten aspects of design quality and quality measurement that have driven this improvement and a brief review is needed to understand the opportunity uncovered by the use of the "Warranty Index" and decision process to improve the quality, reduce the warranty and improve the Life-Cycle ownership experience. In each of the two lists provided the last or tenth item is related to the study and has little depth of development in practice.

Research into Reliability Centered Maintenance, RCM practices can be developed for integration into the design process. Many measures and data elements are shown in this section and the key ones are defined when used throughout the study and within the glossary at the end of the report. The "Warranty Index" methodology serves as a tool to identify and explore the next level of innovation in improved quality of service and Ebling (1997) indicates a list of program planning elements to incorporate into a Maintainability Design Action List (p.225) and Maintenance Time Categories List (p.190), Refer to the Figure below listing such activities included in design maintenance action types for improving maintainability and tracking time to repair elements of a given repair process.

Figure 32. Maintainability Design Actions List and Maintenance Time Categories.

Design Maintainability Actions	Maintenance Time Categories
Fault Isolation & Self Diagnosis	Supply delay
Parts Standardization	Maintenance delay
Modularization	Access
Accessibility	Diagnosis
Repair vs. Replacement	Replacement / Repair
Proactive Maintenance Preventive	Verification
Proactive Maintenance Predictive	

In work by Stadler and Brideau (2004), human factors are discussed that form part of the skill set needed for maintainability engineers and service engineers. If the automobile companies have not formalized this process it would be important to develop this competency. Similarly, Woolford (1995) develops a full strategy for design for maintainability. These types of requirements are developed by O'Conner, (2005) where he has related a program's needs in terms of serviceability (p. xxx). Again, this goes to developing competency in the design for service arena.

Ten Elements of Quality in Vehicle Design

Table 2. Ten Elements of Quality in Vehicle Design.

1. Design Considerations – customer based
    a. Mission
    b. Duty Cycle
    c. Expectations
    d. Satisfaction
2. Business Considerations
    a. Goals
    b. Targets
    c. Initiatives
    d. Communication
    e. Contracts
3. Reliability
    a. FMEA
    b. 150,000 miles
    c. 10 year life
4. Durability
    a. Loading Studies
    b. Durability Testing
5. Safety
    a. Regulation
    b. Due Care
6. Survivability
    a. Fit for use
    b. De-rating
7. Design Philosophy
    a. Sustainability
    b. Useful Life
8. Design Standards
    a. Warranty Agreement
    b. Warranty Standards
    c. Test Standards
9. Assembly Standards – Design for Assembly
10. Design for Serviceability
    a. Guide Lines
        i. Common Tools
        ii. Access
        iii. Modularity
        iv. Maintenance Concept, RCM
            a. Depot
            b. Flight Line
            c. In-Flight

Ten Related Quality Measures

Table 3. Ten Related Quality Measures.

1. Rs/1000
2. Months In Service
    a. High Time In Service
    b. Low Tim In Service
3. Cost Per Unit
    a. Factors of Labor
    b. Factors of Material
4. Cost per Repair
    a. Statistics
    b. Car Lines
5. Scheduled Maintenance
6. Unscheduled Maintenance
    a. Normal Usage
    b. Accident
7. Warranty - Parts & Labor
    a. In Warranty
    b. Out of warranty
    c. Extended Warranty
8. Data Collected
    a. FCPS
    b. Consumer Reports – Annual Survey
    c. JD Powers IQS/CSI – TGWs/PPH
    d. GQRS - Things gone wrong 1MIS?, 3MIS, 12 MIS, 36MIS
    e. Warranty
    f. Extended Warranty
9. Dealer Service
10. Service Actions
    a. Labor Rate
    b. Labor Hours – Empirical
    c. Labor Hours - Design
    d. Top Problem lists
    e. Service Center
    f. Supplies Training
    g. Manual – in vehicle - Tools
    h. Corporate Centers – Trouble Shoot Typical Wear Items
    i. Top 100
        i. Characteristics
        ii. Goals – %improvement YOY
    j. Benchmarking
        i. Internal
        ii. External

Brief Review of Reliability, Maintainability and Availability

Maintainability is often grouped within the broader subject of engineering called design assurance. To capture the related tasks within design assurance it can be referred to RAMS which stands for "Reliability, Availability, Maintainability, and Safety or Supportability." One article on the subject of RAMS presented by Beugel-Kress, (2006), refers to a table out of the NASA standard [[8729.1]] that identifies several formulas for a function related to an equipment's "availability" - - a relation between uptime and downtime. Within the variations of the Availability function are the progressive elements of downtime classifications that contribute to the total downtime of equipment.

Availability = Uptime /(Uptime + Downtime)

The definition of Downtime is further classified into constituent elements that give rise to variations of Availability, shown in the table below, with the Mean Time Between Failures, MTBF as the rate at which unscheduled events are expected to occur in usage.

Table 4. Availability Classifications.

	Uptime	Downtime Classifications			
Availability	**MTBF**	**Corrective Maintenance**	**Preventive Maintenance**	**Administrative Downtime**	**Logistics Downtime**
Inherent	X	X			
Achieved	X	X	X		
Operational	X	X	X	X	
Total	X	X	X	X	X

Table 5. Formula for Availability (total).

$$\text{Availability (total)} = \frac{\text{MTBF}}{\text{MTBF} + \text{Corrective Maintenance} + \text{Preventive Maintenance} + \text{Administrative Downtime} + \text{Logistics Downtime}}$$

What is important to the design of a system is to know that these parameters may be understood in terms of the as built consequences of specific design practices. This is pointed out by Ebling (1997), in that “Availability Inherent is shown to be based on the failure and repair time distributions and therefore can be viewed as an equipment design parameter” (p. 257).

Table 6. Formula for Availability (Inherent).

$$A(inh) = \frac{MTBF}{MTBF + MTTR}$$

It is possible to set up design goals and their appropriate validation in probabilistic terms. If the design team has achieved its goal for MTTR, a demonstration would confirm that with a 1-alpha confidence that a certain repair (time to repair, ttr_i) and (time to failure, ttf_i) would be equal to or better than the goal, given by:

$$\Pr\left\{\frac{ttr_{avr} - MTTR}{s/\sqrt{n}} > -ttr_{\alpha,n-1}\right\} = 1-\alpha$$

And similarly for illustration only similarly for MTBF, the designers might demonstrate a given Reliability using ttf_i by:

$$\Pr\left\{\frac{ttf_{avr} - MTBF}{s/\sqrt{n}} > -ttf_{\alpha,n-1}\right\} = 1-\alpha$$

Note:

$\{ttf_{\alpha,n-1}\}$ comes from a probability density defined by the student-t distribution with parameters α and (n-1) with n, being the number of observations or repair / failure events of the ith failure type. A comparative study on variations of the Availability formula will define a similar breakdown of the time factors as may be appropriate for management and control of the time it takes to restore equipment to service. This is the time needed to meet objectives of a system's intended effectiveness through adequate design and service requirements. From a retail automobile owner's point of view, these time elements are indistinguishable under maintenance on a vehicle covered by warranty. However, what is experienced by the vehicle owner is how long transportation is unavailable and in what manner it became unavailable which can affect owner experience and satisfaction.

Being stranded with road-side service, with rental service or with a free loaner are conditions of purchased warranty, insurance, or dealer policy that can ease dissatisfaction of being denied use when the vehicle requires scheduled or unscheduled service.

Generating High Leverage Frequency Lists

To explore the vehicle ownership point of view and service experience further a traditional event driven model can be constructed into four downtime initiations:

Table 7. High Frequency Lists from Service Event Driven Effects.

1. Accident or failure without warning
    a. Effect essential to transportation
        i. Stranded, requires towing / repair at event site.
        ii. Severely degraded performance, may require towing.
        iii. Limp home, able to continue operation with slightly degraded performance, repair needed of convenience.
    b. Feature lost or attributes fail but not essential to transportation.
2. Failure or condition yielding a warning or cue to the driver
    a. Timing Effect
        i. Time sufficient to seek service
        ii. Time insufficient to seek service
    b. Warning Type
        i. Dash Indicator (typical – manual will instruct driver as to meaning)
            1. Information (blue or white)
            2. Warning (yellow or amber)
            3. Serious (red)
        ii. Visual or audible cues prior to failure – Brake Pads worn – whistle / grinding or even observed symptom.
3. Condition, Monitored, Threshold Monitored
    a. User Serviceable
        i. Cycle the key to clear codes and restore function
        ii. Add Fluids Oils, Water, Washer, Fuel, air,
    b. Seek Service Soon – Amber light
    c. Seek Service Immediately – Red light
4. Preventive Maintenance, a recommended maintenance manual scheduled on time or cycles.

With respect to item 3, Condition Monitor – high or low conditions of temperature, pressure, time, vibration, cycles and actionable service condition that would precede a fault – even the popular On-Star service found on General Motor's models / employ condition monitoring to enhance ownership experience. This is related to reliability and the degree to which an operational diagnosis and a prescriptive solutions can foresee avoiding a more serious downtime consequence allowing the user to get his vehicle repaired effectively in a more event driven but service friendly way – see

Vacante, (2001). Reliability Centered Maintenance or RCM is used to guide design of systems through a support strategy typically related to fleet operations and maintenance level effectiveness.

Take the example of evaluating and establishing design strategy that considers failure effects or life-limited wear-out event as it is a common practice to lay against a population failure distributional effects and how that product knowledge might be managed. Set "Design-To" objectives and targets can then be evaluated early in a design by a method of interrogation of features and characteristics with the purpose to maximize uptime and hence customer satisfaction or mission effectiveness.

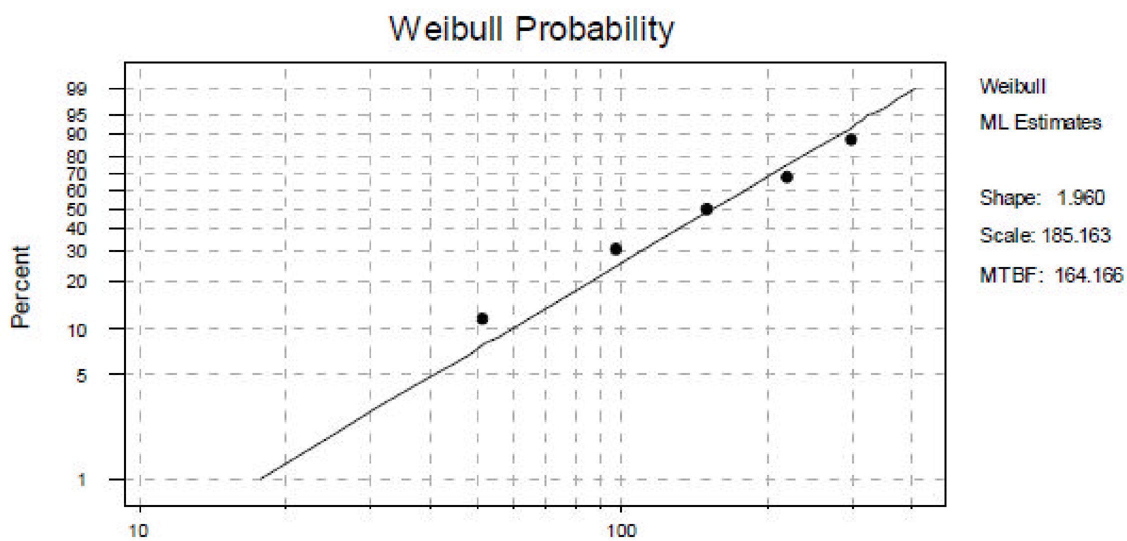


Figure 33. Weibull Analysis of Fatigue Data.

Analyzing data provided by Johnson, (1964) provides one example that shows a part that has failed due to high cycle fatigue that results in a Weibull shape (or slope) parameter of 1.96. The slope/shape factor greater than one, as evaluated in MiniTab™

12, a statistical software package, depicts an wearout or life limiting failure rate with additional usage. This is considered an increasing failure rate over cycles of usage. If the data showed that 10 percent correlated to 100,000 miles then the likelihood of failure in service would be past the warranty level of 5 years or 50,000 miles. The failure would likely occur out of warranty and be born by the customer. If it were an axel it might have a high price and in comparison a lower labor content to fix and seem fair as to cost. However, the effect of an axel failure could have serious satisfaction issues as it is during a time that the customer may be expecting to have it last the duration of his Life-Cycle. The life-limit at a 10 percent life might be interpreted to say it needs to have scheduled maintenance to replace the item and would be in the customer's cost of ownership window.

In the "Warranty Index" method, the interrogation would consider improving the reliability by lengthening the life-limit outside of the sustainability limit of the vehicle or warranty challenge the basic architecture for a more fundamental change needed. Else, it would be transferred to the maintainability element of the assessment and interrogate effectiveness of a scheduled maintenance scenario (element 1.4 in the flow chart ref, Figure 6) rather than a failure event like one with warning cue that can be heard by the driver such as a "clunk sound" or worse, failure without warning. Note – a design failure modes effects analysis or DFMEA risk assessment might capture the undesired effect. To say a component has a life-limit within the window of Life-Cycle ownership then it may need to be improved as in the fatigue life or make the component more easily replaced with respect to the failure.

If the interrogation could lead to a review of design attributes of system architecture - then the system might be able to respond to foundational elements that most products are built upon and are hardest to change in a design cycle. As in the automotive field, the vehicle cycle plan may be conceived many years before a derivative vehicle even gains program status in a development stage relying on past structural design elements and surrogate studies of related systems. Therefore, mitigation of this type of design element is not realizable in the standard product development cycle practiced by the OEM and was similarly proposed by Bryan, et al., (1992), but without follow through within their computer model using an approach as an expert system design approach to serviceability.

Examples of this are found in platform choice to build a top hat or upper portion of a vehicle but commonizing on the chassis components of another exiting vehicle structure that may be too ridged to give a smoother ride desired.

This lack of flexibility carries over into many design elements of the structure. A two-year-to-market needed for a new model builds on known architectures and surrogate data that cannot easily adapt to a desired concept of supportability or serviceability. The consequence expressed in time-to-market is an added delay if one is to improve or fix vehicles with poor serviceability. The consequence of not being able to fix these design requirements will be a continuation of poor quality, warranty losses and customer dissatisfaction and likely loss of market share.

Fault Avoidance and Fault Tolerance in Design

To the above events the treatment in design may consider fault avoidance and fault tolerance to avoid a service event. However, if a component or system is prone to join the low reliability or high frequency of failure classification proposed for use in the binary decision algorithm then the questioning "if reliability can be improved?" is answered by designing systems with improved Fault Tolerance and application of Fault Avoidance. Each method is distinct in approach to increase reliability of systems to overcome challenges or loads that may be greater than strength or capability of a vehicle in the intended using environment as reported by Souza et al., (2005).

What is important in this discussion is not so much what one can do to improve reliability of a component or a system but having systems and design rules that will adequately address systems that will not have improvements for these weaknesses that have historically failed and are therefore candidates for maintenance and strategies of maintainability for individual or fleet owners of automotive vehicles. How this is managed and designed into a vehicle's architecture and will provide a sense of durability and satisfaction when such failures occur or in the contrary levels of dissatisfaction and loss.

A proper design strategy can then take the frequency of occurrence knowledge and the cost of repair (being a function of labor rate, labor time, part costs, and any related other costs) over a warranty period and any out-of-warranty period into the cost of ownership experience or company risk exposure and have a process to minimize this exposure.

If we conclude that the characteristics of Reliability and Maintainability are characteristics of design then one can encompass a broad range of design rules to overcome the notion that maintainability is not a factor in automotive design.

While this paper will treat the objectivity within a maintainability program plan for automotive companies it is sufficient to list the various tools to apply to improve or rather minimize the costs of a repair factor in or out of warranty. Consider the following tools also cited by Souza et al., (2005).

- Redundancy – physical or software; Standby or active.
- Coverage – the property of a system to tolerate failures.
- Diagnosis through – Built in Test and Evaluation, or BITE;
- Failure Detection and Isolation which can be used to activate tolerance features as well as be used by vehicle activities such as in ON-Star.

Clearly, if a failure over time is characterized by increasing increments of time the risk of failure increases. This aging aspect of a design is found in moving components or those that age or degrade with integrity over time and to this end, our modeling for application in our decision logic is to add items like this to the high frequency of failure list but specifically called them life-limited frequency list.

If one wants to improve the reliability, the approach is to add strength to increase fatigue life for example to allow a longer cycle life in comparison to the cycles expected within some safety factor. However, things like tire wear are known and accepted life-limits. These items become maintenance interval items with replacement recommendation to allow maximum performance until they should be discarded or serviced in some way to restore specified performance criteria.

If one considers an engine and its useful life one also considers the lubricant and proper fuels and applications of coolant and its maintenance or change rules to assure optimum performance per a preventive schedule. The obvious lengthening of service life on these items or making an engine more robust to in the presence of noise (dirty oil) the longer life and sense of durability will.

Assessments commonly done that reveal the condition of parts to act in a certain manner when failed or failing is covered in analysis methods such as:

Design Failure Modes and Effects Analysis – a single failure effect understood to be caused by any one of possible several single mechanisms of failure.

Fault Tree Analysis – able to identify multiple concurrent effects of failures to lead to certain failures not identified in a DFMEA – e.g. chance of unintended ignition (spark and fuel rich air).

Reliability Block Diagram - to consider budgeting of failure rates and interfaces and location within a structured system with other methods to estimate and or identify concerns of a reliability performance nature and how to enumerate and validate a prediction for a part or system.

In each case one applies strategies to mitigate the occurrence or changes Design to even minimize the effect. Clearly stated is the finding that fault tolerance methods are applicable to automotive applications due to the complexity to have many micro processor driven systems in a vehicle.

Even systems such as antilock brakes interpret data that is smoothed in averaging while trying to interpret a signal is representing a failed state or just spurious noise yet being able to respond quick enough to offer stability control responses in real time. These design practices prevent a user from seeking service under these less than exact sensing systems where codes set and recover with a key cycle that may have intermittently indicated a fault – this would be the application of fault tolerance.

The "Warranty Index" Interrogates the Design

The proposed "Warranty Index" provides a way to allow an interrogation of the design through a binary decision algorithm and would require a part or work breakdown structure assessment that is respecting architecture and function. The proposed interrogation process asks in a logical and hierarchical way to determine if an outcome referred to as a dependability (D) factor is implemented in a design – which is the "Green Box" (low freq and cost) showing a design is satisfactory and is not on a high frequency list. The designation of three frequency lists comprehensively differentiates design challenges – one for accident caused another for life-limited components and one for low Reliability. The challenges that are failure caused are considered a company risk when a repair is covered under warranty and upon the customer when outside of warranty. The risk due to failure of components due to accidents is significant to the customer especially when not covered fully under collision or comprehensive. Accident causal items are often overlooked beyond the industry standard that evaluates costs of repair benchmarks for public review such as that given for 5 mile per hour crash test cost comparisons given by Mayes and Wassilak, (2004).

A review of the literature by Klyatis and Klyatis, (2006), showed that there is no time in the traditional product development cycle to solve architecture issues. Additionally, this is clearly where data, design concept and true gains as maintenance costs can be optimized. This is especially true concerning the maintained frequency lists from older surrogates. Reliance on surrogate data is a weakness in establishing Design-To-goals for service with no real-time data developed to assess future cycle plans for serviceability. Even a review of service manuals are no longer used to assess design standards for service actions. The assessments, if timely, would influence warranty reduction by design and customer satisfaction thereby improved.

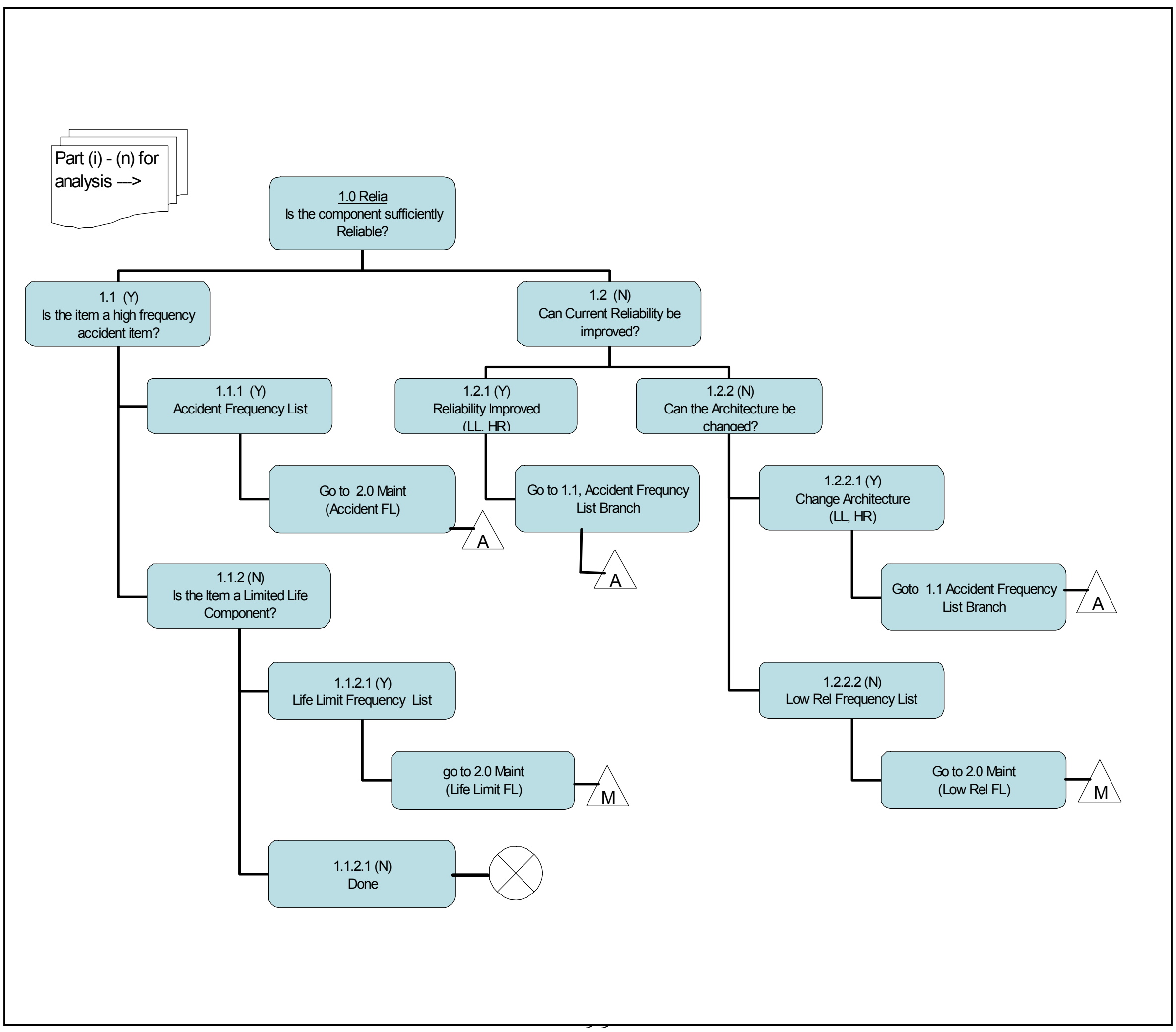
One leverage point to the OEM today is to improve warranty and then offset with an incremental increase in warranty period for same dollar exposure. This ability to stand behind the product reduces consumer risk and is likely to increase consumer buying decisions and is a factor of Durability and longevity.

Additionally, service and support philosophies can be more actively defined that will, by design, have a direct effect and an economic impact on the vehicle warranty, ownership costs and experience.

To capture much of the design concepts in customer – vehicle interface (reference Figure 7) and what drives a service event and what may be included in a service manual. Design efforts and applications of design analysis such as design failure modes and effects analysis considers system effect from the customer point of view but rarely service. Seldom will a design team add service objectives to their design goals and it is rather a specialized team that will try to leverage limited resources to make a design more serviceable with respect to known problems.

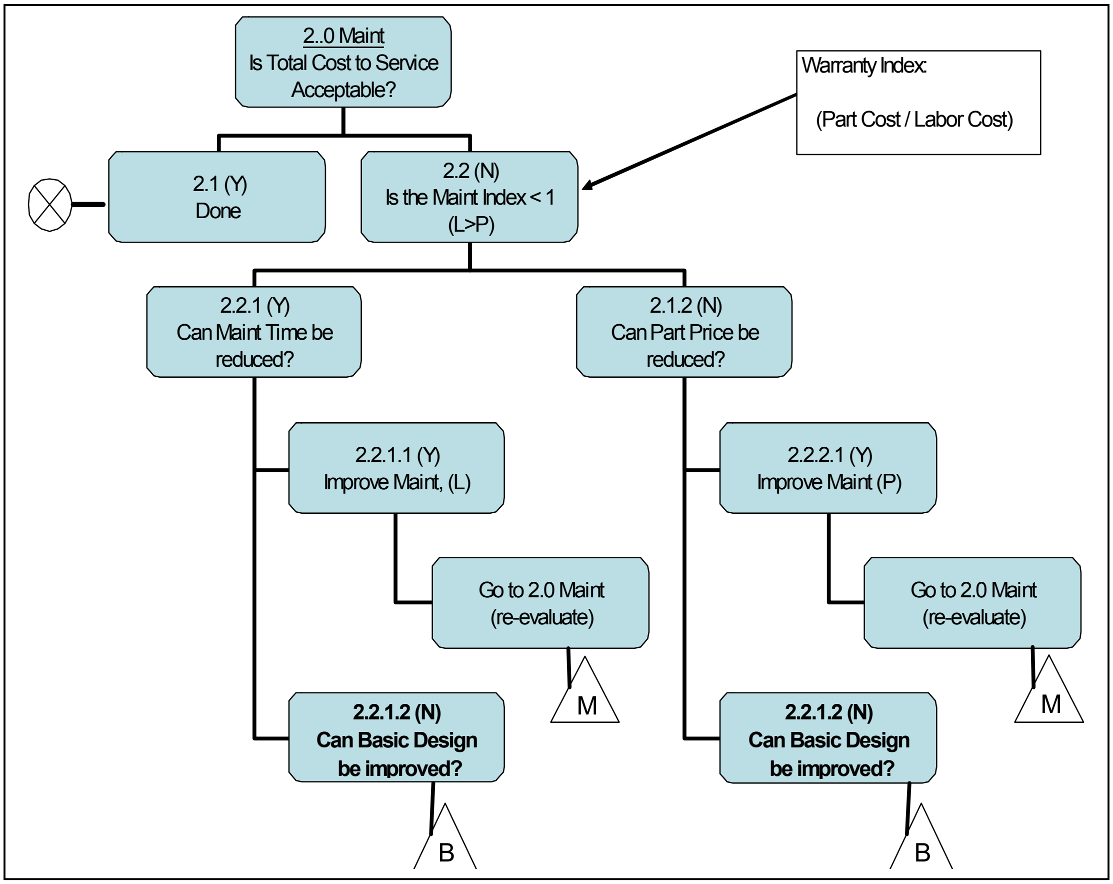
The binary algorithm approach with the "Warranty Index" methodology considers the frequency of occurrence of a service driven event model. Once the design has been interrogated in this way then the maintainability interrogation takes place based on the prioritization of the Warranty Index to prescribe the opportunity in service to improve ownership costs and warranty expense.

Figure 34. Binary Algorithm for Event Frequency.



Here the Part II – Binary Algorithm Model with Warranty Index can interrogate the design for service opportunity. If the total cost of service is low or acceptable, the frequency is not sufficient to drive a change.

Figure 35. Binary Algorithm to Identify Application for Design for Serviceability.



In 2002, Ford Motor Co. published a manual entitled "Designing for Improved Serviceability – NEO" Grzanowski and Long, (2002), and conspicuously the title indicates that it needed improving serviceability in design and that is commendable. This was a revamp from a 1990s version that included reliability in its title. The objectives were to reduce Life Time Costs and improve customer satisfaction and charged the design community with the responsibility. The concept of Life-Cycle cost was also introduced to focus on customer satisfaction rather than warranty cost reduction. The enablers expressed in the training included an understanding of certain check lists to evaluate any "new design."

The buying motives discussed showed a focus on customer's needs and included not just the sales experience but a list of service items:

- Quality repair work.
- Repair when promised.
- Quick service response.

Then the design interrogation for Serviceability would indicate a need to remove labor out of the design. Then the question is asked by how much and what are the obstacles – it appears obvious but access would be one design challenge to consider. Ergonomics might be another. Few can explain why these approaches in the design are so deep but it goes to the interface analysis and the Design-To targets that have not been communicated or benchmarked against best practices.

If one would think that Design for Assembly would cover this as an inverse solution in reverse just consider building from start to finish in sequence to finding the needle in the haystack and trying to break into that orderly building of a system. If one built in modules and it could come at anytime into a series of logical building blocks with few obstacles in the route to take. It is as if you would need a Garmin to do the job well due to the lack of training or skill level that threatens self service. This automated approach may be a good idea for future study to help interactively service of vehicles.

In summary there are 4 areas addressed:

- Scheduled Maintenance – to develop the manuals.
- Cost of Ownership, a life time cost assessment that attempts to understand part and labor costs with the goal or reducing those costs. Part costs are often contractual and labor becomes the biggest opportunity.
- Damageability,
- Serviceability – support in the field and parts availability.

Chapter Five

Conclusion and Findings

A summary of the implications of the study and a discussion of future research show that the study objectives have been satisfied. In addition there was one surprise finding not planned by the study. The study focus was an OEM in an automotive sector.

The study sought to:

- Identify a need for quality improvement
- Utilize existing data structures
- Develop a robust Binary Decision Logic Model to interrogate the data
- Operationalize the change process
- Challenge business process for cost of parts in service
- Establish a means to develop design rules for Design-To Life-Cycle
- Interrogate the logic model with a created index to guide the design
- Create a path to change vehicle architecture or basic design
- Exercise the methodology so it could be repeated by others.
- Identify the scope of the process.

These findings jointly support the objective to:

- Lower warranty costs and
- Lower costs of ownership

The surprise in the study was the confirmation that there is a technology gap or lack of a skill set for the Design Assurance Field within product engineering. However, this might be easily filed by available military program / commercial contracting firms.

With the increase in cost and warranty pressures, Design-To Life-Cycle Costs can satisfy the need to find improved ways to reduce warranty costs and lower the cost of ownership – a period outside of warranty - by leveraging the same cost factors, Parts and Labor in service.

Demonstrating the application of the Algorithm in the Binary Decision Logic Model allows for future study to see how much warranty improvement is possible. The model also introduced that a branch can take the form of a design glide path – where a new function should find its application – e.g. branch 1.2.3 reference the Failure Event Tree, Figure 17. Binary Decision Logic Model – Criteria Defined, where the designer, in response to a failure mode that has no warning can plan to limp home by design rather than be stranded (e.g. current state of a design). The designer selects a branch for the highest degree of safety and customer satisfaction possible.

The approach to identify variability in a given repair code effectively targets the design for improvement. Also, identifying the 3rd quartile upper limit as a threshold “find and fix” is one approach to task a team for improvement as shown in Figure 27. Generating Targets for Design-To Life-Cycle, Cost Category Variability. It has long been understood to reduce variation improves quality. This is another source of variation that can be measured, is developed from a robust data structure, and has common meaning to stakeholders within an organization and therefore can be controlled.

The application of the Warranty Index is a simple tool where it acts as a weighting factor to consider the more expensive element of service costs for the given repair. Using the same factor to understand variability of those cost elements is also open for more investigation to help a design team leverage prospects to reduce variability.

Design weaknesses in the Life-Cycle challenge part pricing strategies and design rules for serviceability. These are activities that are not familiar to the product development community. By use of a fairly simple but hierarchal structure, a binary algorithm being applied, more organizational responsibility can be a part of the design process.

Future Research

It would be a significant advancement if two things could follow this work:

An OEM applies the technology

A durable goods provider with a warranty system applies the technology.

The support for a truly focused DTLCC model is long over due for the industrial markets and building on the RCM methods and strong data sets in this approach is a new green field.

On a more futuristic note, it is the author's findings that the idea of bringing "Maintainability by Design" deeper into the auto industry one can then lead to a new generation of auto-industry profits with a new customer-focused model. Today, many plant capacities are under-utilized due to lower sales volumes. While this may not continue and demand may surge, there is more reason to focus further on the capacity issue where economic pressure has been mounting on dealers with their service claims shrinking due to increased reliability almost universally across the car lines. This decrease in activity needs to be bolstered by increase in sales which is not happening with the current dealer density. Dealer density is likely over capacity and will need some form of consolidation to remain profitable.

This may appear to be the downfall of the historical dealer model. However, a "Maintainability by Design" initiative as revealed by this study will serve better the customer and evolve the dealer network to be an "i-car" personalization dealer or customizer for the customer. With a concept coined herein as the "i-car" - personalization dealers will offer a new view of the dealer service center – one that not just orders options that are a challenge for OEM profitability – but provides a new and vital profit while offering exceptional personalized service. Here the designs for complexity are reduced by modular design concept and the dealer showroom would be a personalization effort. Pricing would be OEM based and not as a service part cost discussed earlier.

This would change the complexity issue with respect to take-rate that has been causing unmanageable configuration control within plants today which do not work out with current sales and marketing methodologies. Removing the complexity would save the system in favor of leaner manufacturing concepts. Modular car themes are not new as they have been displayed at various auto shows but no one has perfected the modularity required for personalization. Commonization, as a cost reduction strategy, would benefit if passed along when complexity is reduced and modularity is developed further into the architecture of the vehicle design.

Appendix

Reliability Bath Tub Curve, Targets and Tasks

The bath tub curve, as a graphical rendering of the failure rate behavior over time, has been used as a training aid in Reliability education. The generic explanation shows a simplification with the Y-axis representing the failure rate, λ, expressed as a function of time or cycles along the X-axis.

The failure rate as a function of time, $\lambda(t)$ as it is more frequently defined as the hazard rate, h(t), that finds its expression in a two parameter Weibull distribution discussed in detail by Roush and Webb (2001):

$h(t) = f(t) / R(t)$ where

$f(t) = dR(t) / dt$ =

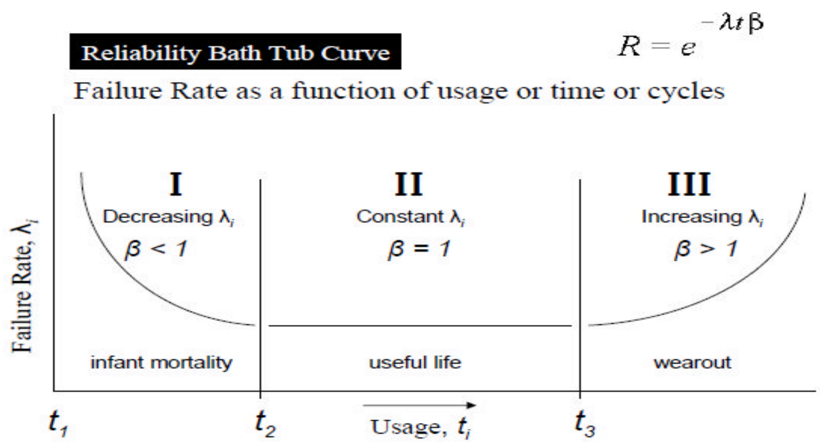
$$f(t) = \lambda\beta(\lambda t)^{\beta - 1} e^{-(\lambda t)^{\beta}}$$

Here, h(t) is just the probability of failure per unit time (failure rate) for those items that have survived to time t, (pp 73-159). Also, the probability density function is given by f(t) and the Probability of Survival to time t is given by the cumulative density function:

F(t) where,

$R(t) = 1 - F(t)$.

Considering how h(t) might vary with time yields three regions of interest that define a useful understanding dealing with aging effects and how one may go about improving the reliability or failure rate behavior. The generalized interpretations as to the cause of the failure rate variation are explained in simplified terms:



Description Region I:

This region has been associated with a range of time or cycles at initial usage at $t_1 = 0$ to t_2, where the failure rate has been observed to decrease with usage. This has often been associated with manufacturing defects due to lack of consistency part to part and assembly to assembly.

Description Region II:

Here the usage ranges from t_2 to t_3 where the failure rate is essentially level where it has been characterized by failures of random and chance. This period has been named the useful life period.

Description Region III:

The period from t_3 to the end of life of an item is where the failure rate is characterized by a wearout condition. Here is where the failure rate increases with each additional unit of time. The onset of this condition can be sudden or gradual as in crack propagation or brake pad wear respectively. What is often referred to as the knee of the curve is the change point where failure likelihood progresses rapidly.

Conveniently, the probability of failure that each of these regions depict is supported by experience and intuition has been modeled by the Weibull cumulative probability density function for which Reliability is expressed as:

$$R(t) = 1 - F(t)$$

or given most simply as the two parameter Weibull model:

$$R = e^{-\lambda t \beta}$$

Where R, is the Reliability and is the probability of surviving to a mission time or cycles.

Given:

t, the mission duration in cycles or time.

β, the Weibull Shape parameter or Weibull Slope.

λ, the failure rate, in the same units as the mission duration

e, the Euler number with approximate value of which is 2.718281828.

$$e = \lim_{n \to \infty} \left(1 + \frac{1}{n}\right)^n$$

Given this landscape of the bath tub curve depiction then each of the three regions can be explored for actionable quality improvement.

Reliability Projects - Region I:

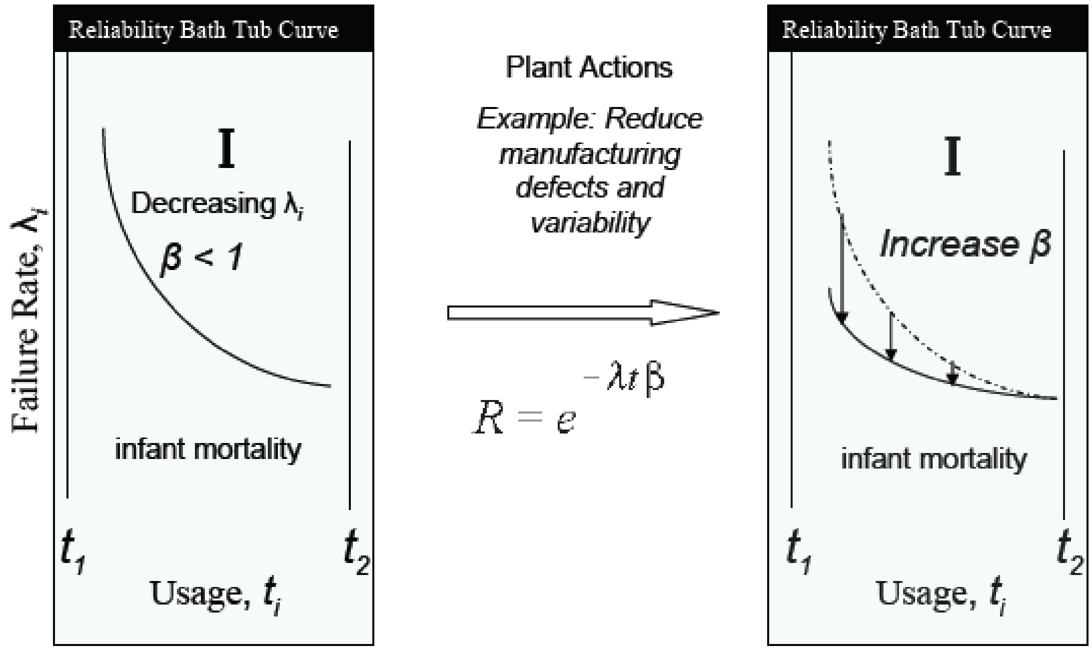
Region I given by: $R(t) = 1 - \int_{t_1}^{t_2} f(t)\, \mathrm{d}t$

The changing failure rate or hazard rate as a function of time decreasing with shape parameter less than unity, one might infer from data modeled in this way that by inspection a flattening of the curve is desirable. Just how to do this given the nature being classified as early life failures can be verified from warranty data that the decreasing failure rate items are made up of start up issues, lack of experience, training, manufacturing defects, and identify that the variability is therefore controllable by the plant directly or indirectly and are not design issues.

Since these types of failures can reveal themselves by in plant data collection, test and inspection and by early fleet or vehicle use it is important to have an early response organizational structure or a focused launch team as processes like burn-in are not typically employed where process controls are of more concern to better quality.

$\beta < 1$

Reliability Projects, Region I.



This would change the effect of the force of mortality over the interval and therefore lower the failure density and improve the overall reliability and lowering warranty costs.

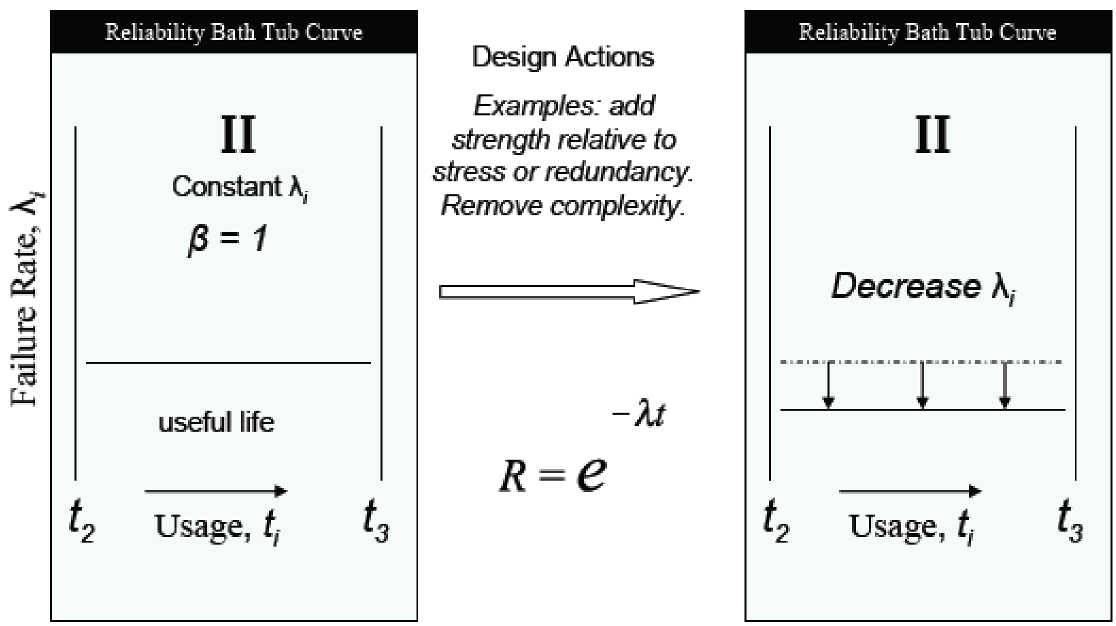
Reliability Projects - Region II:

Region II given by: $R(t) = 1 - \int_{t_2}^{t_3} f(t)\, \mathrm{d}t$

In region II, the hazard rate is flat or constant and does not vary significantly with time. The Weibull Reliability model shape parameter, being equal to unity in this region reduces the two parameter Weibull model to the exponential model:

$\beta = 1$

Reliability Projects, Region II.



The idea that the failure rate is constant over this interval embraces the notion that failures are the result of random loads against random strengths and when the load exceeds the strength as a challenge, a failure results. To correct issues related to loading greater than expected requiring an engineering solution.

One could address the intrinsic reliability of the constituent parts involved and influence event occurrence by adding strength or reducing the load through a transfer function or masking the fault or adding redundancy to mention several reliability actions that can be defined at the mechanism of failure level. One investigation shown by Collins (1993) expresses the use of fracture mechanics by use of critical strength parameters to assure failure predictors can reveal a strength that is greater than stress or loading (p 62) by design.

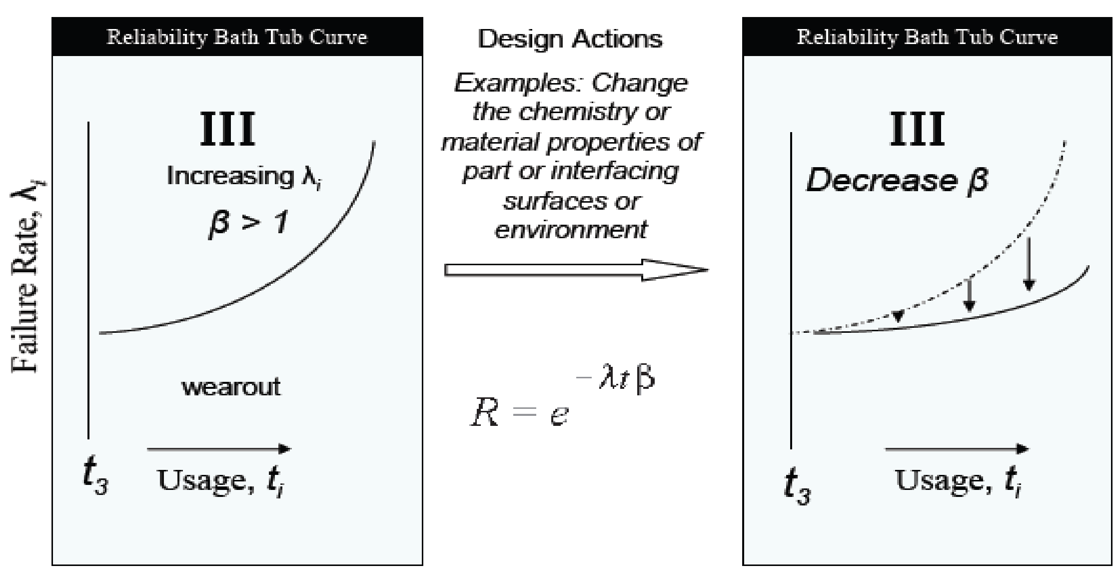
Reliability Projects - Region III:

Region III given by: $R(t) = 1 - \int_{t_2}^{\infty} f(t)\,\mathrm{d}t$

The mechanisms of failure in region III are those that require periodic service or replacement over the Life-Cycle of the product. The design being subject to accumulating damage or increasing degradation with each additional increment of usage cycles needs to be managed in terms of Life-Cycle design practices. With the hazard rate increasing with time or cycles, there is greater risk of failure on the effected systems and components. Items of wear may require maintaining an operating condition such as clean lubrication where the oil itself is a life limited item.

$\beta > 1$

Reliability Projects, Region III.



"knee" of the curve at t_3

Clearly, if the oil change rate can move from 3,000 mile intervals to 6,000 mile intervals, to even 10,000 mile intervals, the reduction in service events, labor and supplies can be dramatic when figured about 10,000,000 cars being driven 50 miles a day over a 10 year life with 1 gallon of oil per change as it would amount to 67,000,000 oil changes and as many gallons of oil to support. When looking at the cost of $25 dollars per event then that would be a cost of $1.67 billion dollars at the 3,000 mile interval rate.

Responsibility for Assurance Actions in the Life-Cycle Design:

In order to more effectively design for the Life-Cycle, a quality organization would need to staff engineering with the needed assurance disciplines. Within in the Design Assurance activities of product design is a skill set that can apply the elements of Reliability, Availability, and Maintainability in a balanced way towards lowest warranty costs and lowest operating costs while maximizing availability.

One needs to ask what is the right value for $\lambda(t)$ and "t_3" for the "knee" of the bath tub curve and address if there is a means to push the curve further out or flatten it. Each manipulation of the design is reducing the density of failure events per unit of time or cycles. Changes that move the failure mechanism and its activation energy might be found in chemical and material properties between interfacing parts to hopefully change the aging effects. Failure mode avoidance may be abated through complex design changes and validation methods.

One other situation may occur if the Weibull shape factor can be increased rather than decreased and be more highly reliable over the Life-Cycle. Here, by more highly organized more highly homogeneous material fabrication it may then possess physicals properties with fewer imperfections that reduce the density of an initiation site of a failure. Instead of failures over a wider area in wearout there is a longer life that does not degrade appreciable until a later in life sharp knee exists.

The type of changes required to affect improvement wear failure mechanisms, latent in a design, require maintenance and maintainability design practices engaged. These latent or hidden life limit failure types required special testing to identify these weakest links in the associated design. One tool shown to be effective as a validation method given by Hobbs (1997) is Halt (Highly accelerated life-testing) or Hass (Highly accelerated stress screening) that looks at validating a design as being able to survive the Life-Cycle (p. 138). In part, testing techniques are applied through overstress tests and then relating them to specific cross sections of application stressors in a multivariate way to help timely identification of a wearout failure mode/mechanism and demonstrate robustness or conformance to a life-limit. Depending on the severity of a given failure, there is significant motivation to avoid potentially and the very high costs of a recall - that goes well beyond fixing a service point.

The Warranty Data Base and Reliability Prediction and Targets.

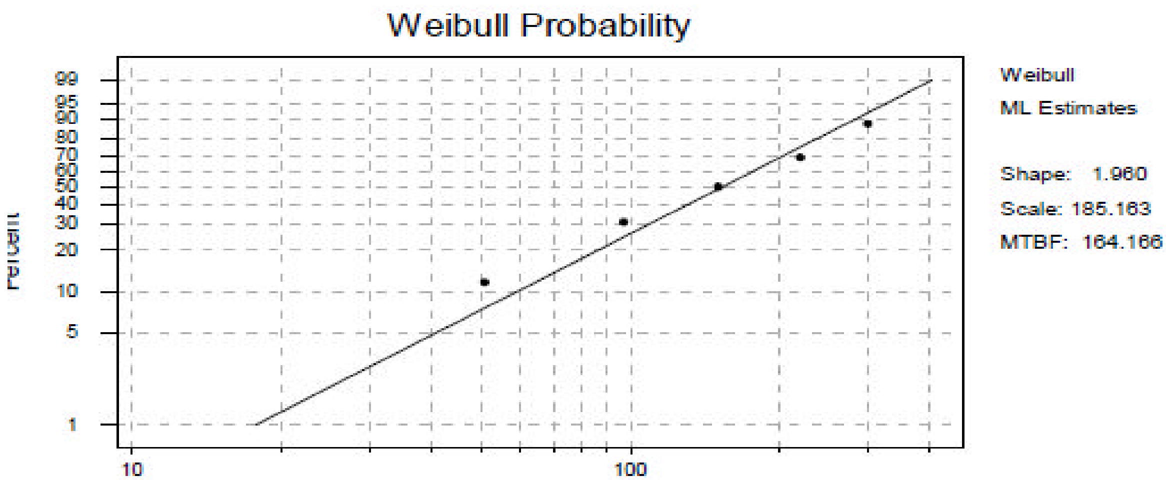
It can be asked, "What enough is or what is sufficient reliability?" The approaches taken can look at a combination of three processes of improvement:

- Benchmark the Competition and Close Gaps.
- A Process of Continuous Improvement drives change.
- Assess the needs and wants of the Customer and develop requirements

Turning to the warranty system to implement improvements one needs to identify specific and contrasting alignments to strategy – that can be complex. One could average data in terms of Repairs per 1000 vehicles sold or one could try to look at component reliability and how requirements have been specified and verified – what ever approach is taken, it must be objective and specific to be actionable.

Towards the objective approach in target setting, one key understanding with respect to the population of service events in a warranty data base is the knowledge that each record represents an independent failed sample. Parts and systems that do not fail are operating as intended. It is often assumed that the rate of usage in warranty is equal to the rate of usage not in warranty.

Once an assessment of the "cadavers" (warranty system records) is conducted and then add to this the population knowledge of how many product are produced representing the sample space one can then project the project population statistics (using Weibull times to failure modeling). The steps are provided below:



Population Statistics from 1st in N.

- Step 1 – Identify the failure code to analyze (3rd Level of depth).
- Step 2 – Collect data of interest
  selecting 1st failure times in sequential building groups of N units or 1st in 1000 statistic where they all have equal months in service.
- Step 3 – Include 5 to 8 groups of N groups.
- Step 4 – Record first failure times in each group.
- Step 5 – Plot the rank order of 1st in N.
- Step 6 – Estimate the Weibull parameters, (λ ,*β)*
  - » Or (characteristic life and slope alternately: (θ ,*β) where θ is the characteristic life or scale parameter of the 1st in N.*
- *Step 7 – Estimate the Population Statistics at the area of interest B.xx life.*

One approach that is closely associated with the repair per 100 vehicles is to consider the production of 100 sequential vehicles and observe the times to first failure per each group. Then through methods developed by Johnson, (1964) the Weibull shape parameter is preserved and an rank order statistic is used to slide the curve with the same shape (slope on a linear graph) by the rank ordering of 1/100 to the full population with failure rate, λ and shape parameter β, (on a linear graph the Weibull slope).

Fatigue Life Assessment

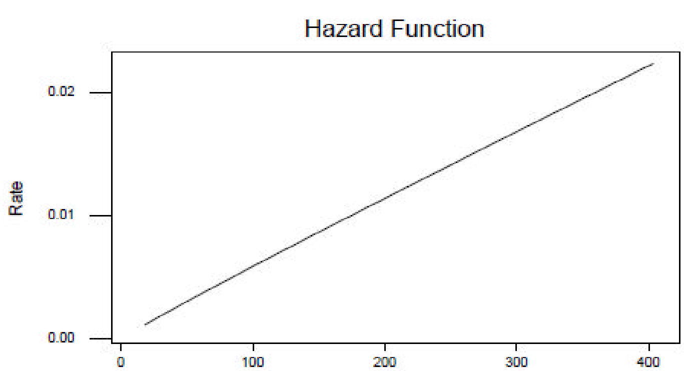
(a fatigue failure mode is found in the field in a high mileage extended warranty fleet)

- Given:
  - Shape Parameter = 1.96
  - Scale Parameter = 185 months.

  (lowest time – 51 months – 1 in 500 and was replaced under basic warranty)

  When:
  - N is groups of 100 sequential same month of production vehicles; failures are first in 100
  - 5 data points plotted
- Rank Ordered projection of Population:
  - Shape Parameter = 1.96 (stays the same)
  - B 63.8% life of sample = B1% life of Population.
  - Read Directly the B1 life of Population = 185 months
  - At 60 miles a day the B1 (or measured life at the B1% failed point) = 333,000 miles.
  - This is a wearout failure slope (β >1) and beyond the 200,000 mile life limit.
- **Observe that the 1st in 100 sampling gives the B1 life of the population.**

The object here is to align programs reliability goals to say a b.01 life in the Life-Cycle period or interval of the fielded system. The b.01 life is that point at which 1% percent of the population will have failed. By taking the first failures per 100 a representation like this in an interval, then one has the characteristic life (scale parameter) point where 63.8% of the population failed at the stated "cadaver" sample life from



warranty and then the population projected directly to the 1% level. The failure sample data set at the 63.8% level equals the population statistic at 1% level - the scale parameter of the cadaver population. From this graphical interpretation that can be made with little knowledge of the entire population that would be prohibited in testing, but having data analyzed in the area of interest (such as the b.01 life) rather than waiting for data over the whole life spectrum. This can help develop testing schemes that are less costly.

To get a sense of the scale of failures in an automotive system it is not unusual that each vehicle on average will come back at least once in 12 months. That would be 100 returns per 100 vehicles per year or an index of 1 return per vehicle in a year – every vehicle returned once in warranty in a first year of service.

Given the usage rate of 60 miles per day and a 10 year period as the Life-Cycle design point, then the average mission is given as 200,000 miles. This would be the durability desired, the point where a sustainable design, one without failure would not have a ‘knee’ until after that point. The variability of the mean life time might strain the Design-To goal of the 95%tile user as the standard. This just goes to show the nature of setting standards for reliability being sufficient and if not make sure it is maintainable.

Glossary

- **Degradation**: Allowable fading of colors, wear, fit, and finish over time.

- **Life-Cycle Cost**s – The process of determining all relevant costs from conceptual development through production, utilization, and phase-out.

- **Maintainability (1)** – a characteristic of design and installation which is expressed as the probability that an item will conform to specified conditions within a given period of time, when maintenance action is performed in accordance with prescribed procedures and resources.

- **Maintainability (2)** - is the measure of the ability of an item to be retained in or restored to specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair.

- **Maintenance** – is the operations – related activities undertaken after a system has failed in the field to keep it operational or to restore it to operational condition.

- **Reliability:** The probability that the product will perform its intended function over time/mileage under specific operating conditions. Expressed another way, reliability is the percent of vehicles, which meet customer requirements (without failure) at a specified time/mileage objective.

- **Reliability Demonstration:** Testing for a useful life period; definition of failure; test conditions (noises); required performance (safety/dependability, high confidence, irritation, cost of ownership); and Sample size.

- **Robustness:** The ability of a product to meet the expectations of the customers (which includes assembly and service as well as the end customers) throughout the range of the noise factors (manufacturing variation, environmental effects, changes over life, customer usage and system interactions). Note: Full Service Suppliers understand these terms rather than to just make parts to specification.

- **Service Contract**: An extended warranty purchased by a consumer to repair an item, reimburse the consumer, and may include a deductible.

- **Useful Life**: 10 years / 150,000 Miles based on 10% of customers will use their vehicles more than 150,000 miles in 10 years.

- **Warranty Cost Sharing**: Financial accountability of the supplier – to reward extraordinary efforts to reduce warranty below the agreed to target or otherwise share in the cost of excess beyond the agreed target.

- **Warranty**: is a contractual guarantee to the buyer concerning product performance. Failure and repair costs are allocated between the manufacture and the buyer. The warranty serves to limit the manufacturer's liability by specifying consumer responsibilities and operating and servicing conditions. Terms may include replacement, repairing, reimbursement.

- **Reliability Centered Maintenance, (RCM) -** developed as a flight line to depot level response strategy for assuring a repair time can be scheduled with little interference to an operational mission.

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