Planning and Validation of Vehicle Degradation using Simulation and Optical Measurements

By

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Submitted to the System Design and Management Program in Partial Fulfillment of the Requirements for the Degree of

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<th>Description</th>
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<tr>
<td>AP</td>
<td>Attribute Prototype</td>
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<tr>
<td>CAE</td>
<td>Computer Aided Engineering</td>
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<tr>
<td>CMM</td>
<td>Coordinate Measuring Machine</td>
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<tr>
<td>CP</td>
<td>Confirmation Prototype</td>
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<tr>
<td>CCD</td>
<td>Capacitor Discharged</td>
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<tr>
<td>DOF</td>
<td>Degree of Freedom</td>
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<tr>
<td>DSM</td>
<td>Design Structure Matrix</td>
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<tr>
<td>DMM</td>
<td>Dynamic Measurement Method</td>
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<tr>
<td>FSS</td>
<td>Full Service Supplier</td>
</tr>
<tr>
<td>FPDS</td>
<td>Ford Product Development System</td>
</tr>
<tr>
<td>J1</td>
<td>Job One</td>
</tr>
<tr>
<td>KO</td>
<td>Kick Off</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
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<tr>
<td>MAST</td>
<td>Multi Axes Simulation table, MTS</td>
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<tr>
<td>NVH</td>
<td>Noise, Vibration and Harshness</td>
</tr>
<tr>
<td>NASA</td>
<td>National Administration and Space Administration</td>
</tr>
<tr>
<td>PA</td>
<td>Program Approval</td>
</tr>
<tr>
<td>PAV</td>
<td>Process, Analysis and verification</td>
</tr>
<tr>
<td>PD</td>
<td>Product Development</td>
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<tr>
<td>PH</td>
<td>Program Hard point</td>
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<td>PR</td>
<td>Program Readiness</td>
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<tr>
<td>QOS</td>
<td>Quality Operating System</td>
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<tr>
<td>RODDYM</td>
<td>Trademark for Krypton Engineering</td>
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<td>RPC</td>
<td>Remote Parameter Control, MTS</td>
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<tr>
<td>RWUP</td>
<td>Real World Usage profile</td>
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<tr>
<td>S&amp;R</td>
<td>Squeak and Rattle</td>
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<tr>
<td>SI</td>
<td>Strategic Intent</td>
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<tr>
<td>SC</td>
<td>Strategic Content</td>
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<tr>
<td>SWIFT</td>
<td>Spinning Wheel Integrated Force Transducer, MTS Corporation</td>
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<tr>
<td>TGW</td>
<td>Things Gone Wrong</td>
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<tr>
<td>VDS</td>
<td>Vehicle Design Specification</td>
</tr>
<tr>
<td>VOC</td>
<td>Voice of Customer</td>
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<tr>
<td>WBS</td>
<td>Work Breakdown Structure</td>
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<td>YIS</td>
<td>Years in Service</td>
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1. Abstract

The present work provides a systemic approach for providing a structural degradation assessment process and technology with respect to high mileage durability attribute of vehicle body structures and suspension modules of automobiles in general.

The focus of this thesis was to develop methodology based on real time system excitations and six degrees of freedom Optical measurement systems for the assessment, prediction and prevention of body structure system and suspension degradation for ground vehicles, which can be customized for a specific vehicle program applications. The goal of the developed technology and methods is to allow program durability engineers and managers to effectively assess, manage and enhance high mileage durability performance targets of automobiles. The thesis work will primarily focus on the car body and suspension degradation measurements and assessments under real time road inputs simulated in the laboratory environment. In this work an attempt will be made to develop procedures and methodology to evaluate implications of structural degradation of a car suspension system and body structures on the high mileage durability attribute design targets such as permanent set of structural elements of the body structures and changes in suspension geometry which affect performance of the subject vehicle during it's useful life.

A combination of real time simulation process and high frequency six degree of freedom (6DOF) Optical measurements will be used to develop systemic methodology to understand relationship between changes in structural degradation of the body and suspension systems and durability mileage of the vehicle in the laboratory environment. Secondly, it also establishes guidelines of how this methodology could be integrated with Product Development process to validate the product specifications and reduce development time and cost. Last but not the least, the proposed method generates a degradation assessment managerial process and its related database that could be utilized to optimize and improve durability metrics that defines the durability performance specifications to maximize customer satisfaction. This implementation of such process may prevent failures such as broken welds, loose screws, cracked sheet metal, and sheet metal movement causing movement of hard points of the structures during life cycle of the vehicles.

This process will help the program development engineers and project managers to define, validate and verify high mileage durability attribute specifications and develop a product design strategy roadmap based on balancing customer requirements and technical feasibility aspects of any program.

Thesis Supervisor: Dr. Daniel Whitney, Senior Research Scientist
Center for Technology, Policy and Industrial Development, MIT.
2. Acknowledgement

I would like to convey my sincere appreciation to Dr. Daniel Whitney, for all his support, guidance and teaching. The relationship with my advisor, Dr. Whitney, through the course of the thesis work remained very open and honest, which was crucial to the planning and completion of this work. During my entire tenure at MIT, Dr. Whitney was very accommodating in listening to my comments, and then provided me with the valuable feedbacks as and when necessary. At the outset of this thesis work, I was very open and ambiguous about my interest to explore several possibilities in this particular emerging technology area in a very loosely defined space, however, continuous and lengthy discussion with Dr. Whitney helped me immensely to bring my focus towards the specific area of high mileage durability attribute in the product development arena. The bi-weekly follow-ups directed me toward different aspects of this issue, which broadened my thought process, and refined the thesis objectives. Since, I completed this work away from the MIT campus, it took an extensive effort in coordinating and conducting the meetings. However, I remain highly thankful to Dr. Whitney, whose patience and experience helped me overcome the difficulties introduced by distance.

Dr. Eleni Beyko's support and vision were essential in the selection of the thesis topic. Dr. Beyko's involvement enabled me to utilize her leadership qualities and expertise in designing and developing the thesis work, which maximized the benefit to Ford Motor Company. I thank Dr. Beyko for finding a time to consult me on the thesis work, and defining a concise direction for thesis. In addition, Mr. Daniel Arbiter's eagerness to make difference at every level of durability attribute and product development process and organization, and his desire to find innovative solutions to the issues of product development
provided me with lots of incentive to work on this topic. Mr. Arbiter recognized the need for a structured solution for high mileage durability assessment, which provided me a lot of encouragement for this work. I would like to thank both Dr. Beyko and Mr. Arbiter for all this support and trust. Last but not the least, I could not fulfill my dream without the vision and support of Mr. R. Folksons and Ms. S. Wrestler.

This acknowledgement would be incomplete without mentioning the timely support of my colleagues: Lynn Morgan, John Good of Dunton laboratory, England, Building#4 Laboratory Support Personnel, Milind Oak, Adnan Khan of Ford Motor Company and Luc Berts of Krypton Engineering, UK. and, my special thanks go to my fellow student and friend, Russ Wertenburg of NASA for his proofreading the thesis and mental support.

Contribution of my family, Mrs. Nanda Mukherjee, my daughters, Anna and Mini, during the entire process is immeasurable. Their immense support and desire to see me excel and succeed, provided me with the much-required perseverance and energy to take upon this challenge, and accomplish it ahead of normal time schedule allowed for the program.
3. Introduction

Ford Motor Company has always pursued a consistent and sincere effort to improve and enhance high mileage durability performances of its vehicles with the objective of maximizing customer satisfaction. Various robust analytical tools such as Finite Element Analysis and Modal Analysis and very crude experimental practices have been deployed to assess the areas that require further improvements upfront in the product development process due to very stringent program requirements definitions. Such metrics and process have paid dividends in the past. Recent customer voices through clinics and independent quality surveys of presently available vehicles have suggested major enhancements required towards high and low mileage durability degradation assessment and improvements of such degradation of body and suspension system, which includes structures, joints and highly non-linear interfaces such as rubber elements etc.

Due to lack of scientific principles and established best practices used to characterize the behavior of body and suspension systems and its interfaces with the chassis elements, significant progress in this particular area has been suppressed in the recent past. Due to severe limitations of CAE process in modeling body structure joints interfaced with highly non-linear material, accurate assessment and prediction of body system degradation and prediction of accurate rigid body movements over life cycle of the vehicle have been highly unsuccessful. It has been proven in the recent past that theoretical evaluation of the body and suspension structures, joints and interfaces along with experimental validation and verification of the analytical results is required to accurately predict body and suspension system degradation over the life cycle of the product.
The primary motive behind the present effort is to develop a systemic approach that will enable product development engineers to assess the degradation and take upfront steps to prevent such degradation to maximize customer satisfaction.

This work takes a systemic approach to the experimental solution of a complex system problem through a holistic view of the durability development and assessment process in the Ford Motor Company. Another focal point of this thesis is to develop a experimental methodology based on real time system excitations and six degree of freedom Optical measurement systems to predict and characterize body and suspension system degradation in the laboratory during structural durability runs and use such database to take upstream steps during product development process to prevent ungraceful or unpredicted body and suspension system degradation during the early and later phases of vehicle life cycles. The project will also make an attempt to validate and verify analytical results as obtained using linear and non-linear finite element principles and tools. The primary goal of the thesis work is to develop body and suspension attribute development procedure, which can be customized to satisfy and optimize any specific vehicle program application. This process will also enable program design engineers to effectively deliver vehicle program body and suspension design targets with a reduced attribute development cycle time allowed for such program.

There are several advantages derived by such process for body systems depending on the type of program styles and requirements. In case of programs with carry over body structures with minimum modifications, such techniques will be used to optimize the body structure to satisfy or improve weight constraints without sacrificing other desirable body attributes such as stiffness, NVH requirements etc. For new platform vehicles with new body styles, the
developed procedure will assist body attribute development team to validate the analytical results and define the improvements required to satisfy body degradation program requirements. In essence, this method, if developed and applied properly, has potential of reducing product development cycle time and satisfies both internal and external customer requirements. In addition, it will assist new program team members in learning the body design and development process and limitations thereof. Management, on the other hand, can utilize the developed process as a primary validated and verified indicator to estimate variation of body system attributes over design life and effects of changes in the vehicle program. Understanding the complexities of body system and its role in vehicle property degradation will also help the management to estimate and effective deployment of resources in the future programs to avoid any program difficulties in advanced phases of the development cycle.

The present thesis work is an attempt to address the following aspects of the development process:

- Methods to predict Body System Structural Degradation Process
- Methods to predict Suspension System Structural Degradation Process
- Determine Tasks and program timing relationships
- Determine complexity level for the Body System Design and steps required to satisfy program requirements
- Establish program timing interferences and resource requirements
- Define roles and responsibilities of the involved teams of engineers
- Define and assess dynamics of interaction between design engineers, durability engineers and test engineers
- Identify tools, resources and guidelines to extend this method for other potential areas in the manufacturing areas
- Identify types of degradation and classify failures due to degradation
- Predict when different kinds of failures occur during vehicle life
- Identify cascade failure situations and design them out
4.0 Historical Background

In recent past, customers are becoming increasingly aware of the high mileage durability issues of automobiles worldwide in addition to features and safety of the vehicles. Product quality now includes durability requirements to achieve highest level of customer satisfaction and stay ahead of the competition. Hence, durability attributes and long term vehicle performances have to be added and monitored in the system design specifications during product development cycle. To respond to this requirement, automobile manufacturers are driven to stringent design and test specifications with respect to robustness and reliability of the vehicles throughout the life cycle of the vehicle. The products are being enhanced to include design targets and specifications that will augment the durability life of the vehicle. Customers are demanding a pre-planned graceful degradation of vehicle's performances instead of random failures or failures during various phases of the vehicle's life. To assess high mileage durability aspects of vehicles, manufacturers and designers are in constant search for innovative process, methods and equipments that can accurately assess performance degradation of critical modules such as suspension and body structures.

The next few paragraphs provide additional overview of durability attribute, degradation assessment and measurement for automobiles in the laboratory and methods to predict such behavior during durability testing using simulated drive files and active measurement systems.

4.1 Emergence of Durable Design Considerations

The history of the early automotive design in the recent past was based initially on a philosophy that emphasized features and styling rather than performance requirements
throughout the life cycle of the vehicle. At that early period, vehicle power, speed, size and even ride characteristics were predominant factors in customer's mind for selecting any particular vehicle. Recent customer satisfaction survey has shifted the focus towards high mileage performances. This emergent requirement with regard to durability performances of any vehicle has become a symbol of quality for automobiles. Moreover, emergence of such requirement has motivated the manufacturers, specially Ford Motor Company to continuously implement durability and performance assessment methods and procedure in the laboratory for the complete vehicle systems both in laboratory and proving ground using real world usage profile (RWUP), various road conditions and environmental conditions. Vehicle Design specifications have been modified to address the high mileage degradation issues for systems and components. Influenced by the competitive environment, durability attribute requirements of vehicles have become intertwined with synonymous to vehicle features, safety and comfort requirements. Today's automotive manufacturers are trying to achieve highest customer satisfaction by proving comfortable transportation, which is more than the worth of the money they spend.

Presently, vehicle design considerations at the system level include specifications that improve high mileage durability issues at a very early stage of product development cycle. The system level design specifications are cascaded for system, sub systems and components. Test and methods are developed to verify and confirm such specifications at several stages of product development. This work also addresses the measurement methods for such durability tests during laboratory verification and confirmation testing. Design, analysis and test engineers all work in unison to design and produce a vehicle, which maximizes customer
satisfaction. Total quality of the vehicle blends all the attributes such as durability, features, safety and aesthetics.

4.2 Evolution of Durability Attribute

Ford Motor Company operates in an incredible competitive and matured market with excess capability and capacity everywhere. Therefore, customer-perceived value becomes central in new vehicle selection. Durability has been determined to be a key element of customer perception at the time of purchase decision. Hence, high mileage durability has become a corporate imperative. Every manufactures is spending enormous amount of resources to become undisputed durability and reliability leader.

The durability applies to the whole vehicle i.e. primary structures such as suspension, body etc., secondary structure such as seats, brake lines etc., tertiary structure such as interior trim etc. and non-structural items such as paint, fabric etc. In Ford Motor Company, the quality target setting for vehicle design specifications (VDS) represents the functional targets over the vehicle life. The basis of the target setting is dependent upon the functional degradation levels over time collected during past durability tests on various vehicles. The goal of durability is to assure that the customers will be satisfied with the function, performance, look, feel and safety throughout the useful life of the vehicle. Durability includes quality, reliability, acceptable NVH and vehicle dynamics for expected life of the vehicle.

The durability is impacted by decisions made by many engineering disciplines of the company. The durability of products delivered to our customers is impacted mainly by design process, usage and service conditions, CAE analysis and prediction of life, physics of failure, testing etc. In practice, many several quality indicators such as 3-year in service (YIS)
customer satisfaction, warranty cost per unit, 3-YIS TGW, have been related to durability attribute of any vehicle.

4.3 Evolution of "Performance Degradation" as a Durability Attribute Requirement

As the automobile market has matured to its present state of affairs, process and quality aspects have gained importance and dominance over the innovations and features of any automobile. Every manufacturer has changed their focus primarily towards monitoring changes in the consumers' hierarchy of attributes and adjusts to changing consumer priorities. The market has shifted big time from type/price/brand dominance towards quality/service orientation. "Performance and Features" has been subdued by "Reliability and Robustness".

Durability and reliability under Real World Usage Profile have been the single most important attributes to achieve highest customer satisfaction. Amount and nature of high mileage performance degradation of the vehicle have been found to determine the reliability and robustness of the vehicle system as a whole. To satisfy this recent customer high mileage durability requirement and address this quality issue, the mission of Ford Motor Company has been defined to maximize shareholder value by developing efficient, durable, and reliable vehicles those are desired by our customers and to provide value and consistent function for 10 years and 150,000 miles for the 90th percentile customer. The mission is also to develop the processes and procedures to design and verify these vehicles at high quality and low cost. Initially, end quality was not given due consideration as much as the "Things Gone Wrong" during first few months of the vehicle in service.
Consequently, prediction and assessment of system performance degradation throughout the vehicle life has become an important design parameter. In addition to features, performance, manufacturability, serviceability, cost and safety of the vehicles, degradation of system and sub-system performances have become a design attribute that will embrace both durability and reliability. The design engineer has to bake all these aspects into design of the vehicle and follow the maxim" Form follows Function".

Performance degradation has been defined to be the undesirable change, over time and real world usage profile (RWUP), in a function of system. Performance degradation data for the systems has to be measured and monitored during vehicle durability testing and the benefits of using degradation data in predicting quality of the vehicle are numerous and they could be summarized as mentioned below:

- Degradation data yields a picture of incremental change of performance over time
- It enables robustness analysis over time
- Such study enhances long term understanding of the system and its failure modes
- It provides higher confidence in quality prediction than failure time analysis
- It may lead to analytical model of the failure mechanism

Understanding the pattern of degradation can allow the design engineers to use shorter test periods with few or no failures to predict long-term performance. Degradation analysis culminates into more meaningful information regarding the failure mechanism of the components of the assembly than provided by a series of tests, which record only failure modes and time at the failure. Eventually degradation testing and measurement of system performance parameters precede degradation analysis. Even if there is no identifiable failure of any system during the use of the vehicle, performance of the system may deteriorate beyond the level of customer's expectation, which is very crucial to achieve highest customer satisfaction.
4.4 Corporate Initiatives to respond to the Durability attribute Requirements

The durability target for any vehicle in Ford Motor Company has been enhanced to 10 years/150K miles to achieve higher customer satisfaction. The move from component orientation to systems orientation has been put in place to focus on system level degradation instead of component failure and robustness. The aggressive vehicle level targets are being deployed through quality and vision strategic change towards increased focus on customer and vehicle function through higher-time-in-service. Laboratory, Proving Ground and fleet data also are collected to indicate the quality of the vehicle. Eventually, "Key Life Test" has been designed for system and sub system level of several modules, such as suspension, body, steering system, brake system etc. to address the high mileage issues. The measurement of performance degradation has been the single most important factor for these key life tests as described below.

The system level key life tests and procedures have been developed to address the high mileage durability issue in the laboratory after years of research and methods development. Engineers used the field data, proving ground experiences with series of vehicles, fleet testing data, real world usage profile and available core technology to design the key life testing procedures to conduct a customer correlated key life test in the laboratory. These testing procedures derived the need for instrumentation, data acquisition and data processing procedures to evaluate the system and sub system level modules such as Suspension, body structures etc. in the laboratory environment. In order to assess the performance degradation, special instrumentation schemes and procedures were required to collect real time behavior of the system. To simulate the road surface events in the laboratory simulation equipments
have been designed and special software has been developed to drive the simulation equipment.

These input devices are meant to provide dynamic inputs to the vehicle in the laboratory to create equivalent proving ground responses for the vehicle system. It took more than a decade to perfect this simulation technology for chassis and body system testing. Recently another new technology has been deployed to measure suspension and body performance degradation during durability testing in the laboratory. This work is about exploring this 6DOF Optical measurement technology in assessing the performance degradation, if any, of systems. The static coordinate measurement (CMM) and dynamic measurements can be done using this technology.

4.5 Degradation Measurement and Testing Requirements

Degradation testing yields an order of magnitude more information per test or prototype than testing-to-failure, just as testing-to-failure yields more information than bogey test that was a norm of the industry sometime back. Both the test-to-failure and bogey test do not yield information on the gradual loss of customer satisfaction due to deterioration of performance prior to "failure". On the other hand, degradation testing provides information about gradual deterioration of performance away from the desired level. Customer satisfaction often decreases substantially when the performance degrades to an undesired level even if there was no hard failure of the components or systems. As an example, customer may notice the gradual or sudden changes in the ride and handling or comfort level of the vehicle during its use. Although the system did not have any failure, customer may be unhappy due to unacceptable rate of deteriorations of the vehicle performances. Increase of
Squeak and Rattle for the body structure or suspension systems may be another example where both system failure and premature or higher rate of degradation of performance may be unacceptable to the customer. Because of this powerful information provided by the degradation testing, it is preferred to the conventional bogey or "test-to-failure" tests. Prerequisites of a successful degradation testing and subsequent analysis could be summarized as follows:

- Time series or repeated measure analysis may be necessary
- Variable measurement time duration may be necessary based upon increase or decrease of degradation rate
- Measurement of the function (degradation characteristic) must not interfere with degradation process being measured
- Proper corrective action should be considered and planned in case of system fails during investigation
- As with any data collection:
  - Dynamic Measurement systems may be required
  - Model or sub system should represent the physics of the whole system
  - Measurement error needs to be much smaller than engineering significant differences that test is trying to detect
  - Measurement system repeatability is also significant in enhancing the confidence of collected data

4.6 Durability Attribute Assessments and Specification Development for "Useful-Life"

Engineers have traditionally relied on a combination of experimental and analytical techniques. In the future, the emphasis for laboratory testing will shift from the development and prove-out of physical components to the development and verification of analytical models. Today, analytical design validation has only been partially realized. For durability, as against for NVH and crash, analytical methods are still competing with experimental tests in an effort to be the first available tool to accurately predict structural performance in a developing vehicle program. Such lagging is primarily due to the nature of attribute being
modeled. Complete modeling of durability attribute, high mileage performance and performance degradation requires that many non linear little known factors to be integrated such as fatigue, abrasion, vibration, rigid body movements coupled with elastic deformation etc. Durability considerations such as fatigue require much more discrete modeling efforts to accurately predict performance degradation.

As mentioned before, the real difference between attributes, however, lies not in how accurately they can be modeled or analyzed, but in how their performance requirements are specified. NVH performance requirements are almost specified with respect to the design-intent structure. Durability performance, on the other hand, is specified over the useful-life of the design. Durability is a progressive phenomenon; analyses for material damage, wear, and corrosion effects must be cumulative. If the "design-intent" structure could be assumed to be unchanged throughout the design's useful-life, the requirements for durability performance would reduce to a simple test of strength.

To enable the development of useful life NVH or durability specifications, NVH and Squeak and Rattle (S&R) performance must be validated over the life of the vehicle. Analytical prediction of high mileage durability characteristics such as NVH or S&R, would, however, depend on accurately modeling the structural degradation associated with all of the durability factors previously discussed. Therefore, to meet extended customer expectations for NVH, S&R, Suspension geometry changes, body structure degradation etc. experimental tools must be employed to simulate both the durability environment, and to measure the affected attribute performances.

To meet the program requirements of developing vehicle in shortest possible time, and due to lack of durability analysis tools, experimental tools for structural vehicle testing such
as Simulation equipments, Krypton 6DOF Optical measurement systems etc. have evolved recently to provide increasing performance and accuracy in simulating the real world usage profiles in the laboratory.

4.7 Durability Attribute Development Procedure

Developing a durable and robust car for its customer in a highly matured and competitive market has always been the primary objective of every vehicle program at the Ford Motor Company. In order to insure that the high mileage durability performance issues are considered at every design level of the vehicle, several measures are placed at the various levels of design and testing process. All the involved personnel in the program including full service suppliers (FSS) and vehicle program management have been held responsible for delivering a vehicle well defined degradation requirements. The objective is to plan the degradation and not to firefight the issue when the failure occurs at random during the life cycle of the product.

However, before discussing about the measurement techniques and test procedures that can capture the durability issues throughout the life cycle of the product, a comprehensive look at the fundamentals of the Product development and Ford's unique product development system (FPDS) is warranted to investigate how and where such issues are addressed in the product development cycle for the vehicle programs. The next chapter will be devoted to get a closer look inside the current FPDS and how durability attributes design and verifications are addressed for the vehicles at the system level.
5.0 Product Development Process and Durability Assessment

This thesis is embedded in the Product Development Track of the System Design and Management Program. It provides useful information in the formulation of product development strategy that will drive program decisions regarding high mileage customer satisfaction requirements and validation and verification of design specifications of system, subsystems and component level design requirements.

This work develops a methodology for building system level durability performance knowledge based to validate and verify system level durability performances at various stages of product development phases. It identifies the structural weakness of a vehicle system and rate of change of structural stiffness and performance requirements with regard to durability, safety, NVH and Squeak & Rattle attributes. The system level performance optimization is also another focal point of this study.

As suggested by Ulrich & Eppinger [1], the prototype is tested to verify that the customer requirements and corporate requirements are simultaneously met. In this stage of the product development process, any shortcomings with regard to attribute requirements should be assessed and resolved before the next stage is launched. Assessment and resolution of shortcoming of product performances with regard to durability and robustness of the vehicle is another important dimension of this phase of PD cycle. In case the problems are not addressed here, product will be launched with unknown and unresolved issues, which will show up during life cycle of the product, and this may mean hefty warranty costs and customer dissatisfaction. Once the product goes through in-house durability assessment and testing, a specific number of vehicles is produced and distributed to a limited number of customers with the idea of evaluation of the vehicle in the real world usage conditions. This
last step is an interim step between confirmation prototype stage and production run. The fleet test resolves many issues that could not be detected during durability testing of the vehicle either in Proving ground or Laboratory as simulated road surfaces and environmental conditions cannot be exactly reproduced.

5.1 Generic Product Development Process

A generic schematic of Product Development Process has been provided by Ulrich and Eppinger [1]. Another version of similar concept for a product development (PD) process consisting of six basic and interrelated phases is illustrated in Figure 5.1.1. Such a generic process starts with planning phase and goes through several sequential phases such as concept development, system level design and detail design, testing and refinement and production ramp up.

The success of product development and PD process implementation depend primarily on the execution of the process. It provides the program management and engineers a roadmap to follow with milestones previously established and well-defined executables and deliverables at each milestone. Follow of such a disciplined process becomes even more critical for automobile production environment where quality, cost and timing need to be simultaneously controlled and managed to remain competitive.
Figure 5.1.1
Matured market environment and stiff competition compel the automobile product development to be highly process oriented and such process has been defined by Ulrich & Eppinger [1] as a "Front-End Process" where high level product related decisions are conceptualized and finalized upfront of the process. The process ends up being a highly iterative and process flow becomes sequential as it passes through the proposed six phases of the development cycle. Although the front-end process starts with the identification of customer needs and ends up with modeling and prototyping, major decisions are taken upfront of the process and actual results are compared at each milestones till the next phase starts. Concept stage of the PD cycle starts with a product direction letter, which is prepared by business planning and Strategy group and marketing group. The product directional letter provides initial program contents, total investment, affordable business structure for the program and program development and launch timings.

In the concept development phase, program team conceptualizes the product design based on the product goals and directives. The conceptual design transforms the customer needs into product objectives using competitive benchmarking, resource estimation and allocation, concept design selection and design target specifications. Vehicle level inputs and requirements are cascaded down for each attributes including durability requirements throughout the life cycle of the product. The process is highly iterative up to the design stage and becomes mostly serial after detail designs are developed throughout system verification and production stages. Moreover, concept selection procedure also depends on the available core technology and manufacturing base of the company.
Design phase emerges out of the concept stage and migrates into product sections at the system level design phase. In system level design phase, system level design specifications and performance targets for each system and sub-system are established. The vehicle level and system level targets are cascaded to the lower level till component specifications and designs are established. In each step, a feasibility study is conducted and feedback is given to the previous level for refinement of specifications at higher levels. Next phase is verification and design validation stages. High mileage requirements for each module are confirmed at this stage to conform to the previously set targets through laboratory, proving ground or field durability testing. The product design may have to be tuned to conform to the specifications that could not be compromised for the product. After confirmation and validation, pilot production is taken up to confirm and validate manufacturing assumptions and requirements. For process-intensive products such as automobiles, production requirements and manufacturing concerns cannot be separated from the design considerations throughout all the phases of PD cycle.

During the full production stage, design-intent production is carried out in a mass production environment. Hard tooling, assembly fixtures and manufacturing strategies are verified in a continuous production environment and manufacturing conditions may have to be tuned to achieve the desired production level for the product. Once pilot production process is established, full production process is launched to ramp up to the desired level of production.
5.2 Ford Product Development Process and High Mileage Durability Attribute

The Ford Product Development Process (FPDS) was introduced in mid 90's. The introduction of FPDS was primarily driven by stiff competition and falling profit. A striking similarity between Professor Eppinger's model of PD process and FPDS can also be observed. Similar to the Eppinger's [1] model FPDS is also very much front-end product development process. The net result of FPDS was an all round success of Ford's success in the years that followed the introduction of FPDS. The themes of the FPDS could be summarized very briefly as follows:

- Voice of the Customer (VOC) focused
- Process driven
- Disciplined and results driven
- Reusability of technology and previous platforms
- System oriented
- Customer Satisfaction
- Shareholder's value maximized

The stages of PD cycles in FPDS are shown in Figure 5.2.1 along with durability attributes' requirements throughout the program. At each milestone of the FPDS process, certain deliverables have to be completed for each attribute. Major deliverables and a proposed scheme of high mileage degradation testing for durability attribute are also outlined in the Figure 5.2.1. The total PD cycle and time durations between the milestones are determined by the nature, complexity and contents of any program. The program complexity is dependent upon its number of design changes required, amount of carry over from previous programs and desired launch time. These levels are designated as scalability levels of vehicle program and higher the scalability value of any program is, higher the complexity and less carry over for the program is expected for any program.
In such cases extreme care is taken to redefine the durability and high mileage degradation requirement for the program as substantial changes are made to negate previously established performances of the vehicle. Scalability level of a vehicle program is established based on amount of design changes and program contents. A common and logical approach will be to start with the available data and record the changes due to change in the design and ensure the new high mileage performances are within the vehicle durability attribute specifications for the program. The assessment of high mileage degradation becomes more critical as the complexity rises.

FPDS has so far played a key role in improving Ford's performance and efficiency. FPDS became a strategic vision of Ford Motor Company. It has helped the corporation to make a bold step towards enhancing quality and corporate image in the eye of its employees and further reducing PD cycle time and cost.

As shown in Figure 5.2.1, the high mileage durability performance testing and analysis at the sub system level (suspension module) should be performed in the laboratory to confirm sub system level requirements of durability attributes. For suspension, castor, camber and toe measurements could be done at different stages of structural durability testing in the laboratory using 6DOF krypton active Optical measurements system when the sub system is excited through simulation corners using road load or analytical input data. The use of 6DOF Optical measurement system in conjunction with the simulation procedures is a new concept in Ford Motor Company and it has been introduced recently in the laboratory for methods development and validation of such method to assess system degradation. The actual displacement measurements can be compared with rigid body movement analytical data to confirm the durability degradation requirements of the module.
As can be seen from the Figure 5.2.1, vehicle level testing is carried out for the CP level vehicle in both laboratory and proving ground for confirmation of durability performance at the system level. At this point, body structure and body joint degradation also could be measured in the laboratory and compared with the vehicle level system design requirements. This proposed method involves the use of both experimental and analytical tools, although analysis methods are becoming pre-eminent to determine many of the structure attributes, which affect the ultimate design. In that case the proposed method could be used for validation of analytical data.

For confirmation of degradation performances, laboratory simulation testing along with sophisticated state of the art active measurement tools using Optical etc. may become a standard combination in the vehicle industry for assessing performance degradations of the vehicle. In addition, use of simulation equipment in combination with active measurement systems allows highly accurate, multi-channel tests to be run in the laboratory in significantly less time than on the proving ground or road. In such proposed method, correlation between accumulated durability mileage and changes in body structural rigid body responses are examined. Using this technique, changes in NVH, Ride and Handling, Squeak and Rattle performances over the life cycle of the vehicle/durability life, can be examined and graceful degradation can be planned and predicted, leading to the eventual development of more comprehensive design specifications which will more effectively address long-term customer satisfaction. This work describes a method how this Optical measurement system could be combined with simulated durability tests in the laboratory to find changes in the system or sub-system performances such as door movements with respect to body or suspension parameters (castor, camber, toe and ride height changes).
SI=Sign Off; SC=Strategic Confirmation; PH=Hard Point; AA=Appearance Approval; PR=Prototype Readiness; CP=Confirmation prototype; SO=Sign Off; LR=Launch Ready; J1=Job One

FPDS/S5 Program

AP Components Available

CP Available

CP Ordered

Sign Off

Corporate/Program Durability/High Mileage Durability Requirements

Instrument Vehicle & Acquire Data

Sub System Level Performance

Suspension Module Performance
6 DOF Optical Measurements

Body Structure Performance
6 DOF Optical Measurements

Engine with Mounts Movement Measurements

COMPARE

Confirmation of High Mileage Performance & Degradation

Laboratory Structural & Body Durability Test

Instrument Vehicle & Acquire Data

Proving ground Durability Test

CORPORATE LOADS DATABASE

CORPORATE LOADS DATABASE

HISTORICAL LOADS

Bookshelf the Data

SUB SYSTEM LEVEL INTEGRATED (CAE & LABORATORY)

FULL VEHICLE SYSTEM LEVEL TESTING, MEASUREMENT & ANALYSIS

FIGURE 5.2.1 Proposed High Mileage Durability Testing and FPDS
5.3 Motivation for Performance Degradation Measurements and Tracking

The primary reason for assessment of performance degradation is to gather data to enhance the performance in the future vehicles. The vehicle level bookshelf data at the production level does help to understand the discrepancy between desired and actual. The objecting of testing analysis is to reduce the error to an acceptable level as per the program requirements.

Due to lack of scientific principles and established best practices used to characterize the behavior of body and suspension systems and its interfaces with the chassis elements, significant progress in this particular area has been suppressed in the recent past. Due to severe limitations of CAE process in modeling body structure joints interfaced with highly non-linear material, accurate assessment and prediction of body system degradation and prediction of accurate rigid body movements over life cycle of the vehicle have been highly unsuccessful. It has been proven in the recent past that theoretical evaluation of the body and suspension structures, joints and interfaces along with experimental validation and verification of the analytical results is required to accurately predict body and suspension system degradation over the life cycle of the product. This work has been dedicated to overcome this difficulty by proving an avenue to measure the body and suspension movements at different level of durability.

There are several advantages derived by such process, as proposed in Figure 5.2.1, for body and suspension systems depending on the type of program styles and requirements. In case of programs with carry over body structures with minimum modifications, such techniques may be used to optimize the body structure to satisfy or improve weight constraints without sacrificing other desirable body attributes such as stiffness, NVH
requirements etc. For new platform vehicles with new body styles, the developed procedure may assist body attribute development team to validate the analytical results and define the improvements required to satisfy body degradation program requirements.

In an highly competitive environment, automobile manufacturers are challenged with designing a vehicle, which satisfies all the customer requirements including safety, features, styling and robust, durable product that has a graceful performance degradation history. It is an enormous task for the engineers to accomplish all the conflicting requirements such as comfortable ride with high mileage durability requirements. These tasks are even further complicated when cost and market considerations are added to these engineering requirements. This has been a historical fact that a long-standing product has always very slow rate of performance degradation.

Survival always goes to the fittest among the competition. Survival strategy is not always a good strategy for long run. Automobile manufacturers must come up with products that excite customers along with assured quality for the product. Since PD cycle time is reduced to such a point that any downstream surprise near the launch time is very detrimental to the success of the program. Hence early evaluation of performances and its degradation characteristics will allow engineers to accurately fix the problem before the problem is dictated during manufacturing or confirmation stage. Vehicle program management and engineering team constantly try to come up with a vehicle that has most features blended with highest quality and durability. The limitation is the vehicle cost and program investment required. Hence, this delicate balance of feature, quality, durable product Vs. cost to manufacture it requires a disciplined product development approach and conscious effort, with the flawless execution in manufacturing.
5.4 Program Specific Advantages of Durability Assessment in Laboratory

The proposed method generates a degradation assessment process and its related database that could be utilized to optimize and improve durability metrics that defines the durability performance specifications to maximize customer satisfaction. This process will help the program development engineers and project managers to define, validate and verify high mileage durability attribute specifications and develop a product design strategy roadmap based on balancing customer requirements and technical feasibility aspects of any program. We also develop a framework on how to use the 6 degrees of freedom Optical guided high frequency real time digital measurement system in combination with the subject vehicle and real time excitation inputs to the body systems and how to utilize and manage the data in predicting and preventing system level degradation worse than customer expectation during the whole life cycle of the product. This process also can be very well used to optimize the system level durability performance for the vehicle.

There are several advantages derived by such process for body systems depending on the type of program styles and requirements. In case of programs with carry over body structures with minimum modifications, such techniques will be used to optimize the body structure to satisfy or improve weight constraints without sacrificing other desirable body attributes such as stiffness, NVH requirements etc. For new platform vehicles with new body styles, the developed procedure will assist body attribute development team to validate the analytical results and define the improvements required to satisfy body degradation program requirements.
5.5 Proposed High Mileage Degradation Planning & Validation Implementation Plan

The durability and test engineers are constantly trying to come up with methods and process for different component level key life tests and full vehicle level simulation tests. Such a design process to address the high mileage durability issues should also consider other considerations as mentioned below:

- In alignment with corporate objectives, time and financial constraints
- In alignment with current FPDS process
- Empowers durability and test engineers to come up with means, process and resources to address high mileage durability issues
- Interacts with management to ask for help whenever desired
- Follows the defined process and be innovative when faced with challenges

In spite of extreme care thoughts given to design the durability process and its targets, more often than not surprising events do occur due to several external noise factors that cannot be controlled in a timely fashion. Environmental conditions such as temperature, chemical reactions with environments, human reactionary forces and emotions under panicky conditions, are very difficult to incorporate in the key life and simulation tests. Such variables are the elements, which should be dealt with in order to have planned performance degradation for the vehicle.

Although unpredictable and difficult to reproduce in the laboratory, such incidents are found to strikingly similar and common for many vehicle programs. One such common incident is the engine mount performance degradation at a much higher rate than anticipated and planned for. The higher rate of performance degradation of stiffness and damping characteristics for the control arm bushings is another example.

Due to temperature dependency and material non-linearity of the rubber material, accurate prediction and design of such elements using purely theoretical and analytical means
becomes almost impossible. Another such example is the body/door squeaks due to changes in hinge properties. In all of these cases, elastic and rigid body movements are involved to affect the performance of these elements. Although some directional trends could be achieved for elastic movements of rubber elements using non-linear CAE analysis, effect of rigid body movements on the performance cannot be assessed and predicted. In such cases displacement and rotation measurements of elements become almost mandatory to predict the behavior. To assess these behaviors, dynamic Optical measurement system along with simulation equipments are only available tools in the industry at the present moment. CAE analysis provides direction and laboratory tests and measurements provide confirmation and validations.

The complete high mileage durability process is shown in Figure 5.5.1. The workflow for this thesis, as shown in the framework, is divided into mainly four segments. The final documentation and program implementation phase will be left for the program engineers to flow depending on the nature and type of program. The complete high mileage durability process has been divided into four interrelated phases: Exploration phase, Execution Phase, Analysis, verification and validation phase and, lat but the not the least, documentation and program Implementation Phase. Due to absence of accurate CAE data for rigid body analysis, CAE correlation of the degradation measurements will not be addressed in this thesis. This work provides a process to layout the plan and methods development for degradation measurement using simulation engineering in the laboratory environment.

These steps are embedded in the durability attribute development and confirmation process, which is required at every stage of the program as shown in Figure 5.5. 1. The
planning for these actions and sequence of events could be developed and planned using DSM developed by Professor Eppinger of Sloan School, MIT.

The flow diagram for various tasks for the proposed generic degradation attribute process is shown in Figure 5.5.2 & 5.5.3. The task and information dependencies are also shown in the Design Structure Matrix (DSM) in Figure 5.5.4. The information flow diagram has several sequential, parallel and coupled task activities as shown in the matrix as well as in the information-processing view [1]. The tasks were listed in the sequential order in which they would be executed during the degradation assessment and resolution. The original order of tasks were sequenced or partitioned such that the tasks are ordered as much as possible according to sequential dependencies of the tasks.
Exploration Phase

Select and Study Vehicle Line
Study Analytical Data for the Vehicle
Study Existing Measurement Systems and Process
Study Body System Design requirements and Process

Execution Phase

Determine Test System Requirements
Determine Test vehicle Excitation Levels
Fix the Measurement Set ups along with Optical Apparatus and Subject vehicle
Set up analog Measurement plans and A/D Conversion
Collect data and validate the data on Line, Static and Dynamic
Interface with Program and CAE for data collection and validation
Finalize the Data Base

Analysis, verification and Validation Phase

Compile and Validate Data
CAE Validation and Verification of Data
Vehicle Degradation and Mode Shape Mapping
Degradation and Mode Shape Prediction
Confirm Results with Program Prediction and requirements
Compile/Verify System Analysis Data

Documentation and Program Implementation Phase

Document/Book shelf data and Process
Share results with CAE and Program Design Engineers
Finalize the Methods for a typical Body System Degradation Measurement Process
Develop, Execute and Implement the process for another platform vehicle Programs for confirmation (Database)

FIGURE 5.5.1
EXPLORATION PHASE

- Select and Study Vehicle Line
- Study Program Timings and Plans
- Study Body System/Suspension Degradation Requirements
- Study Existing Measurement Systems and Process
- Determine Mode shapes, Measurement points

EXECUTION PHASE

- Determine Test System Requirements
- Set up analog Measurement plans and A/D Conversion
- Fix the Measurement Set ups along with Optical Apparatus and Subject vehicle
- Collect data and validate the data on Line, Static and Dynamic
- Finalize Data collection plan, number of data sets along with CAE, Program
- Determine Test vehicle Excitation Levels
- Finalize the Data Base

TO ANALYSIS AND VERIFICATION PHASE

FIGURE 5.5.2
ANALYSIS AND VERIFICATION PHASE

FROM EXECUTION PHASE

Compile and Validate Data

CAE Validation and Verification of Data

Degradation and Mode Shape Prediction

Compile/Verify System Analysis Data

Vehicle Degradation and Mode Shape Mapping

Confirm Results with Program Prediction and requirements

DOCUMENTATION AND PROGRAM IMPLEMENTATION PHASE

Share results with CAE and Program Design Engineers

Document/Bookshelf data and Process

Finalize the Methods for a typical Body System Degradation Measurement Process

Develop, Execute and Implement the process for another platform vehicle Programs for confirmation (Database)

FIGURE 5.5.3
FIGURE 5.5.4

**Task Legend:**

A= Select and study vehicle line;
B= Study program timings and plans;
C= Study Body/suspension Degradation Requirements;
D= Study Analytical Data, Vehicle
E= Determine Mode Shapes, Measurement Plan;
F = Study Existing Measurement Plan
G= Determine the Measurement Process and Plans in Laboratory;
H= Interface with Program and CAE for data collection and validation;
I= Determine Test System Requirements;
J= Set up measurement plans and A/D conversion;
K= Finalize Data Collection Plan, number of data sets along with CAE diagram;
L= Determine Test vehicle Excitation levels;
M= Fix measurement set ups along with Optical apparatus and subject vehicle
N= Collect Data and validate the data on Line, static and dynamic;
O= Finalize the data base; P= Compile and Validate Data;
Q= CAE Validation and verification of data
R= Degradation Results with program prediction and requirements;
**Task Legend:**

S= Compile/verify system analysis data;
T= Vehicle Degradation and Mode shape mapping;
U= Confirm results with program prediction and requirements;
V= Share results with CAE and program design engineers
W= Document/Bookshelf data and process;
Y= Finalize the methods for a typical body system and suspension degradation measurement;
Z= Develop, Execute and Implement the process for another platform for confirmation
5.6 Deliverables of Degradation Planning and Validation Process

As previously mentioned, every vehicle product development process is derived from the currently approved Ford Product Development System, FPDS. Project management team and engineers are responsible for customizing this development process for a specific program without violating clearly laid hard points and deliverables at each milestone. The nature and amount of such customization is primarily based on vehicle program complexity, scalability, and Job1 date and program contents. These factors lead to the definition of deliverables for each attribute at each milestone. The degradation aspect of the product development process becomes a sub set of durability attribute, which has deliverables throughout the development process.

Degradation, being one of the important aspects of durability attribute, drives the design and durability attributes inside the overall umbrella of FPDS process. The performance degradation deliverables along with durability deliverables are aligned throughout the vehicle program milestones, deliverables and durability objectives. The Figure 5.7.1 shows a generic performance degradation development process with respect to vehicle program milestones. The generic durability development including degradation process as illustrated in the Figure 5.6.1 shows that, degradation work starts with from the initial stage of the vehicle program, Kick-off<KO> and continues until the last stage, <J1>, milestone.

The degradation and durability development ramps up after Strategic Intent Stage, <SI>, where vehicle level targets are specified and vehicle architecture is defined in line with the program direction letter. Also, vehicle program prototype requirements, new technology requirements such as simulation and measurement system requirements, and
high level design trade offs are established to obtain a preplanned degradation requirements for the full life cycle of the vehicle. At the Strategic confirmation, <SC>, milestone, system level degradation and durability targets are specified, initial verification plans are developed, equipment supplier selection is finalized and durability team along with CAE and test engineers verifies vehicle level degradation objectives and process to fulfill the requirements.

After the Strategic confirmation milestone, <SC>, durability engineers lead the degradation and durability attribute and guide the design engineers to achieve the required specifications. The team specifies sub system and component level designs to have enough robustness so that when they are assembled together, the system level performance degradation will be met. This may mean to have higher factor of safety at the component level. The sub system level targets are specified at the program hard points, <PH>, milestones, which are derived from the combination of durability and design requirements and specifications.

The program approval milestone, <PA>, seems to be a pivotal point in the process where the whole program team commits itself to the vehicle level design requirements that will satisfy the degradation and durability objectives of the vehicle throughout the life cycle of the vehicle. This process could be termed as planned degradation objectives of the vehicle. The design and durability team together resolve all the major design and testing issues, establish design and durability specifications and establish the verification and confirmation plan. The transition from design intents to verification process occurs at the program approval stage, <PA>. 
The verification stage starts with the confirmation of component level targets. Since, full service suppliers, FSS, are selected at this stage to manufacture and deliver the components with desired level of durability requirements, this stage is very crucial for development of degradation planning. Component level verifications and testing plans are established at the SI stage. The design and durability verification process continues till program readiness milestone, <PR>. The intended product design from the component to the vehicle level should be verified, and durability team is responsible for analytically sign-off the vehicle program durability attribute objectives along with degradation requirements.

FIGURE 5.6.1
The high mileage degradation team has to interface with the program durability team as shown in Figure 5.6.2. The degradation team takes the input from the customers and design group and come up with the degradation plan for the vehicle and relays the requirements back to design, CAE and durability teams. The requirements are then taken into consideration while designing the parts and the same information is passed to full service suppliers to design and test the components accordingly. The high mileage degradation team will confirm the requirements at the CP level during sign off stage as shown in the flow diagram.
FIGURE 5.5.2

Design Specifications (SDS) using Core technology

Customer Inputs from Quality Survey

Relevant Design Information from Previous Programs

Program Durability Team

Confirmed Design Concepts to support Degradation Specifications

PAV CAE Team

VEV Testing

Full Service Suppliers (FSS)

High Mileage Degradation/Durability Validation and Sign Off

CP Sign Off
6.0 Test Procedures and Set Up for Simulation and Degradation Measurement

The current procedures for vehicle level structural simulation testing and 6 DOF Optical measurement system involve the use of both experimental and analytical tools, although analysis methods are becoming pre-eminent to determine many of the body and suspension degradation over the life cycle of the vehicle. For durability performance, however, experimental methods are still the primary tools used for structural degradation validation and structural durability performances. Laboratory simulation testing has become a standard tool within the ground vehicle industry for assessing structural durability and degradation. In addition, the use of response simulation software such as RPC™ allows highly accurate, multi channel tests to be run in the laboratory in significantly less time than on the road or proving ground.

6.1 Degradation Assessment: Experimental and Analytical

To verify a vehicle's degradation of performance in the areas of body and suspension system and durability, engineers have traditionally relied on a combination of experimental and analytical techniques. Increasing availability of low-cost computing power in the recent past has allowed the engineers to develop analytical CAE tools and procedures which ha shifted the focus of PD process from the physical testing to digital world. A gradual migration of physical testing to digital world has been noticed during last two decades due to reduction of development time and cost. Increasingly, laboratory facilities are being viewed as interim tools for design evaluation and such tools are being gradually replaced by robust analytical method to evaluate and confirm designs. While long rage visions do call for the
laboratory facilities and equipments, their projected role is imminently changing. In the immediate future, emphasis for physical testing in the laboratory will gradually shift from development and prove out of physical components to the development and validation of analytical models to make the analytical tools and process more robust.

At present, the success of analytical tools is very marginal and limited and the achievement has not been very spectacular. State of the art tools for modeling vehicle structural performance for NVH and Safety attributes are fairly mature, given a thorough understanding of the associated system structure and loading conditions. While physical testing for NVH and Safety are still being conducted, these are very often required to verify performance that has been predicted analytically, and as an aid to improve the modeling tools. On the other hand, for durability, analytical methods are still behind the physical testing arena with respect to structural performance and degradation evaluations. Analytical methods are still competing with experimental methods for such verification as present analytical tools fall short of high confidence level that is required for such tests. Accurate prediction of degradation and confirmation of specifications have been far away from the actual behavior of vehicle system as such.

The deviation of predicted results from the real life experiences is mainly due to the fact that methods for modeling structural durability performance are incapable of modeling real life situations within the stipulated time. Part of the explanation is due to the nature of durability attribute being modeled. Complete modeling of durability performance requires that many integrated and simultaneously active variables and factors such as fatigue, corrosion, vibration, friction etc., should be considered. These variables are mostly noise of the system and accurate prediction of these factors are extremely time consuming and costly.
to gain high level of confidence in the data and sometime impossible. Another reason for
such large-scale deviation is the inclusion of accurate boundary conditions required to make
the model close to the real life situations. Hence, experimental methods and physical testing
have been mostly used to complete the degradation measurements and assessments.

Moreover, durability attributes are specified over the life cycle of the vehicle and not
with respect to the design intent structure. Durability is a dynamic, cumulative and
progressive phenomenon that depends on the customer usage and vehicle robustness in
general. In that case all the analysis performed to assess such performances should also be
performed using material damage, wear, friction and corrosion etc. If the design intent
structure did not change over the life of the vehicle, static and one-time measurements for
durability performance would be sufficient and strength test would be same as durability test
in the laboratory.

From safety standpoint, durability specifications are developed in part to ensure that
customer safety is maintained over the life of the vehicle and safety models are developed
assuming the component characteristics remain same over the life of the vehicle. Degradation
is somewhat different from durability of any vehicle. While durability specifications are
gereed to ensuring that customers are not stranded due to abrupt and sudden mechanical
failures, degradation planning consists of specifications that provide the rate of performance
degradation over duration of vehicle life. This brings the design focus to design components
and systems that have preplanned and predicted life for 3 or 4 years in service (YIS) or
reducing things gone wrong (TGW) for the vehicle. To gain customer confidence and ensure
continual customer satisfaction by maintaining the performance "as new" over the life of the
vehicle, degradation measurements and assessment become very critical. It has been
demonstrated that for Japanese automobiles, degradation of performances stabilizes over time to an acceptable low value where as American made automobiles continuously degrade and at a much higher rate.

To enable the development of useful-life NVH and robustness specifications, NVH, durability and Squeak and Rattle performances must be validated over the durable life of the vehicle and degradation of such performances below the expected levels must be prevented. In absence of accurate analytical models to predict such dynamic behavior, experimental tools must be employed to simulate both the durability environment, and to measure the affected durability attributes such as suspension characteristics, body component rigid body movements. This may be the key point to meet an extended customer expectation and once met, customer satisfaction will be achieved.

6.2 Structural Testing for Durability Attributes using Simulation

To meet the pressures of compressed development timing, and in the absence of durability analysis tools for degradation assessments, experimental tools for structural vehicle testing and Optical measurements have evolved over the years to provide increasing performance and accuracy in simulating the service environment. A typical state of the art set up for such simulation and measurement of durability attributes includes high performance mechanical road simulators, sophisticated control software to control the simulator and 6 Degree of Freedom Optical measurement system. Both of these systems will be explained in the following sections.
6.2.1 Full Vehicle Structural Simulators

The standard simulator configurations used for structural degradation testing many include any of the following configurations along with a common 6 DOF Optical Measurement System from Krypton™.

6.2.1.1 Six DOF Spindle Coupled Simulators (Figure 6.2.1.1)

Spindle couple simulators are designed to provide general vehicle structural durability and degradation assessment. They are normally configured to provide from 6 forces, displacement, or moment inputs to each vehicle spindle, simulating all road induced suspension, chassis, and body loads. In addition, auxiliary inputs are often used to simulate non-road induced loads, such as powertrain torque reaction, or driver-induced maneuvering and braking.

When used properly, spindle coupled simulators provide the most comprehensive, integrated vehicle structural durability test technology available in the present time emulating the proving ground road test conditions. Except for components subject to rotational powertrain-induced loadings all vehicle components and systems are loaded correctly in terms of both amplitude and frequency contents.

The systems are normally operated in an inertial load reaction mode, which limits their ability to reproduce low frequency maneuvering inputs without supplemental restraint systems. These restrained causes undesirable localized reactionary loading to the structure or body structure, which may reduce validity of such tests. In addition, control mode does not comprehend the effects that tire compliance and dynamics can have on the vehicle response as the structure changes due to degradation or design improvements or tire inflation levels.
6.2.2 Vehicle Tire Coupled Simulators (Figure 6.2.2.1)

The tire-coupled simulators are employed to assess body and body system structural durability testing. These systems consist of four vertical displacement inputs coupled directly to the vehicle tire-patch. Vehicle motion is normally only passively restrained in the lateral and longitudinal direction, and vertical tire input is controlled in vertical direction only.

These simulators could be very well used for body degradation assessment and for interior body component degradation testing. Other uses include subjective evaluation of S&R, and for calibrating and tuning suspension characteristics for Racing Vehicles. Lack of significant loading in the lateral and longitudinal directions prevents these systems from being good tools for evaluating overall suspension or chassis system performance, although, tire coupling does provide effects of tire compliance on the body rigid body movements.
6.2.3 Front and Rear Suspension Subsystem Simulators (Figure 6.2.3.1)

The suspension subsystem simulator uses similar mechanical input fixturing as that used for full vehicle configuration, providing 3 to 6 inputs per corner to either front or rear suspension spindle test setup. Suspension component reaction loads are normally generated either by including a portion of the full vehicle structure as part of the tests set up, or by generic suspension mounting fixtures.

These systems are generally used for up-front evaluation and development of suspension or chassis sub systems, in advance of full prototype availability. They're fully restrained or semi inertial configuration allows for simulation of the complete suspension-loading spectrum, including maneuvering and braking events. These systems have very limited capability for body structural testing. It can be very well used for suspension degradation
testing in the laboratory using the proposed method. The accuracy of such measurement in this test is highly dependent on the design of component restrained system, since the suspension system boundary conditions must be satisfied for all components to be loaded correctly under both static and dynamic conditions.

FIGURE 6.2.3.1

6.2.4 Multi-Axes Simulation Table, MAST (Figure 6.2.4.1)

MASTs are generally 5 to 6 degrees of freedom rigid vibration tables used for testing vehicle sub-structures. The planar input motion is imparted into systems, which are inertially self-loaded. Auxiliary torque inputs are sometimes used to simulate engine torque conditions.

MAST systems are used to test frame or body mounted sub structures such as engine mounting systems, instrument panels, tire support structures etc. They are particularly useful for testing systems whose dynamic effect on the system forcing function is negligible. This allows the simulator control input to remain valid even as the system being tested changes or is modified. Supplemental inputs are required with these simulators anytime non-rigid-body
dynamics need to be controlled. The absence of complete vehicle structure presents significant challenges when attempting to match system boundary conditions.

**FIGURE 6.2.4.1**

6.2.5 RPC™ Simulation Control and Software

All of the simulation configurations described above are controlled by closed loop servo hydraulic systems. These control systems, however, do not have the inherent performance required to accurately reproduce the dynamic high-frequency structural inputs, with the proper multi channel phase relationships, that are required to simulate the road environment. To develop the correct test inputs, an external control system must be used which incorporates a model of system dynamics. This model can predict servo-loop control vectors required to generate the proper simulator inputs or responses. This test control technique is known as response simulation and designated by a trade name called RPC, which is a software product of MTS Systems Corporation. Such process includes four different and sequential process steps as described below.
6.2.6 Structural Simulation Process Steps

Data Acquisition from Road The vehicle is instrumented with Transducers at the spindles and remote sensors and operated in its service environment. System response time histories are recorded when driven over the proving ground road surfaces, which represent the significant test specimen input conditions. Such data is processed further to retain most damaging portion including the frequency content of the signals. (See Figure 6.2.6.1)

System Identifications A non-linear model of the test/simulator-combined system is developed using system identification methods based upon broadband excitation depending upon data acquisition sample rate. These models, which can be in either the frequency or time domain represent dynamic model of the test system including the simulator structures. (See Figure 6.2.6.2)

Drive file Creation Through the use of the system, as described in the last step, initial control inputs are predicted which are expected to generate the desired specimen response. Since a linear model is used in approximating the non-linear system, an iterative procedure is used to create the final input from incremental correction vectors calculated from the residual response errors. (See Figure 6.2.6.3)

Durability Test The specimen is tested using a sequenced playback of the drive file database to simulate the system's useful life in its intended service environment. This is step where the rigid body movements of various components or systems are recorded using Optical Measurement System at 0%, 25%, 50%, 75% and 100% of the durability test in the laboratory. The data thus recorded is compared and degradation of performance is assessed over the life of the vehicle. (See Figure 6.2.6.4)
6.3 Krypton™ 6DOF Optical Measurement System Setup and Procedure

The Optical measurement optical system consists of three lenses CCD camera system, a space probe for CMM and LED identification, individual Light Emitting Diodes (LED) and RODDYM™ dynamic software for data analysis using analog signal received by camera lenses and from the individual LEDs fixed on the body or suspension systems for which degradation rate has to be assessed.

6.3.1 Measurement set-up

The measurement set up for a typical body degradation measurement setup is shown in Figure 6.3.1.1. The red dots are individuals LEDs fixed to the body and door. The vehicle coordinates for measurement system is shown for the LEDs.

**FIGURE 6.3.1.1**
The measurement equipment consists of the following:

- Computer Systems with RODDYM Software
- Three lenses CCD Camera Systems
- Space Probe for CMM of LED identifications
- Strobe units to group the LEDs
- ADC600: allows measuring analog, digital and counter signals and allows external synchronization
- Synchronization module: this optional RodymDMM module allows measurement scripts to be synchronized with external equipment by using digital compatible signals.

**FIGURE 6.3.1.2**
6.3.2 Measurement procedures

6.3.2.1 Instrumentation

- Attach all LED’s on the body system and connect the force/torque transducers to the analog acquisition unit (for load synchronization only)
- Connect external trigger for starting measurement and other digital signals for synchronisation of the measurement scripts

6.3.2.2 Identification

- Camera position 1 to 6
  - Static frame, camera-car relation identification on basis of nominal points that can be found on the car body or use PowerInspect to align on basis of a CAD file.
  - Use min 3 LEDs to make a dynamic frame of the car coordinate system. This dynamic frame can afterwards be used to easily re-align the camera system with the car body

6.3.2.3 Measurement

- Measure the LED outputs for desired number of cycles and channels
- Camera position 1 to 6
- Use dynamic frame to align camera with car body
- Make a static measurement (using good reference for finding back all the positions of the LED’s)
- Dynamic measurement of LED’s and analog channels, involving white noise excitation of test bench or drive file excitations that could be used every 25% of the durability run

6.3.2.4 Camera calibration Procedure

The camera system is pre-calibrated. This means that the calibration of the camera is performed in-factory. There are three different levels of calibration. The first two levels are performed in factory. The third one can optionally be performed on site to extend the
accuracy for large distances when the environmental conditions i.e. temperature, humidity and light brightness etc. are not optimal. The data for the first two levels is acquired on a large-volume CMM in a conditioned environment. The first level of calibration is completed in a situation where the optical parameters and the geometrical parameters are identified. This step results in a mathematical camera model. The second level of calibration is based on special filtering techniques eliminating the residual errors caused by non-linear higher order phenomenon. An operator can perform the third level of calibration on site, if required. A rotating ball bar is used to instantly correct small deviations in the linearity of the system, which can be caused by environmental influences. The resolution of camera system is about 0.005 mm within a measurement distance of 6-10 feet.

6.4 Test Procedures for Body and Suspension Systems

6.4.1 Objective

The objective of the test is to perform measurements similar to evaluate suspension and body performance degradation throughout the durability life of the test vehicle. The body degradation measurements will be limited to door movements compared to body over the durability life of the test vehicle in the laboratory.

6.4.2 System Configuration

A fully floating body with suspension and doors will be used along with 6 DOF 329 corners and Krypton RODDYM 6D Optical active and measurement systems, synchronized with load/displacement inputs at spindle points, to record transnational motions of the spindle and door assemblies, as described in the previous section. Each corner and the door will be
equipped with a set of LED’s to measure system spindle and door displacements at pre-specified points. All measurements will be translated to global vehicle coordinates as shown in the attached drawing. (See Figure 6.3.1.1 for LED arrangements and Figure 6.3.1.2 for Measurement system configuration).

6.4.3 Degradation Requirements Scope

**Suspension System:** The suspension degradation over the durability life will be measured against the followings:

- Suspension Steering Dynamics Inputs (Full Displacements and Moments)
- Suspension Alignment Measurements (Camber, Castor and Toe)
- Suspension Static compliance measurements

**Body/Door System:**

- Door Alignment Measurements (Full displacements and rotations)

**Drift Specifications:** The suspension alignment and body door movements can be summarized as follows.

**Assumed Suspension Alignment requirements:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>+/-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camber</td>
<td>0.50</td>
</tr>
<tr>
<td>Castor</td>
<td>0.50</td>
</tr>
<tr>
<td>Total Front Toe</td>
<td>0.30</td>
</tr>
<tr>
<td>Indicated Rear Toe</td>
<td>0.20</td>
</tr>
<tr>
<td>Cross camber</td>
<td>0.50</td>
</tr>
<tr>
<td>Cross castor</td>
<td>0.50</td>
</tr>
</tbody>
</table>

A typical spreadsheet that could be used to track the suspension parameter degradation assessment is shown in Table 6.4.3.1
**Assumed Wheel Frequency Requirements:**

The wheel frequencies at design weight should fall into the following ranges at zero Mileage conditions:

<table>
<thead>
<tr>
<th></th>
<th>Front Wheel Frequency, CPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sport</td>
<td>70-80</td>
</tr>
<tr>
<td>Family Sedan</td>
<td>60-70</td>
</tr>
<tr>
<td>Luxury</td>
<td>50-60</td>
</tr>
</tbody>
</table>

**Front/Rear Side Door Structure/SDS Requirement:**

Seal Gap must be within +/- 2.5 mm (or smaller) of nominal dimension (Nominal Seal gap is program specific) to ensure that air leakage, water leakage and CO concentration requirements can be met. Correlation between theoretical rigid body motion of the door panels and the physical test measurements using Krypton systems should be established to establish the accuracy and validity of such measurement process.

(Disclaimer: These specifications are assumed and fictitious values and have no bearings on the actual suspension design parameters followed by Ford Motor Company)

**Test types and metrics:**

The primary test objective is to use periodic measurements of spindle, body and door motions under specified inputs to monitor suspension and door panel degradation while durability test is in progress.

For each test type, load data from the Spinning Wheel Force Transducer (SWIFT™) and displacement data from the Krypton will be acquired. Spring rates, alignment parameters for the suspension will be calculated and seal gap between door panel and body will be measured.
The rates, alignment parameters and seal gap will be compared to the initial value and difference checked against preset limits. The test types could be as described below:

- Vertical in/out phase, displacement control measure load
- Lateral aiding/opposing, load control measure displacement
- Longitudinal brake/acceleration, load control measure displacement
- Alignment torque aiding/opposing, load control measure displacement

**Test Procedure:** The following procedure will be carried out at 0, 25%, 50%, 75% and 100% of durability test:

75% and 100% of durability test:

- Tests are to be run quasi-statically using sinusoidal inputs at 1–2 Hz
- Stop Durability test. Bring all channels to nominal ride positions. Zero all forces and moments
- Measure FRF at each corner. The FRF models will be used to determine degradation in wheel hop frequency etc.
- Iterate test command at each corner to achieve zero forces on non-programmed channels within about +/- 2 to 5 lb.
- Run test and acquire data from SWIFT and Krypton of the spindle and body fender motions. Tests are run quasi-statically with sine wave @ 1 or 2 Hz
- Calculate spring rates and check alignment values against degradation limits
- Repeat each test 3-5 times for consistency and averaging the results
- Measure Door panel and body movements under following road surfaces at the start of each segment of durability sequence (0, 25%, 50%, 75% and 100%)
  - Curb Strike
  - Cobble Stone
  - Chuck Hole
  - Railroad crossings
- Continue durability schedule depending upon results of limit checks
**In-Test Measurements:**

**Ride Height** - Adjust suspension ride height to achieve the vertical force (FZ) equal to corner weight of the test vehicle while all other forces and moments @ SWIFT/Spindle (i.e. Fx, Fy, Mx, My and Mz) set to zero or iterated to achieve near zero value possible, measure the gap between Lower control arm or any other suitable point of suspension near spindle) and frame for framed vehicle or spindle and a fixed point in the wheel well area (The measurement points should be consistent throughout the test). The ride height loss due to suspension settling shall not exceed 20 mm from initial measurement during durability life of the vehicle.

**Suspension Alignment** - Adjust suspension ride height to achieve the vertical force (FZ) equal to corner weight of the test vehicle while all other forces and moments @SWIFT/Spindle (Fx, Fy, Mx, My and Mz) set to zero or iterated to achieve near zero value possible, measure the LED positions on the SWIFT face and calculate castor, camber and Toe angles on all the wheels. The alignment change from the initial settings shall not exceed +/- 0.5 degrees total or side-to-side for caster and +/- 0.25 degrees for Toe (For further details see and fill up attached spreadsheet).

**Vertical Rate** – With brakes applied, steering angle fixed and longitudinal, Lateral forces, moments inputs (Fx, Fy, Mx, My and Mz) set or iterated to near zero possible, apply equal vertical displacements (Sinusoidal inputs @ 1 cpm) to both wheels, left and right, to cycle between full jounce and rebound. Record load and displacements in all 6 degrees of freedom (Loads by SWIFT and displacements by LEDs) at each wheel for 2 warm up and 4 data record cycles. Plot hysteresis loops and calculate linear rate. The change in linear rate shall not exceed +/- 15% from initial value.
**Vertical Roll Rate** – With brakes applied, steering angle fixed and longitudinal, lateral forces, moments inputs (Fx, Fy, Mx, My and Mz) set or iterated to near zero possible and with suspension ride height set to achieve a vertical Force (FZ) equal to vehicle corner weight for all the corners, apply equal vertical displacements to both wheels in front, out of phase, to cycle between a roll angle of +/- 4 degrees, with a cycle time of approx. 60 seconds. Record loads and displacements in all 6 DOF at each wheel for 2 warm up and 4 data record cycles. Repeat the above procedure for rear wheel also, if required. Plot hysteresis loops and calculate linear rate. The change in linear rate shall not exceed +/- 15% from initial value.

**Lateral Compliance** – With brakes applied, steering angle fixed and longitudinal force, brake and steer moments inputs (Fx, My and Mz) set or iterated to near zero possible and with suspension ride height set to achieve a vertical Force (FZ) equal to vehicle corner weight for all the corners, apply equal lateral force to both wheels in front, out of phase, to cycle between a lateral force of +/- (0.7*(vertical force/2)), with a cycle time of approx. 60 seconds. Record loads and displacements in all 6 DOF at each wheel for 2 warm up and 4 data record cycles. Repeat the above procedure for rear wheel also, if required. Plot hysteresis loops and calculate linear rate for all the corners. The change in linear rate shall not exceed +/- 15% from initial value and there shall be no backlash in excess of 0.25 mm.

**Longitudinal Compliance** – With brakes applied, steering angle fixed and longitudinal force, brake and steer moments inputs (Fx, My and Mz) set or iterated to near zero possible and with suspension ride height set to achieve a vertical Force (FZ) equal to vehicle corner weight for all the corners, apply equal longitudinal force to both wheels in front, out of phase, to cycle between a lateral force of +/- (vertical force/2), with a cycle time of approx.
60 seconds. Record loads and displacements in all 6 DOF at each wheel for 2 warm up and 4 data record cycles. Repeat the above procedure for rear wheel also, if required. Plot hysteresis loops and calculate linear rate for all the corners. The change in linear rate shall not exceed +/- 15% from initial value and there shall be no backlash in excess of 0.25 mm.

**Dynamic rates** - Apply white noise signal (shape of 1/f up to Nyquist frequency, 10% of full scale load applied to vertical, lateral and longitudinal directions) to vertical, longitudinal and lateral actuators. Record loads and displacements in the three directions and compute frequency response functions between each input load and the resultant spindle displacements.

**Body/Door Panel Movement** - Measure all 6 DOF measurements at all the locations in the door panel and the body under the four drives mentioned before. Repeat the procedure for left and right side doors. Calculate the maximum relative movements of the door strategic points with respect to the corresponding Body locations. The maximum relative movements should not exceed +/- 2.5 mm over the durability life of the vehicle.
<table>
<thead>
<tr>
<th>CDP (%)</th>
<th>Front Ride Heights</th>
<th>Remarks</th>
<th>CDP (%)</th>
<th>Rear Ride Heights</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>LF Camber</td>
<td>RF Camber</td>
<td>Cross Camber</td>
<td>LF Castor</td>
<td>RF Castor</td>
</tr>
<tr>
<td>25</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Maximum Allowable Drift:**
- LF: 0.5
- RF: 0.5
- Cross: 0.5
- LF Castor: 0.5
- RF Castor: 0.5
- Total Toe: 0.3

**Exceed Allowable Drift?**

**Mileage of Cumulative Drift:**

**Remarks Description**

---

**Table 6.4.3.1**

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6.5 Risk and Concerns for Measurement Procedures

First of all, the repeatability of the simulation equipment and control software could be an issue if not controlled properly. The accuracy for such measurements would very much depend on nonlinearities, hysteresis, bushing damping consistencies etc. To resolve this issue and reduce the chance of measurement uncertainties, simulation repeatability studies conducted at regular intervals and components could be changed to ensure uniformity of results.

Next concern could be the repeatability, resolution and signal to noise ratio for the SWIFT transducers used for load measurements. The resolution for load and moment measurements should be within 75-100N to be consistent in degradation prediction and confirmation. The SWIFT, when mounted in the spindle housing, may induce an error due to end constraint stiffness, which may exceed these degradation specifications to be measured. To resolve this issue, the SWIFT could be calibrated after the unit is mounted in the spindle housing and remove at the end of the durability test.

An investigation should be carried for all the instruments before measurement to differentiate between cross talk and linearity errors. Any cross talk and non-linearity must be demonstrated in a calibration fixture only without any compensation to make for the instrument insensivities.

Measurement accuracy over long range of time could be the toughest challenge in such measurements. The resolution of the transducer has to be around 0.5% of the full scale of the transducer. End to end calibration may be required to resolve the issue.
Overall, resolution of the transducers should not be a major issue. Repeatability is going to be governed and dominated by hysteresis and fixture issues and calibration process. Since the comparison is from point to point measurements over time, comparative performance results should provide insight into the system degradation over time and robustness of the system as a whole.

6.6 Structural Assessment Degradation for Durability, S&R and NVH

Many efforts are being made in the automobile industry to gain insight in predicting structural degradation to assess NVH, Body and suspension behaviors and S&R characteristics in the context of high mileage durability for the vehicles. To aid in predicting TGW and other customer satisfaction indices occurring at extended vehicle mileage levels, the traditional body structure development process and suspension design process are being constantly modified to include a series of combined vehicle durability simulation and model tests. A series of similar vehicles with different structural body configurations and suspension structures are being tested to determine the impact of design improvements on high mileage NVH and Ride and Handling degradation.

The present work will consist of collecting data for the body/door combination and suspension parameters at various points during durability runs in the laboratory. The data will be used to show several methods of quantifying parameter degradations such as castor, camber, and toe values over time. The data analysis presented, by no means, is exhaustive due to time and equipment constraints. Moreover, detailed analysis of such data to accurately predict the degradation behavior of the vehicle is outside the scope of this thesis as they vary quite widely and vehicle specific. In order to assess vehicle degradation characteristics for
chosen design parameters of the vehicle, an exhaustive analytical and experimental results need to be collected and analyzed simultaneously to make an accurate and meaningful prediction. The rigid body movements for door/body and suspensions were collected using the above procedures to prove the viability and potentials for such measurements in predicting degradation behavior of the vehicle. The next chapters will deal with data analysis and management of the data that was collected using above equipments and procedures.
7.0 Body Structure Test Data Management and Analysis

A typical test set up to assess degradation of a Door sub system is shown in Figure 7.1. The accuracy of degradation testing is dependent on many factors including the quality of the road data, road surfaces being simulated, the simulation equipment design, drive file generation process, accuracy and resolution of measurement systems and durability process the vehicle is subjected to. When using multi-axis full vehicle road simulation along with the Optical active measurement systems, the degradation assessment becomes "vehicle dependent" and factors such as vehicle suspension geometry and transducer and LED locations also influence the degradation measurement accuracy.

7.1 Test Set Up Details

The test set up for the body degradation measurement, as shown in Figure 7.1.1, consists of a seven-actuator road simulator, a representative body system with the subject door with representative hinges and structures, strategically located LEDs, 3 lens measurement camera system with associated computer hardware and software.

A six-degree of freedom Optical measurement system is used to collect the data. The Krypton™ measurement is an active Optical measurement system that tracks the translational displacements of the LEDs in three X, Y and Z directions. The locations of the 16LEDs are shown Figure 7.1.2. The system has fully programmable signal conditioning capabilities. The measurement accuracy is 0.005 mm. The measurement system is calibrated to maintain this accuracy up to 3000 Hz of sampling rate. In the present case, a sampling rate of 100 Hz with 16 LEDs was used for the body degradation data collection.
The sample door with design intent level hinges and structures were assembled as a sub system and then put in the body structure. The body system is then mounted on the simulator and the strings were attached for all the seven inputs. The doors were also assembled with all the hardware and trims. The hinge bolt torques was tightened as per the specifications and the hinge bolts were painted to detect movements.

7.2 Development of Input Drive Files

The test procedures called for data collection at 0%, 25%, 50%, 75% and 100% of durability run in the laboratory. A specific sequence of road surfaces was followed as per the FORD durability requirements to conduct the structural durability test. The laboratory drive files were simulated using the proving ground data. The iteration process consists of generation of frequency response function for the system and development of input requirements that will generate the seven accelerations at the strategic locations corresponding to the actual vehicle run in the proving ground. The process uses RPC™ software (Remote Parameter Control software) to conduct the simulation process at a sampling rate 204.8 Hz. When the best accuracy achievable for the RPC channels was obtained the final drive signal was put together in a particular sequence to reproduce the proving ground events. For data collection, a white noise random noise file and high frequency cobblestone drive file was used for all the degradation data collection.
7.3 Test Sequence and Data Collection procedure

The data collection sequence was kept as follows:

- Collect the data for all the 16 LEDs at the beginning of the durability using white noise and cobblestone drive files.
- Run the durability sequence.
- At 25%, 50%, 75% and 100% of the durability stop the test and play out the two drive files, cobblestone and white noise, and collect data for all the LEDs in predefined local coordinates. If required, three sets of data could be collected and averaged for final data comparison.
- After each data collection compare the data with the previously collected data to ensure the collected data is in alignment and consistent.

7.4 Measurement System Details

The RODYM™ 6D system is a camera based dynamic position measurement system. The X, Y and Z coordinates of static or moving LED's are measured in real time with a high accuracy. Velocity and acceleration profiles can also be derived. It uses 3 CCD units to measure the position of one or more infrared LEDs. By using multiple LEDs, the position and orientation of the subject can be calculated. The system is pre-calibrated by Krypton Electronic Engineering so that exact relative position and orientation of the cameras is known to a common camera coordinate system. The system has high accuracy and wide measurement range with a maximum sampling rate of 3000Hz. The system has on-line feedback capability. The system has a resolution of 0.0005 mm at 2.5 meter distance and accuracy of 0.05 mm in X, Y and Z directions at 2.5 meter.
The sequence of operation during the measurement and analysis phase of such system is as follows:

- Identification of reference coordinate system
- Identification of the car body as a rigid system
- Measurement data converted to the common reference coordinate system
- Synchronization of the measurement points
- Calculations of translations and rotation of each LED point

7.5 Results

- A typical value of the maximum displacements in X, Y and Z directions for LED 1, 7 and 13 were calculated and given in Table 7.5.5, 7.5.6 and 7.5.7 at various stages of the durability run. LED 1 is at the body as shown in Figure 7.1.2 and LED 7 and 13 are located on the door. At every interval, the vehicle was excited with seven channel random white noise displacement inputs and displacements of each LED were taken. The maximum displacements for Location 1,7 and 13 were calculated and presented in these tables.

- The displacement for each LED, RMS value was calculated for various stages of durability. These values are given in Table 7.5.1, 7.5.2, 7.5.3 and Table 7.5.4. The difference in each direction between the adjacent LEDs were computed and given in the same table.

- The power spectral density (PSD) for the displacement signals of the LED7, Body structure location, in X, Y and Z directions was calculated at various stages of the durability, namely, 0, 50 and 100%. The power spectral density is a presentation of the energy content in the signal. The peaks of this signature could also represent the system resonant frequencies. The vehicle is
most sensitive in the frequency range between 10 Hz and 35 Hz. This becomes the zone of interest. All the PSDs were calculated for this zone. The PSDs for LED7 for displacement signals in X, Y and Z directions are displayed in Figure 7.5.8, 7.5.9 and 7.5.10 respectively.

- The PSDs for LED 13, Door structure location, in the Y and Z directions were calculated for various stages of durability and these are displayed in Figure 7.5.11 and 7.5.12 respectively.

- The comparison of PSDs of the displacement signals in X, Y and Z directions for two adjacent locations, LED 1 (Body) and LED 7 (Door), are shown in Figure 7.5.13, 7.5.14 and 7.5.15 respectively at various levels of durability runs.

7.6 Discussion of Results

The LED 1 and LED 7 were strategically placed close to each other and at same levels where LED1 is fixed to the body structure and LED 7 is fixed to the door structure. The relative displacements of these two points in X, Y and Z directions will change as the vehicle degrades during laboratory simulation tests which are equivalent to the damage of the vehicle in the Proving Ground or real world usage. We can vectorially add these relative displacements in three vehicle coordinates to find the resultant movement and keep track of these resultant displacements during the durability run. The relative displacement could also represent the looseness of the joint for the door hinges and could give an indication when the door movements could be unacceptable. The tables, 7.5.1 thru 7.5.4, show a typical calculation for two adjacent points. The same procedure could be repeated for all the
strategic points in real test situation and movements for different locations of the door and body structure could be mapped. In this fashion, the maximum displacement near the joint could be determined and the joint which has lost the stiffness most, could be singled out for further design improvements. The worst joint could be identified easily and proper steps could be taken to improve the hinge stiffness if required. From these tables, the maximum change during the run was found to be in X direction (Fore and Aft) between 1 and 7 where as the change was negligible in other directions. Due to gravity directions, the change is normally negligible in vertical direction (preloaded direction) and the movements normally occur primarily in fore and aft direction. The result of this experiment also tends to be in alignment with real world results.

Another way to understand the permanent set of two structures could be to compare the RMS value of the displacement in all three directions for any two strategically placed locations of the body and door structure. The relative difference between the RMS values of two adjacent locations could be interpreted as permanent set of those two points when the values are compared between the start and end of the test. In practice, computations could be done for several points and average value could be determined. The maximum changes in RMS values of the two adjacent points, Point 1 and 7, were found in the fore and aft directions. Although these values are small, this could point the designers to the direction of looseness that may appear as the vehicle ages. The rate of change and maximum change are both important to assess the degradation of the vehicle attributes. The relative changes seem to be another important factor for degradation assessments.
Another way to assess the degradation is to compare the power spectral density or energy content of the signals for the movements of the structures. In this case, the relative changes of these spectrums at various levels of durability are the most important element. For example, from Figure 7.5.8 it could be seen that as the vehicle degrades, the energy content of the signal goes up indicating higher movements in the frequency zone of interest. That means more movement of the door and more looseness of the joint. A specification for such energy changes could be established for specific vehicle to limit degradation. There also could be a frequency shift that could be possibly be determined from this diagram. In case of loss of joint stiffness, the frequency will reduce, as the mass of the rigid body remains constant. A design specification for such shift could also be specified to keep such changes within desired limits. By comparing the PSDs for the LED 1 (Body) and LED 7 (Door), it can be observed that door has a tendency to have higher energy content in all the directions. The rigid body movements for the body structure are mainly due to suspension characteristics where as door movements relative to the body structure, could be due to loss in joint stiffness. The door was found to move more than the body structure, which is more robust than the door.
FIGURE 7.1.1 Seven-actuator Road Simulator with test component

FIGURE 7.1.2 Location for 16 LEDs
Figure 7.1.3 Location for LED 1 (Body) and 7 (Door)

Figure 7.1.3 Strober Locations
### Table 7.5.1 RMS Displacements @ 0% Durability

<table>
<thead>
<tr>
<th>Direction</th>
<th>LED 1 (Body)</th>
<th>LED 7 (Door)</th>
<th>Difference</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>2.265 mm</td>
<td>2.261 mm</td>
<td>0.04 mm</td>
<td>0% durability</td>
</tr>
<tr>
<td>Y</td>
<td>1.642 mm</td>
<td>1.604 mm</td>
<td>0.038 mm</td>
<td>0% durability</td>
</tr>
<tr>
<td>Z</td>
<td>1.807 mm</td>
<td>1.780 mm</td>
<td>0.027 mm</td>
<td>0% durability</td>
</tr>
</tbody>
</table>

### Table 7.5.2 RMS Displacements @ 100% Durability

<table>
<thead>
<tr>
<th>Direction</th>
<th>LED 1 (Body)</th>
<th>LED 7 (Door)</th>
<th>Difference</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>2.349 mm</td>
<td>2.346 mm</td>
<td>0.003 mm</td>
<td>100% durability</td>
</tr>
<tr>
<td>Y</td>
<td>1.689 mm</td>
<td>1.654 mm</td>
<td>0.035 mm</td>
<td>100% durability</td>
</tr>
<tr>
<td>Z</td>
<td>1.863 mm</td>
<td>1.836 mm</td>
<td>0.027 mm</td>
<td>100% durability</td>
</tr>
</tbody>
</table>

### Table 7.5.3 RMS Displacements @ 0% Durability

<table>
<thead>
<tr>
<th>Direction</th>
<th>LED 1 (Body)</th>
<th>LED 13 (Door)</th>
<th>Difference</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>2.265 mm</td>
<td>2.254 mm</td>
<td>0.011 mm</td>
<td>0% durability</td>
</tr>
<tr>
<td>Y</td>
<td>1.642 mm</td>
<td>1.570 mm</td>
<td>0.072 mm</td>
<td>0% durability</td>
</tr>
<tr>
<td>Z</td>
<td>1.807 mm</td>
<td>1.750 mm</td>
<td>0.057 mm</td>
<td>0% durability</td>
</tr>
</tbody>
</table>

### Table 7.5.4 RMS Displacements @ 100% Durability

<table>
<thead>
<tr>
<th>Direction</th>
<th>LED 1 (Body)</th>
<th>LED 13 (Door)</th>
<th>Difference</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>2.349 mm</td>
<td>2.337 mm</td>
<td>0.012 mm</td>
<td>100% durability</td>
</tr>
<tr>
<td>Y</td>
<td>1.689 mm</td>
<td>1.626 mm</td>
<td>0.063 mm</td>
<td>100% durability</td>
</tr>
<tr>
<td>Z</td>
<td>1.863 mm</td>
<td>1.818 mm</td>
<td>0.045 mm</td>
<td>100% durability</td>
</tr>
<tr>
<td></td>
<td>LED 1(Body)</td>
<td>LED 7(Door)</td>
<td>LED 13(Door)</td>
<td>Comment</td>
</tr>
<tr>
<td>----------------</td>
<td>-------------</td>
<td>-------------</td>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>X Direction</td>
<td>6.206 mm</td>
<td>6.033 mm</td>
<td>6.103 mm</td>
<td>0% durability</td>
</tr>
<tr>
<td>Y Direction</td>
<td>4.153 mm</td>
<td>4.044 mm</td>
<td>4.112 mm</td>
<td>0% durability</td>
</tr>
<tr>
<td>Z Direction</td>
<td>7.118 mm</td>
<td>6.941 mm</td>
<td>6.539 mm</td>
<td>0% durability</td>
</tr>
</tbody>
</table>

**Table 7.5.5 Maximum Displacements @ 0% Durability**

<table>
<thead>
<tr>
<th></th>
<th>LED 1(Body)</th>
<th>LED 7(Door)</th>
<th>LED 13(Door)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Direction</td>
<td>6.404 mm</td>
<td>6.265 mm</td>
<td>6.198 mm</td>
<td>50% durability</td>
</tr>
<tr>
<td>Y Direction</td>
<td>4.209 mm</td>
<td>4.243 mm</td>
<td>4.236 mm</td>
<td>50% durability</td>
</tr>
<tr>
<td>Z Direction</td>
<td>7.221 mm</td>
<td>7.052 mm</td>
<td>6.585 mm</td>
<td>50% durability</td>
</tr>
</tbody>
</table>

**Table 7.5.6 Maximum Displacements @ 50% Durability**

<table>
<thead>
<tr>
<th></th>
<th>LED 1(Body)</th>
<th>LED 7(Door)</th>
<th>LED 13(Door)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Direction</td>
<td>6.510 mm</td>
<td>6.365 mm</td>
<td>6.304 mm</td>
<td>100% durability</td>
</tr>
<tr>
<td>Y Direction</td>
<td>4.359 mm</td>
<td>4.286 mm</td>
<td>4.386 mm</td>
<td>100% durability</td>
</tr>
<tr>
<td>Z Direction</td>
<td>7.337 mm</td>
<td>7.145 mm</td>
<td>6.624 mm</td>
<td>100% durability</td>
</tr>
</tbody>
</table>

**Table 7.5.7 Maximum Displacements @ 100% Durability**
Figure 7.5.8 Power Spectral Density for LED 7, X-axis

Figure 7.5.9 Power Spectral Density for LED 7, Y-axis
Figure 7.5.10 Power Spectral Density for LED 7, Z-axis

Figure 7.5.11 Power Spectral Density for LED 13, Y-axis
LED13, Z axis Displacements

Figure 7.5.12 Power Spectral Density for LED 13, Z axis

LED1 and 7, X axis Energy Content Comparison

Figure 7.5.13 Power Spectral Density for LED 1 & 7, X-axis
Figure 7.5.14 Power Spectral Density for LED 1 & 7, Y-axis

Figure 7.5.15 Power Spectral Density for LED 1 & 7, Z-axis
8.0 Suspension Degradation Test Data Management and Analysis

A typical fixed body structure with suspension module test set up to assess degradation of a suspension assembly is displayed in Figure 8.1. The accuracy of degradation testing for suspension assembly is dependent on many factors such as method of testing and restraining the body structure and frequency band for simulation including the quality of the road data, road surfaces being simulated, the simulation equipment design, drive file generation process, accuracy and resolution of measurement systems and, last but not the least, durability process the vehicle is subjected to. When using multi-axis half vehicle sub-system road simulation along with the Optical active measurement systems, the degradation assessment for suspension parameters, namely kinematics and compliance degradation, becomes "set-up and frequency dependent" and factors such as vehicle suspension geometry and load measuring transducers also influence the degradation measurement quality.

8.1 Test Set Up Details

The test set up for the suspension degradation measurement, as shown in Figure 8.1.1, consists of two 6 DOF road simulators, a representative body system with the subject suspension module with representative shocks and springs, strategically located three LEDs on the transducer plane, 3 lens measurement camera system with associated computer hardware and software to synchronize load and displacement measurements.

A six-degree of freedom Optical measurement system is used to collect the data. The Krypton™ measurement is an active Optical measurement system that tracks the translational displacements of the LEDs in three X, Y and Z directions. The locations of the 3 LEDs are
shown Figure 8.1.2. The system has fully programmable signal conditioning capabilities. The software filters the LED outputs and has the capabilities to trigger the load and displacement signals, which are very important for determination of suspension compliances. In the present case, a sampling rate of 200 Hz with 3 LEDs was used for the displacement data collection.

The suspension module with design intent level shocks springs, toe links etc. were assembled as complete system and then assembled in the body structure. The suspension system is then mounted on the simulators. The load transducer is placed in between the spindle face and the load simulator housing. The input forces go through the load transducer and then subjected to the spindle of the suspension.

### 8.2 Description of Analysis and Automation Software

The analysis software is required to take the measured displacement and load time history information at a number of points throughout a durability test from each of the performance listed below:

- Ride height at predetermined spindle vertical load
- Suspension Alignment at constant load input condition
- Vertical Rate in-phase and out-of-phase – Hysterisis Loop
- Lateral compliance-Hysterisis Loop
- Longitudinal compliance-Hysterisis Loop
- Dynamic Rate

The automation software is required to operate in conjunction with the test rig control system, to integrate the durability test schedule, periodic performance test measurements and test stop/continue decision process. The software has the following functions:
• Insertion of performance tests at user defined points within the durability test sequence.
• Communication as required with any separate hardware or software system to initiate simultaneous data collection of load and displacement measurements.
• Communication with the analysis software system to determine whether any of the static "Zero" load values or calculated parameters lies outside of the preset limits.

8.3 Test Sequence and Data Collection procedure

The data collection sequence was kept as follows:

• Collect the data for all the 3 LEDs at the beginning of the durability using white noise and several previously determined sinusoidal load drives
• Run the durability sequence.
• At 25%, 50%, 75% and 100% of the durability stop the test and play out the all the drive files, and collect data for all the LEDs in predefined local coordinates. If required, three sets of data could be collected and averaged for final data comparison.
• After each data collection compare the data with the previously collected data to ensure the collected data is in alignment and consistent.

8.4 Measurement System Details

The vertical wheel rate indicates how much force is needed for a certain vertical displacement. It is very similar to the spring constant. The ride height is the initial 6D position of the wheel-hub or initial vertical height between road and wheel-hub. The ride height change calculates a distance by dividing the changes in force by the spring constant. Lateral compliance is the ratio between camber-change and lateral force change. Longitudinal compliance is the ration between length-change and longitudinal force change.
The sequence of operation during the measurement and analysis phase of such system is as follows:

- Identification of reference coordinate system
- Identification of the car body as a rigid system
- Measurement data converted to the common reference coordinate system
- Synchronization of the measurement points
- Calculations of translations and rotation of each LED point

### 8.5 Results

- For the determination of vertical rate, vertical sinusoidal displacements are provided to both the wheels in-phase and out-of-phase conditions. The in-phase input gives the suspension vertical movements whereas the out-of-phase input provides roll motion of the suspension and body in addition to the vertical inputs of each spindle or hub. Figure 8.5.1 displays the relationship between vertical input and the resisting force measured by the load transducer attached to the spindle. The resultant curve is the hysteresis loop curve for the vertical rates.

- During the sinusoidal displacement input to the spindle, the force at the transducer that is the rig response or suspension response is also measured to see if the resisting force of the suspension has changed. Figure 8.5.2 displays the relationship at various levels of durability between vertical force and time duration during which the sinusoidal inputs are provided.

- In a similar fashion, while providing the lateral force inputs, the rolling moment, \( M_x \), is measured. Due to lateral force input off the hub center, lateral force creates a lateral force and camber moment at the spindle centerline. This is the moment that is measured by the load transducer. Figure 8.5.3 displays
the relationship between the camber moment and time duration during which the sinusoidal drive file is played out.

- While providing the off-center lateral force inputs to the wheel, the lateral force response, $F_y$, is measured at the hub centerline. An opposing lateral force is provided to the both spindle centerline to create a compressive force in-bound of the wheels. This is the force that is measured by the load transducer. Figure 8.5.4 displays the relationship between the lateral force and time duration during which the sinusoidal drive file is played out.

- Figure 8.5.5 is a similar graph for the longitudinal direction input. For the longitudinal direction, both the wheels are excited in-phase in the longitudinal with sinusoidal forces for a predetermined duration at 0%, 25%, 50%, 75% and 100% of the durability.

- The next figure, Figure 8.5.6, displays the hysteresis curve in the longitudinal direction. The represents the relationship of the suspension force response in the longitudinal direction against the longitudinal displacement inputs. Due to sinusoidal inputs, the resultant graph displays a closed loop fashion. The area of the hysteresis loop normally represents the frictional losses of the suspension during such inputs.

- The following graph, Figure 8.5.7, displays the location of the spindle centerline without any input to the spindle, defined as "Stop Test". Such measurement is taken at 0%, 25%, 50%, 75% and 100% of durability run. The forces and moments of the rig transducers are adjusted to zero before each such measurement. The primary objective of such test is to measure the
spindle center location to determine the settling of the suspension in three directions. This also allows the determination of the ride height changes for the suspension.

- The last graph, Figure 8.5.8, displays the force transducer outputs against time duration during which an in-phase sinusoidal displacement is provided for both the wheels. Such measurements are taken at uniform interval during durability run as mentioned before.

8.6 Discussion of Results

In general, the vertical tests, in-phase and out-of-phase, are done using displacement inputs and spindle force and movements are recorded to develop kinematics and compliance relationship for the spindle. In lateral and longitudinal directions, force inputs are provided and the spindle reactions and movements are recorded at predetermined intervals during the durability test. Since, various parameters and variables are required to accurately assess the degradation of the suspension modules, various tests are performed to determine the degradation of performance of such module.

The suspension stiffness, damping and deflections are important parameters to be tracked during durability as they affect the ride and handling characteristics of a vehicle. Kinematics tests measure wheel position changes that occur due to vehicle position changes such as roll and ride height while horizontal forces are zero. Compliance tests measure wheel position changes due to horizontal force inputs. As a result of performing both of these types of tests, degradation of suspension parameters can be assessed in a very precise manner.
To determine the suspension rate changes, backlash and friction losses, the hysteresis loop, as displayed in Figure 8.5.1 and 8.5.6, is often used. The slope of the line when the displacement is gradually increased in any direction, determines the vertical stiffness of the suspension. In this case, at 0% durability, it was found to be about 23 N/mm. If the vertical stiffness degrades during durability or backlash changes, the slope of this line will change. As can be seen from this figure, the suspension vertical rate slightly changed but such changes are to be compared against required or specified variation of the rate during the lifetime of the vehicle so that ride and handling of the vehicle does not change beyond the expectation level of the customer. Another important aspect is the area inside the hysteresis curve. This is an indication of the frictional losses in the system. If the area grows in size and shape, it may mean that damping and bushing characteristics have changed. A large hysteresis loop area at any point of time may point towards highly damped shock etc. and this can be used to tune the shocks at any level of the durability. The changes of the shock behavior is more important than the absolute value of the damping once the shock has been adjusted to its desired level in the initial stages. Another important aspect of such curve is the change in the direction of the gradient of the line that may mean backlash has been introduced in the system. The backlash is the phenomenon where the suspension hesitates to response for a range of force inputs. This makes the suspension insensitive to the changes in external forces. In general, all these parameters, kinematics and compliance parameters, are to be tracked during durability and compared against specifications. The suspension degradation assessment should include racking down these parameters and rate of changes are more significant than absolute values at any point of time.
Another important degradation parameter is the change in ride height or permanent settling of the suspension. This may occur due to permanent changes in the springs and bushings. Once the ride height is minimized due to permanent settling of springs or bushings, the jounce and rebound travels gets affected. In that case, component interferences could be increased. This may severely affect the fatigue life of the chassis components as the vehicle ages during the life of vehicle. Such phenomenon could be observed in the Figure 8.5.7 and Figure 8.5.8. Any horizontal shift of these graphs against time is an indication of suspension changes with regard to spring and bushing stiffness rates.

In general, suspension degradation assessment and steps taken to keep the changes within a specified range are the most important aspects of vehicle durability performance tests in the laboratory. Once such changes are specified in the system design specifications, such performance measurement techniques could be employed to confirm the requirements during the durability tests in the laboratory. Once the confirmation is completed, vehicle can be sent to proving ground for other chassis durability tests. The controlled laboratory environment make the degradation assessment of any vehicle make such tests more suitable and preferred to the proving ground tests where tracking such minute changes could be time consuming and difficult.
FIGURE 8.1 6 DOF Road Simulators with Transducers and LEDs
FIGURE 8.1.1 Location for 3 LEDs on the Transducer Housing
Figure 8.1.2 Three Lens Camera System
Figure 8.5.1 Hysteresis Curves for Out-of-Phase inputs, $F_z$ Vs. $Z$

Figure 8.5.2 Vertical Displacement, $Z$, Vs. Time
Figure 8.5.3 Rolling Moment, Mx, Vs. Time

Figure 8.5.4 Lateral Force, Fy, Vs. Time
Figure 8.5.5 Longitudinal Force, Fx, Vs. Time

Figure 8.5.6 Hysteresis Curves for Out-of-Phase inputs, Fx Vs. X
Durability 0%  
Figure 8.5.7 Stop Test Vertical Output for In-Phase inputs, Z Vs. Time

Durability 100%  

Durability 25%  

Durability 75%  

Figure 8.5.8 Vertical Force, Fz, Vs. Time
9.0 Implementation and Management of the proposed Degradation Assessment Process

9.1 Background:

The implementation and management of a high mileage degradation process requires the following of a step-by-step process. The implementation planning process could be defined as planning the integration of customer objectives with those of management and program engineers while establishing team interaction among all the stakeholders of the process. The planning and implementation of a high mileage degradation process for any vehicle introduces a new challenge to the standard principles of durability attribute management, graceful. The high mileage degradation management and graceful degradation planning are two relatively new concepts that will bring, in my opinion, the highest possible customer satisfaction if it is followed and managed in a religious fashion. Implementation therefore follows a general plan normally associated with robustness and durability training.

9.2 Implementation of Degradation Process:

The implementation planning process converts all the degradation requirements into a logically sequenced set of negotiated work authorizing agreements and subcontracts. This process is driven by the objectives and need to communicate and obtain agreements and commitments among durability engineers, program engineers, and management. A possible overview of the degradation plan development objectives and process is shown in Figure 9.2.1. It highlights the role and responsibilities of the high mileage degradation attribute project manager in the integration of customer requirements with those of management. The success of degradation planning and assessment ultimately depends on the level and quality of team interaction among program, durability, and CAE Engineers and Program management.
Figure 9.2.1 Degradation Implementation Overview
The project objectives for the degradation assessment and implementation for any vehicle program include:

- **Project Strategy**
  - System level Control or Component Level Control
  - Short Term or Long Term Vision
  - Attribute Degradation
  - Budget
- **Level of Degradation Management and Control**
  - Bath Curve Assessment
  - Degradation planning for Attributes
  - Life Required
- **Time Requirements**
  - Program Milestone Requirements
  - Attribute Degradation
- **Degradation task Deliverables**
  - Input of the system
  - Output of the system
  - Noise Level and Management
- **Manpower Requirements for each program**
- **Team/Task Relationship**
- **Critical Path**
  - Suspension System
  - Chassis System
  - Body System
  - Electrical System
- **Risk Management and Assessment**
  - What if degradation is not managed
  - Program Timing Issue
- **Degradation/Robustness Action and Control Issues**

The sequential implementation process must:

- Define System Variables to be considered for degradation assessment and control for each major system of the vehicle
- Define the requirements and milestone requirements
- Define work requirements to satisfy all the deliverables
- Sequence and link each task into a project network
  - Suspension degradation task
  - Body Structure degradation task
  - Electrical
- Identify the critical path
- Define and evaluate risk associated with not satisfying the requirements
• Develop schedules and establish contingencies
• Plan for the physical requirements, equipments, set-ups, fixtures etc.
• Plan the type and number of personnel requirements and time when they are required
• Assess the budgetary requirements and make sure the budget is available
• Perform Iteration if required to make the plan a real plan
• Obtain Management and engineers' buy-in
• Execute the plan for the program

9.3 Generic Degradation Implementation Plan

The primary task of the degradation attribute team engineers is to envision realistic and down-to-earth degradation requirements for each component of any attribute of the vehicle, decompose those requirements into deliverables, and then simulate the workflow smoothly through the system without causing unnecessary strain on the system. The planning flow chart, shown in Figure 9.3.1, shows a systematic way to transform the degradation requirements into an activity and control plan suitable for successful achievement of a degradation plan for the vehicle. The elements of such a planning diagram or flow chart can be described as given below.

9.3.1 Determination of Project Deliverables:

The first step is to determine all the project deliverables and provide a detailed description of each such project. For suspension degradation planning, the deliverables could be to limit the change in the suspension parameters every 25% of real world usage life for the vehicle. The suspension parameter could be ride weight; castor, camber, and toe changes; suspension stiffness; and damping rate of change; etc. The product architecture could be decomposed into a hierarchical structure and for each level of sub system, degradation requirements or deliverables could be mentioned. The system decomposition, historical facts,
experience with the system, and its behaviors are the key elements to the success of this step of the process. In this a way, a complete list of projects and its deliverables could be determined.

9.3.2 Development of Degradation Strategy

Next, for each system and sub system of the vehicle, a degradation strategy has to be developed with regard to NVH, S&R, stiffness, damping, hard point interferences etc. The program team has to decide whether an incremental improvement or revolutionary change is required to satisfy the customer requirements. The vehicle level strategy and requirements have to be cascaded down to system, subsystem and component level requirements. For a borrowed platform vehicle, incremental improvement could be sufficient. For a new platform, an revolutionary strategy may be more suitable.

9.3.3 Development of Risk Strategy

For each control element or degradation parameter the opportunities and associated risks should be evaluated. For many system parameters it may not be possible to determine a clear cause. In that case, spending of resource and time may be not worthwhile at all. A risk strategy also has to be developed for preventive, causative, and contingent plans. This should be referred back to a previous history or data book of the company, or it could be put it into the database of "lessons learned" for future platforms.

9.3.4 Definition of Tasks and Network of Tasks

Next, all the tasks have to be defined to ensure completion of each deliverable. Once the complete set of tasks is developed, it should be logically sequenced and a network of sequenced tasks has to be developed for smooth execution. The logical arrangement of tasks will portray the best delivery approach. The critical path also should be determined. As an example, frame degradation has to be assessed and controlled before the body mount
degradation is controlled. Sequencing of the tasks must be maintained to ensure the integrity of the test.

9.3.5 Development of Work Breakdown Structure (WBS)

The WBS is used, as defined by NASA, to depict the system assemblies, sub assemblies, and component rather than by discipline or functions of the system. Hence the suspension will be broken down into components (e.g. lower and upper control arms, upper ball joint, shocks, springs spindle etc.). It is a mandatory document for the implementation plan since it is the basis for work assignments, budgeting, scheduling, and other critical components of the overall process. The work package is developed for each element of system at its lowest level.

9.3.6 Schedules, Resources and Commitments

After the sequencing and critical path for the tasks are determined, work schedules should be developed. The combined set of work schedules will establish the resources, personnel, equipment, and facilities required for the program to address degradation assessment for the program. Commitments from higher management to deploy the required resources (including financial) for each task should be obtained before execution and implementation of the plan.
Vehicle level Degradation Requirements

Degradation Timing alignment with FPDS Timing and Milestones

Program Timing Schedule

Sequenced Degradation task Network

Degradation Team

Program Management

Cost Management

System Design Specifications

System/Product List

Work Breakdown Structure (WBS)

Program Organization

Degradation Timing

Project Plans and Updates

Testing Plan

Manufacturing Plan

CAE Plan

Modal Test Plan

PG Test Plan

CAE/Test Correlation

System Engineering Management Plan

Task/Responsibility Matrix
- Test Engineer responsibility
- CAE Responsibility
- Manufacturing Responsibility
- High Mileage Degradation
- System Integration
- Design Team Responsibility

Design Changes If Required

Project Review And Control

Figure 9.3.1 Implementation Flow Sheet
9.4 Suspension/Body Structure Degradation Implementation

The generic implementation plan described in the previous section could be applied to the suspension degradation scheme for any program. The following six steps are required:

Step 1:
- Formation of High Mileage Degradation Team for the program
- Establish communication channel with Program Durability team

Step 2:
- Obtain Customer Requirements for suspension/Body Degradation
- Obtain SDS available from Core Technology group
- Relevant design information from previous program’s "lessons learned"

Step 3:
- Formalize Suspension/Body Degradation Specifications for the vehicle
  - Castor, Camber and Toe changes for the useful life
  - Ride Height Changes
  - Ride and handling Changes required
- Confirmation of Design Concepts to support the Degradation requirements
  - CAE Analysis and Prediction
  - Modal Analysis
- Develop Test Plan for the vehicle for verification of CAE results
  - Develop Optical Measurements plan – CMM and Dynamic
  - Strategic Locations and measurements Plan
  - Durability Road Surfaces and Correlation Road Surfaces
  - Simulation or Block Cycle
  - Vehicle Level testing or Sub System level testing

Step 4:
- Inform FSS the degradation requirement and testing plan and requirements
- Inform Test Operation Team about the test plan
- Line up Test Facilities

Step 5:
- Conduct Suspension related testing foe degradation parameters
- Validate and correlate the degradation of suspension parameters
- Report back to program management any anomalies, if required
- Decide the design fix
- High Mileage Degradation Sign Off

Step 6:
- Complete High Mileage Degradation Verification for other attributes
- CP Sign Off
- Fill up the "Lessons Learned" database
- Confirmation of Degradation Parameters for Launch"QOS" Vehicle
- Update the database, if required
10.0 Conclusion

The focus of this thesis was to develop methodology based on real time system excitations and six degrees of freedom Optical measurement systems for the assessment, planning and validation of body structure and suspension system degradation for ground vehicles. The intention of this work was not to determine the level of degradation of any particular Ford vehicle cited in this thesis but rather introduce a preliminary concept of degradation planning and validation using active measurement and simulation in the laboratory using a system level approach.

The thesis framework was developed to address two critical elements of the degradation aspect of the durability attribute of the development of any vehicle: Process planning and validation method suitable for structural tests in the laboratory environment. Inputs from such experimental measurements and analysis of the data are highly useful in product development process to provide representative and timely information for decision making in the early stages of the automobile body design process. This work also pointed towards systemic development of procedures and methodology to evaluate implications of structural degradation on the high mileage durability attribute targets such as Noise, Vibration and Harshness (NVH) and Squeak & Rattle performance of the subject vehicle. A combination of real time simulation process and high frequency Optical measurements was recommended to develop systemic methodology to understand relationship between changes in structural degradation of the body and suspension systems and durability mileage of the vehicle in the laboratory environment.

The first portion of this thesis framework was dedicated to describe the deliverables, process optimization and program interfaces required to make this systemic approach successful and useful to achieve highest customer satisfaction. The rest of the work provided a methodology for verification and confirmation of degradation requirements for system level design intent parameters of suspension modules and body structures. The content of these modules are sufficient and necessary to develop a holistic strategy to plan for a graceful degradation of system level performances for any automobile under the scope. The content is
also recommended as a necessary pre-requisite for the durability attribute team to enhance robustness of the vehicle during real world usage. The primary purpose of this work was to create a strategic direction for planning and controlling degradation of structural performances and not to pinpoint limitation or severity of degradation for any vehicle that has been used here to develop these tools.

The proposed method generates a degradation assessment process and its related database that could be utilized to optimize and improve durability metrics that define the durability performance specifications to maximize customer satisfaction. This process will help the program development engineers and project managers to define, validate and verify high mileage durability attribute specifications and develop a product design strategy roadmap based on balancing customer requirements and technical feasibility aspects of any program. A systemic test planning and methodology were developed for using the 6 degrees of freedom Optical guided high frequency real time digital measurement system in combination with the subject vehicle and real time excitation inputs to the body systems and how to utilize and manage the data in predicting and preventing system level degradation worse than customer expectation during the whole life cycle of the product. This process also can be very well used to optimize the system level durability performance for the vehicle.

In essence, this proposed method, if developed and applied properly, has potential of reducing product development cycle time and satisfies both internal and external customer requirements. In addition, it will assist new program team members in learning the body design and development process and limitations thereof. Management, on the other hand, can utilize the developed process as a primary validated and verified indicator to estimate variation of body system attributes over design life and effects of changes in the vehicle program. Understanding the complexities of body system and its role in vehicle property degradation will also help the management to estimate and effective deployment of resources in the future programs to avoid any program difficulties in advanced phases of the development cycle.
This work was meant to develop a methodology for building system level durability performance knowledge base to validate and verify system level durability performances at various stages of product development phases. Such process and methods, if developed properly, will help to identify the structural weakness of a vehicle system and rate of change of structural stiffness and performance requirements with regard to safety, NVH and Squeak & Rattle attributes.

The deliverables and tools suggested in this proposed methodology can be further modified and verified for a specific vehicle application. The durability team can customize the procedure by including specific design specifications for degradation and robustness for system, sub-system or components. Specifically, including methods to verify and confirm laboratory findings in the proving ground can further enhance the suggested procedure. Although the suggested procedure concentrated on the suspension module and body structure, it can be easily modified for other vehicle sub systems as deemed necessary by the durability team and management. Moreover, a vehicle specific database, showing the relationship between degradation and nature and amount of actual abnormalities in the structure, also has to be developed over time so that the past experience could be used for future platforms.
11.0 Bibliography

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