System Redesign within Complex, Technically Integrated Products

by

Robert Giammatteo

S.B. Mechanical Engineering, Massachusetts Institute of Technology, 1994
M.S Mechanical Engineering, Rensselaer Polytechnic Institute, 1997

Submitted to the Sloan School of Management and the
Department of Aeronautics and Astronautics in
Partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration
and
Master of Science in Aeronautics and Astronautics

In Conjunction with the Leaders for Manufacturing program at the
Massachusetts Institute of Technology
June, 2000

Signature of Author ______________________________
Department of Aeronautics and Astronautics
Sloan School of Management
May 5, 2000

Certified by ______________________________
Paul A. Lagace
MacVicar Faculty Fellow
Professor of Aeronautics and Astronautics and Engineering Systems
Thesis Advisor

Certified by ______________________________
Arnold Barnett
George Eastman Professor of Management Science
MIT Sloan School of Management
Thesis Advisor

Accepted by ______________________________
Margaret Andrews
Executive Director of the MBA Program
MIT Sloan School of Management

Accepted by ______________________________
Associate Professor Nesbitt Hagood
Chairman, Graduate Committee
Department of Aeronautics and Astronautics

(This page intentionally blank)

System Redesign within Complex, Technically Integrated Products

By

Robert Giammatteo

Submitted to the Sloan School of Management and the
Department of Aeronautics and Astronautics on May 5, 2000
in Partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration
and
Master of Science in Aeronautics and Astronautics

Abstract

The process by which complex, technically integrated products are designed and introduced can be a source of competitive advantage, especially when marketplaces are sensitive to product quality levels. An extension of this competitive advantage is the process by which ongoing production programs are supported. The ongoing support of complex products involves periodic evaluation of critical systems that effect overall customer satisfaction with the product. Such evaluation is performed to identify systems whose performance has dropped to levels that require full system redesign. In this study, a methodology is proposed that can be utilized in the redesign process of systems embedded within complex products. The overall methodology involves identification of critical target systems, a failure mode analysis of the identified system(s), use of benchmarking and/or statistical tools as necessary to characterize features that can be utilized to improve system performance, and finally, conceptual design activity to implement such features. Specifics of each of the aforementioned process steps within the overall methodology are illustrated through work performed on a project sponsored by Ford Motor Company to address poor performance of the water seal system on the SN-95 Mustang convertible.

In addition to the technical issues encountered during execution of the proposed system redesign methodology, organizational issues significantly impact the overall effectiveness of ongoing production program support. Organizational structures can raise barriers to efficient organizational knowledge transfer, thus introducing inefficiencies into the overall product development process. This study examines the relationship between organizational structure and knowledge flow amongst the various stakeholders of ongoing production programs. This relationship is used to characterize mechanisms that promote effective transfer, management, and growth of the product development knowledge base within an organization's overall product development community. Examples of mechanisms that were characterized as promoting effective knowledge transfer, management, and growth include the use of aligned organizational metrics against which the different stakeholders responsible for support of a specific program are judged, and rigorous use of a formal process for documentation of experience-based lessons-learned.

Thesis advisors: Arnold Barnett, Professor, Sloan School of Management
Paul A. Lagace, Professor of Aeronautics and Astronautics and Engineering Systems

(This page intentionally blank)

Acknowledgements

The author wishes to gratefully acknowledge the help and support of the following individuals and organizations, without whom/which, this work would not have been possible:

- First and foremost, to my parents, thank you for all your love and support over all these years, and for providing me the opportunity to succeed. I would not be in this position without both of you. I love you both more than anything.
- To my many friends at the Leaders for Manufacturing Program, both colleagues and staff, thank you for providing an incredible learning experience and camaraderie both inside the classroom and out. I will miss you all, and wish you the best of luck in your careers.
- To my thesis advisors, Arnie Barnett and Paul Lagace, thank you both for your guidance, support, patience, and friendship during my internship and the thesis writing process.
- To Scott Ball, thank you for your help developing the Visual Basic source code utilized herein.
- To Abizer Gaslightwala, thank you for your help in testing activities at Dearborn Assembly Plant.
- To Greg Christensen, Karen Raggio, Terry Somers, Lisa Moore, Mike Whitens, Hossein Nivi, and the SN-95 water leak quarterback team at Ford Motor Company, for their participation in, and support of this project.
- And finally, to Ford Motor Company, for its generous sponsorship of this project, and continued support of the Leaders for Manufacturing Program.

(This page intentionally left blank)

Table of Contents

Chapter 1 - Introduction 13
  1.1 Design/Assembly Evolution as a Source of Competitive Advantage 13
  1.2 Case Study Introduction - Mustang Convertible Water Seal System 16
  1.3 Proposed Methodology for Performance Enhancement Projects 17
  1.4 Thesis Overview 19
Chapter 2 - Target System 21
  2.1 Target System Selection Process: An Overview 21
  2.2 Target System Selection - Case Study 23
  2.3 Baseline Characterization - Generally Accepted System Design Methodology 24
Chapter 3 - Failure Mode Analysis of Current System 31
  3.1 Principles used in Failure Mode and Effect Analyses: An Overview 31
  3.2 FMEA Case Study Methodology 33
  3.3 Test Procedure Development – Case Study 37
  3.4 Failure Mode and Effect Analysis – Case Study 40
    3.4.1 Pivot Joints 42
      3.4.1.1 'A-Pivot' Joint 42
      3.4.1.2 'B-Pivot' Joint 44
      3.4.1.3 'C-Pivot' Joint 45
    3.4.2 'Wet Area' 47
    3.4.3 Glass System Division Bar 48
      3.4.3.1 Glass System Assembly Process Description 49
      3.4.3.2 Glass System Assembly Process Limitations 51
  3.5 FMEA Case Study Results 53
  3.5.1 Pivot Joints 53
  3.5.2 Glass System 54
  3.5.3 Summary 55
Chapter 4 - Quantitative Process Control Analysis 57
  4.1 Variability Analysis: An Overview 58
  4.2 Grid Search Statistical Methodology 59
  4.3 Grid Search Analysis - Case Study 64
  4.4 Case Study Results 67
  4.5 Summary 77
Chapter 5 - Benchmarking Study 79
  5.1 Benchmarking Process: An Overview 79
  5.2 Benchmarking Study - Case Study 81
    5.2.1 'A-Pivot' Region 83
    5.2.2 'B-Pivot' Region 84
    5.2.3 'C-Pivot' Region 87
    5.2.4 Glass System Division Bar 88
    5.2.5 Wet Area 90
  5.3 Benchmarking Study Results 90
Chapter 6 - Conceptual Design Activity 93
  6.1 Conceptual Design – An Overview 94
  6.2 Conceptual Design – Case Study 96

    - 6.2.1 Mock-Up Phase ... 97
        - 6.2.1.1 'A-Pivot' Region ... 98
        - 6.2.1.2 'B/C-Pivot' Regions ... 103
    - 6.2.2 Prototype Phase ... 107
  - 6.3 Conceptual Design - Results ... 111
- Chapter 7 – Effect of Organizational Structure On Knowledge Flow ... 117
  - 7.1 Organizational Structures: General Background ... 117
  - 7.2 Organizational Structure Used in New Product Introduction – Overview ... 119
  - 7.3 Knowledge Flow Between Functional Organizations ... 122
    - 7.3.1 Research and Vehicle Technology (RVT) ... 126
    - 7.3.2 Product Development (PD) ... 129
    - 7.3.3 Plant Vehicle Team (PVT) ... 131
    - 7.3.4 Vehicle Operations (VO) ... 133
  - 7.4 SN-95 Program Launch Characterization (1993) ... 134
  - 7.5 Current State of SN-95 Program Organizational Learning and Knowledge Flow ... 139
    - 7.5.1 Supplier Management ... 140
    - 7.5.2 - Reverse Flow of Lessons Learned ... 144
    - 7.5.3 - Alignment of Organizational Metrics ... 149
  - 7.6 Current State of SN-95 Program - Conclusions ... 157
- Chapter 8 - Evaluation of Product Development Community ... 159
  - 8.1 System-Level Ownership ... 159
  - 8.2 Organizational Issues ... 162
    - 8.2.1 Knowledge Flow and Management ... 163
    - 8.2.2 Balance Between Corporate Cost and Quality Goals ... 169
    - 8.2.3 Abandonment of Organizational Support Roles ... 173
    - 8.2.4 Development of Environment that Promotes Proactive Design Activity . 176
  - 8.3 Engineering/Technology Issues ... 178
  - 8.4 Broader Implications ... 179
- Chapter 9 - Summary ... 181
- References ... 187
- Appendix A - Supporting Figures ... 189
- Appendix B – Grid Search Analysis Details ... 193
- Appendix C - Spearman Rank Test Results ... 197
- Appendix D - Grid Search Source Code ... 201
- Appendix E - Raw Data Utilized in Grid Search Analysis ... 215

List of Figures

Figure 2.1: Side View of Mustang Convertible - Seal System Regions. 25

Figure 2.2: Current Mustang Seal System - Convertible Rail to Top ('B' region from Figure 2.1). 26

Figure 2.3: Current Mustang Seal System - Convertible Rail to Glass System 27

Figure 2.4: Current Mustang Seal System - Glass System Division Bar ('C' region from Figure 2.1). 27

Figure 2.5: Current Mustang Seal System - Rear Quarter 'Wet Area' ('D' region from Figure 2.1). 28

Figure 3.1: Test Fixture Representation 38

Figure 3.2: SN-95 Water Seal Failure Mode Locations. 41

Figure 3.3: 'A-Pivot' Joint Design and Related Leak Location 42

Figure 3.4: 'B-Pivot' Joint Design and Related Leak Location. 45

Figure 3.5: 'C-Pivot' Joint - Roof Partially Cycled. 46

Figure 3.6: 'C-Pivot' Details and Related Leak Path. 46

Figure 3.7: 'Wet Area' Leak Path. 47

Figure 3.8: Glass System Joint – Convertible Top Down. 48

Figure 3.9: Glass System Setting Process Flow Diagram 49

Figure 3.10: Door Glass Setting Fixture – Clamped Position. 50

Figure 4.1: Expected Fundamental Variables of Division Bar Region 65

Figure 4.2: Driver Side Scatter Plot – Fundamental Variables 3 and 4 Versus Leak Volume 69

Figure 4.3: Passenger Side Scatter Plot - Fundamental Variables 3 and 4 Versus Leak Volume 70

Figure 4.4: Two-dimensional Representation of Effect of Glass System Skew and Up/Down Mismatch on Division Bar Seal Gap 75

Figure 5.1: Best-In-Class 'A-Pivot' Region of Chrysler Sebring. 84

Figure 5.2: Mercedes 'B-Pivot' Joint Water Seal in Deployed Position. 85

Figure 5.3: Mercedes 'B-Pivot' Joint - Roof Partially Cycled 85

Figure 5.4: Best-In-Class 'B-Pivot' Region of Chrysler Sebring. 86

Figure 5.5: Best-In-Class Division Bar/Weather Strip Seal of Chrysler Sebring. 89

Figure 6.1: Preliminary Mock-Up of Bulb Seal/Vinyl Top Bonded Interface Concept... 97
Figure 6.2: Existing Forward Weather Strip Detail – 'A-Pivot' Region 99
Figure 6.3: Existing Forward Weather Strip Detail (installed) – 'A-Pivot' Region........ 99
Figure 6.4: 'A-Pivot' Water Seal Mock-Up – Forward Weather Strip Detail............... 101
Figure 6.5: 'A-Pivot' Water Seal Mock-Up – Roof Clamping Hooks Disengaged 102
Figure 6.6: Discontinuity in Retainer Seal Lip Detail at SN-95 Mustang 'B-Pivot'..... 103
Figure 6.7: Discontinuity in Retainer Seal Lip Detail at SN-95 Mustang 'C-Pivot'..... 104
Figure 6.8: 'B-Pivot' Joint Mock-Up.. 105
Figure 6.9: 'B-Pivot' Molded Detail Mock-Up 106
Figure 6.10: 'C-Pivot' Joint Mock-Up.. 106
Figure 6.11: Rubber Extrusion Vinyl Top Mounting Design Concept – Current and Proposed.. 111
Figure 6.12: Prototype System 'A-Pivot' Detail.. 114
Figure 6.13: Prototype System 'B-Pivot' Detail. 115
Figure 7.1: Organizational Structure Supporting New Vehicle Line Launch/Support.. 120
Figure 7.2: Overarching Structure of Ford's Product Development Organization 124
Figure 7.3: Knowledge Flow Model Between Functional Organizations on Specific Vehicle Programs... 125
Figure 7.4: Warranty Claims Against Water Seal System Versus Time in Service...... 137
Figure A.1: Behavior of Convertible Top Assembly During Roof Retraction..............189
Figure A.2: Comparison of the 'A-Pivot' Region of the SN-95 Convertible Water Seal System in its Current Configuration and in its Prototype State.........................190
Figure A.3: Comparison of the 'B-Pivot' Region of the SN-95 Convertible Water Seal System in its Current Configuration and in its Prototype State.........................191
Figure A.4: Comparison of the 'C-Pivot' Region of the SN-95 Convertible Water Seal System in its Current Configuration and in its Prototype State..............................192

List of Tables

Table 4.1: Preliminary Mock-Up of Bulb Seal/Vinyl Top Bonded Interface Concept........67
Table 4.2: Spearman Rank Test on Original Thirty-Vehicle Data Set...........................71
Table 4.3: Spearman Rank Test on Twenty-Vehicle Holdout Sample.......................... 73
Table 6.1: Action Items Taken for Design Concept Implementation..........................108
Table 6.2: Detailed Design Changes...113
Table 7.1: Organizational Metrics Utilized to Judge Performance.............................150
Table C.1: Driver Side Spearman Rank Test for Original Thirty-Vehicle Test Sample.....197
Table C.2: Passenger Side Spearman Rank Test for Original Thirty-Vehicle Test Sample198
Table C.3: Driver Side Spearman Rank Test for Holdout Test Sample........................199
Table C.4: Passenger Side Spearman Rank Test for Holdout Test Sample...................200

Nomenclature

DAP	Dearborn Assembly Plant
n	Number of data points used in Spearman rank test
OPD	Ongoing Product Development
PD	Product Development
PVT	Plant Vehicle Team
RVT	Research and Vehicle Technology
VO	Vehicle Operations
X1	Fore/aft gap between door glass trailing edge and quarter glass leading edge at top of glass system interface
X2	Fore/aft gap between door glass trailing edge and quarter glass leading edge at mid-height of glass system interface
X3	Inboard/outboard gap between door glass trailing edge and quarter glass leading edge at top of glass system interface
X4	Inboard/outboard gap between door glass trailing edge and quarter glass leading edge at mid-height of glass system interface
X5	Up/down mismatch between door glass trailing edge and quarter glass leading edge at top of glass system interface
x	Axis representing fore/aft direction of vehicle (see Figure 2.1)
y	Axis representing up/down direction of vehicle (see Figure 2.1)
z	Axis representing cross vehicle direction (see Figure 2.1)

Chapter 1 - Introduction

There are many sources of competitive advantage in the marketplace. The time horizon over which these advantages can be exploited varies greatly. An innovative idea that is embodied in a new product will give the introducing company a first mover advantage. However, competitors can quickly combat the first mover advantage with similar new product introductions that utilize the innovative idea. Conversely, a company that has become a low cost producer of high quality products will be able to compete successfully on price for extended periods without adversely affecting its profit margins. By investing resources in development of efficient manufacturing processes, it is much easier for the low cost/high quality producer to defend its position in the marketplace against competing companies with higher cost structures. It is therefore desirable for companies to focus resources on developing some form of sustainable competitive advantage. This study asserts that companies that successfully manage the evolution of products/assembly processes to reflect changing customer demands can maintain a competitive advantage in the marketplace in the form of customer satisfaction with the quality level of their products.

1.1 Design/Assembly Evolution as a Source of Competitive Advantage

The need for consistently high quality levels in the products manufactured for today's demanding marketplace is critical for the continued success of all manufacturing companies. Maintaining high quality levels of complex products that are sold to individual consumers can be an especially challenging task. This is due to the system interactions inherent in complex products[1], as well as rapidly changing customer preferences and usage patterns that are difficult to predict.

Complex products are comprised of numerous systems, with each system having certain responsibilities. Together, these systems ensure acceptable overall product performance. An example of a complex product designed for individual consumers is the automobile, which has numerous systems upon which it relies to function as designed. Examples of automotive systems are the braking system, suspension system, powertrain (engine and transmission), and climate control system. Some of these systems are critical to safety and overall product functionality. For instance, an automobile could not be operated safely without a capable braking system, nor could it remain operational without a functioning powertrain. However, an automobile could remain functional for transportation even if its climate control system has failed.

In the context of such discussions, it is important to define key words such as *functionality* and *critical*. *Functionality* is defined herein as the ability of a product to meet user expectations during its operation. For this study, a system is considered *critical* if its performance directly impacts overall product safety, functionality, or customer satisfaction. The difference between critical and non-critical systems is important to understand, as it is suspected that such characterization of a system affects the rate of its design evolution (in the form of committed budget, manpower, and schedule). This is a key concept that is further explored.

---

[1] Case Studies in Engineering Design, Clifford Matthews, John Wiley & Sons, 1998. Page 232.

Critical systems (i.e. those affecting safety, functionality, and overall customer satisfaction) usually experience design evolution at a much faster clockspeed than do non-critical systems. This occurs because effective design evolution of critical systems can be a source of competitive advantage in the market.[2] As a result of resource constraints, and the design complexity of highly integrated, technically advanced products, the performance of non-critical systems may degrade to and remain at inadequate levels due to slow design evolution. It is this author's opinion that slow design evolution can cause initially non-critical systems to become critical systems over the production life of a product, should monitoring of system performance not be in place to ensure that adequate performance levels are maintained. This issue is explored in further detail in subsequent chapters.

Sub-optimal system performance upon initial introduction points to an ineffective new product introduction (NPI) process. However, even initially robust systems (in-service performance unaffected by varying external factors) can experience performance degradation over the course of their life as a result of evolving assembly processes and/or unexpected environmental factors such as changing customer usage. The importance of identifying and addressing deteriorating performance levels of specific systems within a complex product is critical to maintaining a competitive position in the marketplace.

---

[2] Clockspeed - Winning Industry Control in the Age of Temporary Advantage, Charles Fine, page 9.

This author's experience has suggested that customer perception of quality levels is typically related to the robustness of product/system designs to customer usage. It is the assertion of this study that the development and maintenance of highly robust engineering systems requires not only an effective new product introduction process, but also ongoing review and revision of design/assembly processes in order to reflect changing environmental factors. Successful product introduction is facilitated by efficient organizational alignment of, and knowledge flow between, various product stakeholders. Product stakeholders within a given company may include, but are not limited to, internal research, design, and manufacturing communities, as well as an external supply base. Experiential observations of this author have suggested that the successful evolution of design/assembly processes requires not only the aforementioned organizational characteristics, but also an effective methodology by which product/system performance can be evaluated and improved within fixed resource constraints.

1.2 Case Study Introduction - Mustang Convertible Water Seal System

In this study, an overall methodology for identifying and improving critical system performance levels within complex, technical products is proposed. This is illustrated through a Leaders for Manufacturing (LFM) internship project completed for Ford Motor Company. This project focused on the performance of the Mustang convertible water seal system and lasted from June 1st to December 17th, 1999. The water seal system (as of the onset of this project) was a strong driver of customer dissatisfaction with the overall vehicle. The poor performance level of the Mustang convertible water seal system points to difficulties with system level ownership and knowledge flow issues on the program team responsible for ongoing vehicle line support. Therefore, in addition to improving system performance by following the proposed system evaluation/redesign methodology, this study attempts to characterize organizational learning and knowledge flow that contributes to the overall system level performance of current and future designs.

1.3 Proposed Methodology for Performance Enhancement Projects

A methodology that can be used to identify and improve sub-optimal system level product performance within highly integrated, technical products is therefore proposed herein. The methodology of this process involves the following sequence of steps:

1) identification of what system(s) to target for improvement
2) failure mode analysis of targeted system(s)
3) performance benchmarking study
4) assembly process variability study
5) conceptual design brainstorming activity
6) prototype generation
7) feasibility study

It is desirable to continuously improve all systems that reside within a complex product. However, resource constraints dictate that improvement efforts be focused on systems that are expected to have a significant impact on the overall competitive position of the product in which the system(s) resides. Changing customer demands on a given product will determine the systems that will have the most impact on the product's competitive position at any point in time. The first and most critical step to improving product quality is to identify customer wants, needs and expectations.[3] To understand and meet evolving customer demands, extensive market research is required to accurately identify target systems on which to focus improvement activities[4]. Once systems have been targeted for improvement activities, a failure mode analysis is essential to understand current system performance limitations and to provide a baseline performance level from which to identify the performance gap between a specific system and the system recognized as the industry best.[5]

Based on the results of the failure mode analysis, two courses of action may be appropriate and can be conducted in parallel. *Quantitative* (statistical) tools are appropriate where variability is suspected as the root cause contributor to a certain system level failure. *Qualitative* tools (concept brainstorming) may be more appropriate where a non-robust design methodology is suspected as the root cause of system level failure. Statistical methodologies alone can identify non-robust assembly processes, identify possible corrective actions that may eliminate sources of variability, and result in significant incremental performance improvements. However, to pursue *breakthrough* performance improvement rather than simply focusing on incremental performance gains, a combination of qualitative and quantitative tools is typically required. By combining quantitative tools with qualitative tools such as benchmarking, breakthrough performance improvements can be realized through "...methodology or equipment changes and the

---

[3] Principles and Practices of Organizational Performance Excellence, Thomas Cartin, 1999, page 63.
[4] Ibid.
[5] Ibid, page 48.

reduction of common causes of variability."[6] Promising design concepts realized during benchmarking activity typically evolve into pre-production, prototype systems that are tested to ensure the new concept meets all performance (design/life) requirements. Once validation prove-out is completed on a prototype system, all affected stakeholders must review implementation feasibility of the selected prototype system to ensure successful integration of the new concept into the current production process.

1.4 Thesis Overview

The ultimate goal of this study is twofold:

- to identify organizational structures that facilitate efficient knowledge flow and engineering design decisions (improving initial quality levels); and
- to provide an analytic framework to evolve existing designs, such that an organization can maintain its competitive position through superior product/system performance (enabling sustainable high quality levels).

This study follows the proposed system evaluation/redesign methodology described within Section 1.3. The generally accepted sealing methodology currently used in industry is overviewed in Chapter 2. A procedure for performing a system failure mode analysis is presented in Chapter 3. In Chapter 4, a discussion of the benchmarking procedure and use of associated results in the overall system redesign methodology is presented. Quantitative statistical models that can be used for incremental, process-oriented improvements are presented in Chapter 5, while qualitative conceptual redesign processes

---

[6] Cartin, page 76.

that can be used to generate breakthrough system performance improvements are presented in Chapter 6. Various organizational structures and attempts to relate how the use of different structures can impact engineering decisions and product/system quality are discussed in Chapter 7. Experience based observations from the LFM internship project are used in Chapter 8 to generate hypotheses for how other manufacturing entities can avoid similar pitfalls experienced by Ford Motor Company on sub-optimal system level performance within a highly integrated, technical product. Finally, a summary of the entire study is presented in Chapter 9. The theoretical content and hypotheses of each chapter are accompanied by concrete, project-based examples taken from the Ford-sponsored case study in an attempt to provide data to support the validity of the overall system evaluation/redesign methodology proposed herein.

Chapter 2 - Target System

One of the first factors that must be considered to promote the success of a performance enhancement project is selection of the target system on which to focus resources. Effective selection of a target system helps determine the proper scope of the overall project, and ensures that the expenditure of resources is aligned with organizational goals.

2.1 Target System Selection Process: An Overview

Literature review[7] has suggested a procedure for selecting a business *process* on which to target efficiency improvement activities:

1) identify organization mission, strategy, and goals
2) identify critical success factors
3) determine process selection criteria
4) identify list of process candidates
5) prioritize and select processes based on criticality, ability to improve and impact

Rather than focusing on procedures for improving business process efficiency, this thesis attempts to identify procedures for improving *product/system* performance. However, a direct analogy can be drawn between business processes and systems within a complex product. A business relies on processes to perform functional tasks much as a complex product relies on its systems for proper functionality. A variant of the aforementioned business *process* selection procedure can therefore be used to select a target *system* for a performance enhancement project.

The selection procedure for identifying a target system within a complex product begins with identification of overall company goals for their product positioning. For instance, if a company chooses to compete on quality, its criteria for product success factors could focus on customer satisfaction with overall product performance. Poor performance of one or more systems within a complex product will ultimately impact overall product performance. However, this author believes that if a company chooses to compete on quality, the true extent to which poor system level performance is a problem is the *visibility* of this performance to the customer. Market research is a tool that can be used to identify the systems of a given product whose performance is most transparent to customers. This research would generate a preliminary list of potential systems within the overall product to target for improvement activities. Taking the automobile as an example, the performance level of a vehicle's powertrain system would be extremely apparent to a customer and would therefore have a large impact on the perceived quality level of the overall vehicle. Several factors would be used to narrow down the preliminary target system list to determine the final systems that should be targeted for improvement projects. Among the factors that should be considered are:

- current level of system performance
- impact that a given system failure has on customer satisfaction with the overall product
- repair cost to the customer for system failure (customer satisfaction)
- repair cost to the company for system failure (warranty costs)
- projected scope of a related improvement project (technical barriers, schedule)

---

[7] Cartin, page 225.

- resources available to drive such a project (manpower, budget)

Consideration of these factors will help focus performance enhancement efforts on systems that ultimately impact overall customer satisfaction.

2.2 Target System Selection - Case Study

The aforementioned target system selection process was performed at Ford Motor Company prior to the onset of the thesis work presented herein. Ford has chosen product quality as the main product characteristic on which it plans to compete. Using analysis of its warranty data, Ford identified the strong drivers of customer dissatisfaction for all its different vehicle lines. For the Mustang vehicle line, one of the main drivers of customer dissatisfaction (as measured by percentage of vehicles registering customer complaints) was the performance of the water seal system of the convertible model. Poor initial seal system performance together with unreliable repair procedures for in-service failures combined to result in extremely high levels of customer dissatisfaction. Service technicians could only adjust door, window, and roof orientation in the hope of realizing improvements in seal system performance, but repairs to each system were unique and non-repeatable.

The annual water seal performance warranty cost to Ford related to convertible Mustangs (as of fall 1999) was roughly $1.5 million. While the magnitude of these related costs were not overly significant compared to Ford's aggregate warranty cost (approximately 1% of total), the poor performance associated with these costs ultimately impacted customer satisfaction with the overall vehicle. According to internal Ford research, *overall* customer satisfaction with the SN-95 generation Mustang is reduced 1.2% because of water leaks alone. The relationship between quality, customer satisfaction and customer retention is difficult to develop, and costs related to poor customer retention due to non-competitive vehicle quality cannot be easily quantified. Nevertheless, concern over the potential size of these 'soft costs' caused Ford to sponsor a performance improvement project targeting the Mustang convertible water seal system. The duration of the project was projected to be ninety days in length, and a ten-person team was assigned to be responsible for project deliverables. The scope of the project ranged from slight modifications to the existing seal system to an entirely new 'next generation' seal system. Sealing concepts were to be based on best practices observed throughout the industry. The ultimate goal of this project from Ford's perspective was to realize breakthrough performance gains in the Mustang convertible water seal system - gains that would leapfrog the performance level of current best-in-class systems used on competitive vehicles.

2.3 Baseline Characterization - Generally Accepted System Design Methodology

Once the selection procedure has been completed and one or more systems have been identified as the target(s) for performance enhancement efforts, it is then necessary to investigate the methodology within the industry that is generally accepted as the standard by which the task of each target system is performed. This study considers the generally accepted methodology used to seal convertible vehicles against leakage.

The vehicle's water seal system and its components are shown in Figures 2.1 through 2.5. An axis system is presented in the aforementioned figures to help orient the reader. The reference x-axis is aligned in the fore-aft direction of the vehicle frame, the reference y-axis is perpendicular to the plane of the vehicle frame, and the reference z-axis runs parallel to the vehicle axles. The convertible top design employs a three-joint/three hinge system, common to all soft-top convertibles currently on the market. The dynamic behavior of the linkage system controlling the roof is illustrated in Appendix A. The overall seal system and its regions are shown in Figure 2.1.

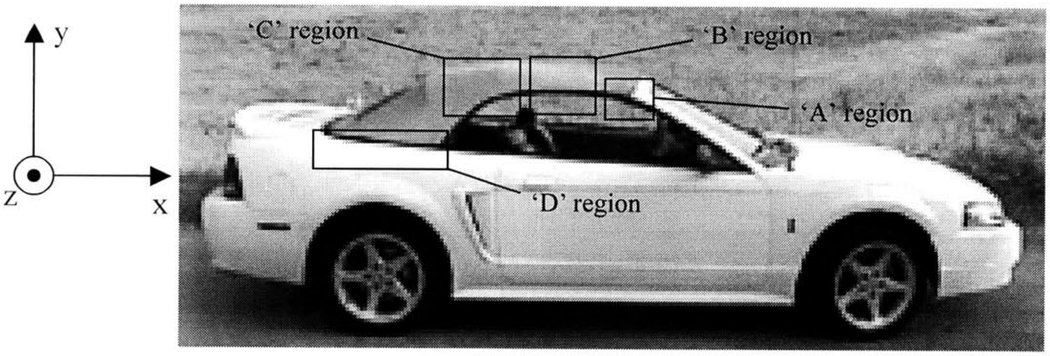


Figure 2.1: Side View of Mustang Convertible - Seal System Regions.

The Mustang's representative convertible top system is comprised of a vinyl top, three structural side rails, structural cross members, and the linkage system used for roof actuation. The overall seal system methodology is based on a combination of water resistance and water management. The convertible roof and the vehicle glass system is set to prevent water entry through all points, with the exception of a 'wet area' at the aft side interfaces between the convertible top and the chassis (discussed later in this chapter). The structural rails seal to the glass system below and the vinyl top above through the use of weather strips and foam seals. Upon roof closure, a roof tensioner pulls the vinyl top taught against foam seals located above the structural rails, sealing the region above the rails. Representative subsystem components that seal the region between the vinyl top and the structural rails are shown in Figure 2.2.

Three weather strips are mounted to the structural rails of the convertible top – one weather strip on each structural rail as shown in Figure 2.2. Closure of the glass system compresses the soft weather strips mounted below the structural rails. The weather strip/glass system interface seals the region below the structural rails. Butt joints between the adjacent weather strips seal the region between adjacent structural rails.

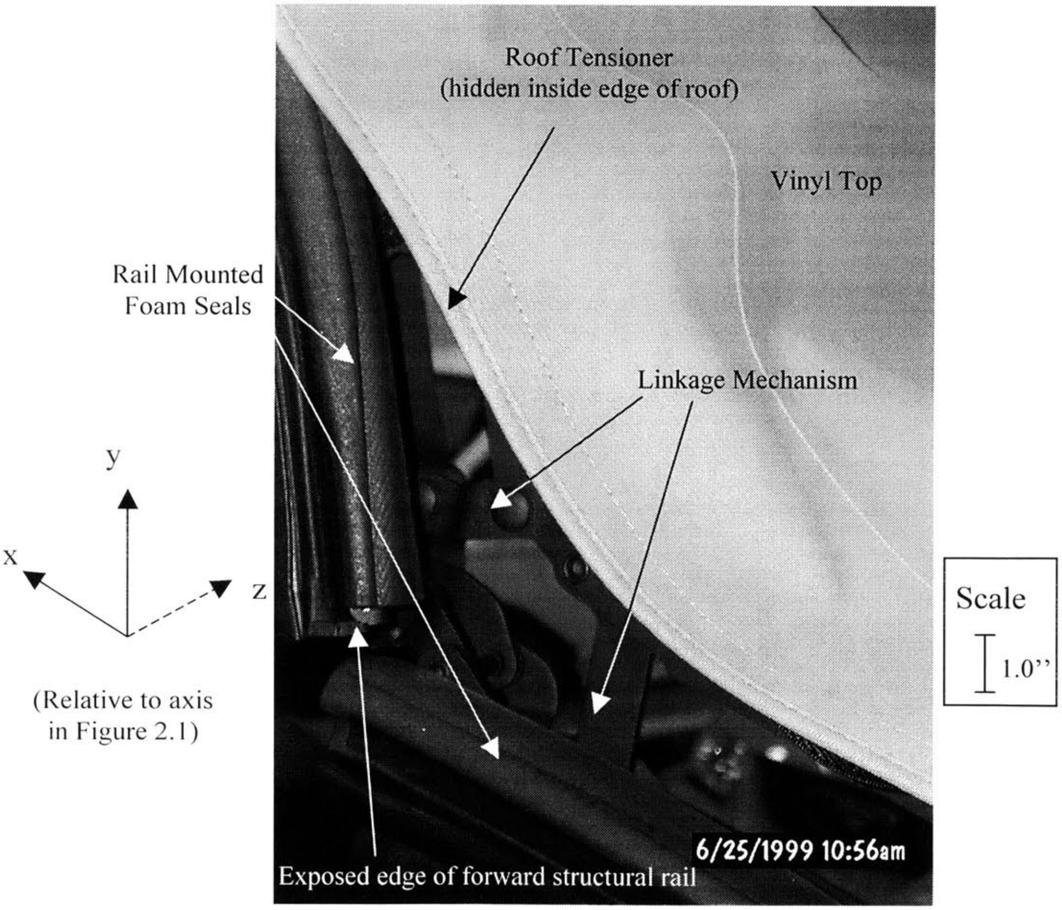


Figure 2.2: Current Mustang Seal System - Convertible Rail to Top ('B' region from Figure 2.1).

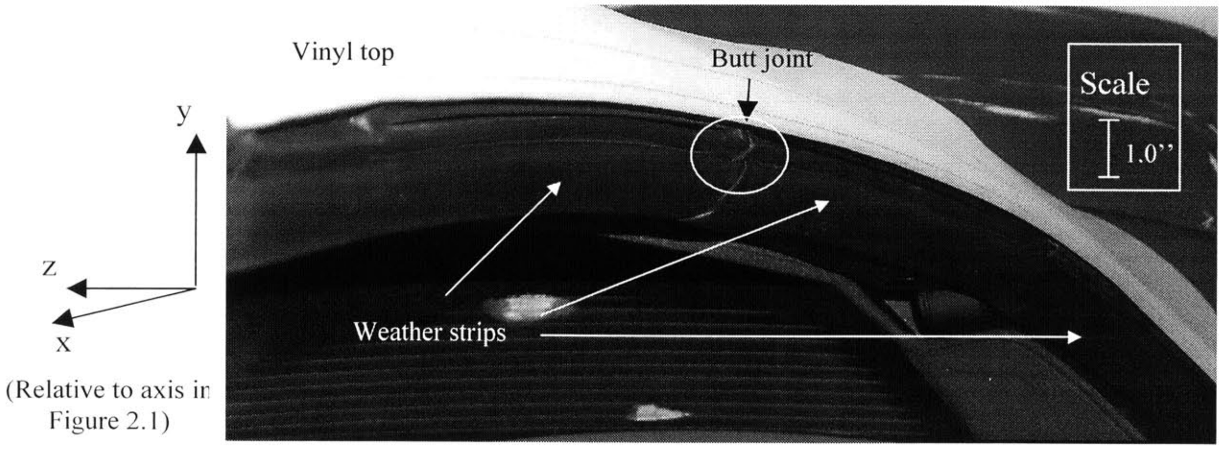


Figure 2.3: Current Mustang Seal System - Convertible Rail to Glass System ('B', 'C' regions from Figure 2.1).

The seal between the front window and rear quarter window is executed through the use of a 'division bar' as shown in Figure 2.4. The division bar is mounted to the rear quarter glass and mates with the weather strips mounted to the bottom of the convertible top structural rails. The run of the door glass causes its trailing edge to slide over and compress the section of division bar seal identified in Figure 2.4.

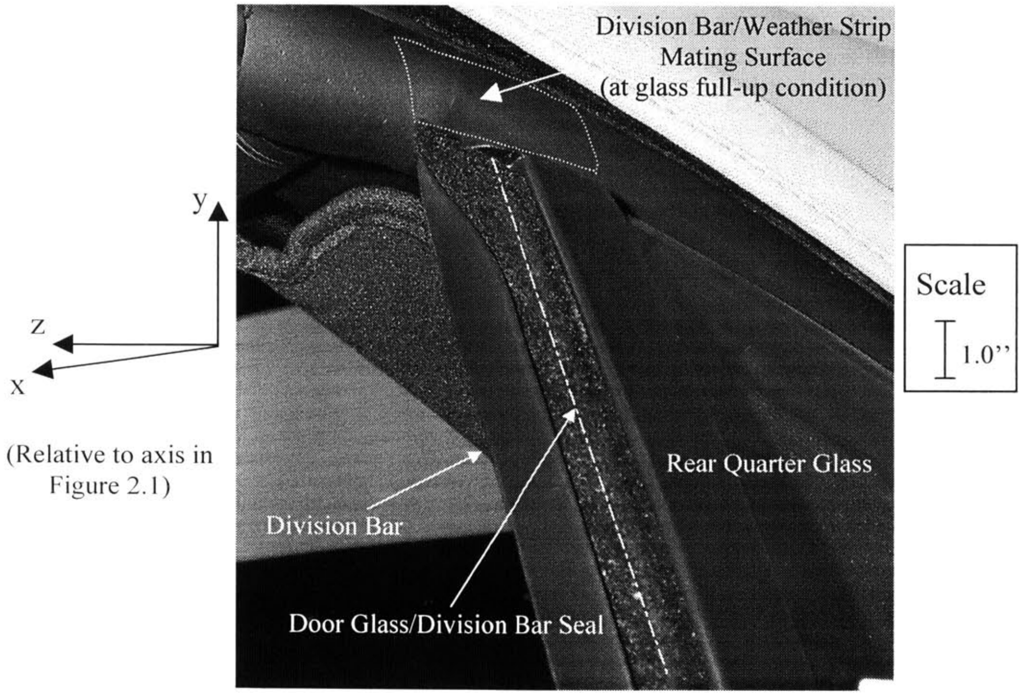


Figure 2.4: Current Mustang Seal System - Glass System Division Bar ('C' region from Figure 2.1).

As discussed earlier, there are regions of the seal system ('D' region from Figure 2.1) that are actually designed to allow water into the vehicle cabin. At these 'wet areas', internal water management is relied upon to keep the passenger cabin dry. This function is accomplished by routing water from its entry point through internal channels, until it reaches drain holes at the chassis base. The 'wet area' shown in Figure 2.5 exists due to coordination difficulties with positional control of the quarter glass, quarter glass belt seal, convertible top, and chassis sheet metal at their common interface.

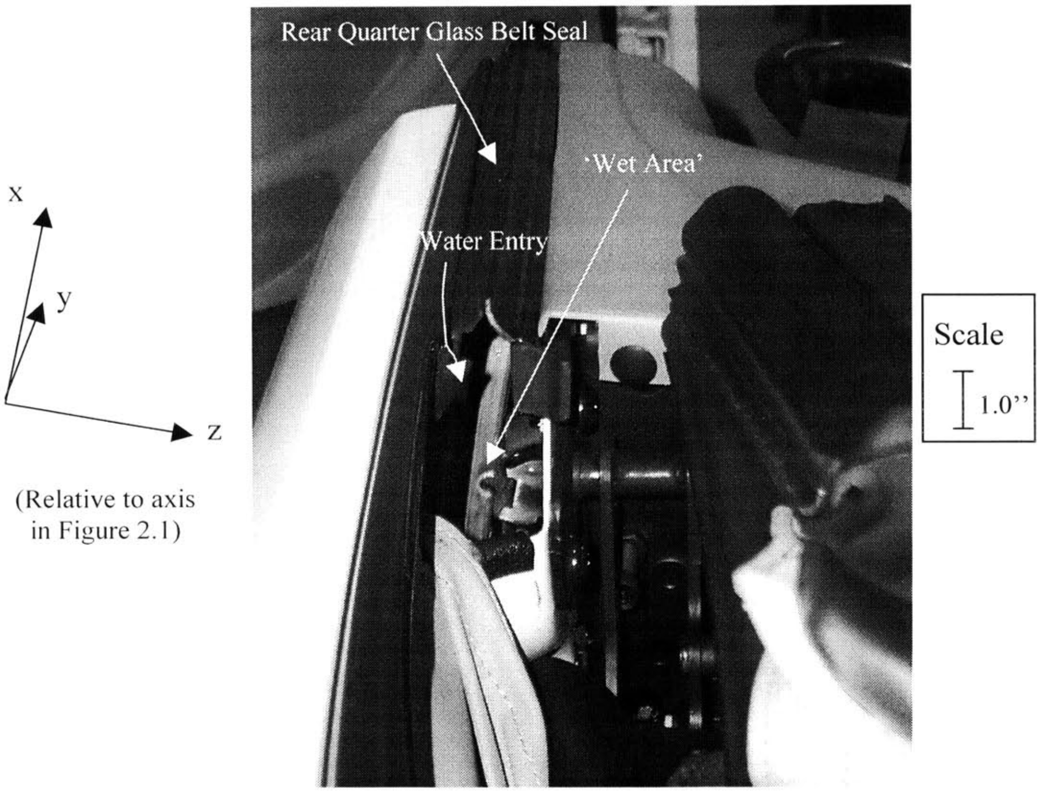


Figure 2.5: Current Mustang Seal System - Rear Quarter 'Wet Area' ('D' region from Figure 2.1).

Market research and benchmarking activities have shown that variations of the aforementioned methodology are used in one form or another to seal all convertible vehicles on the market today. While there are differences in the execution of this methodology, the main design concepts used in today's seal systems focus on optimizing butt joint effectiveness, maximizing glass system positional control, and minimizing overall system variability by utilizing relative assembly positioning of system components in lieu of absolute positioning.

The current system design has not undergone significant review since the introduction of the SN-95 generation Mustang in 1993 - an indication of slow design evolution clockspeed. While the water seal system is not classified as a critical system, its steadily degrading performance level has become one of the top drivers of customer dissatisfaction with the overall vehicle. Suspect design concepts and assembly process repeatability are expected to be contributing factors to the sub-optimal seal system performance.

(This page intentionally blank)

Chapter 3 - Failure Mode Analysis of Current System

Understanding the root cause mechanisms that drive system failure is essential to promoting the successful design evolution of complex products. System failure within a complex product can actually be leveraged to help focus performance enhancement efforts on features that have a strong influence on overall customer satisfaction with the product. If utilized in a positive manner, system failure can facilitate successful design evolution, as "...factory and field problems, service reports, and customer complaints provide invaluable information for upgrading the design process."[8] A failure mode and effects analysis is performed herein to address the failure of the Mustang convertible water seal system. The generic principles of the approach are described, followed by specific application of these principles and analysis results.

3.1 Principles used in Failure Mode and Effect Analyses: An Overview

A 'Failure Modes and Effects Analysis' (FMEA) is often utilized to identify root cause mechanisms that drive system failure(s) in complex products. Literature review[9] has identified a process for performing an effective system FMEA, comprised of the following steps:

1) definition of the system
2) description of system operation
3) description of environmental conditions
4) failure detection

---

[8] Product Design Engineering for Quality Improvement, Lucca and Wright, SME, 1983. Page 136.
[9] Learning from Failure, Fortune and Peters, 1995. Page 247.

5) analysis of failure mechanisms
6) analysis of failure effects
7) compensation for failure

The individual process steps are subsequently described in detail.

The first step of an FMEA, *system definition*, requires identification of system boundaries, system mission, inputs and outputs, and relationship with the external environment. This first step ensures that the overall performance enhancement project will be bounded and it begins to narrow the scope of activities. System definition is followed by a *description of system operation*. This includes the nominal system behavior, the effect of component failure on system inputs and outputs, and system response to input changes. Once system operation is reviewed, it is necessary to *characterize the physical environment* in which the system is expected to operate. Understanding the nominal behavior and environment of a target system is essential in order to develop a criterion by which system failure is established. In the context of this study, system failure is said to occur under nominal environmental conditions when system output does not meet performance specifications. Using this definition for system failure, actual *failure modes are detected* in the fourth step of the overall FMEA process. In the context of this study, a failure mode describes component behavior when system failure is observed. In order to facilitate failure mode detection, test parameters and methods must be developed. Identification of manifestations that reveal the occurrence of failure modes can be used to develop system test parameters. Testing is especially valuable when a single component failure does not render the entire system inoperable, and this can be used to diagnose and initiate corrective repair on the affected portion of the overall system prior to general system failure. A thorough FMEA will detect all modes of failure, including failure at discrete points in time as well as progressive failure resulting from system degradation. After all failure modes have been identified, the root cause failure mechanism(s) that drives each failure mode must be identified. This is achieved in step five through *analysis of system characteristics* when failure is observed. Once root cause failure mechanisms have been established, it is necessary to evaluate the robustness of a system to a single component failure. To evaluate system robustness, it is necessary to perform an *analysis of failure effects*. This analysis determines the impact that each foreseeable component failure will have on the overall system. The seventh and final step of the FMEA process, *compensation for failure*, is facilitated by knowledge of the root cause mechanisms that drive system failure modes. This knowledge, obtained during earlier steps of the FMEA process, helps develop corrective design concepts to combat known system weaknesses.

3.2 FMEA Case Study Methodology

Failure of a system occurs as a result of a design failure or an assembly process failure. In the context of this study, a design failure represents the category of failures resulting from both design of the actual product/system and from design of the assembly process required to build the product/system. Failures in design of the actual product/system could manifest themselves in the form of a fatigue failure or a loss of functionality. Failures in design of assembly processes could manifest themselves in the form of a finished product not meeting design specifications as a result of an incorrectly designed tool or fixture used during assembly. An assembly process failure represents the category of failures resulting from the inability of an assembly process to build a product/system consistent with product/process specifications, and from issues such as unapproved creation/refinement of individual assembly process steps that are needed to facilitate overall system assembly. Unfortunately, a system with a capable design can still experience failure if the assembly process used to create it does not result in the system meeting the original design intent. Based on a preliminary review of the Mustang convertible water seal system, it was expected that both design and assembly related failure modes were present in the current system. Therefore, it was necessary to develop a methodology that was capable of characterizing both system failure mode variants.

The *definition of the system* currently under analysis is the Mustang convertible water seal system. The seal system is comprised of the vehicle glass system, convertible top assembly, and individual seal components. A *description of system operation* has already been presented earlier in Chapter 2 of this study, and discusses individual system component behavior and interaction during nominal operation. The seal system is expected to operate under a wide range of *environmental conditions*. Design specifications require system functionality within a temperature range of –40°C to 90°C for 6750 user cycles (equivalent usage of 10 years/150,000 miles). The seal system will be exposed to natural rainstorms, dust particles, icing, temperature soaks (extended periods of high or low temperatures), wind loading, and high-pressure car washes, and is expected to exhibit adequate performance levels under all aforementioned conditions.

Failure detection was facilitated through use of information obtained from customer feedback and from the development and application of general system tests. A combination of these two mechanisms is needed to complete an accurate failure mode analysis. Customer feedback alone may suggest certain failure modes, yet these failure modes could be the result of a 'root cause' mechanism of which the customer is not aware. General system tests alone may identify failure modes as observed by the team conducting the test. However, these failure modes may not be the actual in-service failures that the customer experiences in the field and therefore would be inconsequential to the customer's overall perception of product quality. In order to ensure that improvement efforts are targeted at critical system characteristics that impact customer satisfaction, it is necessary to integrate customer feedback and development of test procedures to identify customer concerns.

Customer feedback is inherently very subjective. Thus, methods capable of extracting objective observations on system performance using subjective feedback are desirable. There are various theories on how best to interpret customer feedback with most requiring direct customer contact. Three customer contact mechanisms were utilized to characterize failure modes of the water seal: review of warranty data from the field regarding in-service system failures, interviews of readily accessible 'internal customers' who were Ford employees, and interviews with external customers. The customer contact mechanisms employed in this FMEA were used to identify specific customer concerns with current seal system performance.

Warranty information was utilized as an objective source of information regarding cost and frequency of system failure. Unfortunately, review of the warranty data on the seal system was hampered by a significant issue early on in the project. Customer data/feedback was relayed to Ford Motor Company through service technicians who performed the actual warranty work to address customer concerns at various franchised dealerships. This dealership 'filter' created a barrier to direct communication between Ford and its customers, as full details regarding the customer's experiences were not available for review. This resulted in the loss of key insight into critical customer concerns, specifically, the exact location of failure mechanisms and the relative customer dissatisfaction that was derived from each failure mechanism. However, one common theme was revealed during review of the incomplete warranty database: customer complaints focused heavily on usage of the product under a specific environmental factor - automated, high-pressure car washes.

Prior to entering the analysis phase of the FMEA process, test procedures must be developed to complete step four of the process. Customer interviews were utilized as a subjective source of information in determining actual characteristics of system performance that drove customer dissatisfaction. The information taken from customer interviews together with that available from review of the warranty data helped identify regions of the seal system design that should be targeted for analysis, and guided development of test parameters to facilitate the analysis. Test procedure development is described in detail in Section 3.3.

The remaining steps five through seven of the overall FMEA process are lumped together as the *analysis phase* of the process since it is difficult to separate activity during this phase into discrete steps. However, each of the steps must be incorporated into the overall analysis phase to ensure that useful results are realized from the FMEA.

3.3 Test Procedure Development – Case Study

In order to pinpoint locations for testing, interviews were conducted to identify the locations and magnitudes of seal system failure that could be expected on current production vehicles. Ford employees who owned current generation Mustang convertibles (internal customers) were interviewed regarding their experiences with their vehicles' water seal system performance under the environment of automated, high-pressure car washes. Test parameters were developed in a heuristic manner to simulate the seal system failures identified using feedback from internal customers. During the development of test parameters, the improvement team focused on developing generalized test procedures that could be easily performed at various sites without the need for specialized resources. These generalized test procedures facilitated field testing of external customer-owned vehicles that had experienced an in-service seal system failure. The test procedures are described in detail.

To facilitate testing, a fixture was constructed to hold the orifice of a garden hose at a certain orientation with respect to the various failure locations of the seal system. The length of the fixture's 'extension arm' was set such that when the fixture base is placed against the glass system and the tip of the arm is in contact with the convertible top weather strips, the water stream from the hose orifice would hit the vehicle directly at the seal system failure locations. A representation of the test fixture is shown in Figure 3.1.

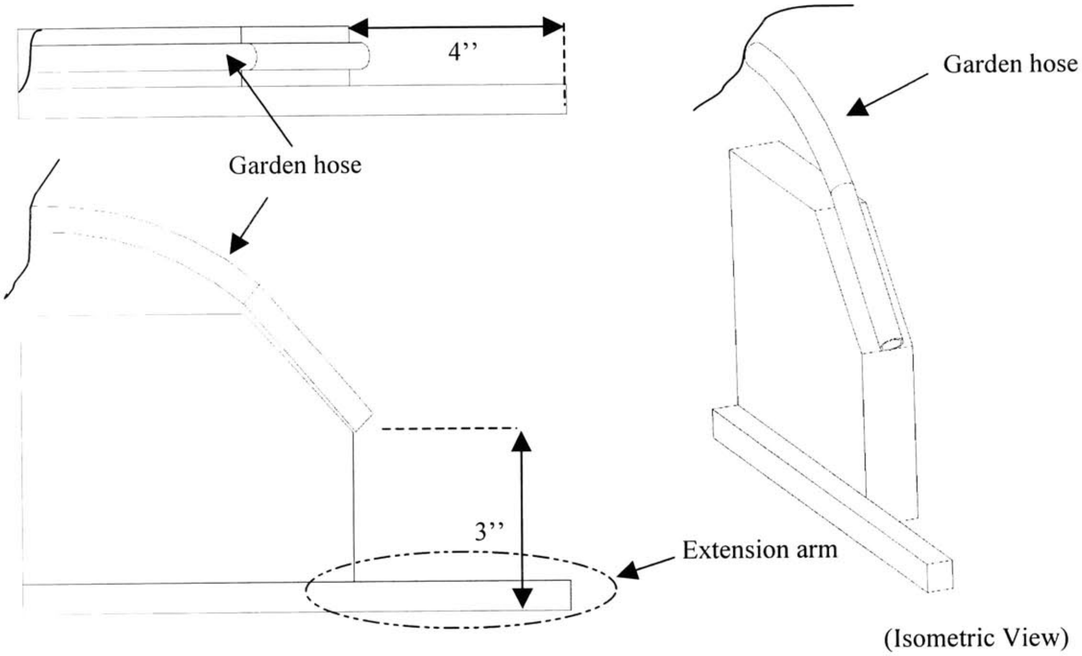


Figure 3.1: Test Fixture Representation.

A flow rate of 14 L/min was used through a hose with a 5/8'' orifice during testing. The bottom plane of the fixture was placed flush against the glass system and the water stream was targeted on each of the system failure points. The water stream was held on each of the failure points for 30 seconds at each of the pivot joints and 20 seconds at the division bar region. The division bar test duration was shorter than the test duration of the pivot joints because of the large volume of leakage that was generally observed at the division bar region. The system test duration was developed through informal water evaluation of the various system failure locations. The test duration was set heuristically such that the expected volume of leakage that was observed for each system would be large enough to provide adequate resolution of performance differences from system to system. Water entering through the seal system during testing was captured in measuring cups and the leakage volume was recorded for each trial.

In order to help validate the test procedures developed from interviews of internal customers, the improvement team met with an external customer who had returned to his dealership several times to have warranty work performed on his vehicle's water seal system. This particular customer had been excessively vocal about his dissatisfaction with the seal system performance. It was expected that his experiences could be utilized to help affirm the validity of the test procedures developed to simulate system failures experienced in the field. During discussions with this external customer, the team was able to confirm that the seal system failure occurred mainly under exposure to automated, high-pressure car washes, and that the failure mechanisms observed were consistent with those identified by internal customers. The improvement team demonstrated the test procedures to the customer on his own vehicle and the use of these test procedures was able to replicate the exact failure modes about which the customer had been complaining. Customer feedback had identified and confirmed likely regions of the seal system on which improvement activities should be focused. This feedback had also helped to develop test procedures on which the merit of new design concepts and/or assembly procedures could be based.

3.4 Failure Mode and Effect Analysis – Case Study

The FMEA steps presented in Section 3.1 are applicable for the characterization of both design related and assembly process related system failure modes. Using the experience-based knowledge of the improvement team, determination of the nature of failure mode (design or process related) was made for each region of the seal system under analysis. Only a slight departure from the overall methodology utilized to characterize design related failure modes was required to characterize assembly process related failure modes. Inspection of key assembly process steps was used in lieu of system testing to characterize assembly process related failure modes.

Customer interviews and system testing identified several locations in the current Mustang water seal system that exhibit inadequate performance. Key sources of concern are located at each of the convertible top hinge points ('A', 'B', and 'C pivot'), at the top corner of the glass system interface, and at the 'wet area' aft of the rear quarter glass (see Figure 3.2). All areas of concern and the related seal failure modes are reviewed and the *analysis phase* of the FMEA utilized in the illustrative performance enhancement project is presented in detail.

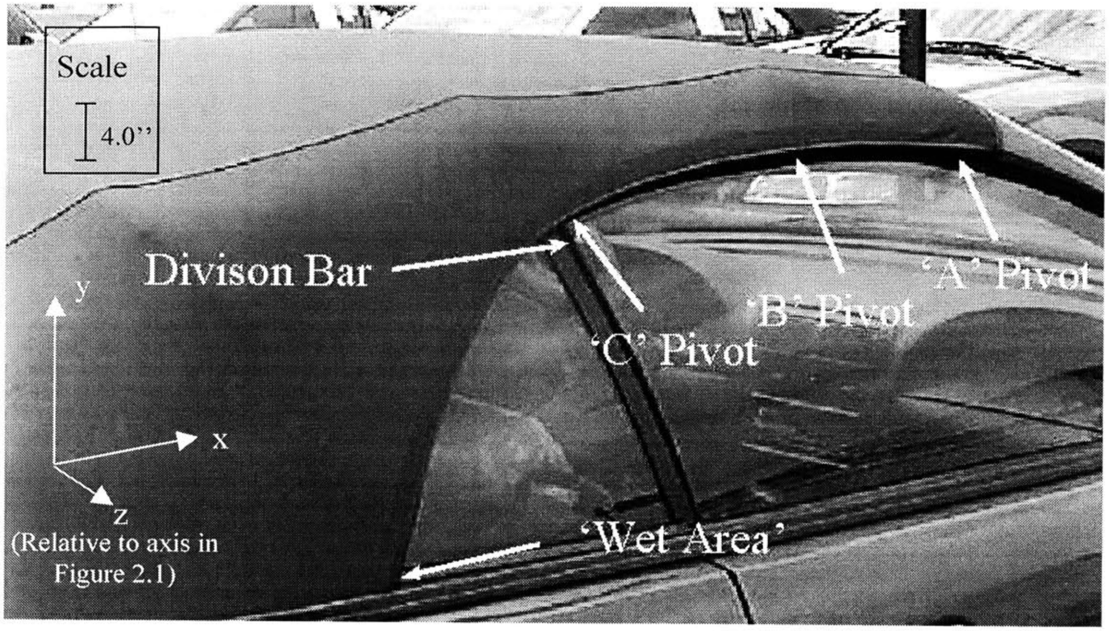


Figure 3.2: SN-95 Water Seal Failure Mode Locations.

Relative motion of seal system components on convertible vehicles causes difficulty in achieving and maintaining an effective water seal over time and system life. Cycling of the convertible top results in fatigue of seal system components. Accumulating usage of the convertible top results in loss of initial control of seal system component positioning. The relative position of mating seal system components has been identified through testing as a critical characteristic of an effective seal system. It is recognized that the behavior of mating components during convertible top system cycling plays a key role in seal system performance both during system infancy and over the system life. Therefore, this failure mode analysis focused on the effect of convertible top cycling on the repeatable positioning of seal system components.

3.4.1 Pivot Joints

The hinge points of the convertible top assembly are referred to herein as the 'A', 'B', and 'C-pivot' joints. These pivot joints are noted in the photograph of Figure 3.2.

3.4.1.1 'A-Pivot' Joint

Located just aft of the windshield header, the 'A-pivot' joint of the convertible top allows the top to flex in the inboard/outboard direction (± z direction in Figure 3.3) when cycled, providing more efficient packaging of the roof in its retracted position. The outward flexing motion of the top during retraction of the roof provides more passenger room in the back seat. The 'A-pivot' joint, shown in Figure 3.3, comprises part of the primary rail to glass system seal.

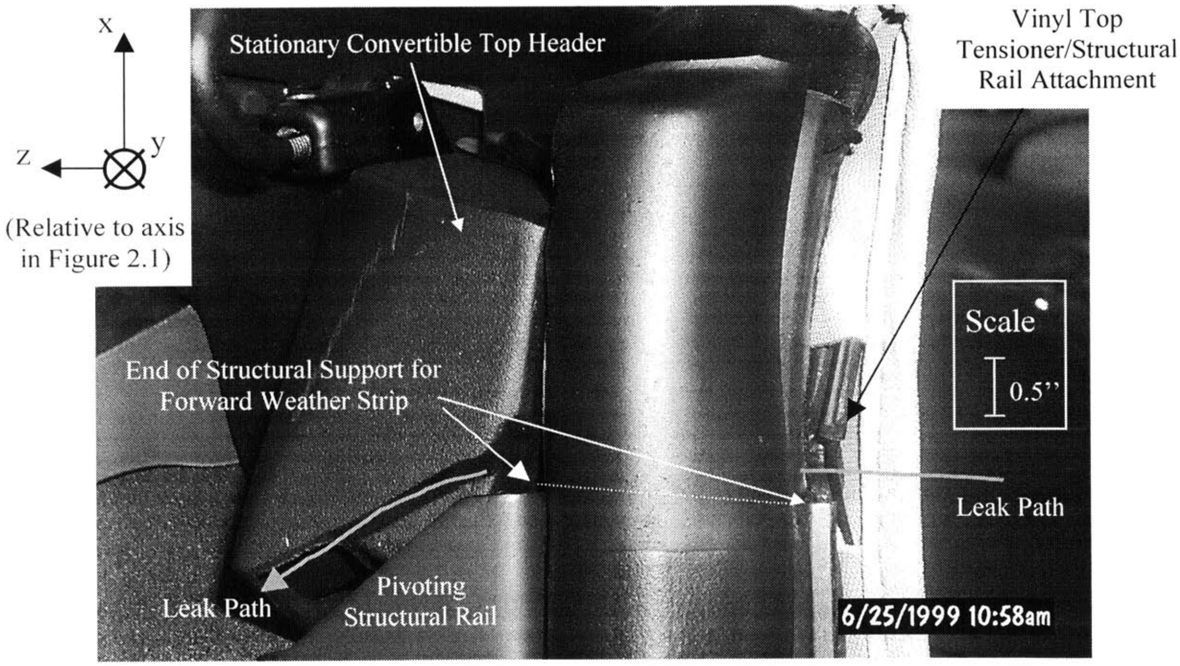


Figure 3.3: 'A-Pivot' Joint Design and Related Leak Location.

The forward weather strips (mounted to the bottom of the front structural rails) are secured rigidly both to the stationary convertible top header and to retainers fixed to the pivoting structural rails. A review of the dynamic behavior of the joint region revealed that the forward weather strips are flexed at the 'A-pivot' joint every time the roof is cycled. This flexure eventually causes the weather strips to either fail to re-attain their original position (due to friction rubbing with neighboring components) or to take a permanent set.

This seal flexure issue further exacerbates the poor water resistance of the seal system local to this region. The vinyl roof is secured to the structural rails of the convertible top through use of a spring-loaded cable tensioner running the entire span of the canvas length. The tensioner attaches to the chassis sheet metal aft of the rear quarter glass and to the forward convertible top header bow at the convertible top/windshield header interface. The tensioner keeps the vinyl taught against the convertible top structure when the top is in its full-up condition. Due to clearance issues with the tensioner attachment and other structural members located in the forward region of the roof, the weather strip retainers and the supporting structural side rails cannot be extended forward to the front of the roof. Since the weather strip retainers cannot be extended, no structure exists on which the weather strip or the foam seal can be mounted. The current design utilizes freely positioned foam (not positively located by any structural member) in an attempt to seal the gap between the weather strips and the top at this location. A thin object can actually be extended through the foam that comprises the primary seal plane in the region local to the tensioner attachment point. The design results in a direct leak path into the vehicle interior above the forward weather strip, as shown in Figure 3.3. The existing leak path is further exacerbated by the flexing weather strip behavior observed local to the 'A-pivot' joint during cycling of the convertible top.

3.4.1.2 'B-Pivot' Joint

The first major hinge of the convertible top comprises the 'B-pivot' joint, as shown in Figure 3.4. The seal between the structural rails and the glass system at the 'B-pivot' joint is achieved by butting the forward weather strip and the middle weather strip against each other as the roof linkage closes the convertible top. Review of the cyclic behavior of this joint shows that the effectiveness of this seal region is dependent upon two factors: the relative positioning of the mating weather strips as the roof closes and the ability of the seal components to retain their original shape and position after repeated cycling of the top. The weather strips and the less flexible foam seal between the structural rails and the vinyl top are typically unable to maintain contact between the forward and middle rails after the roof is cycled. The resulting gap results in a direct leak path into the vehicle interior.

A complicating issue with the effectiveness of the 'B-pivot' joint is the relative fore/aft positioning (± x direction in Figure 3.4) of the mating weather strips. The positioning of these adjacent weather strips is not controlled by any sort of positive location methodology with respect to the structural members of the convertible top. This results in variability at the butt joint, and should be addressed in any future redesign of the seal system.

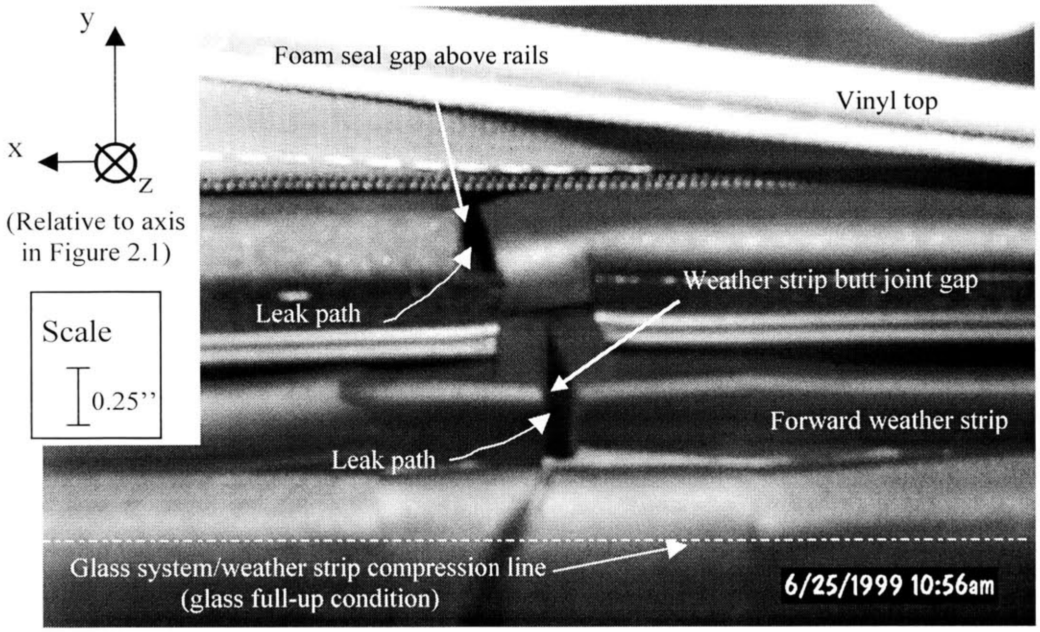


Figure 3.4: 'B-Pivot' Joint Design and Related Leak Location.

3.4.1.3 'C-Pivot' Joint

The second major hinge of the convertible top comprises the 'C-pivot' joint, as pictured in Figures 3.4 and 3.5. This joint has the same characteristics as the 'B-pivot' joint described in Section 3.2.1.2. The middle rail pivots with respect to the aft rail, creating a butt joint between the middle and aft weather strips under the structural rails. As with the 'B-pivot' joint, the foam seals above the rails cannot maintain contact between the middle and aft rails after the roof is cycled. This results in a direct leak path into the vehicle interior. The partially cycled behavior of the 'C-pivot' joint is shown in Figure 3.5.

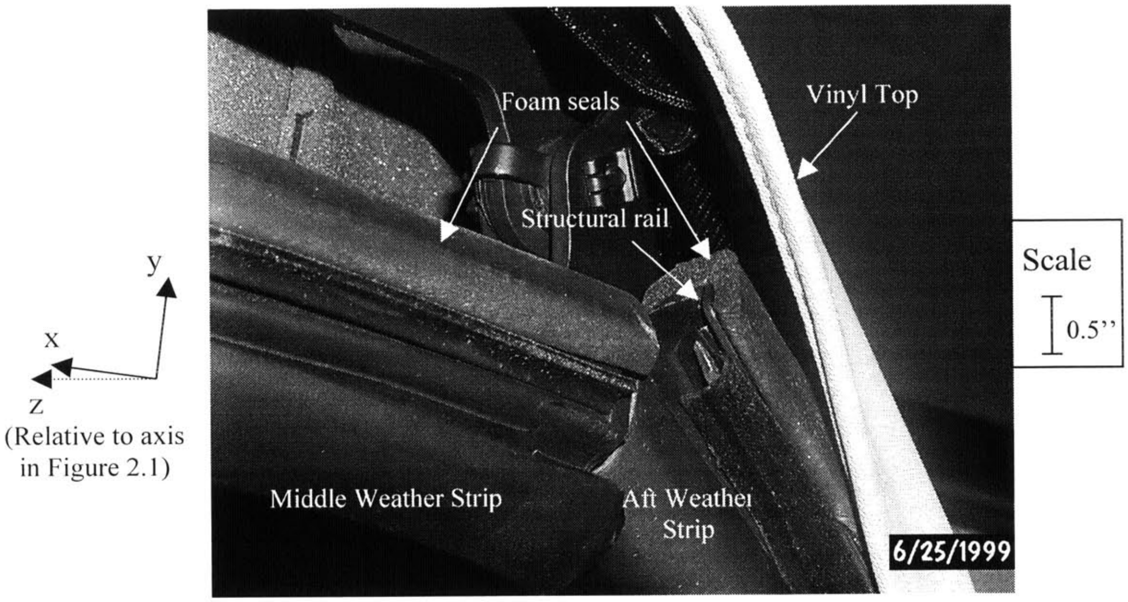


Figure 3.5: 'C-Pivot' Joint - Roof Partially Cycled.

Whereas Figure 3.5 shows the 'C-pivot' joint in a partially cycled position, the position of the water seal system components during nominal operation is shown in Figure 3.6.

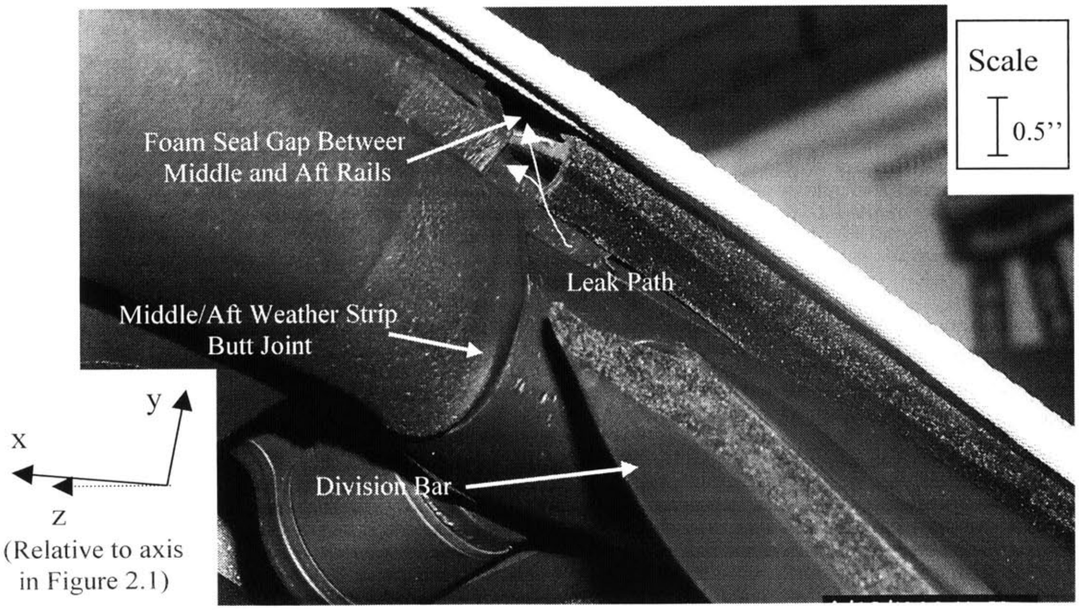


Figure 3.6: 'C-Pivot' Details and Related Leak Path.

3.4.2 'Wet Area'

The so called 'wet area' behind the rear quarter glass on each side of the vehicle is designed to capture water that leaks between the aft edge of the base of the rear quarter glass and the forward edge of the convertible top. This captured water is routed through the chassis and exits the vehicle through drain holes in the chassis. The sheet metal comprising the wet area design is not large enough to capture the water flow coming through the interface at the base of the rear quarter glass and the convertible top. Water draining from the 'wet area' spills over the sheet metal, as noted in Figure 3.7, and eventually seeps into the vehicle interior behind the back seat.

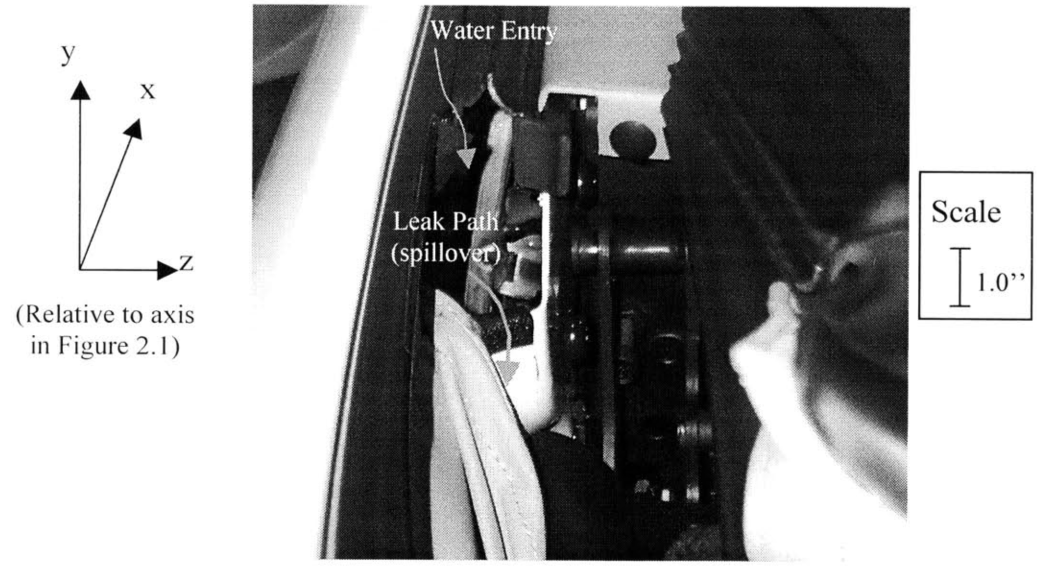


Figure 3.7: 'Wet Area' Leak Path.

It is noted that this particular failure mechanism was not specifically identified by any of the customers interviewed by the improvement team. It was identified through diagnosis of the overall seal system performance during testing activities performed by the improvement team.

3.4.3 Glass System Division Bar

The frameless glass system on the SN-95 Mustang convertible is shown in Figure 3.8. This system consists of the door glass and rear quarter glass, mounting and attachment hardware, and the regulators that actuate the glass. The interfaces between the front door glass and the rear-quarter glass, and the positioning of the glass system with respect to the chassis and convertible top, are critical to the local water seal system performance. Coordination difficulty between the glass system and the mating weather strips of the convertible top assembly results in a physical gap between mating glass system components and subsequent leakage, as indicated in Figure 3.8. The glass system installation process is reviewed to understand current limitations and to identify potential areas for improvements.

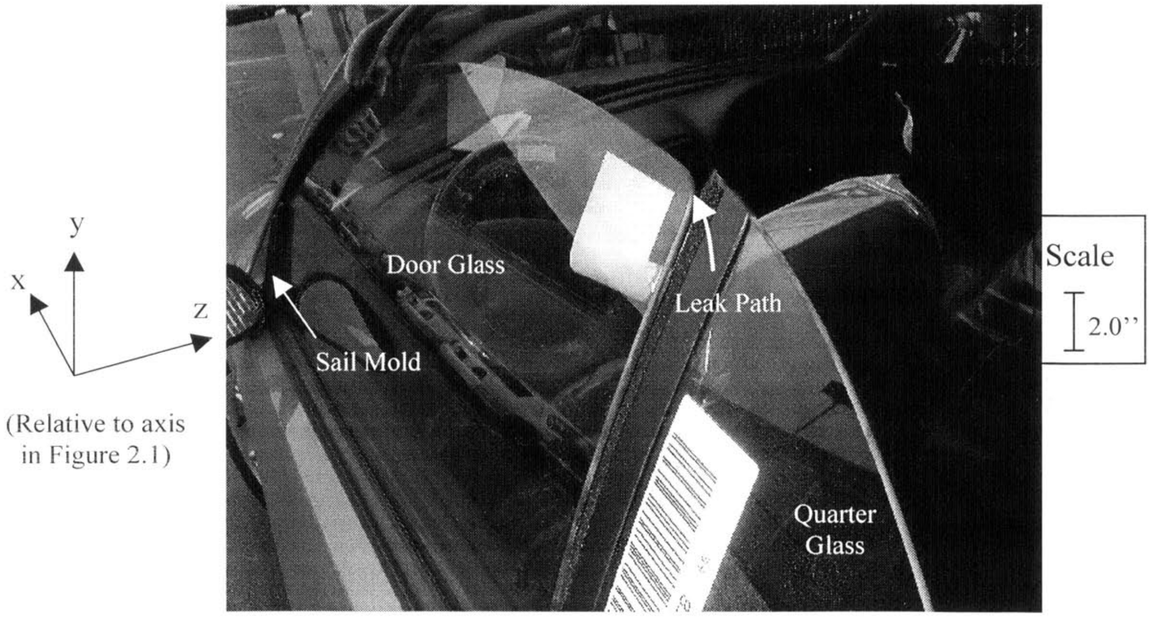


Figure 3.8: Glass System Joint – Convertible Top Down.

3.4.3.1 Glass System Assembly Process Description

The current assembly process for setting the glass system is accomplished in a component level fashion. The overall process flow chart is shown in Figure 3.9.

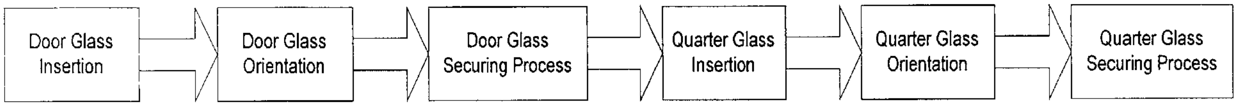


Figure 3.9: Glass System Setting Process Flow Diagram.

The front door glass is installed first and reaches the setting station on the assembly line with its adjustment hardware loose. A setting fixture is used for door glass orientation. This fixture, shown in Figure 3.10, has mount holes in the doors for support and positioning pins to locate two datum points on the vehicle - one on the windshield A-pillar and one on the middle rail of the convertible top assembly. After inserting the mount holes of the setting fixture into the door, the operator closes the door and uses the positioning pins to locate the reference datum points. The operator then actuates the door glass to its full-up condition inside the setting fixture, which has been set to locate the door glass in its proper orientation with respect to the mating sections of the convertible top and the windshield A-pillar. At this time, the operator torques adjustment bolts for the door glass, fixing the glass in the proper orientation as determined by its full-up position inside the setting fixture.

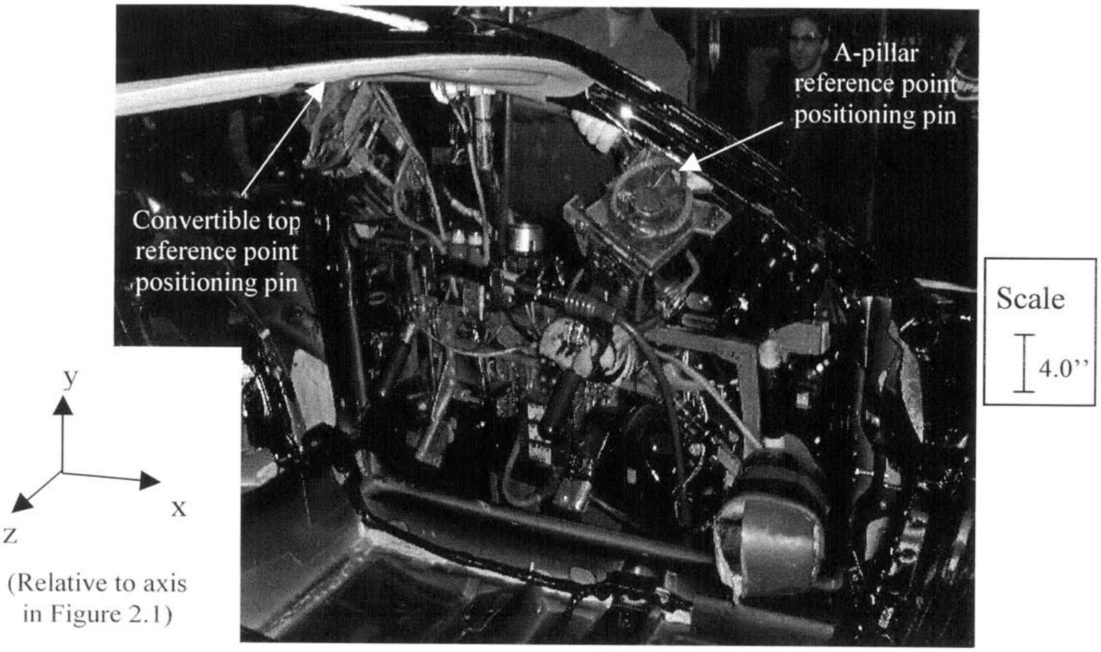


Figure 3.10: Door Glass Setting Fixture – Clamped Position.

After the front door glass is installed, the quarter glass installation process begins on the assembly line. The rear quarter glass setting process does not utilize any positive locating scheme as it involves a manual adjustment of the rear quarter glass to the front door glass. The rear-quarter glass is placed freely onto the rear glass regulator and allowed to 'float' during the adjustment process. The rear glass regulator is actuated to its full-up position. Once the full-up position is reached, line workers pound on the quarter glass with their fists to adjust its position such that a relatively consistent fore/aft position of the quarter glass is achieved with respect to the front door glass (through visual inspection). Once the manual adjustment has been made, the quarter glass is fixed to its regulator by torquing down three fasteners.

It is noted that hand adjustment of the quarter glass is called for in the actual assembly process, but no guidance or tool/fixture is provided to the line workers to facilitate this adjustment process. The current state of the adjustment process described earlier is an emergent process that has evolved due to an ambiguously defined process step. Because simple visual inspection and hand adjustment of glass system component positioning cannot guarantee an effective local seal, the design of the glass system setting process has failed.

3.4.3.2 Glass System Assembly Process Limitations

One of the major issues observed during review of the glass system is a lack of control in the cantilevered position of the glass system in the full-up position. Dimensional control of the chassis and door sheet metal is inconsistent, thus necessitating mounting of the door glass relative to the vehicle's A-pillar and the convertible top rails in order to achieve somewhat consistent water seal performance. The front door glass setting fixture allows control of the door glass position with respect to the A-pillar and the convertible top. Unfortunately, through evolution of the door glass setting process on the assembly line, the process no longer utilizes the active fore/aft adjustment feature of the setting fixture. The fore/aft door glass position is set when the operator actuates the door glass to its full-up position, prior to securing the glass attachment hardware. During its travel to full-up position, the door glass contacts the inside of the window sail mold (see Figure 3.8), which helps guide the glass to its final cantilevered position. Since the interface between the door glass and the window sail mold drives the final fore/aft position of the door glass, repeatable coordination of the windshield A-pillar, window sail mold, and door glass is difficult to achieve. Coordination difficulties at this interface contribute to the poor seal system performance local to the division bar region

Positional control of the rear quarter glass can be even more troublesome than that of the door glass. The rear quarter glass is not positively located in any direction during installation. The pliable weather strips that are mounted to the convertible top structural rails provide inboard/outboard ($\pm z$ direction in Figure 2.1) support of the rear quarter glass during installation. These weather strips (shown just above the quarter glass in Figure 3.6) do not have the stiffness required to provide repeatable positional control.

Although it is not currently controlled, the consistency of the inboard/outboard position of the rear quarter glass is a major concern from vehicle to vehicle. The inboard/outboard position of the rear quarter glass is suspected to directly affect the water seal performance at the top of the glass system division bar. Poor relative inboard/outboard positioning of the glass system components will result in misalignment of the curvatures of the rear-quarter glass and front door glass, and consequently, pinching of the glass system at a localized region of the division bar. This glass pinching ultimately contributes to the poor division bar seal compression consistency and the resulting gap at the top of the glass system interface in the full-up, unrestrained (top down) condition shown in Figure 3.8. The inboard/outboard positioning of the glass system also impacts the cantilevered position of the glass system in the full-up position, thereby directly affecting seal preload along the weather strips of the convertible top assembly. There is no feature in the current SN-95 design that provides inboard/outboard positioning or support for the glass system in service. This is expected to contribute to the degraded capability of the seal system in this region.

Another difficulty with the glass system is the fore/aft positioning of the rear quarter glass with respect to the front door glass. As discussed previously, this adjustment is done manually with virtually no repeatability built into the process. Line workers pound the quarter glass forward to mate with the door glass prior to tightening the quarter glass fasteners. While this process improves the fore/aft gap between the door glass and quarter glass, it does not provide for proper inboard/outboard positioning of the quarter glass and consequently, for adequate water seal performance at the division bar. Since there are water leak concerns local to the rear quarter glass, it is necessary to introduce adjustment processes for the rear quarter glass that can be controlled, or at the very least, understood.

3.5 FMEA Case Study Results

In summary, the current generation water seal system utilizes a number of design practices that are not robust to assembly variability. There is significant cascading of variability in both the manufacturing and assembly processes from the vehicle sheet metal to the glass system to the convertible top. It is desirable to identify current design/assembly practices that should be avoided in order to remove as much seal of the seal system sensitivity to the overall assembly process variability as possible.

3.5.1 Pivot Joints

Reviewing the failure mode analysis performed on the current generation seal system, several design features and assembly processes used to create the pivot joints have been characterized as non-robust, including:

- discontinuity of primary seal plane (design issue)
- unnecessary relative motion of primary seal plane components (design issue)
- localized use of foam barriers to 'plug' known problem areas (design issue)
- poor coordination of mating components (design/process issue)
- lack of positive location methodology for seal system components (design issue)

These features and processes are suspected of directly contributing to the current quality problems experienced by customers in the field and are therefore identified as targets for performance enhancement activities. These items are addressed in the conceptual design activity phase of this project.

3.5.2 Glass System

The difficulties with the glass system (Section 3.4.3) can be attributed to one of two root causes, or a combination of both: lack of incorporation of a positive location methodology in the glass system design or poor process control during assembly. To address the poor glass system positional control, use of a positive location methodology on the assembly line is investigated. In addition to the glass system locating methodology, variability in the mounted glass system position must be analyzed, as this variability is suspected of affecting seal system performance local to the division bar. Unfortunately, due to poor sheet metal control inherent in the vehicle platform, there is no practical manner to record absolute measurements of the glass system positioning (with respect to a fixed reference point). Relative measurements are the only available data source for analysis. Two avenues exist to address the glass system positionability issue: analysis of process capabilities and implementation of process controls, and inclusion of new design features to positively self-locate the glass system. Both avenues are explored in the performance enhancement section of this study.

3.5.3 Summary

Completion of the seal system failure mode and effect analysis has illustrated the process by which customer feedback can be used to target areas on which to focus performance enhancement activities. The overall methodology used to address inadequate system level performance within complex products now shifts to the process by which the actual improvement activities are driven.

(This page intentionally blank)

Chapter 4 - Quantitative Process Control Analysis

Performance enhancement activities can be driven through one of two paths. Statistical evaluation of current system performance levels can be used to identify root cause mechanisms for system failure, and design/process changes can be implemented to address the identified failure mechanisms. Alternatively, conceptual redesign activities may be more appropriate when either statistical evaluation is inappropriate (e.g. no practical data collection methodology) or the current design concept is no longer capable of fulfilling its mission, due to obsolescence or changing performance standards.

During completion of the seal system FMEA, it became apparent that system knowledge of the analysis team alone would not be able to identify the root cause of the system failure local to the top of the glass system division bar. It was therefore necessary to resort to statistical tools to gain an understanding of the root cause mechanism responsible for the system failure in this region (see Figure 3.8) and to drive performance enhancement activities in this region. Statistical methods aimed at characterizing assembly process variability are used to determine whether certain numerical measurements taken during vehicle assembly can act as indications of potential future leakage problems. This determination is made based on any relationship observed during testing (or lack thereof) between seal system characteristics and the output function (leakage volume). If a predictable relationship can be established between system performance levels and numerical measurements of system characteristics, then control of assembly process variability can be used to control system performance levels. If, however, no such relationship can be established, poor system performance levels may be the result of design shortcomings as well as assembly process variability. In this case, it may be difficult to ever isolate the underlying mechanism that drives system performance.

4.1 Variability Analysis: An Overview

Variability has been defined as "...the technical tool with which we find problems, errors, complexities, and waste."[10] However, in order to leverage variability to drive process improvements, it is crucial to identify the so-called 'fundamental variables' that affect overall system performance. To identify these fundamental variables, research suggests consulting with 'experts' who have intimate association with the system. In a manufacturing environment, expert knowledge may lie with design engineers responsible for the initial design concept, line workers responsible for actual component installation, and manufacturing engineers responsible for assembly process design/control. Educated hypotheses taken from those with expert system knowledge should be used with subsequent trial-and-error hypothesis refinement (driven by system testing) to clearly identify the fundamental variables that drive system performance.

Once the fundamental variables are identified, a measurement scheme must be developed to take data that is needed to characterize system variability. This measurement scheme should take into account factors such as cost, precision, ease of use, and practicality. An appropriate statistical methodology needs to be selected, based on the nature of the measurement data. Regression methods, rank tests, or even simple visual reviews of measurement data in the form of scatter plots can be utilized in a variability study. With

---

[10] Conway, page 48.

any variability analysis, there is the possibility that measurement noise or special underlying causes could prevent successful identification of the root cause failure mechanism(s). However, should patterns exist in the data that characterizes system variability, careful analysis of both the data (using analytic tools) and the underlying assembly processes (using qualitative process knowledge) should be able to identify common causes that adversely impact system performance.

4.2 Grid Search Statistical Methodology

Grid searching is a statistical methodology that allows one to use data to suggest a root cause failure mechanism when the mechanism is not readily apparent to those familiar with the system under investigation. The end goal of a grid search analysis is the determination of a relationship between a system's fundamental variables and the response of its output function. The fundamental variables selected for use in the analysis should reflect characteristics that the analysis team believes directly affect overall system performance. Initial speculation as to the identity of a system's fundamental variables is generally based on historical experience with similar systems. The fundamental variable characterization, actual system performance rankings (based on testing), and projected system performance rankings (based on initial hypothesis) are all used to identify root cause system failure mechanisms.

The first step in a grid search analysis requires definition of an output function, the response of which is the subject of the investigation. The fundamental variables that drive the output function response must be identified through preliminary testing or use of existing knowledge of the overall system response. A random sample of as-built systems is selected for use in the analysis. Based on an initial hypothesis of the relationship between fundamental variables and the output function response, the sample systems are ranked in expected order of performance. The expected system performance ranking is developed using a weighted average of the system's fundamental variables.

The weighted average of fundamental variables used in a grid search analysis is achieved using an exhaustive and distinct array of scaling factor permutations that sum to one. Each scaling factor thereby represents the percentage contribution of that variable to the overall system performance. The size of the array is based on the number of fundamental variables used in the analysis and a user-selected discretization. For example, in an analysis considering three fundamental variables and a discretization scale of 0.02, the array of scaling factor permutations would assume the form [0,0,1], [0.02, 0, 0.98], ..., [1,0,0]. The overall resolution of analysis accuracy depends upon the selected discretization. Performing a series of grid searches with different discretizations can optimize use of computational resources - rough (large) discretizations can be used to locate local maxima of the output function, and ultimately, finer discretizations can be used to converge to the global maximum. The appropriate discretization is therefore analysis-specific and is selected based on previous experience with the grid search methodology.

The aforementioned scaling factor array is used to develop a weighted score for each system tested (trial) in the analysis. The weighted score for each trial is equal to the sum of the products of the scaling factor array and the fundamental variable measurements. For example, in a three parameter model, one of the permutations of the overall scaling factor array [w_1, w_2, w_3] would be used with the fundamental variable measurements [f_1, f_2, f_3] to yield a weighted score of ($w_1f_1 + w_2f_2 + w_3f_3$) for the specific scaling factor permutation. The calculated weighted score is used with the initial hypothesis to predict the relative performance for each system in relation to the other systems included in the test sample population. The initial hypothesis regarding the relationship between fundamental variable characteristics and the output function is used to develop the ranking order. For example, revisiting the case study, an initial hypothesis could be that 'smaller seal gaps result in optimal seal performance'. For this hypothesis, the grid search would be set up to assess through statistical means whether vehicles with lower weighted scores would have better seal performance than vehicles with higher weighted scores. This set-up is appropriate because the weighted scores offer a weighted average of gap sizes, with the weighting factors chosen to achieve the closest correspondence between model predictions and actual seal performance. The grid search then ranks the expected performance of test systems within the sample population, based on weighted scores (from lowest value to highest value).

The expected system performance ranking (from best to worst) is compared with actual system performance ranking, as determined through actual testing of the systems in the random sample. For example, for a single scaling factor permutation, assume that the predicted ordinal performance ranking of the different systems in a five trial grid search model is [1, 3, 5, 4, 2]. Assume also that the actual ordinal performance ranking based on testing is [3, 4, 1, 5, 2]. For this illustrative case, the sum of squared error for the specific scaling factor permutation is simply:

$$\Sigma_{\text{error}} = [(1\text{-}3)^2 + (3\text{-}4)^2 + (5\text{-}1)^2 + (4\text{-}5)^2 + (2\text{-}2)^2]$$

The sum of the squared error between the predicted system performance ranks and the actual seal performance ranks is taken as a measure of the predictive ability of each specific scaling factor permutation. The minimum sum of squared error observed is taken to be the best estimate for the contribution of the fundamental variables to the output function response. For instance, assume that for a three variable grid search analysis, the scaling factor permutation [1,0,0] resulted in the minimum sum of squared error between the predicted system performance ranks and the actual seal performance ranks. This analysis result would indicate that controlling the first fundamental variable would directly affect the output function response, while controlling the second or third fundamental variables would have no effect on the output function response. Similarly, an optimal scaling factor permutation of [0.5,0,0.5] would indicate that the first and third fundamental variables contribute roughly the same amount to the output function response, while the second fundamental variable under consideration does not impact the output function response. Process controls should then focus on control of the first and third fundamental variables.

It is noted that performing a grid search analysis of any size and resolution requires computational resources and can quickly lead to scarcity of such resources. As factors are added to a grid search and discretizations are refined, the array of weighting factors grows exponentially. For example, a relatively small grid search involving only three parameters and a discretization rate of 0.02 requires an array of 1326 distinct scaling factor permutations. Further details regarding the least squares methodology utilized by the grid search can be found in related literature.[11]

In performing a grid search analysis, it is important to note that this methodology allows objective assessment of the data to identify actual fundamental variables from the expected set of fundamental variables initially under consideration. However, if a critical parameter is not included in the initial set of fundamental variables, the analysis could come up with non-representative or incomplete results. It is also important to ensure that an adequate data set size is taken such that measurement noise does not adversely affect the grid search. Determination of the data set size required to filter out measurement noise often requires an experience-based heuristic approach. Care must be taken in setting up the study parameters (size of data set) and in performing measurements of fundamental variables. It is noted that under certain conditions, measurement activities may need to be performed in a hostile environment that does not allow for suitable testing conditions. In these cases, a trade-off between measurement accuracy and feasibility may be required. If, due to the environment under which testing is performed, measurement accuracy is a concern, it is prudent to repeat the study in a more controlled environment prior to adjustment of assembly processes. A refined study that allows use of a more robust measurement scheme would improve test resolution and improve confidence in the analysis results.

---

[11] Numerical Methods of Curve Fitting, Guest, P.G., Chapter 11.

4.3 Grid Search Analysis - Case Study

A grid search analysis can be quickly modified to facilitate examination of several different hypotheses regarding the relationship between fundamental variables and system performance. Therefore, the grid search methodology was selected to facilitate improvement activities local to the division bar region of the Mustang convertible water seal system, where the underlying mechanism was not understood. The team of engineers involved in this study represented both the design and manufacturing communities within Ford. Team members included glass system designers, sealing engineers, manufacturing engineers, and supplier personnel. Based on members' experience with the current generation seal system, the team generated initial hypotheses regarding the identity of the fundamental variables that drove the water seal system performance local to the glass system interface (corresponding leak path shown in Figure 3.8). The relative position of the door glass with respect to the rear quarter glass was identified as a likely contributor to the localized seal performance. However, it was necessary to narrow this identification down to specific fundamental variables. Based on experience-based hypotheses (seal gap dimensions drive overall system performance) and qualitative insight gained through informal, preliminary testing of the division bar region of the seal system (using methods presented in Section 3.3), an initial set of fundamental variables was developed. The fundamental variables are listed below and illustrated in Figure 4.1:

1) fore/aft gap between door glass and quarter glass at top of glass system interface
2) fore/aft gap between door glass and quarter glass at mid-height of glass system interface

3) inboard/outboard gap between door glass and quarter glass at top of glass system interface
4) inboard/outboard gap between door glass and quarter glass at mid-height of glass system interface
5) up/down mismatch between trailing edge of door glass and leading edge of quarter glass

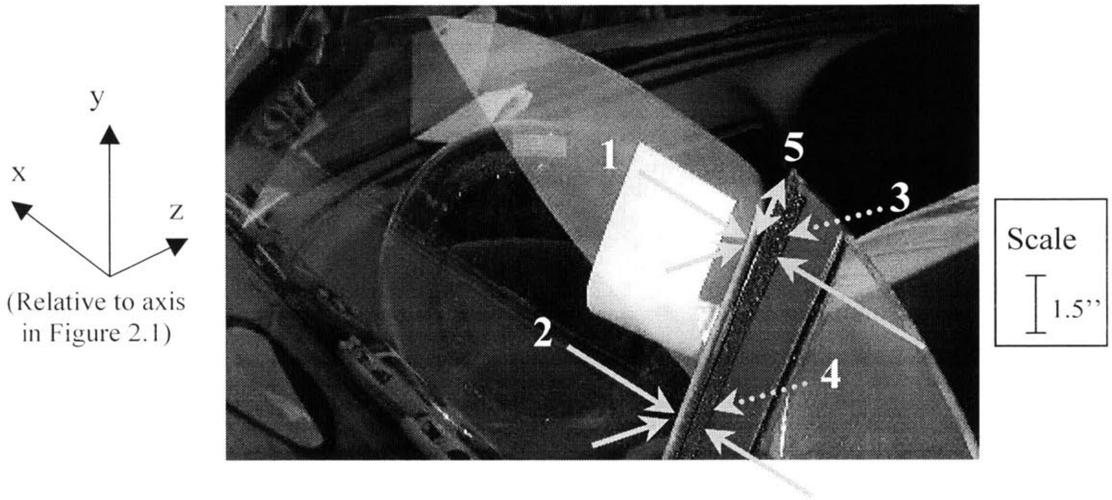


Figure 4.1: Expected Fundamental Variables of Division Bar Region (numbers refer to variables introduced in text).

Digital calipers were utilized to measure the suspected fundamental variables on every vehicle included in the variability analysis sample. These measurements were paired with the corresponding leakage volume captured during testing of the division bar region of each vehicle. The question of interest was whether, among these five measurements taken during assembly, some appropriately weighted subset provided a strong indication of whether leakage would be observed during subsequent testing, and if so, how much could be expected. Water testing was performed using the test procedures identified earlier in Section 3.3.

In order to accommodate flexibility in selection of hypotheses by which system performance levels are predicted, and to provide the capability for dynamic generation of scaling factor permutations used in the grid search, it was necessary to develop a dynamic model using a selected computer language. For this project, Visual Basic was selected due to its compatibility with Microsoft Excel spreadsheets (used for data entry and storage). The dynamic model was developed to allow quick changes of the initial hypothesis for critical parameters, as well as the discretization scale. The Visual Basic source code (presented in Appendix D) automates all but the data entry process of the grid search analysis, and can be modified for use in any generic grid search analysis. Data taken from 30 vehicles was used to develop the final hypothesis of the grid search model, while data taken from a holdout sample of 20 vehicles was used to verify or refute the initial hypothesis. The Spearman rank sum test was utilized to judge the various hypotheses made during the statistical evaluation of the seal system.

The Spearman rank sum test is based on the difference between the predicted ranks and actual ranks of a sample population. The difference of the predicted and actual rank for each test trial is squared, and the squared error for each trial is summed to determine an overall sum of squared error for the sample population. The null hypothesis for a Spearman rank test is defined as the assertion that the predicted ranks from a particular model have no better predictive ability than does random guessing. The test provides a 95% confidence interval for the sum of squared error for a given population. For a sample of n data points, the null hypothesis is valid for the range:

$$n*(n^2-1)/6 \pm 2*[(n^2*(n-1)*(n+1)^2)^{1/2}]/6$$

If the sum of squared error falls outside the 95% confidence interval, the null hypothesis can be rejected under usual statistical standards. Consequently, the model used to generate the predicted ranks is said to have predictive ability at the 5% significance level.

Further details of the analysis are presented in Appendix B, and the raw data utilized in the analysis are presented in Appendix E.

4.4 Case Study Results

The grid search was performed using the five fundamental parameters identified in Figure 4.1. The results are presented in Table 4.1.

Table 4.1: Initial Grid-Search Results

Grid Search	Best-fit Scaling Factor Permutation (X1, X2, X3, X4, X5)	Minimum Sum of Squared Error from Model	Sum of Squared Error Expected for Random Guessing*
Driver side	(0.3, 0, 0, 0.6, 0.1)	4012	4495
Passenger side	(0.1, 0.5, 0, 0.4, 0)	2706	4495

* Equal to half the worst-case sum of squared error.

Note that the sum of squared error expected from random guessing is only reduced slightly for the driver side data, and by a factor of between one and two for the passenger side data by the best-fit scaling factor permutation from the grid search analysis. This indicates that the predictive ability of the grid search may not be significant for the twenty-vehicle holdout sample yet to be tested under the hypothesis that smaller gap sizes result in optimal system performance. Also of concern is that the best-fit scaling parameter permutations are different for the driver and passenger side, as there is no reason to expect that the underlying mechanisms driving the seal system failure would vary from one side of the vehicle to the other. These initial results suggest that there may be excessive measurement noise present in the data. However, the fundamental variables suggested by the grid search results on the original thirty-vehicle data set are evaluated using the Spearman rank sum test to judge their predictive ability. Specifically, the grid search suggests that a combination of fundamental variables X1 and X4 may have predictive ability for the driver side seal performance, while a combination of fundamental variables X2 and X4 may have predictive ability for the passenger side seal performance. These hypotheses are evaluated against a holdout sample of twenty additional vehicles that were not included in the grid search analysis used to develop the results presented at the beginning of Section 4.4.

Formulas arising from use of the grid search methodology are useful because the technique is objective, and are not prone to misconceptions that can arise from merely 'eyeballing the data'. However, human beings are sometimes better at pattern recognition than computers, so it is worthwhile to supplement the grid search hypothesis with others that arise from less formal inspection of the original data set. To further interrogate the original thirty-vehicle data set, a visual examination of the test data is performed prior to use of the Spearman rank test. Based on the visual examination of the test data, alternative hypotheses regarding the identity of system fundamental variables are developed. Scatter plots of fundamental variable data from vehicles in the original thirty-vehicle data set are reviewed in an attempt to further develop trends in the data set. Based on review of the scatter plots, the leakage volume appears to be dependent upon two fundamental variables – the inboard/outboard gaps at the top and middle of the glass system interface. The trends exhibited by the data taken from the driver and passenger sides of vehicles in the thirty-vehicle sample population are shown in Figure 4.2 and Figure 4.3, respectively.

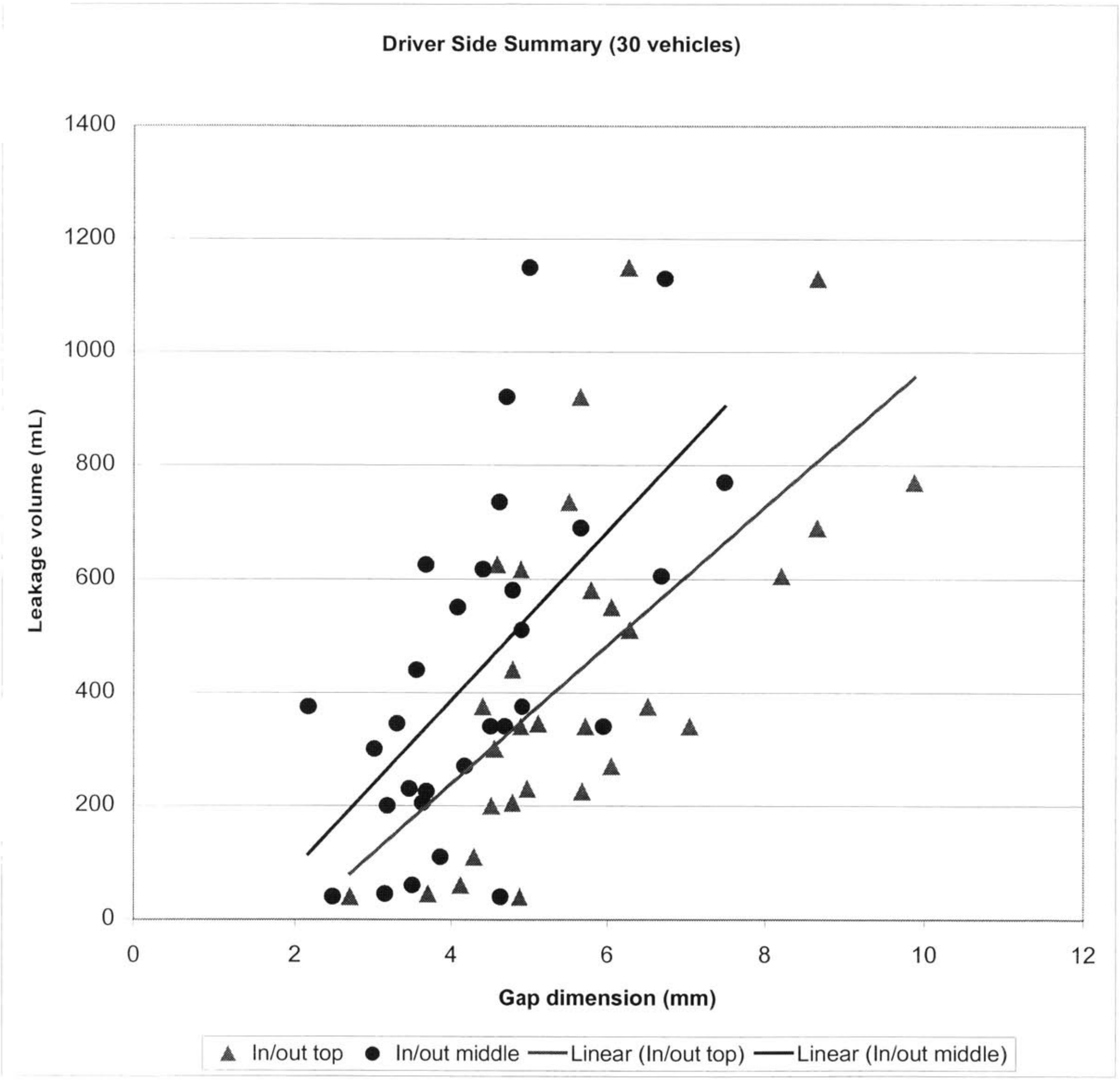


Figure 4.2: Driver Side Scatter Plot – Fundamental Variables 3 and 4 Versus Leak Volume

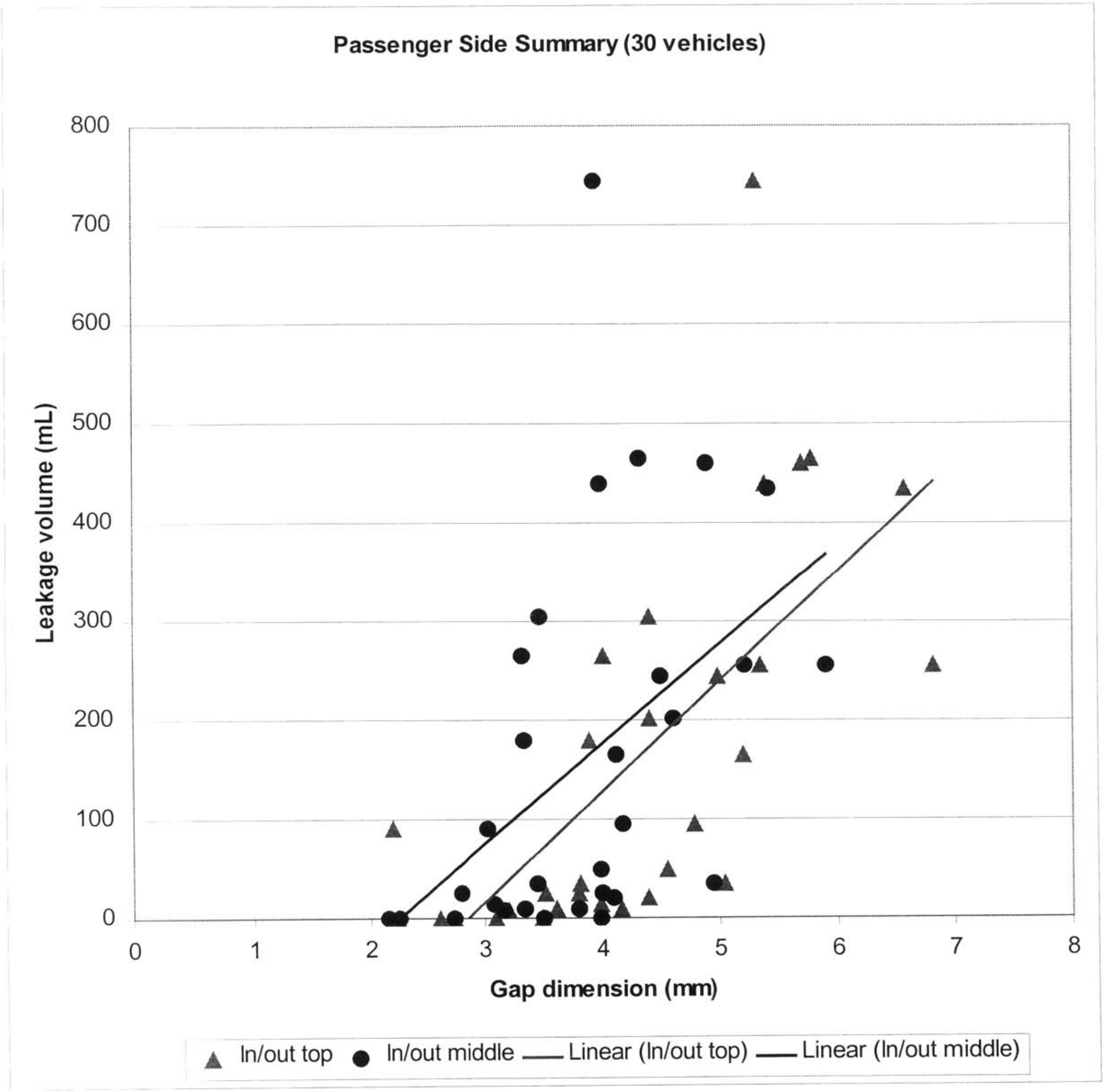


Figure 4.3: Passenger Side Scatter Plot - Fundamental Variables 3 and 4 Versus Leak Volume

To further examine the trends exhibited in Figure 4.2 and Figure 4.3, the inboard/outboard gap at the top of the glass system interface (X3) is also evaluated as a potential fundamental variable using the Spearman rank test (recall X4 has already been identified as a potential fundamental variable by the grid search). Since these variables both relate to the relative inboard/outboard position of the glass system components local to the division bar region, there is a potential for amplification of the contributory effect of each variable to seal system performance. In order to examine such possible amplification of poor seal system performance due to combinations of X3 and X4, the product of these variables is also evaluated as a potential fundamental variable. Results of the Spearman rank tests performed on the original thirty-vehicle data set are shown in Table 4.2. These results are used to develop the final hypotheses that are tested against the twenty-vehicle holdout sample to validate the predictive ability of selected fundamental variables. Note that the 95% confidence interval for the sum of squared error for a thirty data point Spearman rank test ranges from 2826 to 6164. A sum of squared error less than 2826 suggests that the specified fundamental variable (or combination of variables) has predictive ability at the 5% significance level.

Table 4.2: Spearman Rank Test Results for Original Thirty-Vehicle Data Set

Fundamental Variable(s)	Driver Side	Passenger Side
X1	5241	N/A$^+$
(X1 + X4)*	3286	N/A$^+$
X2	N/A$^+$	5801
(X2 + X4)*	N/A$^+$	3886
X3$^\#$	1615	884
X4$^\#$	1745	2020
X3*X4	1625	1118

* hypothesis suggested from grid search results

$^\#$ hypothesis suggested from visual inspection of scatter plots

$^+$ variable(s) not tested – test variable not determined to be significant for specific vehicle side

The results of the Spearman rank test on the original thirty-vehicle data set suggest that fundamental variables X1, X2, and their linear combinations (X1+X4) and (X2+X4) do not have any significant predictive ability for the seal system performance on the driver and passenger sides of the vehicle, respectively. Therefore, these fundamental variables are not included in the final hypotheses regarding the actual identity of fundamental variables of the seal system. In contrast, fundamental variables X3, X4, and the product X3*X4 appear to have predictive ability at the 5% significance level. These fundamental variables are therefore evaluated using a Spearman rank test on the remaining twenty-vehicle holdout sample to *validate* the relative predictive ability of each fundamental variable or variable combination.

The results of the Spearman rank test on the holdout sample of twenty vehicles are shown in Table 4.3. The hypotheses tested were:

- X3 alone (inboard/outboard glass system gap at the top of the glass system interface) has predictive ability for the seal system performance local to the division bar.
- X4 (inboard/outboard glass system gap at the mid-height of the glass system interface) has predictive ability for the seal system performance local to the division bar.
- The product of X3 and X4 has predictive ability for the seal system performance local to the division bar.

Note the 95% confidence interval for a twenty data point Spearman rank test ranges from 720 to 1940. A sum of squared error less than 720 suggests that the specified fundamental variable (or combination of variables) has predictive ability at the 5% significance level.

Table 4.3: Spearman Rank Test Results for Twenty-Vehicle Holdout Sample

Fundamental Variable(s)	Driver Side	Passenger Side
X3	762	627
X4	710	696
X3 * X4	788	612

The Spearman rank test results suggest that fundamental variable X4 (inboard/outboard glass system gap at mid-height of glass system interface) has predictive ability at the 5% level for *both* the driver and passenger sides of the vehicle seal system. Fundamental variable X3 and the product of fundamental variables X3 and X4 are shown to have predictive ability for the passenger side of the vehicle seal system *only.* Fundamental variables X3 and X4 are related to one another through the curvature of glass system components and the mating characteristics of component curvatures at the glass system interface. Therefore, since fundamental variable X4 is shown to have significant predictive ability for seal system performance local to the division bar, X3 would also be expected to have significant predictive ability for seal system performance in this region. While assembly process variability may introduce differences from one side of the vehicle to the other, the fact that the seal system design is identical on the driver and passenger sides of the vehicle suggests that the fundamental variables driving seal system performance would be similar from one side of the vehicle to the other. Therefore, the failure of fundamental variable X3 to pass the Spearman rank test for the driver side of vehicles in the holdout sample is examined further.

The measurements of all fundamental variables examined in this analysis were taken with the convertible top in its retracted position, allowing the glass system to assume its unconstrained, full-up position. However, when the seal system is in steady-state operation, the convertible top is in the full-up position. In this position, the convertible top weather strips apply a force to the glass system components that tends to reduce the inboard/outboard glass system gap at the top of the interface. Therefore, the interaction between the convertible top weather strips and fundamental variable X3 may mask the predictive ability of X3 as measured in the glass system's unconstrained position. However, since the current door glass setting process occurs in the glass full-up, unconstrained condition, measuring fundamental variable X3 with the convertible top in its full-up position to capture the effect of weather strip interaction was not considered.

It is noted that while fundamental variable X3 is not shown to have significant predictive ability for the driver side of the vehicles, it does appear to have significant predictive ability for the passenger side of the vehicles. Since fundamental variable X3 passes the Spearman rank test for the passenger side of vehicles and only *slightly* fails the rank test for the driver side of vehicles, the most reasonable interpretation of the evidence might be that X3 has *marginal* predictive ability for seal system performance local to the division bar region. This, together with the significant predictive ability of fundamental variable X4, suggests that the mating characteristics of the glass system component curvatures are critical to establishing adequate seal system performance local to the division bar region.

Because the glass system components have identical curvatures, two parameters drive the mating characteristics of the glass system curvatures and consequently, the inboard/outboard gap that develops along the division bar seal. In order to closely match the curvatures of mating glass system components, the relative up/down positioning of the quarter glass with respect to the door glass, and the angular skew present at the base of the glass system components are critical parameters that must be controlled. Poor management of these parameters will lead to development of inboard/outboard gaps along the division bar, as shown in Figure 4.4.

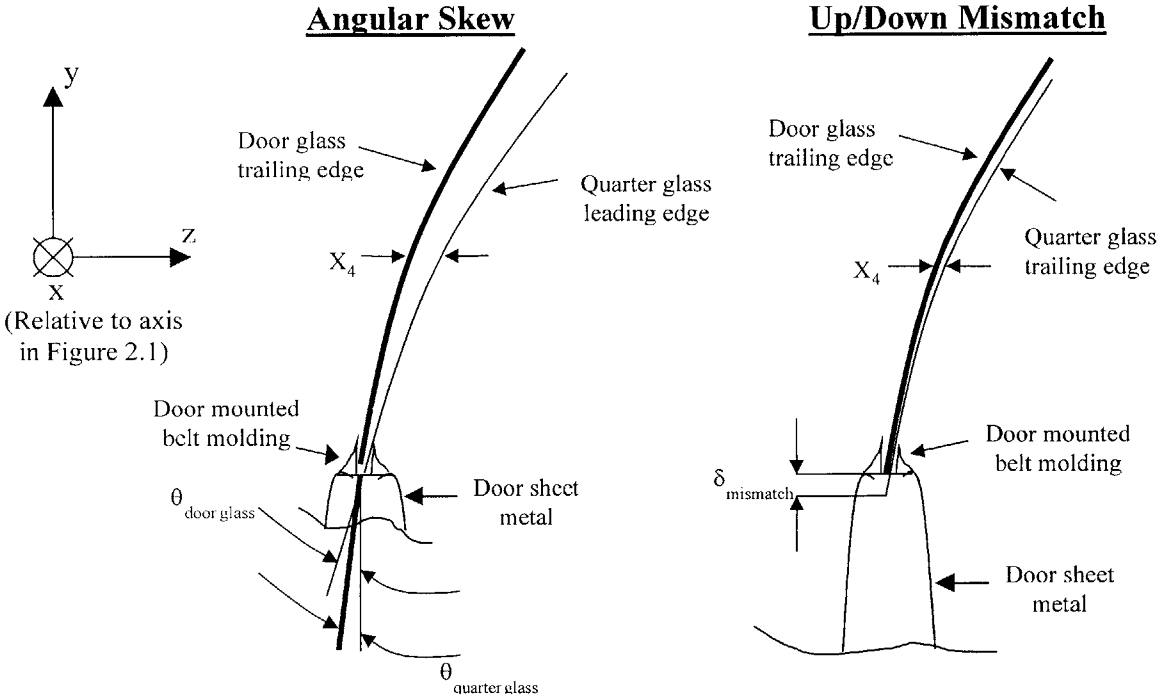


Figure 4.4: Two-dimensional Representation of Effect of Glass System Skew and Up/Down Mismatch on Division Bar Seal Gap

Scatter plots of the raw data (Figure 4.2 and Figure 4.3) show that increasing values of fundamental variable X4 are correlated with larger leakage volumes local to the division bar region. This conclusion suggests that minimizing the inboard/outboard gap at the mid-height of the glass system interface will help reduce seal system leakage local to the division bar region. However, it is noted that the seal system is considered to have failed once *any* water penetrates the seal system. Therefore, developing a specific quantitative relationship for the magnitude of the inboard/outboard glass system gap and resulting leak volume does not add value to this analysis. Rather, the apparent identity of the mid-height inboard/outboard glass system gap as a fundamental variable that drives seal system performance local to the region should be used to tune the current glass-setting process to minimize this parameter. The positioning of the glass system components depends upon the positional control of the regulators in which they sit, and consequently, on the positional control of the sheet metal that comprises the vehicle doors. Since it is known that significant sheet metal variability exists on the SN-95 platform, accurate control of the relative glass system up/down positioning and skew during vehicle assembly will be difficult to achieve with the current glass-setting process without extensive hand adjustment of each vehicle's glass system components. The time that would be required to complete such adjustment for each vehicle's glass system on the assembly line without some modification to the existing glass-setting process would make this process step infeasible for the current line rate utilized at Dearborn Assembly Plant.

However, it is a reasonable assumption that modifications can be made to the glass system setting process currently in use on the assembly lines. The results of this analysis suggest that the trend setting the glass system components to minimize the mid-height inboard/outboard gap may help improve seal system performance local to the division bar region. The current glass setting fixture sets the door glass with respect to the windshield 'A-pillar' and a datum point on the convertible top. Incorporating a feature/process to adjust the inboard/outboard fit between the mating glass components may help prevent poor glass system interfaces similar to those shown in Figure 4.4 from developing.

4.5 Summary

Positional control of the glass system components (and the associated local seal system performance) is dependent upon not only the mating characteristics of the glass system components, but also upon the interface between the glass system and the convertible top assembly. This, in turn, is dependent upon the interface between the convertible top assembly and the structural sheet metal of the vehicle body. Because the positional control of the glass system is dependent upon the variability of so many parameters, the team working on the performance enhancement project was unable to resolve the seal system failure associated with the glass system interface local to the division bar region. However, it is noted that the results contained herein can be used as a base for continued development work on the design of the seal system local to the division bar.

In order to verify or refute the conclusion suggested by the statistical evaluation performed herein, seal systems must be built with specified mid-height glass system inboard/outboard gaps. Unfortunately, Dearborn Assembly Plant does not have the capability to build vehicles on the line with specified gaps at various locations of the glass system interface. An independent design of experiments is suggested to confirm or refute the conclusions presented above. This analysis should include a sample of as-built vehicles with different inboard/outboard gap at the glass system interface mid-height, and should seek to reproduce the relationship between the system's fundamental variable (X4) and the output function response as suggested in this analysis. Independent verification of the results suggested by the analysis herein will add significant credibility to the analysis results.

Finally, while the problems with positional control of the glass system components will be difficult to resolve on the SN-95 platform (due to the aforementioned difficulties with cascading sheet metal variability), the conclusions herein should be carefully considered for the S-197 platform to avoid similar seal system failures local to the division bar region.

Chapter 5 - Benchmarking Study

Benchmarking is a widely accepted process used during quality improvement projects. If performed properly, the benchmarking process can be very effective in bringing fresh ideas and new approaches into an organization and can result in more effective design concepts. While benchmarking studies can be utilized for both business process reengineering and product/system redesign projects, this study focuses on the latter use of the benchmarking process.

5.1 Benchmarking Process: An Overview

The overall benchmarking process can be used as a powerful quality improvement tool, but must be focused and organized in order to maximize overall results. Five main steps can best describe the benchmarking process as manifested in this study:

1) analyze current system to assess strengths and weaknesses
2) identify competitive systems across sector
3) determine performance gap between current system and best-in-class system
4) identify 'best practices' from target system and/or competitive systems
5) target specific 'best practices' upon which conceptual design activities can be focused to narrow/eliminate performance gap

The first step in the overall benchmarking process, analysis of current system strengths and weaknesses, builds off the failure mode and effect analysis (FMEA), presented in Chapter 3. The FMEA is performed to characterize failure modes and mechanisms for a given system. Thus, the results of a FMEA illustrate system *weaknesses*. However, an

FMEA may also reveal *strengths* that are inherent in the current system design. Any strengths that are observed during the system FMEA should be noted, as potential refinements of the underlying mechanisms responsible for these strengths could result in improvements to the overall system performance. It is important to note system strengths to ensure that they are not overlooked during the redesign phase of the project, especially since redesign activities tend to focus on system weaknesses.

Once the strengths and weaknesses of the current system are understood and documented, it is necessary for a company to identify competitive systems against which it will benchmark its own system's performance. Competitive systems are typically found performing identical functions in products that are similar to the product in which the target system resides. However, such systems can also take the form of indirectly related systems in the same or different products. For example, in the current water seal system project, competitive systems are found in the convertible top assembly of convertible vehicles produced by manufacturers other than Ford Motor Company. However, 'best practices' in sealing methodologies may also be revealed from review of indirectly related systems, such as those used to seal a vehicle's door region. The inclusion of a broad range of systems from which to benchmark increases the effectiveness of a benchmarking study, and consequently, the probability of a positive outcome.

Once competitive systems have been identified for inclusion in the benchmarking study, actual comparison of the target system performance with that of the competitive systems must be performed. To facilitate this comparison, test parameters developed for use in the failure mode and effect analysis (see Section 3.3) are applied to the competitive systems. Direct application of the same test parameters to the different systems involved in the benchmarking study allows identification of systems with markedly better or worse performance levels. The systems that exhibit 'stand-out' performance levels can then be examined by a company to identify 'best practices' that should be incorporated into its own system design. Equally important, comparison of the performance of different systems can be used to identify practices that should be avoided, due to robustness, cost, or manufacturability issues. The system performance comparison allows a company to establish a performance gap between its system and the 'best-in-class' system (i.e. the system judged to have the best performance). The performance gap between the target system and the best-in-class system can be utilized to develop goals for target system performance. These goals can vary from narrowing the performance gap between the target system and the best-in-class system by a certain amount, to meeting the best-in-class performance level within a certain time frame, to leapfrogging the best-in-class performance level. Whatever the desired goal, knowledge of the existing performance gap between a company's target system and the best-in-class system helps to characterize the scope of the overall system performance enhancement project.

5.2 Benchmarking Study - Case Study

In developing a best-in-class Mustang convertible top seal system, a broad benchmarking study was performed to identify best practices in sealing methodology from across the industry. The water seal system of a convertible vehicle exhibits unique characteristics. During steady-state operation, the water seal system is designed to function with no relative motion between its components. However, the system components must be capable of undergoing large displacements during system deployment without incurring damage. Based on the specific characteristics unique to this type of system, the benchmarking sample was restricted to water seal systems used on other convertible top vehicle models. The following convertible models were selected for inclusion in the benchmarking study:

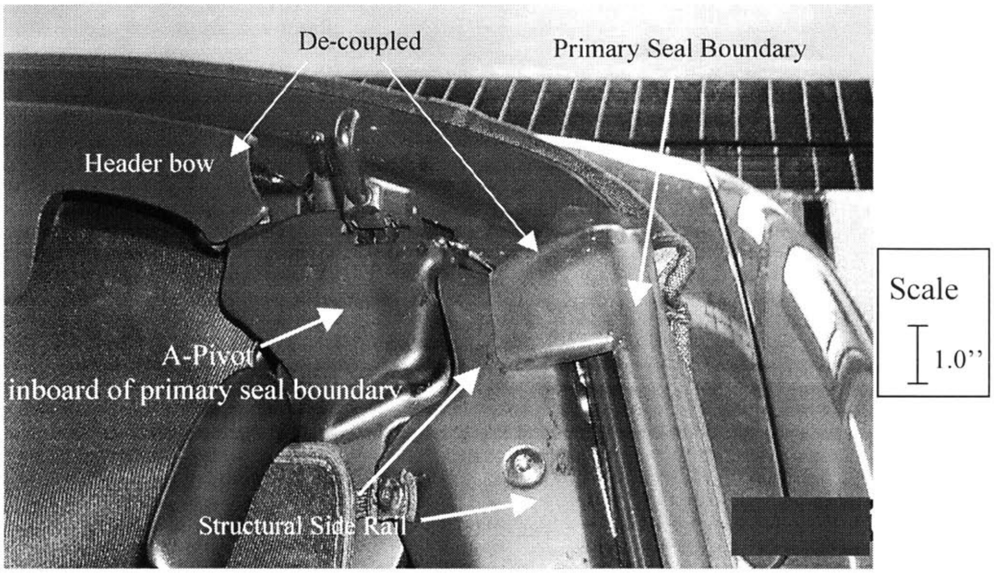
- Chrysler Sebring
- Volvo C70
- Mazda Miata
- Jaguar XK8
- Mercedes SLK

A combination of factors was used in the selection of these competitive systems. The Mustang convertible is positioned by Ford to compete in the sporty, mid-range convertible class. The Chrysler Sebring and Mazda Miata are selected because they are positioned as direct competitors in the Mustang's class. The Volvo C70, Jaguar XK8, and Mercedes SLK are positioned above the Mustang's class, and therefore, are not direct competitors. However, due to the less cost sensitive nature of the consumer segment that purchases these higher cost models, it is anticipated that the water seal systems of these vehicles may incorporate additional features/design concepts that are not currently utilized in the Mustang's system. Although these higher cost vehicles do not compete in the Mustang's class, they are included in the benchmarking study to facilitate the search for underlying mechanisms that can be applied to the development of the Mustang seal system in a cost effective manner. This combination of in-class and out-of-class competitive systems is expected to provide a broad range of performance levels and design concepts. Best practices derived from the benchmarking study are discussed in detail for each of the problematic locations on the current Mustang water seal system.

5.2.1 'A-Pivot' Region

The first region under review for design changes is the 'A-pivot' region. As discussed in Chapter 3, the 'A-pivot' is utilized in the Mustang convertible top system to allow the top to flex outward during actuation. This outward flexing provides increased passenger room in the rear seat area and more efficient roof packaging in the retracted position.

Benchmarking activities performed on the best-in-class Chrysler Sebring showed that the Sebring's seal system performance local to the 'A-pivot' region is superior by an order of magnitude to that of the Mustang. In the context of this analysis, an order of magnitude performance difference represents the difference between a system that allows either no leakage or minor leakage (roughly 10mL), and one that experiences hundreds or thousands of mL leakage during a given test. This difference in seal performance has been traced to the convertible top header/structural side rail joint. The Mustang header/side rail joint is part of the primary seal boundary while the Sebring header/side rail joint is executed inboard of the primary seal boundary, as shown in Figure 5.1. The Sebring design methodology eliminates a joint in the primary seal boundary, thereby providing clearance that allows extension of the structural rails and weather strip retainers along the entire length of the forward weather strips. The full-length structural rails and seal retainers of the Sebring keep its forward weather strips supported in the correct position per design intent. Furthermore, the convertible top header bow is not coupled to the forward weather strips in any manner (see Figure 5.1), thus eliminating the weather strip flexing experienced with the Mustang system (see Figure 3.3). Consequently, the Sebring design methodology provides much more robust local seal performance.



[redacted]

Figure 5.1: Best-In-Class 'A-Pivot' Region of Chrysler Sebring.
(looking rearward toward vehicle trunk at partially cycled roof)

5.2.2 'B-Pivot' Region

The seal above the structural rails at the Mustang’s 'B-pivot' joint is an area of primary concern, as there often is a direct leak path into the vehicle at this location. Segmented, cantilevered foam (currently used on the Mustang) does not provide a robust seal at this location. The Mercedes SLK utilizes an alternate approach to sealing this region - a uniform rubber extrusion attached to the front and middle structural rails. This design offers one key benefit over the current split foam system that is expected to result in improved seal performance - the design provides a continuous seal across the structural rail breaks. Two views of the Mercedes alternate design approach for the 'B-pivot' region are shown in Figure 5.2 and 5.3.

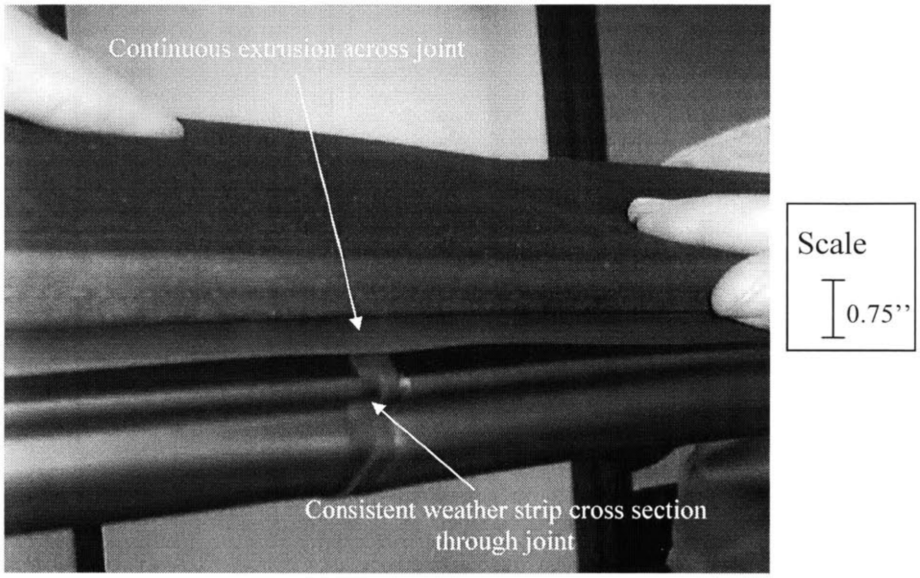


Figure 5.2: Mercedes 'B-Pivot' Joint Water Seal in Deployed Position.

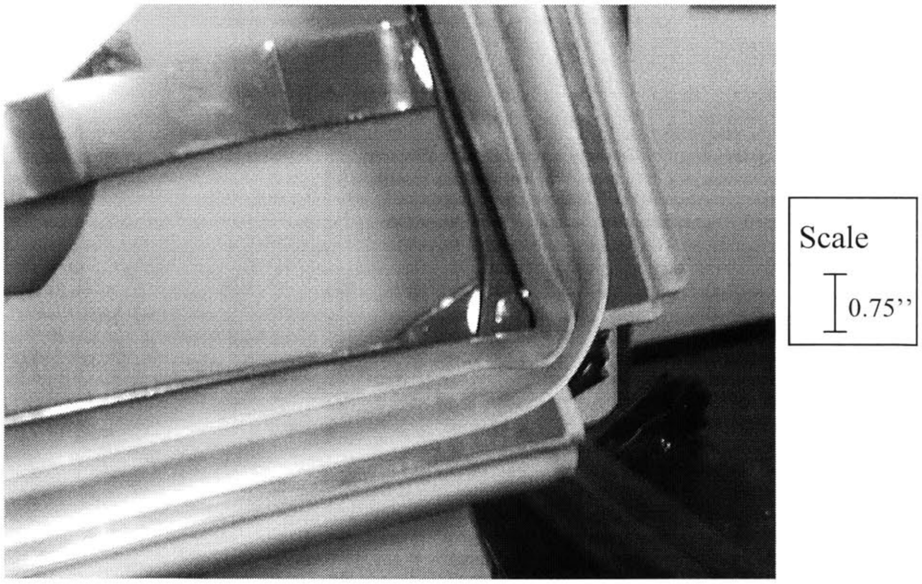


Figure 5.3: Mercedes 'B-Pivot' Joint - Roof Partially Cycled.

The glass system/weather strip interface local to the B-pivot joint also appears to be an underlying factor that improves the overall quality of the water seal in this region. Through a qualitative visual inspection of the Sebring seal system, stiff weather strips are observed to improve the glass system/weather strip interface transition. Stiff weather strips are also expected to help with inboard/outboard positional control of the glass system and prevent glass system induced weather strip distortion. Such distortion can cause incorrect glass system positioning for the glass full-up condition, and result in exacerbation of the division bar leak path shown in Figure 3.8. The improved inboard/outboard positional control of the glass system may also help improve the consistency of the division bar seal compression between the door glass and quarter glass. The best-in-class 'B-pivot' region and the localized weather strip/glass system interface is shown in Figure 5.4.

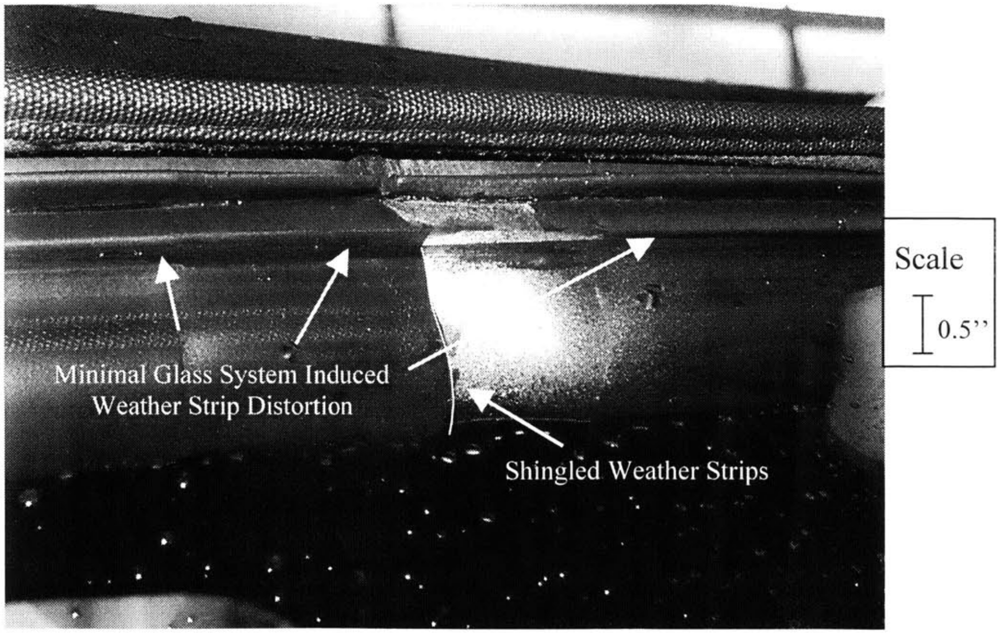


Figure 5.4: Best-In-Class 'B-Pivot' Region of Chrysler Sebring.

5.2.3 'C-Pivot' Region

Perhaps the most difficult design issue to resolve for the regions above the structural rails is located at the 'C-pivot' joint. The same weakness inherent in the use of segmented, cantilevered foam directly above the 'B-pivot' joint also exists above the 'C-pivot' joint. Unfortunately, the linkage mechanism of the roof results in large relative displacements of the mating ends of the middle and aft structural rails during roof cycling, thereby precluding use of the extrusion concept derived from the Mercedes design in the previous section. Benchmarking activities were unable to identify a single vehicle in the Mustang class that completely prevented water entry in this region.

The water seal system of the Jaguar XK8 did perform significantly better than all other vehicles in this region, but the improved performance of the Jaguar is based on a design concept that requires significantly higher cost per unit vehicle. This design concept utilizes a ‘C-channel’ in the convertible top. This 'C-channel' allows the frameless glass of the vehicle to enter a structurally supportive region at the end of travel in its full-up condition. Because it is a structural region, the 'C-channel' provides seal quality similar to that found on vehicles that have framed glass systems - designs with sheet metal surrounding the entire glass perimeter.

Use of a 'C-channel' requires incorporation of a ‘drop glass’ feature, as once the glass system is inside the structural C-channel, the vehicle doors cannot be opened without damage to the glass system or convertible top. The Jaguar 'drop glass' feature lowers the glass system a predetermined length of travel immediately upon actuation of the door handle. This feature requires the use of logic modules and the system results in significant cost to the vehicle. On the more price-sensitive Mustang, it is therefore an option that can only be considered if the additional cost can be justified by expected warranty savings. The magnitude of the per unit cost of a 'drop glass' feature (estimated at anywhere from \$20 to \$60 per vehicle) makes incorporation of such a feature on the Mustang unlikely.

While it was not investigated as to its effect on seal system performance, another issue that should be considered is the proximity of the 'C-pivot' joint to the glass system joint on the Mustang. None of the competitive vehicles reviewed during this benchmarking study had the 'C-pivot' joint directly in line with the glass system joint. The proximity of the 'C-pivot' joint to the glass system joint is not an issue that can be addressed without a significant redesign of the entire aft region of the convertible top assembly. Moving the 'C-pivot' joint affects packaging space of the top, as well as dynamic clearances, and the overall appearance of the vehicle when the convertible top is in its full-up position. Consequently, this issue is a long-term issue, and should be addressed if a full convertible top redesign is considered during S-197 (next generation platform) Mustang development work.

5.2.4 Glass System Division Bar

The division bar/weather strip interface is another challenging region of the SN-95 water seal system. Currently, poor control of glass system positionability necessitates the use of weather strips manufactured from soft rubber to prevent damage to seal components. Unfortunately, the glass system positionability results in weather strip pinching for the glass full-up condition, thereby distorting the design intent position of the weather strips. This distortion is exacerbated by the fact that the Mustang weather strips are very compliant. Review of the Sebring division bar/weather strip interface shows no distortion of the weather strips and very effective shingling of the division bar over the weather strips (see Figure 5.5). Use of stiffer weather strips is expected to contribute to the smooth division bar/weather strip interface observed on the Sebring. Effective management of the transition from the division bar to the weather strips at this interface requires capable glass system positional control. To this end, improvements to the current glass system setting methodology are under active investigation for Mustang. However, these efforts are hampered by poor sheet metal control inherent in the vehicle platform, as discussed earlier.

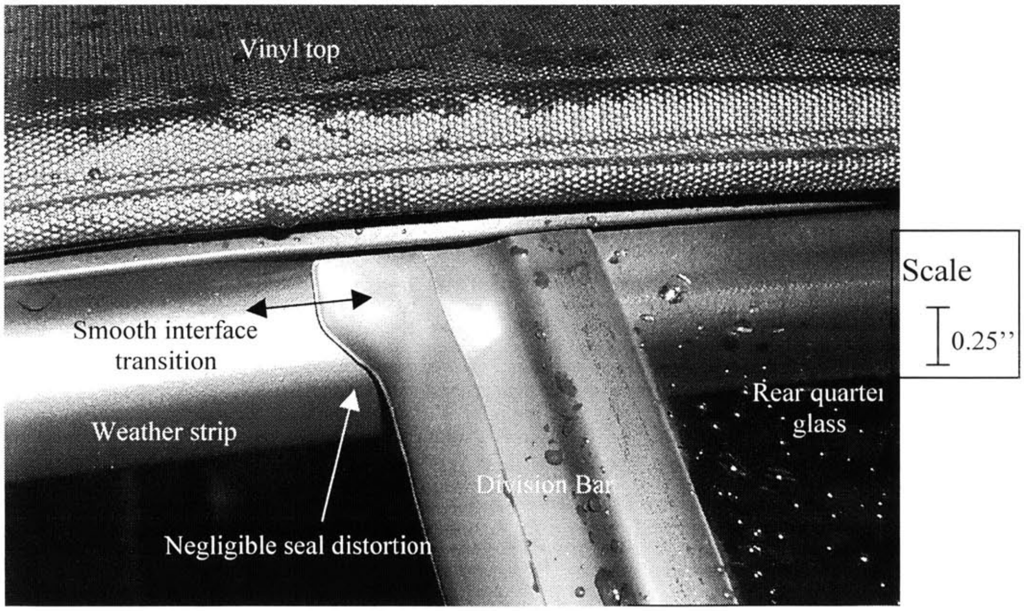


Figure 5.5: Best-In-Class Division Bar/Weather Strip Seal of Chrysler Sebring.

5.2.5 Wet Area

The Chrysler Sebring performs much better than the Mustang in the 'wet area' region. However, the coordination of the mating components on the Sebring (convertible top, chassis sheet metal, and rear quarter glass) does not appear to be as efficient as that on the Mustang. The performance edge of the Sebring design was traced to a significantly larger wet area and a better internal water management system. The larger wet area is facilitated by the current sheet metal design and it efficiently captures all water entering the Sebring in this region. It is noted that as a result of its larger 'wet area', more water enters the Sebring than the Mustang in this region, and consequently, more noise exists with the Sebring design. The larger wet area could be incorporated on the Mustang without changing the joint coordination currently provided by the vehicle. However, redesign of the wet area requires sheet metal changes and would therefore need to address convertible top packaging area and dynamic clearance concerns.

It is noted that this region is not considered as critical as other regions under evaluation as the customer cannot physically see the related leak path. Since this failure mode is not considered as critical as the previously discussed failure modes and since sheet metal changes are needed to facilitate changes, this issue is considered an S-197 issue, and should be addressed during related design activity for the next generation platform.

5.3 Benchmarking Study Results

Order of magnitude performance differences are evident between the Mustang convertible water seal system and one or more competitive systems at every region under investigation. Although there were no inherent *strengths* observed from review of the current SN-95 seal system, several 'best practices' were identified through review of the competitive systems included in the benchmarking population. Some of the best practices can be easily adapted for use on the Mustang seal system, while others would require significant system modifications. However, it is important to understand how the mechanisms resulting from the best practices at each of the failure mode regions affects the local seal system performance.

The following design concepts currently utilized on the Mustang convertible water seal system were identified during the benchmarking study as major contributors to the performance gap between the Mustang system and the competitive systems:

- location of 'A-pivot' joint in primary seal boundary
- use of segmented, cantilevered foam to seal regions above structural rail joints
- use of non-continuous seal components
- lack of positive location methodology for seal system components
- use of soft rubber to accommodate poor glass system positional control

These aforementioned design concepts will be reviewed during the conceptual redesign phase of this project.

(This page intentionally blank)

Chapter 6 - Conceptual Design Activity

The focus of conceptual design activity within a product/system performance enhancement project depends greatly upon the constraints of the project. The author's past experiences have suggested that projects that have constraints on the final form of a product or system tend to cause conceptual design activity to focus on modifications to existing system components, rather than creation of new components. Such projects typically result in incremental performance improvements to the existing product or system. In contrast, projects that do not have constraints on the final form of a product or system do not restrict the focus of conceptual design activity, and can therefore generate leaps in system performance levels. Flexibility during the conceptual design phase of a project can result in an innovative, all-new product/system design rather than incremental evolution of an existing design. 'Blue sky' performance enhancement projects – those with little or no constraints on the final form of a product/system – offer the inherent possibility of design innovation due to flexibility of the conceptual design process.[12] However, the author believes that it is also possible to bring innovation into the conceptual design process of projects that have constraints on the final form of a product/system. Fostering innovation during the conceptual design phase in a constrained project is difficult, but offers the potential for leaps in product/system performance that would not have been possible otherwise. This point is examined in detail.

---

[12] Radical Product Innovation, Bengt-Arne Vedin, IMIT, 1980. Page 6.

6.1 Conceptual Design – An Overview

The conceptual design phase of a performance enhancement project is the phase in which best practices are embodied in an existing design. As discussed in Chapter 5, benchmarking studies are useful in identifying best practices currently applied in competing products or systems. Therefore, effective conceptual design activity should build on the best practices observed from benchmarking studies. However, the author believes that truly effective conceptual design involves innovation in the application of best practices to a new or existing design.

Innovation within large corporations is considered intuitively based, high-risk, and often "...quite at variance with incremental technological change and the management of the present."[13] While innovative conceptual design can therefore encounter organizational resistance, it nevertheless "represents the best opportunity for achieving a truly proprietary competitive advantage."[14] Due to the creative nature of the conceptual design process, there is no methodology that ensures innovation will occur during the process. Based on the author's past experiences, innovation appears to result from the ideas of creative individuals working within risk-tolerant organizations. However, creating an environment based on observed traits of creative individuals[15] can help inject creativity into the conceptual design phase of even highly constrained projects. The effect that organizational structure and culture have on innovation and creativity is discussed further in Chapter 7.

---

[13] Ibid. Page 7.
[14] Ibid. Page 32.
[15] Ibid. Page 35.

To foster creativity in the design process, heterogeneous teams should be formed that are capable of 'conceptual fluency'[16] – the ability to produce a large number of ideas quickly. Creativity is further enhanced if the 'conceptual fluency' of a design team is accompanied by the ability to generate 'out of the box' ideas, and the ability to suspend judgement on, or delay commitment to, a single idea. Adherence to the aforementioned principles during conceptual design activity should help facilitate successful idea generation.[17] The following steps can be used to describe the overall conceptual design phase of a performance enhancement project:

- review of best practices observed during benchmarking study
- brainstorming/concept generation
- demonstration of concept feasibility (mock-up generation)
- preliminary evaluation of mock-up performance
- demonstration of production feasibility (prototype generation)
- durability/life cycle testing
- development of production implementation plan

These steps are illustrated through the conceptual design activity performed as part of the water seal system performance enhancement project.

---

[16] Ibid.

[17] Innovation, Milton Rosenau Jr., Lifetime Learning Publications, 1982. Page 77.

6.2 Conceptual Design – Case Study

As discussed earlier, project constraints can result in boundaries for the conceptual design activity performed during a performance enhancement project. As with this project, a driving project constraint is often cost. To minimize the cost of the total system redesign, it was desirable to utilize as many components/features of the existing design as possible. Using best practices derived from benchmarking activities, conceptual redesign of the Mustang convertible top water seal system was pursued for each of the current generation seal system leak points identified in Section 3.4. Of the five leak points present in the current seal system, four could be addressed without sheet metal changes. These will be the focus of the conceptual design phase of the project.

Review of all the sealing methodologies examined during the benchmarking study identified continuity of the primary seal plane as an essential, effective seal system characteristic. Team brainstorming sessions focused on creation/modification of seal system components that would facilitate a primary seal plane. The conceptual design activity resulted in a sealing concept derived from the Mercedes design (pictured in Figure 5.2). This sealing concept provides continuity across each of the convertible top joints in the region between the structural rails and the convertible top canvas. This sealing concept proposes use of a continuous rubber extrusion to seal the region between the convertible top canvas and the structural rails, in lieu of the segmented foam currently utilized in this region. In this design concept, the extrusion is sewn into the convertible top canvas along the entire convertible top length, resulting in the desired continuous seal plane identified as a best practice through the benchmarking study. The preliminary mock-up of this sealing concept is shown in Figure 6.1.

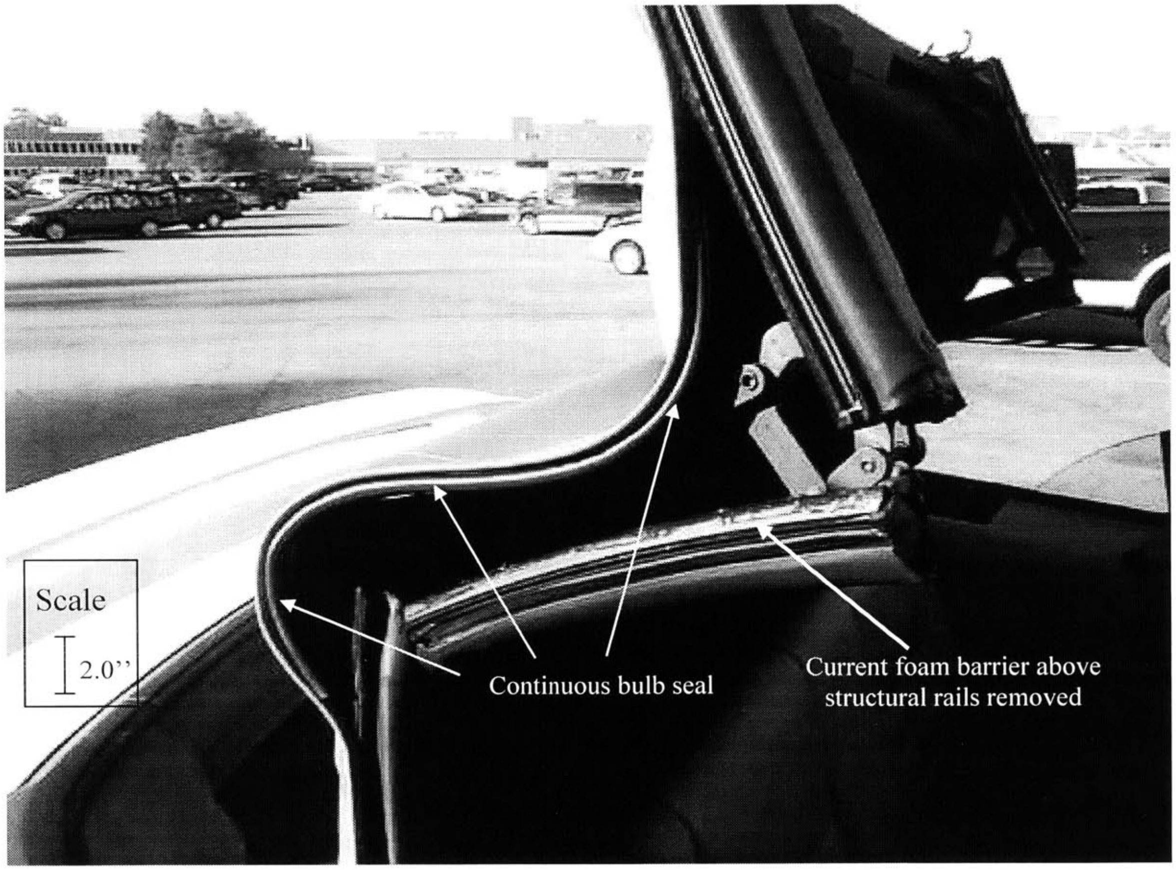


Figure 6.1: Preliminary Mock-Up of Bulb Seal/Vinyl Top Bonded Interface Concept

Challenges to implementation of a continuous primary seal plane based off of this sealing concept must be addressed at each of the failure locations of the current seal system.

6.2.1 Mock-Up Phase

The failure mode and effects analysis for the overall water seal system was presented in Chapter 3. The mock-up phase of the project's conceptual design activity required modification of specific, component-level details that were not presented by the general

FMEA described in Chapter 3. These component-level details contribute to the overall system-level failure and are therefore reviewed in detail herein.

6.2.1.1 'A-Pivot' Region

The current generation seal system design utilizes a foam barrier to fill the gap between the back of the unsupported portion of the forward weather strip and the vinyl top. The current design also utilizes an extruded rubber lip on the forward weather strip. The design intent is for the extruded lip of the weather strip to continue the retainer seal lip cross section forward to the windshield header seal. Unfortunately, due to a lack of positive location methodology in the current design, neither the foam barrier nor the extruded rubber lip on the forward weather strip is effective in sealing the 'A-pivot' region. The aforementioned weather strip details are shown in Figure 6.2, and the discontinuity between the retainer seal lip and the forward weather strip, as installed, is shown in Figure 6.3. Note the distortion of the extruded seal lip of the weather strip in its installed position.

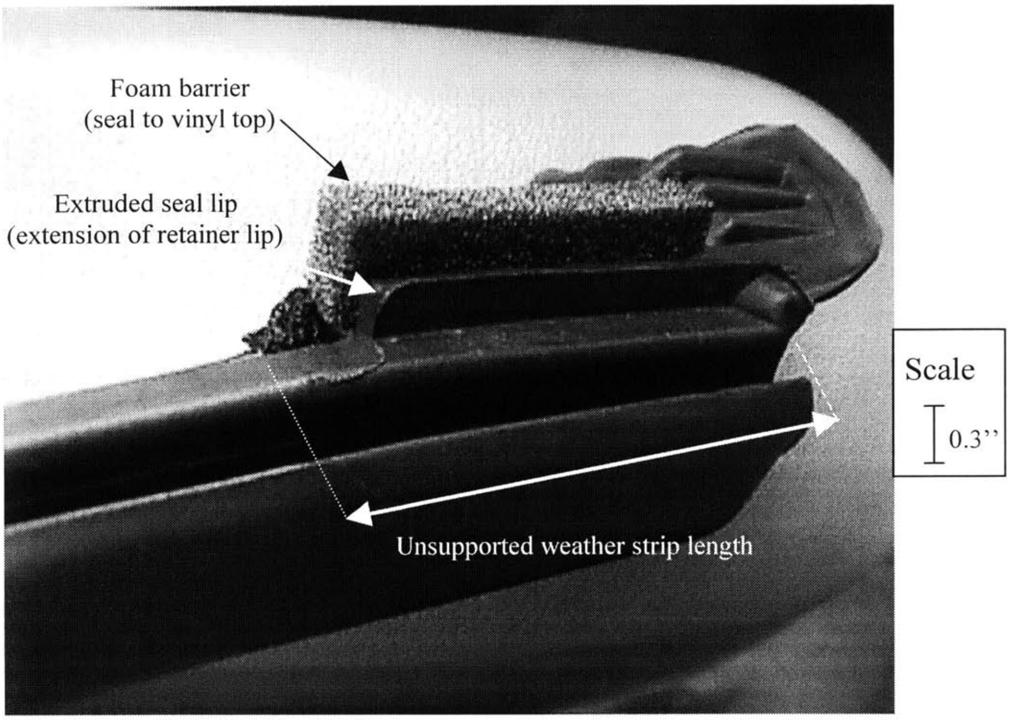


Figure 6.2: Existing Forward Weather Strip Detail – 'A-Pivot' Region

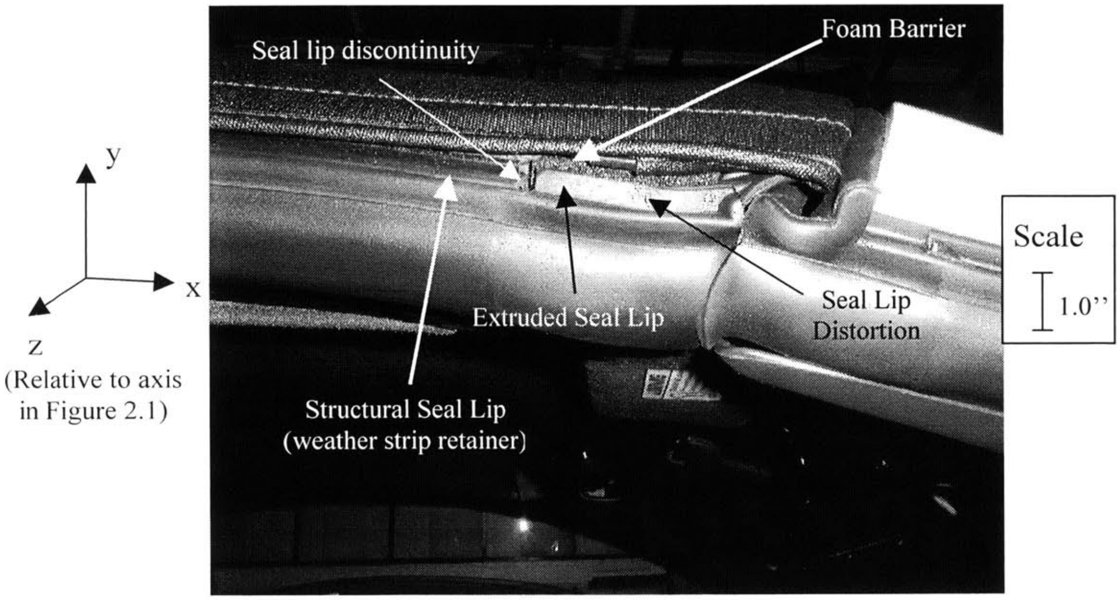


Figure 6.3: Existing Forward Weather Strip Detail (installed) – 'A-Pivot' Region

The intent for the redesign of this region is to move the retainer seal lip/weather strip discontinuity forward from its current position to a region local to the windshield header seal. By moving the seal lip discontinuity forward to the windshield header seal region, new design features can be incorporated in the seal system to manage water entry at this point and route the managed water through currently existing drainage holes in the windshield header seal. Movement of this discontinuity requires forward extension of the weather strip retainer. Extension of the weather strip retainers is expected to improve the design robustness of this region by providing structural support for the forward weather strips along their entire length. This structural support would help prevent the distortion of the forward weather strip shown in Figure 6.3.

Because the current forward weather strip lies in the projected path of the retainer seal lip, extension of the forward retainer requires modification of the end mold detail of the forward weather strip. To minimize tooling changes, the current weather strip/windshield header seal interface is kept as close to the current design as possible. A small region of the end mold detail of the weather strip is notched out (as noted in Figure 6.4) to allow the full extension of the retainer seal lip and the continuous vinyl top mounted extrusion forward to the windshield header. The retainer seal lip extension forward to the windshield header is shown in Figure 6.5. Extending the retainer seal lip through the end mold detail of the weather strip allows the primary seal plane to be maintained for the full length of the convertible top assembly. The changes to this region can be illustrated by comparison of Figure 3.3 with Figure 6.4.

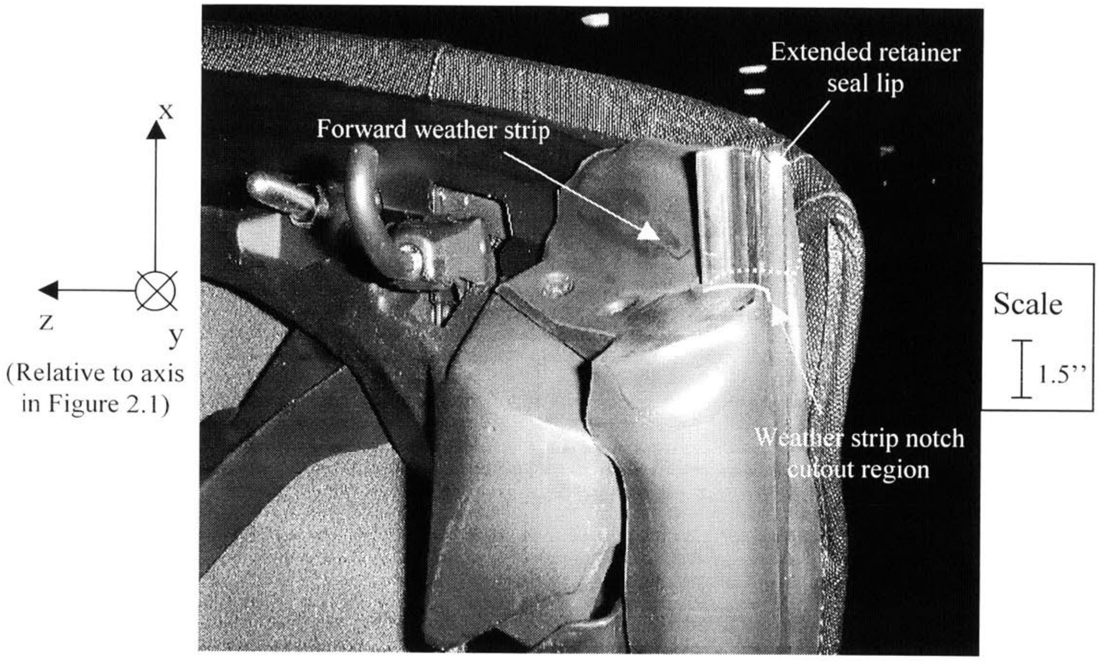


Figure 6.4: 'A-Pivot' Water Seal Mock-Up – Forward Weather Strip Detail

Preliminary water evaluation of the 'A-pivot' concept mock-up showed that significant performance improvements were made with the design changes. Under the standardized water test described in Section 3.3, the new design concept completely prevented the leak that is inherent in the 'A-pivot' region of all SN-95 Mustangs currently in production. Under a more severe test (direct application of pressurized water onto the joint), water entry was observed directly aft of the windshield header at the header seal/forward weather strip interface. Diagnosis of the leak observed during testing identified two parameters that contributed to the root cause failure of the joint mock-up. The absence of a drainage hole in the forward weather strip (allowing water to pool up inside the weather strip) and the poor transition between the weather strip and the back of the retainer seal lip. The former issue can be addressed by simply adding a drainage hole in the weather strip that allows trapped water to flow down the windshield A-pillar. The latter issue is a result of the mock-up quality and is expected to be resolved when production seal components are obtained. A retest of the joint mock-up with a simulated drainage hole resulted in a completely water tight seal at the 'A-pivot' region.

The overall result of the design work is that the position of the 'A-pivot' seal plane discontinuity (pictured in Figure 6.3) has been moved forward to the windshield header seal region, as observed in the mock-up shown in Figure 6.5. Water entry through the seal plane discontinuity at this location can be better managed, as the windshield header seal has internal drainage passages that can route entering water away from the passenger compartment out through chassis drain holes.

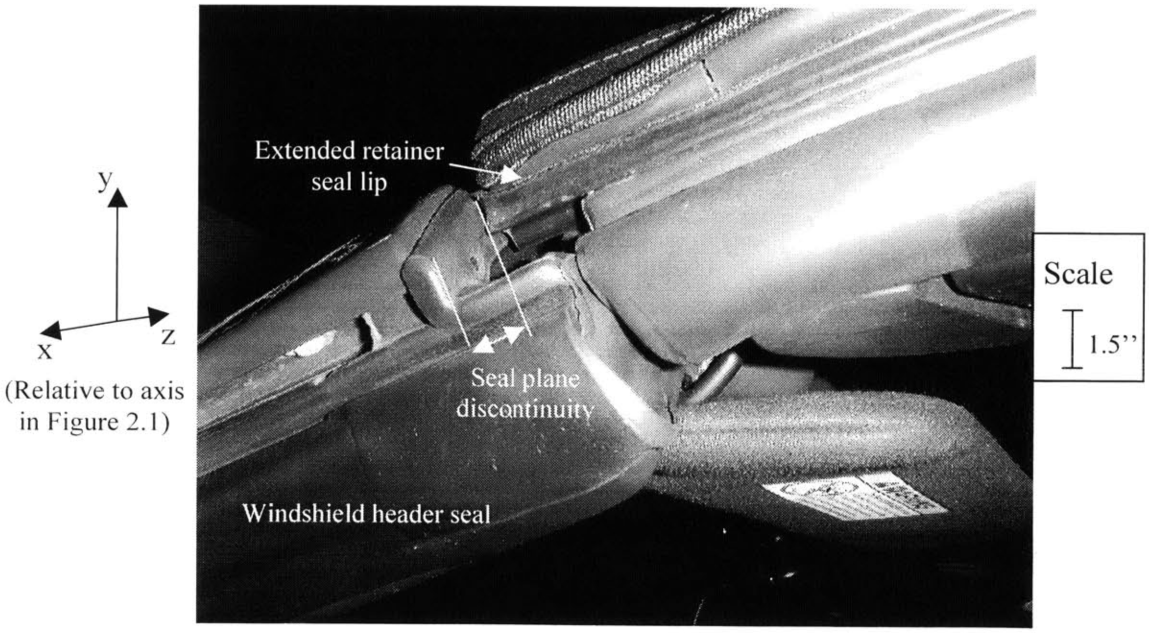


Figure 6.5: 'A-Pivot' Water Seal Mock-Up – Roof Clamping Hooks Disengaged

6.2.1.2 'B/C-Pivot' Regions

There are two factors that contribute to the seal plane discontinuity at the 'B-' and 'C-pivot' joints. As discussed in Chapter 3, water entry is possible through the segmented foam above the structural rails of the convertible top and through the retainer seal lip discontinuity as shown in Figure 6.6 and Figure 6.7. These two figures are similar to those presented in Chapter 3, but provide different angles to help accentuate seal lip gap details. The continuous extrusion concept derived from the Mercedes SLK convertible top only eliminates the discontinuity concerns created by use of the segmented foam in the current design. The discontinuity concern regarding retainer seal lip consistency across the 'B-' and 'C-pivot' joints still remains. Note the cross section continuity across the butt joints on the Mercedes convertible top shown previously in Figure 5.2. In comparison with the Mercedes design, the current generation Mustang design has a large discontinuity in the retainer seal lip at the 'B-' and 'C-pivot' butt joints by design.

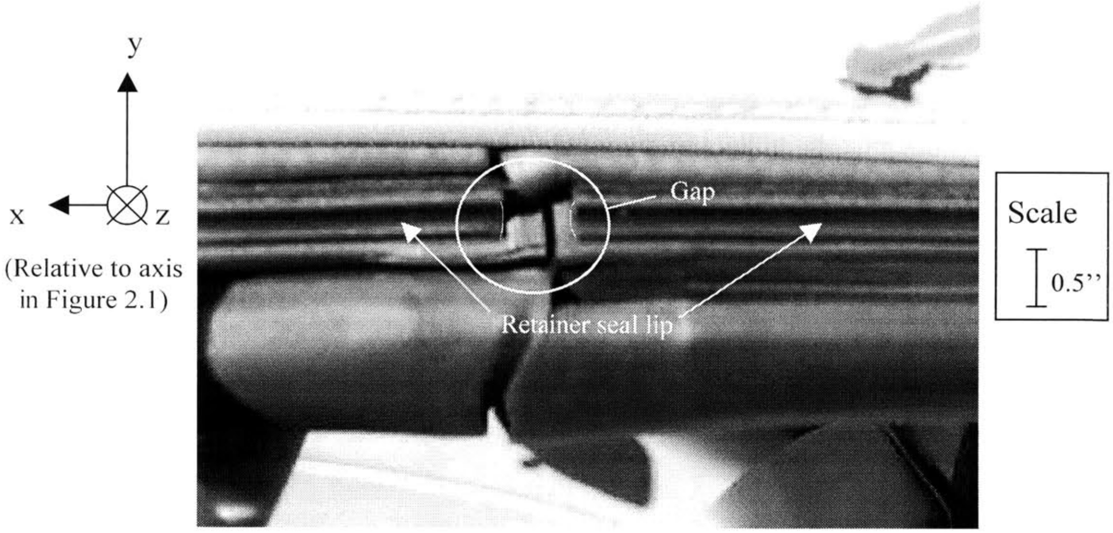


Figure 6.6: Discontinuity in Retainer Seal Lip Detail at SN-95 Mustang 'B-Pivot'

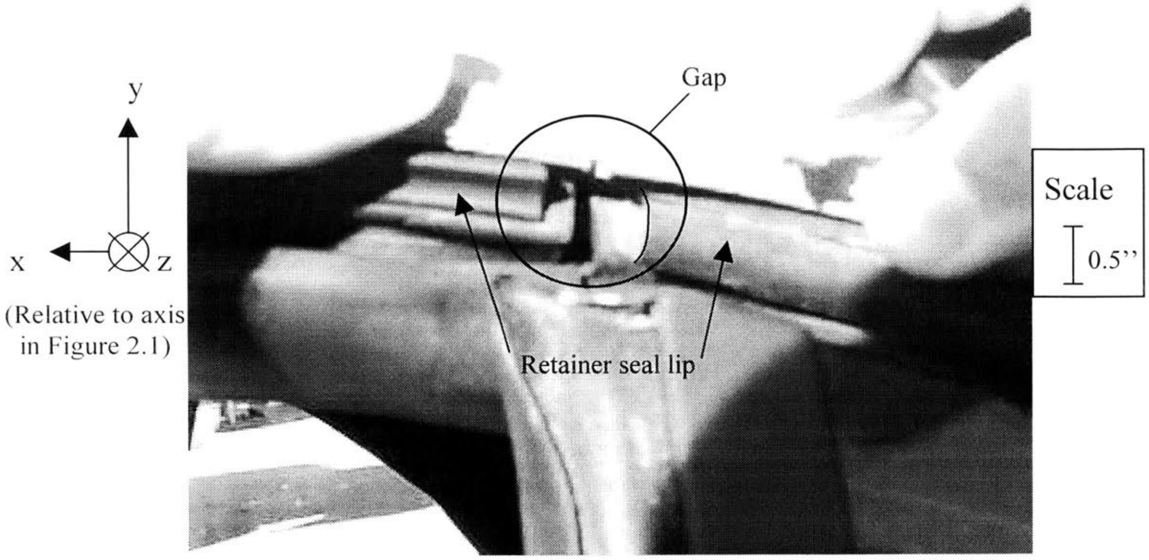


Figure 6.7: Discontinuity in Retainer Seal Lip Detail at SN-95 Mustang 'C-Pivot'

The conceptual design change for the Mustang convertible top focuses on modifications to the molded detail at the ends of the rail-mounted weather strips. These modifications consist of the addition of weather strip material in line with the fore/aft (± x direction in Figure 6.6) projection of the retainer seal lip across each pivot joint. The addition of this material (shown in Figure 6.9) results in a much better seal plane consistency across the 'B-' and 'C-pivot' joints. Pictures of the initial mock-up of the 'B-' and 'C-pivot' regions are shown in Figures 6.8 through 6.10. Note in Figure 6.8 that the continuous extrusion located above the retainer seal lip eliminates the seal plane discontinuity above the structural rails and the seal lip gap 'plugs' eliminate the seal plane discontinuity below the structural rails.

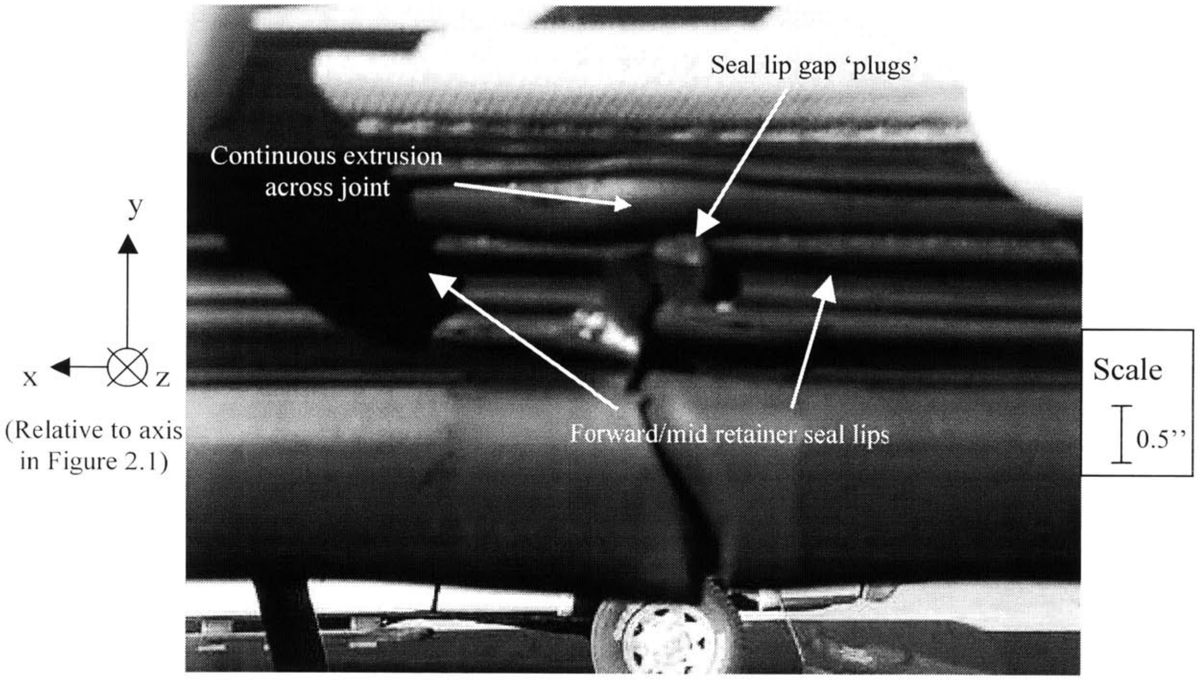


Figure 6.8: ‘B-Pivot’ Joint Mock-Up

The seal lip gap 'plugs' represent additional rubber that will be added to the end detail of the weather strips through changes to the existing weather strip mold cavities. Note that the mock-up changes are not exactly representative of the actual design intent for molded detail changes. The dashed white lines in Figure 6.9 represent the design intent for the material to be added to the molded detail for actual production weather strips. As shown in Figure 6.9, the mock-up material is slightly larger than this.

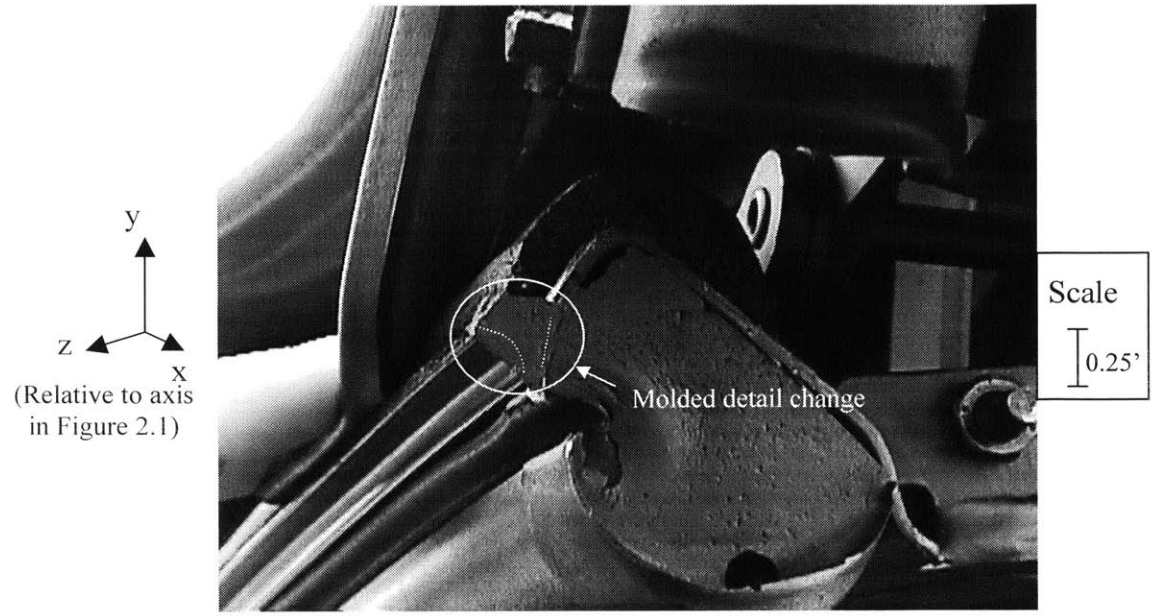


Figure 6.9: 'B-Pivot' Molded Detail Mock-Up

The aforementioned design features are also shown for the 'C-pivot' joint in Figure 6.10.

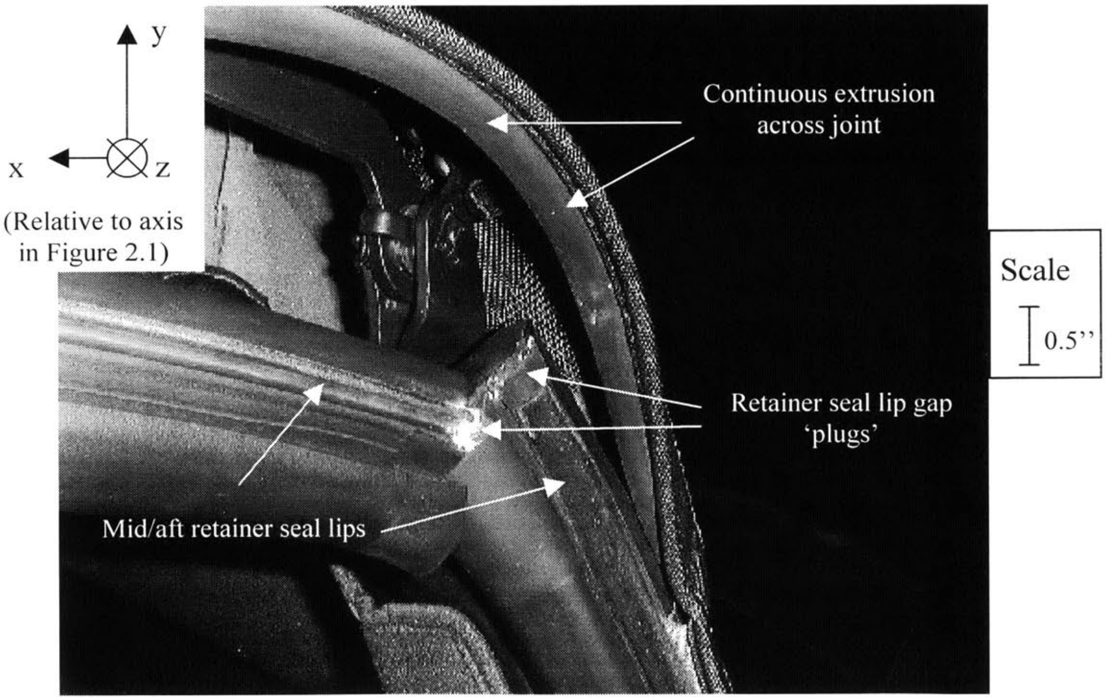


Figure 6.10: 'C-Pivot' Joint Mock-Up

In preliminary testing, combination of mock-up molded detail changes (to maintain a uniform retainer cross section across the joints) together with the extrusion attached to the vinyl roof resulted in a completely water tight seal at both the 'B-' and 'C-pivot' regions. Benchmarking activities to date have not identified any convertible in the Mustang class that performs well at the 'C-pivot' joint. Therefore, the initial mock-up performance was extremely encouraging. However, there are several issues regarding the feasibility of this design concept that must be addressed, specifically, manufacturability and serviceability. However, the concept appears to have significant potential for greatly improving the water seal performance at the problematic pivot joint regions of the Mustang seal system. The alternate design concept also appears to be rather robust with respect to positioning, as no hand adjustment of any of the seal components was required to achieve the watertight seal.

6.2.2 Prototype Phase

To ensure feasibility of any proposed design concept implementation, it is necessary to investigate the effect that the design change will have on the entire supply chain. In addition to supply chain issues, concept prove-out (for performance, manufacturability, and assembly) is required before actual changes to current production are implemented. In order to ensure the smooth transition of a new design concept into production, a prototype system must be built and tested. Prototype testing includes not only the testing described in Section 3.3 (to characterize performance of the new concept), but also life cycle testing (to assess system durability).

Successful design and assembly of the water seal system depends upon a number of suppliers. For the water seal system project, the supply chain consisted of three suppliers: two Tier I suppliers (the convertible top supplier and the weather strip supplier) and a Tier II supplier (fabric supplier). The Tier II fabric supplier provides vinyl top assemblies to the Tier I convertible top supplier for use in the convertible top assembly process. The Tier I convertible top supplier provides convertible top assemblies for final assembly onto vehicles at Ford's Dearborn Assembly Plant. The Tier I weather strip supplier provides weather strips to Ford for assembly onto the convertible top assembly. Ford performs weather strip assembly after the convertible top assembly is mated to the vehicle body.

The action items that were developed to ensure successful implementation of the proposed seal system design concept are summarized in Table 6.1. Each of the action items, and the issues that they resolved, are discussed in detail.

Table 6.1: Action Items Taken for Design Concept Implementation

Issue	**Action(s)**	**Responsibility**
No extrusion mounting scheme exists	- Design concept exploiting hidden vinyl flap - Develop sewing process for extrusion/vinyl flap	Tier II fabric supplier
Extrusion/table contact during sewing process results in friction drag, slowing throughput	Apply slip coat to extrusion, reduce friction drag	Tier I weather strip supplier
Potential for extrusion sewing process to result in scrap of vinyl top assembly	Sew extended length extrusion into vinyl top assembly, trim to length after sewing process completed	Tier I convertible top supplier

Development of the sewing process to be used for fastening the extrusion to the convertible top vinyl required coordination of the Tier I convertible top supplier, the Tier I weather strip supplier, and the Tier II fabric supplier. The vinyl top is currently delivered from the Tier II fabric supplier to the Tier I convertible top supplier with two 'binding lines' - stitch marks resulting from the sewing process used during vinyl top assembly. Of the two binding lines, one line is functional (creates the pocket that houses tensioner cable) and the second line is cosmetic. The sewing process at the Tier II supplier is highly sensitive to factors such as the sliding friction between the fabric and the sewing surface. As a result, the scrap rate is extremely sensitive to process variability. The vinyl top is rejected if the two binding lines are not precisely parallel over the entire length of the convertible top. Because of the parallelism requirement, incorporation of a third binding line that would secure the rubber extrusion to the vinyl top was considered inadvisable. The parallelism of the third binding line was expected to be more difficult to control than the cosmetic binding line parallelism due to the variability introduced in the sewing process from the presence of the rubber extrusion.

Through discussion with the Tier II fabric supplier, a concept was developed in which a hidden flap of vinyl was incorporated inside the convertible top assembly. The hidden flap would be sewn to the vinyl top using the existing functional binding line and the rubber extrusion (provided by the Tier I weather strip supplier) would in turn be sewn to the hidden flap. Whereas the existing design relied on the interface between the vinyl top and segmented foam barriers to seal the region between the vinyl top and structural rails, the new design concept utilizes the rubber extrusion in lieu of the segmented foam barriers. Compression of the extrusion cross section by the vinyl top executes the seal. An illustration of this design concept is presented in Figure 6.11.

The presence of the rubber extrusion caused difficulty during the sewing process. The process utilized at the Tier II fabric supplier required the rubber extrusion to be in contact with the table on which the sewing process was performed. Due to difficulties with friction drag between the extrusion and the table, the Tier II supplier suggested a slip coat be applied to the extrusion to minimize friction drag and help improve throughput rate. The slip coat application was performed by the Tier I weather strip supplier and allowed continued use of the existing sewing process at the Tier II fabric supplier.

One final design issue that needed resolution was control of the overall fore/aft length (± x direction in Figure 6.11) of the rubber extrusion. A 'short' extrusion would result in an excessive seal plane discontinuity above the retainer seal lip, as shown in Figure 6.5. A 'long' extrusion would interfere with closure of the convertible top. Although a 'long' extrusion is not desirable, it can be trimmed following the sewing process. However, a 'short' extrusion cannot be lengthened in a robust manner and its presence during the sewing process therefore represents the potential for a scrapped vinyl top assembly. After sewing operations have taken place, significant manufacturing costs have been invested in the vinyl top assembly and the assembly represents significant value. Therefore, in order to preclude the potential for rubber extrusion length variability to result in scrap vinyl top assemblies, it was determined that an extended length extrusion would be sewn into the vinyl and trimmed to its final length following completion of the sewing process.

Although this required an additional process at the Tier I convertible top supplier, it helped reduce the scrap potential for high value subassemblies.

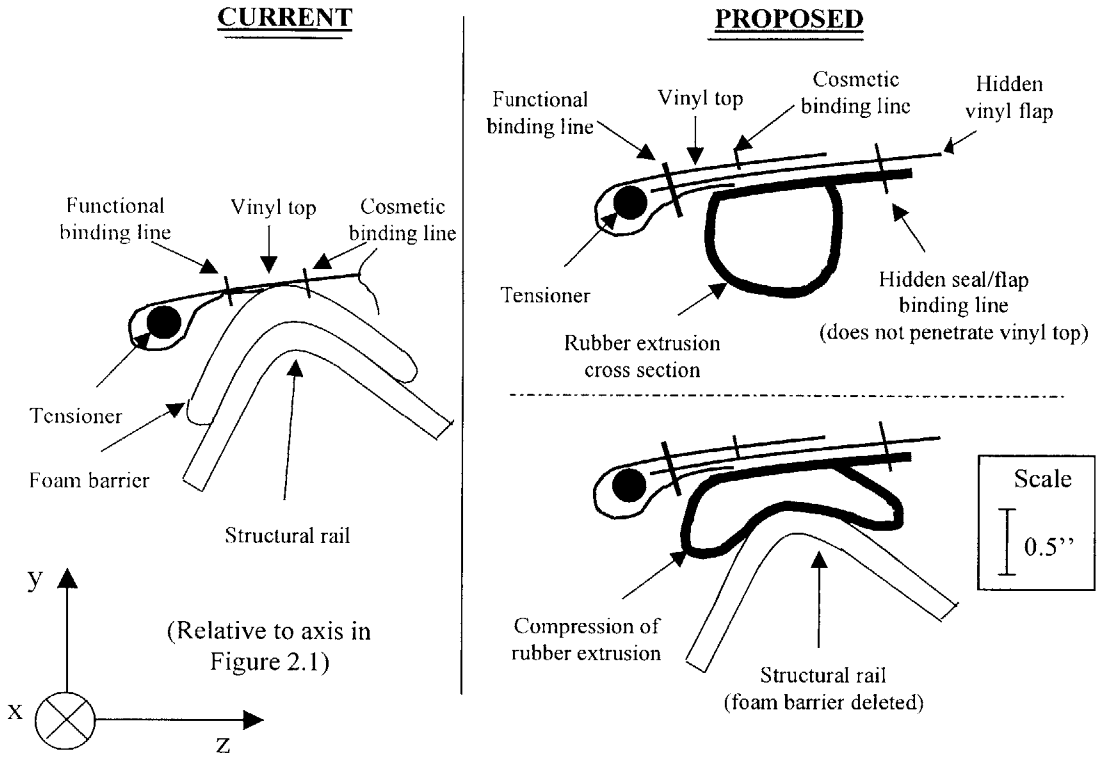


Figure 6.11: Rubber Extrusion Vinyl Top Mounting Design Concept – Current and Proposed

Implementation of the aforementioned action items ensured the supply base could provide convertible top assemblies at a rate that could support the rate of vehicle production at Dearborn Assembly Plant. The new processes and design changes were implemented for construction of an initial prototype system that was earmarked for use in preliminary system performance testing.

6.3 Conceptual Design - Results

Application of the general system tests (described in Section 3.3) did not result in leakage at any of the pivot joints. It is important to note that the design concepts presented in this section do not address the seal system performance at the division bar region of the seal system. Therefore, these design concepts do not result in performance improvements local to this region. However, based on the performance increases demonstrated by the design concept at the pivot joints of the seal system, five additional systems were assembled for life testing. Life testing of the first prototype system did not result in any performance degradation of the system. At the time of the writing of this document, life cycle testing of the five additional systems was still ongoing.

Consistent with the cost-sensitive nature of this performance enhancement project, the proposed water seal system design concept presented in this chapter is based on many of the existing components of the current system. All changes to the current seal system and new components needed to assemble the proposed seal system are summarized in Table 6.2 along with a projection of related costs.

The proposed design concept builds off of the best practices identified during the benchmarking study of competitive vehicles, and addresses several of the non-robust features of the existing seal system. Recall the non-robust system features identified in Chapter 5:

- location of 'A-pivot' joint in primary seal boundary
- use of segmented, cantilevered foam to seal regions above structural rail joints

- use of non-continuous seal components
- no positive location methodology utilized for seal system components
- use of soft rubber to accommodate poor glass system positional control
- use of stamped structural rails
- reliance on preload of cantilevered glass to seal region below structural rails

Table 6.2: Detailed Design Changes

Component	New or Modification	Description	Projected Cost(s)
Forward weather strip	Modification	- Modification of existing forward cross section to create notch allowing forward extension of retainer seal lip - Modification of aft cross section to create seal gap 'plug' at 'A-pivot' joint	\$32,000 – new mold (fixed)
Middle weather strip	Modification	- Modification of both forward and aft cross sections to create seal gap 'plug' at 'B' and 'C-pivot' joints, respectively	\$32,000 – new mold (fixed)
Aft weather strip	Modification	- Modification of forward cross section to create seal gap 'plug' at 'C-pivot' joint	\$32,000 – new mold (fixed)
Rubber extrusion	New	- Creation of mold for extrusion process - Creation of sewing process for extrusion attachment	\$4-\$6 / extrusion (variable) \$2-\$4 / sewing process (variable) \$32,000 – new mold (fixed)

Of these seven features, the proposed design concept successfully resolves concerns with the first four. The *'A-pivot' gap* has been successfully *removed from the primary seal plane* as shown by a comparison of Figure 6.3 and Figure 6.12. While the 'A-pivot' joint remains in close proximity to the primary seal plane boundary, the discontinuity it created in the current design was eliminated. This was achieved through extension of the forward retainer seal lip forward to the windshield header seal, and through use of the continuous rubber extrusion above the retainer seal lip in lieu of the foam barrier shown in Figure 6.2.

The *segmented, cantilevered foam utilized in the current design was eliminated* and replaced by the *continuous rubber extrusion* that spans the entire convertible top length. Finally, changes to the weather strip end mold details resulted in creation of 'seal gap plugs' on the weather strips as can be seen in Figure 6.13. On the proposed system, alignment of the mating 'seal gap plugs' can be easily verified through visual inspection, and helps ensure that the weather strips are *located properly* during installation.

The total cost for implementation of this design includes fixed costs of roughly $130,000 and variable costs of roughly $6 to $10 per vehicle. The warranty cost to Ford for seal system failures 10 months into service is over $8 per vehicle. It is noted that these costs are actual out-of-pocket costs and do not represent the potential cost savings that are expected to result in improved customer perception of vehicle quality. The proposed water seal system design presented herein can be justified on both performance level and cost, and is therefore recommended for implementation into the existing convertible top assembly.

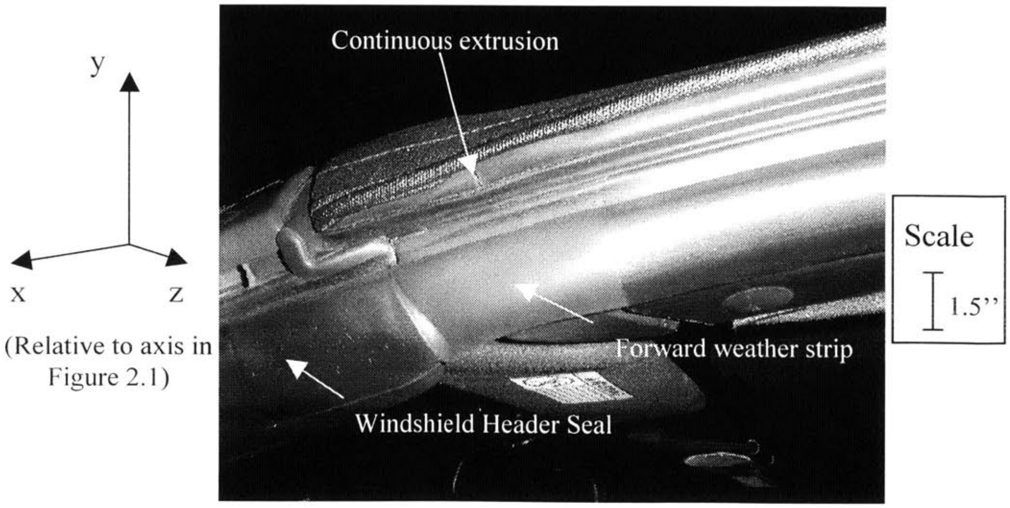


Figure 6.12: Prototype System 'A-Pivot' Detail.

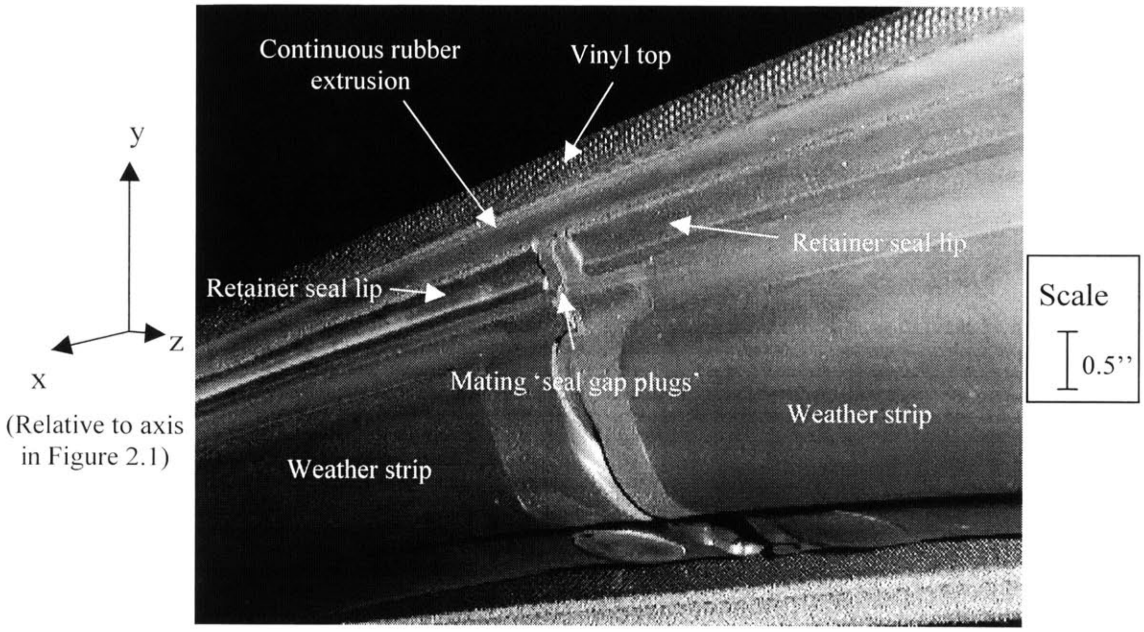


Figure 6.13: Prototype System 'B-Pivot' Detail.

(This page intentionally blank)

Chapter 7 – Effect of Organizational Structure On Knowledge Flow

The difficulties experienced with component integration on the Mustang convertible water seal system point to a lack of system-level ownership within the current SN-95 program. Although the observations made herein are based on work performed within the SN-95 program, this lack of system-level ownership may also be symptomatic of systemic knowledge flow and communication problems on other programs elsewhere within Ford Motor Company. In order to help prevent such difficulties from arising on future programs, and to correct existing conditions that lead to such difficulties, it is necessary to understand what factors contributed to the lack of system-level ownership on the SN-95 program. To this end, the functional organizations chartered with new vehicle design and support, and the knowledge flow mechanisms between these organizations are examined in detail in the following sections.

7.1 Organizational Structures: General Background

Organizations create internal structures to help manage the complexity of their overall product development process. Functional groups within an organization are utilized to develop specific expertise within a given functional area. Almost all organizations rely on the participation of and interaction between functional groups to successfully bring their product to market. While creation of these groups can indeed facilitate development of specific expert knowledge in various functional areas, it can also become an impediment to the overall product development process. This impediment arises because "...important information and communication flow horizontally through the boundary between functional organizations,"[18] whereas work and responsibility within functional groups flow vertically. Vertical and horizontal refer to knowledge flow as illustrated by an organizational chart. Vertical flow occurs between different levels of responsibility within specific functional 'silos', while horizontal flow occurs within and between different functional 'silos'. An example of horizontal knowledge flow that is critical to the success of the overall product development process occurs between engineering and manufacturing. Without adequate engineering support for the manufacturing group, the design of manufacturing processes required to build the product can suffer greatly. This can result in product/process redesign, increased design/build cycle time, and increased product development costs. Once engineering has released a design to manufacturing, there is a natural tendency for engineering to feel that the overall product development process has moved outside the boundary of their functional group, and consequently, to lose motivation to remain active in the development process.[19] Because functional organizational structures can result in artificial boundaries within the overall organization, such structures can promote inadequate levels of support across functional groups. Therefore, in order to develop and maintain an effective product development process, it is critical for an organization to ensure that its overall structure does not introduce organizational barriers that prevent efficient knowledge flow and communication mechanisms between functional groups.

Any organization must address several concerns to prevent organizational barriers from creating inefficiencies in its product development process. Functional groups within

---

[18] Cartin. Page 66.

organizations tend to develop their own internal culture and goals, thereby creating the potential for conflicting goals and poor organizational alignment. Because of this, functional organizations must clearly establish which functional group (or combination of groups) is responsible for ownership of cross-functional systems within the overall product. Since "...work gets done through a process crossing organizational boundaries,"[20] functional organizations must be able to focus on a systemic approach to product development. A systemic approach involves a high degree of coordination between different functional groups that are stakeholders of the system. Revisiting the Mustang seal system project, various functional groups have a stake in the seal system. These include sealing engineering, glass system engineering, sheet metal engineering, manufacturing engineering, and external suppliers. Unfortunately, these different functional groups have different goals and metrics. Therefore, horizontal organizational communication mechanisms must be in place to create an environment in which all groups focus on the ultimate goal of driving quality into both system design and manifestation.

7.2 Organizational Structure Used in New Product Introduction – Overview

Introduction of a new vehicle line within Ford requires the interaction of several internal Ford design and manufacturing groups, as well as an external supply base. Based on the author's experience within Ford's overall product development organization, new/existing products appear to be currently introduced/supported using the organizational structure shown in Figure 7.1.

---

[19] Ibid.

Research and Vehicle Technology (RVT) and Product Development (PD) are the two main design organizations within Ford. RVT typically focuses on development of technology from external suppliers and Ford's scientific research labs into 'concept-ready' designs. Ford uses 'concept-ready' to characterize technology that has been developed to the point where actual implementation of the technology into production vehicles can be achieved during a typical design cycle for a new program. PD typically focuses on implementation of these 'concept-ready' designs, and support of assembly plants for emergent design issues experienced on current production vehicle programs. Vehicle Operations (VO) is the central manufacturing organization at Ford, and is responsible for operations across all assembly plants. The aforementioned organizations are all comprised of functional groups such as body engineering, sealing, and powertrain operations.

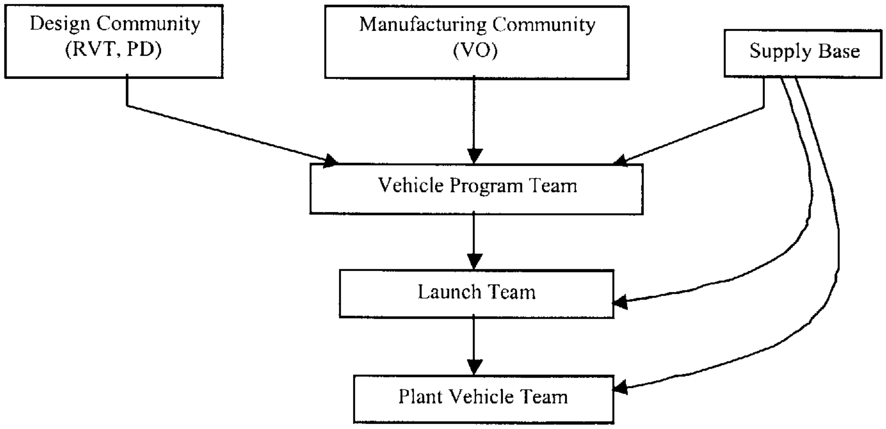


Figure 7.1: Organizational Structure Supporting New Vehicle Line Launch/Support

---

[20] Ibid. Page 90.

Design engineers taken from RVT and PD staff vehicle program teams, in which all program design activity takes place. Note that while these RVT and PD engineers staff the vehicle program teams, they remain members of their respective 'home' organizations. They work on vehicle program teams to apply the functional expertise of their home organization to specific vehicle programs. This overall program design activity involves heavy integration of external supply base activity, as Ford relies heavily on ‘full service’ suppliers to autonomously provide components/systems design to the program center. Ford engineers integrate supply base design activity by developing effective relationships with supplier engineers that help ensure effective two-way communication. Manufacturing process knowledge is supplied to the vehicle program teams by manufacturing engineers, who are taken from Vehicle Operations. Design cycles for new models typically follow 36 to 48 month cycles. During this pre-production work period, it is not uncommon for engineers to rotate on and off vehicle program teams. While Ford’s intent is to maintain continuity of the vehicle program team by keeping engineer rotation on and off the program to a minimum, the company must deal with a delicate balance between maintaining continuity of the program team, and maintaining employee satisfaction with their job positions. Vehicle program teams are ultimately responsible to the Chief Program Engineer, who is responsible for all aspects of the specific vehicle program.

Roughly eight months prior to 'Job 1' (commencement of vehicle sales to general public), RVT personnel leave the program team and a Launch Team is formed to support initial roll-out of the design into the assembly plant. Launch teams are comprised of engineers who have worked on the vehicle development, as well as new functional specialists from Product Development and Vehicle Operations who are assigned to support the vehicle launch. Launch teams are essentially subsets of original vehicle program teams. These teams are responsible for ramping up production of the assembly plant to the target production volume and addressing all emergent build/quality issues experienced during ramp-up. Because of the different areas of expertise that are needed at different times of a vehicle launch (strong design capability upstream, strong manufacturing process capability downstream), a launch team's composition changes with time. As the launch progresses, the design community presence on the launch team decreases, while the manufacturing community presence increases. This promotes a smooth transition from vehicle program design to actual production. Once the target production volume has been reached and a repeatable quality level has been established, the Launch Team hands all production/build responsibility to the Plant Vehicle Team (PVT). The PVT then supports the vehicle line at a specific assembly plant until the vehicle line is either redesigned or dropped. Some original launch team members will continue to support the vehicle line as PVT members, while others rotate back into their original functional organizations.

7.3 Knowledge Flow Between Functional Organizations

Successful introduction of a new or redesigned vehicle line and long term sustainability of high vehicle quality levels require tight integration of all the groups described in Section 7.2 and effective knowledge flow mechanisms between them. The interaction of these design/manufacturing groups is examined in the hope of characterizing the effectiveness of group integration, and the effect of this integration on organizational knowledge flow and learning.

The different design/manufacturing groups within Ford's overall product development organization are all chartered with different responsibilities. Communication and interaction between these groups is essential to ensure optimal vehicle design and performance. Poor knowledge flow between even one group and the others can lead to sub-optimal engineering designs and/or manufacturing processes, and consequently, poor product performance.

Overall Ford product development is organized into four main divisions – RVT, and the three vehicle centers SVC, LVC and TVC (Small Vehicle Center, Large Vehicle Center and Truck Vehicle Center, respectively). RVT is used as the mechanism to push both new and experience-based knowledge across all vehicle lines. Based on the author's experiences within the overall product development community, RVT's interaction with the vehicle centers is illustrated in Figure 7.2. The arrows in Figure 7.2 represent organizational support in the form of new/revised design specifications and/or expertise that can be applied to address specific functional issues experienced during design development.

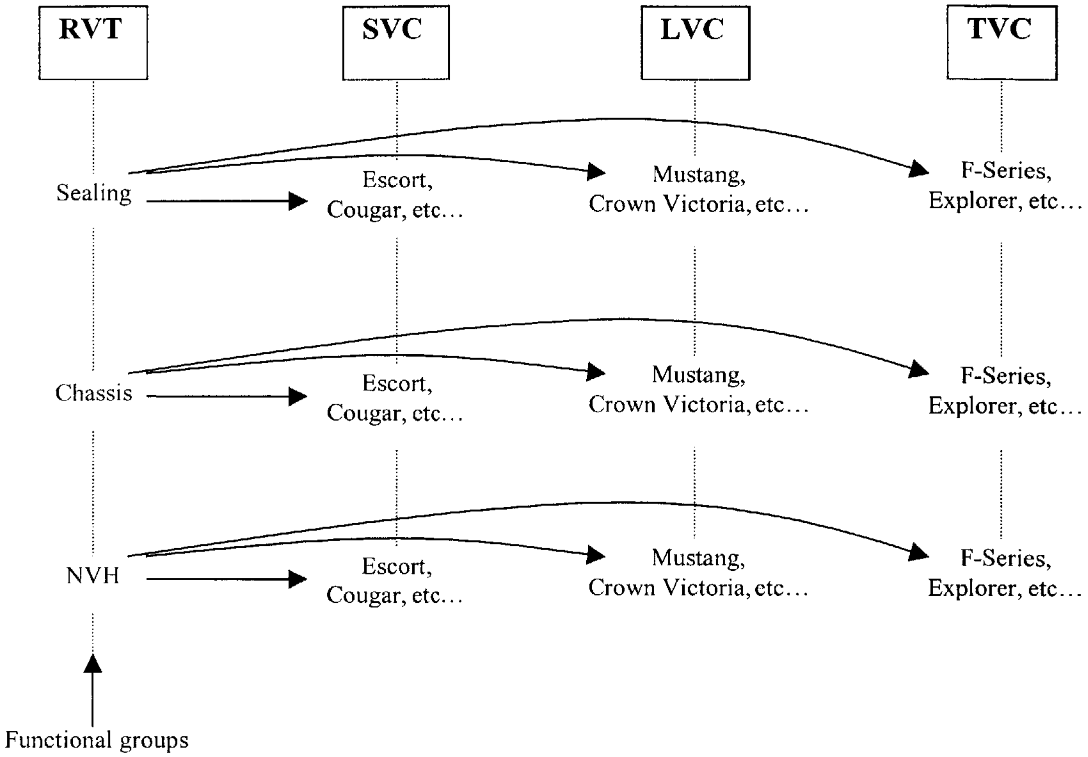


Figure 7.2: Overarching Structure of Ford's Product Development Organization

RVT engineers are organized into various functional groups such as chassis, body engineering, sealing, and NVH (noise, vibration, and harshness). Functional specialists within RVT interact with corresponding functional PD engineers located within each of the vehicle program teams to ensure that the most recent lessons learned from each functional area are incorporated into the design of all vehicle programs across Ford Motor Company. Ford attempts to leverage organizational learning from individual design centers across the entire product development organization through this 'matrixed' interaction of functional specialists.

While Figure 7.2 presents the overarching structure of Ford's product development organization, the author's interpretation of the present knowledge flow model used for introduction and support of a specific new/reintroduced vehicle program (e.g. for SN-95 Mustang) is shown in Figure 7.3.

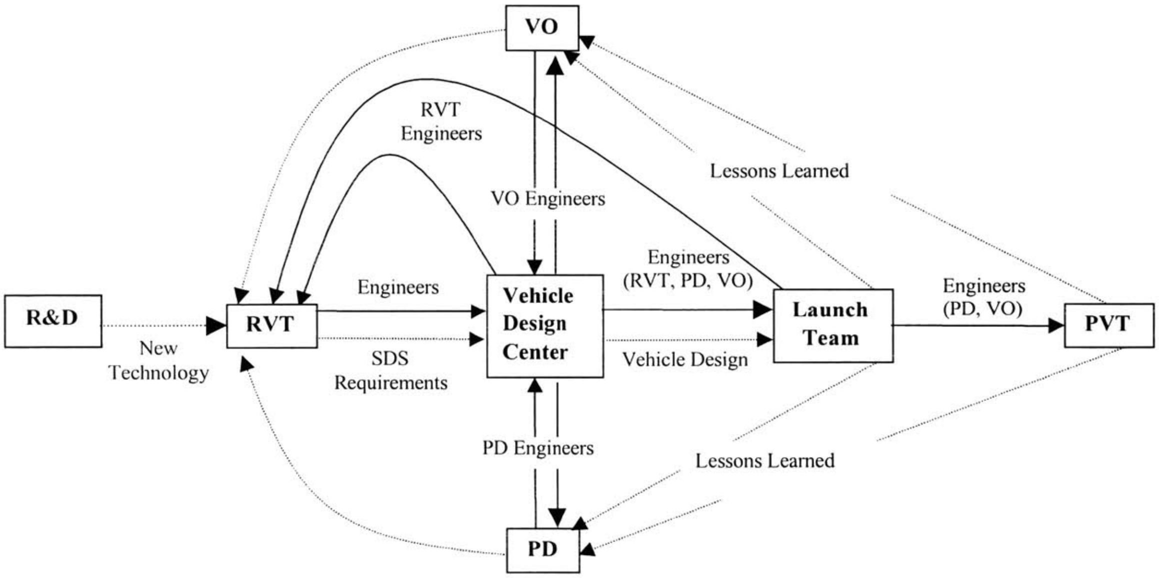


Figure 7.3: Knowledge Flow Model Between Functional Organizations on Specific Vehicle Programs

In Figure 7.3, solid lines represent direct transfer of engineers from one organization or team to another. Dashed lines represent knowledge flow in the form of lessons learned, design specifications, and new concepts, as transferred either via design manuals or via interpersonal communication between engineers within the different functional organizations. The organizational knowledge flow within the overall product development community on a given vehicle program consists of both new concepts/technology (generated by R&D) as well as experience-based knowledge that is gained through ongoing operations and captured in a lessons-learned database.

Knowledge flow within Ford's overall product development is examined in the following sections by characterizing the knowledge transfer mechanisms utilized within each of the individual design/manufacturing groups shown in Figure 7.3.

7.3.1 Research and Vehicle Technology (RVT)

RVT is the design organization within Ford that is tasked with taking new technology generated from Ford's scientific research labs and external supply base, and integrating this technology into 'concept-ready' designs. RVT is also responsible for the promulgation of technical and organizational lessons-learned from ongoing operations across all vehicle programs.

Knowledge flow to and from RVT mainly takes the form of direct personnel transfer across teams involved at different stages of product development. Once pre-program work is complete, RVT engineers move from their functional groups directly onto vehicle program teams, effectively taking the functional knowledge base from within RVT and working with the rest of the design community to further develop 'concept-ready' designs into implementation-ready designs. During new program development, RVT engineers work on design teams with PD and VO engineers, pushing best practices from across all vehicle programs into the specific vehicle program under development. Once the pre-program work is complete, most of the RVT engineers that have been working with the vehicle program team return to their functional groups within RVT, taking with them experience-based knowledge obtained from their work on the program team. These RVT engineers remain resources that launch teams can call on for support on any emergent issues that cannot be adequately resolved by launch team engineers. However, for certain functionalities that require ongoing active management of system-level interaction (such as NVH (noise, vibration, and harshness) and sealing), RVT engineers continue program development work as part of the vehicle launch team. RVT engineers that follow the vehicle design onto the launch teams facilitate continuity of knowledge flow in the development process for these functionalities until the vehicle is launched at the assembly plants.

The organizational model in Figure 7.3 was presumably developed to facilitate knowledge transfer from pure R&D into the vehicle design centers and the assembly plants. The direct transfer of RVT engineers into the vehicle centers and in some cases, onto launch teams, facilitates effective knowledge transfer from pure research to applied vehicle technology. However, developing vehicle program teams that are comprised of RVT, PD, VO, PVT, and supply base engineers also creates a mechanism to facilitate knowledge flow in the reverse direction in that knowledge flows to RVT engineers through their personal interaction with other engineers working on program development or launch teams.

Experience-based knowledge is captured within RVT when its engineers return from assignments supporting vehicle program teams or launch teams at assembly plants. As these RVT engineers return to their functional areas within RVT, they take with them lessons-learned that were gleaned from their participation in the program design and launch processes. These lessons-learned are either formally documented (in the form of technical reports or official web sites on Ford's intranet), or informally maintained in the personal knowledge base of individual RVT engineers. There is significant latitude for RVT engineers to decide how best to make this knowledge available to the greater product development community. In either case, RVT engineers use the knowledge captured from their participation in ongoing program development work to either create new, or revise existing design specifications as needed to reflect ongoing lessons-learned from across all Ford vehicle programs. Since all current/future designs must meet the evolving design specifications owned by RVT, lessons-learned resulting from development work within any specific vehicle program are filtered into continuing development work for all other vehicle programs. In this manner, lessons-learned are promulgated by RVT across all vehicle lines as shown in Figure 7.2.

The reverse knowledge flow back to RVT continues even after the PVT has assumed responsibility for the vehicle line support. PD design engineers and VO manufacturing engineers work with the PVT as needed to address emergent design or process related quality issues that arise at the assembly plants. When such emergent quality issues require advanced technical guidance, PD/VO engineers will communicate this need to RVT. In this manner, PD/VO engineers serve as information conduits between the PVT and RVT, providing upstream support from either their own organizations, or if necessary, from RVT. This two-way knowledge flow between design centers and RVT helps develop and maintain best practices in design and assembly processes both for new product development and ongoing production support.

7.3.2 Product Development (PD)

PD is the primary organization responsible for design development activity associated with new and current production vehicles. In addition to controlling design/release activities for production and service components, major responsibilities of PD are to:

- perform design verification (testing) for production components
- pursue warranty and cost reduction opportunities
- address emergent design issues (safety, customer quality concerns, etc...)
- assist the Plant Vehicle Team (PVT) with resolution of production problems
- facilitate communication between Ford and full service suppliers

PD is a functional organization with several groups such as chassis engineering, sealing, and powertrain. PD engineers typically perform one to two years of service in a specific assignment and then move to another assignment. Subsequent assignments are usually within the same functional group (i.e. chassis engineering), but may or may not be on the same vehicle program.

One of the major divisions within PD is Ongoing Product Development (OPD) – the organization that supports current production vehicle programs. Mustang OPD is the design body that is currently responsible for support of SN-95 Mustang production – the focus of this internship project. Ongoing Product Development is the main design organization that supports the PVT on major design efforts that are undertaken to address emergent quality issues. While the PVT handles smaller design changes, it is not staffed to handle larger design changes that involve long lead times, extensive design development, and validation testing (such as the water seal system redesign).

Similarly to the RVT model, knowledge is transferred within PD through direct transfer of engineers onto different teams throughout the overall vehicle development process. PD engineers staff vehicle design centers, follow the vehicle design onto launch teams, and finally, into vehicle program support on plant vehicle teams. PD engineers returning from the vehicle design centers, launch teams, and plant vehicle teams all bring experienced-based knowledge from the vehicle lines back into Product Development. Program teams are required to develop a lessons-learned document regarding launch experiences to help grow the existing PD knowledge base. Unfortunately, there is no set process for developing a formal lessons-learned document.

Knowledge is also transferred to PD engineers by a system known as WERS (Worldwide Engineering Release System) to track the details of design changes on ongoing programs such as descriptions of the changes, cost, and implementation timing. They also rely on the system design specifications (SDS) established by RVT for guidance on changes and verification. PD engineers can initiate revisions to current SDS requirements by passing experience-based knowledge back to RVT, but no formal process currently exists to facilitate this process.

7.3.3 Plant Vehicle Team (PVT)

PVT engineers are taken from both Product Development and Vehicle Operations, thereby providing a working knowledge base that consists of both design and manufacturing elements. Some engineers assigned to PVT have been with the vehicle line since initial development work began in the program design centers while others are assigned following the vehicle launch. Engineers who follow the vehicle design throughout the entire program duration onto the PVT are key to the personal interactions between the design and manufacturing communities that ensure consistency of knowledge flow from the program design center into factory floor production.

As discussed in Section 7.3.1, following 'Job 1', vehicle launch teams transfer direct support of the vehicle line to the PVT. During this transfer of support responsibility to PVT engineers, it is critical that the launch team/PVT hand-off be effective. Hand-off of responsibilities from the vehicle launch team to PVT engineers occurs from 'Job 1' minus three months to 'Job 1' plus three months. This six-month period facilitates personal interaction between current launch team engineers (who have worked with the vehicle during the entire vehicle life cycle) and PVT engineers, who have had no ties to the vehicle until this point. This direct interaction helps to bring new PVT engineers up to speed with both unresolved design issues and historical design information. The transfer of vehicle responsibility is also assisted by historical data for all components in the form of design books and on-line intranet web pages. All aspects of components are reviewed together between launch team and PVT engineers during this six-month period. This includes component functionality, component interfaces, and supply base issues.

The PVT is tasked with full support of the assembly plant and has responsibility for all emergent build/quality issues that arise at the plant. The PVT addresses both design and process issues that affect vehicle quality levels and is accountable for warranty claims against its vehicle program. Besides addressing all assembly related design/process issues following vehicle launch, the PVT also focuses on supplier management – both supplier relations and the quality level of outsourced components/systems.

As part of its assembly plant support role, the PVT is responsible for all ongoing design changes to current production vehicles. The PVT focuses on smaller, near-term design changes that are typically incremental in nature. These incremental changes are often made through collaboration between the PVT and the supply base, and they focus on either customer quality perception or cost reduction efforts. To ensure that all PVT-initiated design changes are compatible with the existing vehicle design, design community (RVT, OPD) approval of any proposed design change is typically obtained prior to implementation. Design community approval is obtained through sign-off on written 'concerns' generated by the PVT. These 'concerns' identify the affected component or system and the proposed design change. Each 'concern' is reviewed and approved by the engineer in the design community who is responsible for the specific component/system that will be affected by the change. 'Concerns' are mechanisms that facilitate knowledge flow upstream to the design community, as the sign-off procedure ensures that the entire design community is aware of the most recent state of a constantly evolving vehicle design. 'Concerns' ensure that no changes to any vehicle components occur without the knowledge of the engineering group responsible for the original component design, and push new ideas and improvement efforts upstream. This upstream flow of information grows the knowledge base within the Product Development functional groups, and when appropriate, is pushed further upstream from PD to RVT for incorporation into new/revised design requirements.

7.3.4 Vehicle Operations (VO)

Upstream in the new vehicle line introduction process, VO works closely with Product Development engineers on program design teams to ensure manufacturability of new designs. Downstream in the process, VO also provides support for emergent quality issues related to process design concerns at assembly plants. VO assumes a support role for PVT engineers and will help to diagnose root causes of emergent quality issues and initiate corrective action to contain such issues. In this capacity, VO acts as a conduit between PVT and PD, transferring knowledge between these organizations and engaging PD support when emergent quality issues during assembly are identified as design related, rather than process/assembly related. Following the launch of a new vehicle line, the majority of organizational learning takes place in VO and at the assembly plants, as the design community becomes actively involved supporting upcoming vehicle launches.

A typical manufacturing engineer at VO spends significant time working to support the assembly plants for which he or she is responsible. There is a continuous flow of experience-based knowledge from the assembly plants to Vehicle Operations manufacturing engineers. This experience-based knowledge is added to a 'living' (constantly evolving) manufacturing 'musts/wants' list, which increases the overall process knowledge base at VO. The evolving musts/wants list is leveraged to help diagnose and resolve future emergent quality issues at assembly plants. The ever-increasing process knowledge base at VO also helps to improve the manufacturability and robustness of new designs, as the manufacturing musts/wants list developed through assembly plant operations are relayed to both PD and RVT engineers for incorporation into new design requirements upstream in the overall product development process.

In this section, the idealized model for knowledge flow between functional groups within Ford's overall product development organization has been presented. In reality, the actual state of knowledge flow between functional groups may deviate from the idealized model. To facilitate an understanding of the current state of knowledge flow within the SN-95 program, it is necessary to characterize the program both during its initial launch period and in its current state.

7.4 SN-95 Program Launch Characterization (1993)

One member of the original SN-95 launch team was interviewed to characterize program experiences during the initial vehicle launch. While this particular interviewee was only involved during the launch phase of the initial vehicle introduction (see Figure 7.1), he was able to provide details regarding the nature of design activity during the vehicle launch as well as design history relating to the water seal system.

When asked to subjectively evaluate the water seal system design, the launch team member indicated that the design was good, given the prevailing conditions that drove program development work. The SN-95 launch was characterized as being extremely cost driven. Consequently, a number of design features that the launch team anticipated would have contributed to improved vehicle quality were not approved for implementation because the projected, incremental quality improvements associated with these features were not adequate to justify program cost impacts. 'Drop glass' (described in section 5.2.3) was specifically mentioned as a feature that could not be incorporated due to cost concerns. However, even without these additional design features, the seal system design was considered by the launch team to be ‘best in class’ at the time the vehicle was finally launched.

Since 1993, Vehicle Operations has established a twenty-test validation process to certify water seal performance for all new designs. However, no set validation process was in place for system performance certification during the SN-95 launch in 1993. The launch team performed convertible model seal system validation testing using a twenty-minute soak booth (simulating driving rain conditions), commercial car washes, and high-pressure hose tests (targeting the seal system with direct, high pressure water). Formal documentation of the seal system performance was generated for management review during the initial program launch, but because the documentation was not organized in a centralized location, it was not accessible for review during the seal system redesign project. Significant experimental work was also performed during vehicle launch, with several design experiments (DOE's) aimed at understanding the relationship between various parameters of the seal system and system performance. Glass positioning and seal component hardness (rubber durometer) were specifically mentioned as being parameters that were investigated in an attempt to optimize the overall seal system design. Unfortunately, due to similar issues with decentralized control of information, related documentation could not be located during the redesign project.

Seal system performance was improved during vehicle launch through small adjustments to various system components. Unfortunately, due to constraints with tooling for the weather strip molded end details, significant changes to the design could not be accommodated. Significant effort was expended to address poor performance at the glass system division bar region, but the launch team was not able to successfully redesign this region. Numerous design iterations were evaluated and many prototypes were actually built up, but seal performance local to the glass system interface remained poor by launch team standards (which were higher than the standards set by design specifications). However, when the launch team handed over responsibility to the PVT, the design was acceptable per design specifications, and the vehicle would not leak when taken through a commercial car wash. Historical data backs up the claim of adequate water seal performance immediately following vehicle launch. Review of Figure 7.4 shows that in 1994, the first full year of production, warranty claims against the water seal system were minimal and did not degrade to any significant degree with increasing service time.

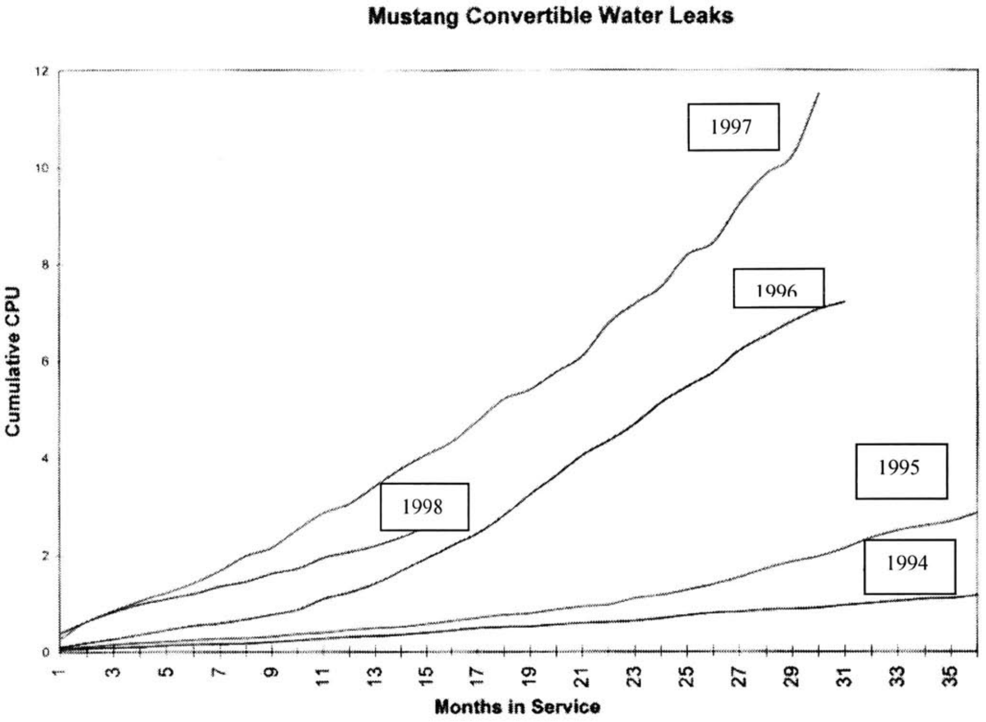


Figure 7.4: Warranty Claims Against Water Seal System Versus Time in Service.

The hand-off of responsibilities from the launch team to the Plant Vehicle Team (PVT) was characterized as 'very efficient' by the interviewee. The launch team worked with the PVT for six months prior to leaving the assembly plant and the interviewee reported frequent contact between the launch team seal engineer and the PVT seal engineer for up to a year after the launch team left the plant. The interviewee reported that the PVT was knowledgeable regarding seal system design and limitations and that a single engineer on the PVT ***did*** assume system level responsibility and ownership for the entire water seal system.

When questioned regarding the warranty trend exhibited in Figure 7.4, the interviewee *speculated* that the difficulty lay with the assembly plant's failure to keep to original assembly processes. He characterized the design as capable, but also noted that the design did not have adequate robustness to accommodate the sheet metal build variability that existed during launch. As he related, the unexpected build variability forced the launch team to work on the seal system in a non-systematic manner during the initial launch of the SN-95 program.

In 1995, the plant manager of Dearborn Assembly Plant attempted to contain the degrading performance of the SN-95 convertible seal system. The plant manager called in the original launch team members to discuss factors that contributed to the poor seal system performance which, by this time, had become worst in class. The launch team members presented a 'laundry list' of factors that they suspected contributed to the poor seal performance. These factors included improper maintenance of door glass setting fixtures, cessation of use of door glass setting fixture features, and inadequate process controls for setting rear quarter glass. Specifically identified was the fact that spacing blocks that had been designed to help set the rear quarter glass/door glass fore/aft gap (parameters 1 and 2 in Figure 4.1) were no longer used during the glass-setting process. According to the interviewee, the plant initially did use the spacing blocks as part of the glass-setting process but stopped using them at some point. The interviewee was not aware of the justification for the decision to stop using setting blocks during the glass-setting process. However, despite these issues, the root cause of the poor seal system performance suggested by the interviewee was that the lack of an adequate process capability for the control of body sheet metal variability resulted in inconsistent seal component positioning. Without capable control of the body sheet metal variability, the interviewee did not feel that the current design was robust enough to seal the vehicle consistently.

Finally, when prompted about supplier performance, the interviewee responded that the engineering competence of seal supplier personnel was excellent, as was that of convertible top supplier personnel. The SN-95 program still uses the same convertible top supplier. However, the seal component supplier is now part of a joint venture between the original seal supplier and another company. During initial vehicle launch, both suppliers provided dedicated personnel to the SN-95 program.

7.5 Current State of SN-95 Program Organizational Learning and Knowledge Flow

The mechanisms used to facilitate organizational learning and knowledge flow between various system-level stakeholders were examined on the SN-95 program in an attempt to identify issues that may contribute to sub-optimal engineering decisions and resulting poor product performance at Ford Motor Company. In the author's opinion, one of the main tenets required for successful knowledge flow and organizational learning is the maintenance of knowledge base continuity. By creating cross-functional program design teams within its vehicle centers, Ford ensures that significant personal interaction develops between engineers from across all design and manufacturing groups within the overall product development community. These personal interactions act as mechanisms that maintain knowledge base continuity through the introduction and support of new vehicle programs. However, several breakdowns of these mechanisms are clearly evident in reviewing the current state of organizational learning within the SN-95 program. The following specific issues are examined:

- supplier management and resulting performance
- reverse flow of lessons learned from Vehicle Centers to RVT
- misalignment of metrics within different organizations

It is noted that the content of this section is based on interviews conducted with current and former members of the SN-95 program team and on the author's personal experiences within the overall product development organization, and is therefore highly subjective.

7.5.1 Supplier Management

Effective supply base management and integration is essential to develop a high level of supply base performance. Ford relies on numerous suppliers for successful design/manufacturing of components and systems on all its vehicle programs. These suppliers are classified as either 'gray box' suppliers or 'full service' suppliers. Gray box suppliers do not have any influence over the most basic and significant design concepts, namely the sheet metal environment local to their systems. Effectively, gray box suppliers have to work with what is given to them from Ford regarding interface characteristics between their components/systems and the rest of the vehicle design. Gray box suppliers are more Ford-driven than are full service suppliers and require more input and support from the Ford design community. Ford can push a specific design concept on the supplier and then release the supplier to develop its design based off of the Ford specified concept.

Full service suppliers have design involvement with all interfacing components on a vehicle including the sheet metal environment local to the system(s) for which the suppliers have cognizance. Suppliers authorized by Ford to be full service have complete authority for all design decisions related to material type and technology selected for application to a specific system design concept. Ford maintains the right to request changes to the design of systems provided by full service suppliers, but rarely reviews the design of such systems aggressively. Accountability for a full service supplier takes the form of cost and performance targets established jointly by the supplier and Ford. Ford validates design performance of a full service supplier's system through internal, independent verification testing. This internal verification process involves laboratory level testing during the pre-build period (e.g. friction drag loads), as well as testing during the initial build period where the supplier system is evaluated under simulated customer usage. Ford is moving more and more away from gray box suppliers and toward full service suppliers. This requires less direct Ford involvement in design activity, but much more Ford involvement to ensure efficient information flow to and from the supplier. Several issues can impact information flow between Ford and its suppliers, including methods used to communicate engineering requests, the relationship between suppliers working together on a given system, and the nature of the overall relationship between Ford and its supply base. Each of these issues is reviewed in detail.

Engineering requests are generally communicated to suppliers in the form of concerns, alerts, or notices. In general, these concerns, alerts, and notices are generic requests for action from Ford to its supplier. However, they can also be directed to specific individuals who work for the supplier. The supply base generally prefers the use of generic alerts when supplier action is required. Although targeted alerts toward specific engineers at a supplier can help develop accountability for concern resolution, they also raise the possibility that input from key people/organizations at the supplier may not be incorporated in the overall solution. In this manner, requests that target individuals can negatively impact information flow, and consequently, system level integration.

The number of suppliers working on any given vehicle system can also impact information flow from the supply base to Ford. Historically, having numerous suppliers working on a single system has been detrimental to system performance. According to suppliers, when three or more suppliers worked on a single system in the past, it was not uncommon for suppliers to hide information from Ford during up-front development. Not bringing issues to Ford's attention during development work kept pressure off of the suppliers. Unfortunately, this course of action often manifested itself in the form of poor system-level performance. When system-level performance was identified as a problem through excessive warranty claims, suppliers could point at each other and cast blame – there was no mechanism in place that ensured accountability.

In certain instances (as with the water seal project), accountability for overall system performance was assigned to the supplier that was 'last on the vehicle'. The phrase 'last on the vehicle' refers to the supplier whose components or system is dependent upon the components or systems of other suppliers. For the water seal project, the seal component supplier was 'last on the vehicle', and consequently, was held responsible for overall system level performance. The problem with this method of assigning responsibility is that one supplier becomes responsible for addressing system-level issues that may be entirely driven by components provided by another supplier(s). According to suppliers, the aforementioned information flow issue is program-specific. On certain vehicle programs, suppliers report that Ford personnel create an environment in which they feel free to raise concerns early and work with Ford to resolve them. However, on other vehicle programs, suppliers view the environment in which they work as much less tolerant of emergent issues that arise during development work. Although not necessarily widespread, this sort of environment is most likely to develop during intense periods of launch activity, when the final launch date will be missed unless emergent issues are successfully resolved on an almost instantaneous basis. When working in this type of environment, suppliers do not proactively raise issues during pre-program work for fear of pressure from Ford. One supplier suggested that the nature of the Ford/supplier relationship could very definitely impact knowledge flow and subsequent engineering decisions made by design teams.

When suppliers must work with one another on development of a given system, the suppliers often have direct contact with one another that is neither initiated nor suggested by Ford. According to supplier personnel, most of the time, suppliers work with one another to deliver the best product. Some issues may arise where one supplier will be unwilling to cooperate with another because such cooperation would result in additional work/cost to the supplier. When this occurs, it is critical that Ford fulfills its responsibility as the system integrator. Ford must work with suppliers to address the issue and resolve it such that an acceptable design develops. Team meetings with Ford and all suppliers working on a given system are very effective if they are held regularly, but at appropriate intervals. Engineers from the supply base feel that once or twice a month is a sufficient interval for these team meetings. More frequent meetings are viewed as Ford micromanagement, while less frequent meetings cause alignment of the supply base and internal Ford design/manufacturing groups to suffer.

A final issue regarding supplier performance is the reactionary position that most suppliers find themselves locked into. Much like internal Ford design/manufacturing groups, supplier personnel are often engaged in 'fire fighting' critical program issues that threaten to shut down Ford assembly plants if they are not resolved immediately. Since the supply base operates mostly in a *reactionary* mode, it often does not have adequate resources available to focus on continuous improvement of existing designs. The ongoing quality of systems that are delivered to Ford by its supply base is impacted as a result of resource constraints. Ford does provides incentives (shared cost savings) to reduce the occurrence of quality defects in its products and to initiate *proactive* design work from its supply base. However, resource constraints (available personnel) of the lean supply base usually prevent significant effort from being expended on proactive continuous improvement projects.

7.5.2 - Reverse Flow of Lessons Learned

The knowledge flow model shown in Figure 7.3 provides effective conduits for reverse knowledge flow from the Vehicle Centers to RVT, provided that no organizational barriers exist. Unfortunately, barriers *do* appear to exist, and they result in the loss of key experience-based knowledge gained from ongoing work in the Vehicle Centers and at assembly plants. The main problem with reverse knowledge flow appears to reside at the critical link between RVT and the rest of the design/manufacturing organizations within the overall product development organizational structure. Two issues must be addressed to ensure effective knowledge flow occurs through this link: maintenance of lessons learned from ongoing operations and communication of these lessons learned. Both issues are examined in detail.

The issue of maintaining lessons learned from ongoing operations is reviewed first. One of the major concerns noted through simple observation of RVT, OPD, VO, and PVT is the relatively short tenure of engineers within these organizations. Engineers typically remain on a job assignment for only one to two years before rotating to another position. Often, subsequent positions that engineers rotate into are not within the same organization. The rapid cycling of engineers through various functional positions raises significant concerns regarding maintenance of the knowledge base within specific vehicle programs. It is noted that such personnel rotation has developed as a conscious effort on the part of Ford managers to minimize organizational attrition by keeping employee job satisfaction high. However, managers must ensure that efficient succession plans/tools exist in order to prevent a loss of knowledge from occurring as a result of rapid personnel rotation. From the author's observations, no formal 'hand-off' process currently exists for departing employees to bring their replacements up to speed with the complete design history of components for which they will assume responsibility, and vacated functional positions can remain unfilled for up to several months. Due to the lack of direct hand-off of responsibilities from departing to incoming engineers, incoming engineers can have difficulty rapidly developing an in-depth knowledge of the components for which they are responsible. In lieu of direct knowledge transfer, engineers typically must fall back on any design history documentation that may exist to develop a working knowledge of best practices and potential problem areas on components for which they are responsible. Unfortunately, because such historical design information can be spread throughout the design community, and because there is no formal process for hand-off of responsibilities from departing to incoming engineers, the build up of experience-based engineering knowledge is far from guaranteed.

To help develop experience-based knowledge within the overall product development organization, a thorough lessons-learned database must be developed and maintained. Based on interviews with product development engineers, the existence of an experience lessons-learned database was confirmed. Yet, engineers within the design community admitted that the database is not used often. The infrequent use of the lessons-learned database is likely the result of one of three root causes, or a combination of these causes. First, the existing database is somewhat decentralized, and engineers within the different functional organizations may not be aware of the exact manner in which to access the database. Second, the database is constantly evolving. Therefore, it may offer little or no guidance on a particular component or system at a given point in time. Engineers who refer to the database on multiple occasions and do not perceive value added in doing so will tend to stop referring to it. Finally, there is no checkpoint in the overall product development process that requires engineers to check current designs against the lessons learned database to ensure best practices have been, or are incorporated into new/existing designs.

Based on interviews with product development engineers, it appears that design activity supporting ongoing vehicle programs (such as SN-95) is not often formally documented. Informally, individuals tend to develop their own lessons-learned database. However, there is no obligation to formally document such information and push it through the overall product development organization. A formal process to document engineering changes and justification for changes does exist within the product development community (known within Ford as the '8D process'). However, several design engineers related that completing the process is tedious and admitted that lessons learned from design activity on ongoing vehicle programs were rarely documented according to the formal process. While this tendency may be specific to the SN-95 program, it may also exist elsewhere within Ford. This raises the potential for an enormous loss of experience-based knowledge across the entire product development organization. The effectiveness of Ford's overall product development process is dependent upon the maintenance and growth of the community's knowledge gained from experiences with ongoing design improvement projects. Therefore, it is critical for the overall product development process to involve both a mandatory review and periodic update of lessons learned for each vehicle system during initial system development and any subsequent performance enhancement projects.

The second key issue surrounding knowledge flow between the overall product development community and RVT is the actual communication of experience-based knowledge from individuals who actually develop the knowledge to those who drive the knowledge into the lessons-learned database and throughout the overall organization. The idealized new program introduction process shown in Figure 7.3 promotes two-way communication between RVT, OPD, PVT, VO, and launch teams through the use of direct personnel transfer at various stages of the development process, as discussed in Section 7.2.1. However, in the author's opinion, the interaction between the design and manufacturing communities that is critical to effective communication and knowledge flow within the overall product development community is not adequate for ongoing SN-95 development work.

Based on interviews conducted with various design engineers, there does not appear to be any obligation or formal process for project teams comprised of engineers from OPD, VO, and PVT to push lessons learned back to RVT. Since RVT is responsible for maintaining and updating SDS documents (design specifications), it is essential that new experience-based knowledge reach RVT in a timely manner. Based on interviews conducted with engineers working on the SN-95 program, lessons learned are not always pushed back to RVT for incorporation into SDS documents. Consequently, experience-based knowledge remains within OPD on specific vehicle programs, within PVT at specific assembly plants, or within the manufacturing community. Engineers relate that the push back of lessons learned to RVT takes a lot of effort, and requests for SDS updates based on lessons learned are not always honored or even addressed. Also, engineers working within the SN-95 program expressed frustration with a difficulty in getting time with RVT members to discuss emergent design issues. This difficulty arises as a result of organizational alignment issues and is reviewed in detail in the following section.

7.5.3 - Alignment of Organizational Metrics

An overall assertion of this study is that companies can create a sustainable competitive position in the marketplace by developing an efficient overall product development process. It is therefore important that performance metrics be established that facilitate alignment of all the functional groups that interact with one another toward overall corporate objectives. Effective alignment must exist not only between functional groups within Ford but also between Ford and its supply base. In this author's opinion, there are alignment problems that are evident both amongst internal Ford functional groups *and* between Ford and its external supply base. Alignment concerns are examined at three different tiers: at the individual contributor level, at the functional group level, and at the organizational (corporate) level.

To ensure the efficient launch/support of a new/current production program, RVT, PD, PVT, and VO must all interact extensively with one another as shown in Figure 7.3. Unfortunately, the metrics currently used to judge performance within each of these organizations tend to drive the organizations in somewhat different directions. For instance, there are three main objectives on which the performance of OPD engineers is judged: material cost reduction, quality improvement, and forward model (next generation design) support. Within SN-95 OPD, there is a clear emphasis on cost reduction efforts.

Dearborn Assembly Plant (DAP) is treated as a cost center, and therefore, is focused almost entirely on driving cost out of assembly processes. In comparison with OPD and DAP, PVT engineers are mainly responsible for vehicle warranty performance, and to a lesser degree, for progress toward cost-reduction targets. While the aforementioned groups all have cost reduction targets to meet, the trade-off between cost and quality raises alignment concerns. A summary of the various metrics by which the different functional groups within Ford's overall product development community are judged is presented in Table 7.1.

Table 7.1: Organizational Metrics Utilized to Judge Performance

Functional group	Metrics	Potential conflicts
RVT	Managerial discretion	-
OPD	Material cost reduction Quality improvement Assembly plant support	PVT warranty reduction efforts
PVT	Warranty performance	OPD cost reduction efforts
VO	Assembly plant support	-

A main driver of organizational misalignment at the individual contributor level is a lack of accountability within the overall product development community. An example of this can be seen by reviewing OPD metrics that are used to determine an engineer's performance on progress toward quality improvement. In order to be objective, these metrics must be based on quantitative figures such as warranty data. Since there is typically a time delay before the results of quality-based improvement efforts are seen from review of warranty data, subjective measures of employee performance must be substituted for use in performance appraisals. These subjective evaluations of perceived contributions to team progress toward warranty reduction do not necessarily reflect true individual performance.

Because of the time delay before true individual performance can be objectively measured by changes in warranty data, the employee rotation issue discussed in Section 7.5.2 raises serious concerns regarding recognition and accountability issues. For example, consider a particular individual who is working to improve the performance level of a particular system. Due to the time delay before results of his/her improvement efforts are seen in warranty data, this individual may rotate out of his or her position before changes in warranty data can be observed. Therefore, the individual may not be recognized for positive effects on warranty data to which he or she contributed. Likewise, negative effects on warranty data resulting from poor individual performance are not tied to individuals who have left their positions working on the specific system. Because there is no connectivity between engineers and the projects on which they work after they rotate to new positions, there is a lack of accountability within the product development community. This lack of accountability promotes a short-term focus on performance enhancement projects, and is inconsistent with the overall corporate objective of creating a sustainable competitive advantage through an effective product development process.

Organizational misalignment at the functional group level can be observed through the interaction amongst the PVT, OPD, and DAP. PVT performance is judged using warranty claims against the vehicle line it supports. Logically, the PVT undertakes projects to combat high warranty cost drivers. Because the PVT is also judged on its performance against cost targets, it tends to focus on developing 'patches' (very minor changes) for existing systems that exhibit inadequate performance rather than performing a thorough evaluation of the system and initiating a system redesign project, if appropriate. Design changes recommended by the PVT must be approved by OPD. OPD is heavily judged on progress toward cost reduction targets, not on warranty performance. Therefore, OPD is not amenable to adding cost to a vehicle for the purpose of reducing high warranty costs. In addition, the PVT typically needs OPD support to complete projects requiring significant design activity such as system redesigns. Because such projects typically result in increases to the per unit vehicle cost and require OPD support, they are not often undertaken. Therefore, system-level performance can remain at inadequate levels for extended periods of time. As an illustration of this point, it should be noted that the water seal system performance had degraded steadily for over five years before any significant design effort was initiated to improve system performance.

A further example of misaligned organizational metrics at the functional group level results in conflict between PVT and Dearborn Assembly Plant (DAP). As discussed earlier, DAP is a cost center and its performance is judged mainly on meeting cost reduction targets. To reduce assembly costs, DAP has actively pursued methods to eliminate labor from the assembly process. Large cost savings were realized by DAP when it eliminated process engineering positions within the plant. However, these process engineers served a critical role in ensuring product quality, as they were responsible for addressing emergent quality issues during the vehicle build process. Without its own process engineers, emergent quality issues were no longer resolved quickly or effectively, and DAP eventually required PVT support to address emergent issues on the shop floor. This additional resource drain on PVT reduced the ability of the PVT organization to concentrate on activities needed to reduce vehicle warranty cost. Because DAP is not as responsible for vehicle warranty costs as PVT, a strong incentive does not exist to focus the assembly plant on quality issues during the vehicle build process. Without this incentive, DAP is not receptive to initiatives proposed by PVT that add cost to the assembly process. For instance, if the PVT determined that an additional operator is required to ensure successful execution of a specific assembly process step, DAP would likely challenge any recommendation to implement such a change as it would increase the assembly process cost, thereby resulting in a hit on DAP's performance rating. Since the PVT works closely with DAP on everyday production activity, the misalignment of these groups is of particular concern.

Finally, organizational misalignment at the corporate level can be observed through the general ***reactive*** nature of Ford's overall product development organization and the inconsistency of internal behavioral drivers with corporate objectives. As noted earlier, the PVT is responsible for the warranty performance of the vehicle line that it supports. Poor warranty performance indicates that either design or assembly process changes must be made to existing systems. The PVT is responsible for driving both design and process related changes for ongoing production programs. In developing such changes, systems with inadequate performance levels can either be patched with minor cosmetic features or completely redesigned as in the water seal system project. Complete redesign of existing systems can result in a significant increase to the cost per vehicle, and therefore, is not actively pursued unless system performance is extremely poor. By the time system performance has fallen to the level at which redesign is required, customer perception of vehicle quality may already have become very negative. Unfortunately, by this time, a complete redesign of an existing system may be the only way to ensure significant improvement in the system's overall performance is realized. Therefore, organizational focus on cost reduction can effectively act as a driver of poor quality. This scenario of ***reactive*** response to poor customer perception of quality represents potentially significant costs to the company, both in terms of warranty claims and impact on quality reputation. There is typically little or no incentive within OPD that encourages proactive evaluation of current design performance and ongoing conceptual design work to improve the existing design. If issues are not identified from warranty data, design activity within OPD focuses mainly on reduction of production costs. A more proactive approach toward product/system evaluation and redesign is needed to facilitate alignment toward the organizational goal of establishing a competitive advantage in the marketplace through a differentiated product development process. Differentiating the product development process is so critical because "...quality is process driven. To improve the quality of a product or service you must improve the process(es) that produce and support that product or service."[21]

Unfortunately, redesign activity on the SN-95 program is typically initiated only upon reaction to warranty data for specific components or systems. Significant evaluation of existing systems is not performed unless the system becomes one of the top ten drivers of

---

[21] The Quality Secret: The Right Way to Manage, William E. Conway, Conway Quality, Inc., 1992. Page 199.

warranty costs for the company. At this point, a 'quarterback team' is formed, which assumes ownership of system evaluation/redesign until system performance achieves targeted quality level, at which time the issue is closed out. A major problem with the 'quarterback team' process is that it is only initiated for systems that are among the top ten warranty drivers at the company. The top ten warranty drivers are clearly critical issues that must be resolved. However, to ensure consistently high product quality levels, it is equally important for the Ford product development community to be monitoring and correcting smaller drivers on an ongoing basis – effectively preventing them from becoming major warranty cost drivers as the top ten warranty drivers are addressed. Again, this lack of proactive activity is driven by resource constraints within the design community[22], similar to that of the supply base discussed in Section 7.5.1.

In addition to raising concerns with product/system quality, the strong focus on cost reduction within Ford's product development community has created a fundamental disconnect between Ford and its suppliers. Ford's focus on cost effectively provides an incentive for suppliers to purposely avoid pursuing innovative design concepts that incorporate unproven concepts/technology. This can be a critical issue, as new concepts/technology offer the potential for leaps in the performance levels of existing systems. As part of its cost reduction focus, Ford requires its suppliers to give money back annually in the form of cost savings. These savings are assumed to arise from design efficiencies gained through production to date. Suppliers must return seven-percent of Ford's costs over the three years following initial vehicle launch, regardless of whether or

---

[22] A New American TQM: Shiba, Graham and Walden, CQM, 1993. Page 53.

not they experience an increase in their own variable costs. This forced cost reduction program encourages suppliers to hedge their risk by designing new systems with cost removal potential as the focal point of the design rather than designing new systems with quality of performance as the design focal point. By encouraging this behavior in its supply base, Ford does not provide incentives for its supply base to control costs ***and*** deliver best in class systems. Rather, it simply encourages delivery of low cost systems. Again, this represents an inconsistency if Ford has chosen to compete on quality.

Organizational alignment issues are also subject to temporal effects. During initial vehicle launch, the entire product development community is focused on optimizing overall product performance. During this phase, the launch team must reach 'first run' quality targets before vehicle launch is completed and quality is the number one driver of development activity. However, once the initial vehicle launch is completed and the launch team has left the assembly plant, the assembly plant begins to focus activities on ease of assembly and overall assembly costs. This change in focus from vehicle quality to ease of assembly and assembly cost typically impacts product performance in the long run. Compounding the cost reduction efforts that target assembly processes in the plants are similar efforts supported by OPD that target product/system design.

Cost reduction teams from OPD constantly take cost out of the vehicle over its production life. There are annual cost reduction targets against which the performance of these teams is measured. However, from this author's observations, there is little consideration given to the potential long term effect that continuing cost reduction efforts have on product/system quality levels. Consequently, the relationship between the level of cost reduction activity and warranty costs for a given product/system is not understood. It is the author's opinion that Ford's product development organization, as manifested in the SN-95 program, is focused on cost cutting objectives in such a manner that poor warranty performance results for systems such as the Mustang convertible water seal system. Cost reduction efforts can be used to help ensure that designs are efficient. However, an overreliance on cost reduction to improve profit margins can actually have a detrimental effect on both profitability and competitive positioning in the marketplace, especially if the company has chosen to compete on quality. Design/process changes *can* be made to facilitate assembly and/or minimize assembly cost without adversely affecting product/system quality. However, such changes must be made only after careful consideration of the potential impact that changes can have on product/system quality. Unfortunately, in the aggressive pursuit for incremental cost savings, many design changes may be made without adequate consideration of such concerns.

7.6 Current State of SN-95 Program - Conclusions

The issues experienced on the SN-95 program may or may not exist on other vehicle programs within Ford Motor Company. However, review of the findings specific to this program may help to preclude such issues from developing in the future or on other programs. Organizational issues factor greatly into the overall efficiency of the product development process. The following issues are considered problem areas that will continue to drive inefficiency on the SN-95 program until they are addressed:

- misaligned metrics between PVT and design community (driven by an ambiguous corporate cost/quality position)
- focus on up-front instead of overall program costs (cost vs. quality trade-off)
- rapidity of personnel rotation
- formal processes for documenting lessons learned
- dependency on supply base for design knowledge
- relationship with supply base
- lack of system-level ownership
- abandonment of system-level integration responsibilities

These issues are subjectively reviewed in detail in Chapter 8.

Chapter 8 - Evaluation of Product Development Community

Based on the author's personal interaction with engineers from the internal organizations of Research and Vehicle Technology (RVT), Ongoing Product Development (OPD), Plant Vehicle Team (PVT), and Vehicle Operations (VO), there appears to be a significant difference in the effectiveness of the sections of Ford's product development organization responsible for new program introductions and that dedicated to support of ongoing programs. This section contains the author's opinions regarding the current state of cultural aspects within, and focus of, Ford's product development organization supporting the SN-95 program, as well as the author's opinions regarding the effectiveness of technical processes utilized for ongoing SN-95 program support. Several aspects are examined, including the drivers of the product development process inefficiencies identified in Section 7.6. It is noted that this section may or may not portray a viewpoint consistent with that of the product development community or management.

8.1 System-Level Ownership

System ownership must be assigned both during new program launches and on ongoing production programs to prevent problems from arising with system-level component integration during design and/or assembly operations. In the author's opinion, the biggest driver of the inadequate water seal system performance on the SN-95 program was the fact that no single organization was assigned ownership of the overall system and given authority to drive development work in other functional groups and at the supply base. Because there was no single system owner, all activity prior to the onset of this project was simply patchwork of existing components that comprised the seal system. The discontinuity of system-level ownership following completion of a program launch is examined in detail.

During pre-production design activity at Ford, the owners of components that comprise an overall system assume system-level responsibility as a team. Effective interaction between these component owners from both design and manufacturing groups is required to meet mandatory pre-launch quality targets for each vehicle system since systems with poor performance levels will not achieve these aggressive quality targets. In this manner, adequate system ownership is ensured during initial vehicle launch.

Unfortunately, the potential for the loss of system-level responsibility exists once the vehicle program goes into initial production. Following launch, the PVT is responsible for all warranty issues on the vehicle, and consequently, for system-level ownership on ongoing production programs. Unfortunately, for certain functionalities such as sealing, the SN-95 PVT does not have adequate resources to address technical issues requiring significant design/development work, and therefore, cannot assume full ownership of design activity on complicated systems. The PVT relies heavily on OPD to assume ownership of such systems.

Effective system-level ownership within OPD involves coordination of design/assembly activity at the sub-system level *and* at the component level. Component level design activity refers to the design of individual components, while sub-system level design activity refers to the design of interaction between mating components. Sub-system level ownership within OPD was evident on the SN-95 seal system project, as a single OPD design engineer was responsible for 'dynamic sealing' of the convertible top seal system. This responsibility included design/release authority at the component level for the weather strips (shown in Figure 2.3), and design/release authority at the sub-system level for the butt joint interfaces of mating weather strips (shown in Figures 3.4 and 3.6). Since OPD *has* assigned responsibility at the sub-system level, component level integration is typically not an issue. However, because overall system-level ownership is *not* assigned within OPD, integration of sub-systems *can* result in design issues that affect overall product quality. This was observed on the SN-95 program, as problems with integration of the seal component sub-system (weather strips), glass subsystem (glass components and division bar), and convertible top sub-system contributed to failure of the overall water seal system.

To prevent such integration difficulties from arising, it is critical that a *systems* mindset be developed within product development communities that are responsible for bringing complex, technically integrated products to market and supporting their ongoing production. A systems mindset provides a "...methodology to assure that all subassemblies and parts work efficiently, and reliably, and will consistently perform to requirements."[23] By developing specialists in various functional areas (as within SN-95 OPD), functional organizational structures promote a focus on individual components rather than a focus on the interdependency of individual components within systems. A

---

[23] Cartin. Page 88.

systems approach to addressing emergent design issues therefore runs against the traditional piecemeal approach that has developed as a result of the widespread adoption of functional organizational structures.[24] Functional organizational structures do not provide mechanisms that resolve emergent systems problems, and as a result, functional groups within such structures are left to address individual system-level issues through informal collaboration on a case-by-case basis. Since functional organizational structures typically do not have formal mechanisms to address system-level issues, it is necessary for one of the functional groups within the overall product development community to be responsible for system integration. By developing an organizational focus on efficient system integration, a functional product development organizational structure can be effective in delivering high quality products.

8.2 Organizational Issues

From the author's observations within this study, it is indicated that several organizational issues within Ford's product development community raise inefficiencies in the processes used to support the SN-95 program, and hinder development of a system-level mindset within the overall SN-95 community. These issues include knowledge base development and management, fulfillment of organizational support roles, and development of a single, consistent cost/quality position at which the company intends to compete.

---

[24] Ibid.

8.2.1 Knowledge Flow and Management

In order to facilitate organizational learning, efficient knowledge flow mechanisms and knowledge management processes must be developed. Problems with knowledge flow and management on the SN-95 program were observed in two main areas - knowledge flow within the Ford product development community, and the development and growth of the internal design community knowledge base. The effectiveness of the overall flow of knowledge within the SN-95 program is examined in detail, and is dependent upon the following issues:

- quality of the RVT 'knowledge conduit' between specific vehicle programs
- rate of engineer rotation through functional assignments
- Ford's management of knowledge flow within the 'extended enterprise' that is created as design responsibility is outsourced to full-service suppliers
- quality of relationship between Ford and its supply base at both the individual personnel and organizational levels

Knowledge flows within the Ford product development community as illustrated in Figure 7.3, and requires significant personal interaction between engineers from various functional design and manufacturing groups. As suggested in Chapter 7, the critical link for knowledge flow between each individual functional group and the overall product development community is RVT, as this organization is responsible for promulgating lessons-learned from R&D, ongoing production programs, and new program launches throughout the entire product development organization. Unfortunately, based on the author's observations with the SN-95 program team, RVT does not appear to be proactive in searching out lessons-learned developed within ongoing production programs. While RVT has the responsibility of pushing lessons-learned across all vehicle programs, it appears to rely on other organizations to push lessons-learned to it, instead of actively developing processes that can be used to monitor ongoing program design activity and seek out new, experience-based knowledge that is developed across the entire product development organization.

From reactions observed during interviews performed with design community members on the SN-95 program, there seemed to be a general sense of frustration working with RVT. Individual contributors within OPD, the PVT, and VO reported that enlisting RVT participation in incorporating lessons-learned into current SDS requirements was difficult, both in terms of scheduling meeting times and securing commitment for RVT action. If the poor interaction between RVT and the rest of the SN-95 product development community is representative of that experienced on other ongoing production programs, a significant amount of critical experience-based knowledge may remain within specific program teams and never reach the greater product development community.

The rapid turnover of Ford design engineers working within functional sealing groups causes further difficulties in development of an in-house knowledge base for sealing methodologies, as sealing knowledge is *experienced-based* and difficult to transfer quickly to new engineers. Because supply base resources are consumed simultaneously by many different vehicle programs at Ford, the support of specific, ongoing production programs is typically 'thin'. Ford's product development community must therefore have an adequate in-house knowledge base that can be used to augment supplier capabilities as needed. This knowledge must be developed through time and must somehow be maintained within each of the vehicle programs. Unfortunately, this conflicts with Ford's current practice of rapid personnel rotation to provide its engineers with broad exposure to many different fields. It is clear that a certain degree of personnel rotation is necessary to maintain employee job satisfaction and prevent significant organizational attrition from occurring. However, a careful balance must be achieved and maintained between the rate of personnel rotation and organizational learning, as it is clear that engineers must possess an in-depth understanding of the components they own in order to identify potential opportunities to improve design on an ongoing basis.

The lack of an overall organizational focus on promulgating lessons-learned, as observed on the SN-95 program, raises the potential for future programs to repeat mistakes made on past projects. Therefore, management within the design community needs to aggressively focus effort toward developing community awareness of the importance of organizational learning. Formal documentation of lessons-learned on all vehicle program launches and performance enhancement products should be strictly enforced, and the resulting documents should be owned and actively managed by RVT, such that organizational learning is optimized.

Based on observations of the author, the importance of developing organizational learning within the design community will continue to grow in importance, as Ford has become *completely* dependent upon the knowledge base of its suppliers for seal system design.

Ford's dependence on its supply base for sealing knowledge contributes to the problems observed with system-level ownership on the SN-95 program. Once the product reaches end customers, Ford is ultimately responsible for overall product performance. Therefore, the integration of all supplier systems into vehicles is Ford's responsibility. If Ford is completely reliant on the supply base for system design, it raises the possibility of poor interaction between vehicle systems delivered by different suppliers. For instance, the supplier responsible for the seal system's weather strip design will not be able to characterize or predict the magnitude of convertible top positional variability without support from Ford, who, as the system integrator, would have insight into how variability cascades from the chassis sheet metal to the convertible top assembly. Since convertible top positionability determines the effectiveness of the weather strip design, it is critical for the supply base to have access to this knowledge within Ford. In turn, if Ford is not monitoring ongoing design activity at the supply base, it may not be able to ensure that the supply base has adequate knowledge regarding system interfaces, and may not realize such voids in the supplier knowledge base until they are observed in the form of high levels of warranty claims and customer dissatisfaction. The overall product development process fails if such issues reach end customers before they are resolved.

In moving toward reliance on 'full service' suppliers to design and deliver complete systems, Ford has reduced the direct need for resources to support system design activity. However, the resources that are no longer needed for direct design activity are very much needed to coordinate and monitor the ongoing design activity of the supply base. Unfortunately, Ford design engineers on the SN-95 program do not appear to actively monitor ongoing design activities at 'full-service' suppliers. As such, Ford's increasing reliance on full service suppliers is reducing the amount of knowledge that flows from the external supply base (where the knowledge base resides) into Ford's product development community, where development of a working knowledge base is needed.

As Ford continues to shift design responsibility for various vehicle systems to full-service suppliers, it is only logical to expect that the knowledge base associated with the outsourced system design will continue to move to the external supply base along with the design responsibility. This trend increases the already critical importance of the relationship that Ford maintains with its supply base. There are two aspects of this relationship that are critical - the effectiveness of communication at the personal level between engineers from the supply base and engineers within Ford's product development organization, and the effectiveness of communication at the program level, involving the free sharing of *organizational* knowledge.

On the SN-95 program, no significant relationship between the design community (RVT and OPD) and the supply base was observed at the personal level. Prior to the seal system redesign project, the RVT engineer responsible for convertible top design related issues for all of Ford Motor Company had never visited the convertible top supplier facility since assuming responsibilities over a year earlier. The SN-95 Mustang is currently the only convertible model that Ford produces, and therefore, this program is the only source of in-house experience-based knowledge regarding convertible top sealing methodologies. Since Ford currently has a number of convertible top vehicles in the development pipeline, the RVT SDS author should have been active throughout development work on the SN-95 water seal system project. Direct RVT contact with the supply base would have greatly improved the efficiency of the flow of experience-based knowledge from the team working on the SN-95 project to RVT. However, because RVT was not actively involved in the SN-95 project, organizational learning was not optimized, as knowledge flow from the supply base only reached the SN-95 development community (OPD, PVT, and VO). Without active initiation of upstream communication from the water leak 'quarterback team' to RVT, Ford would have lost out on the opportunity to leverage the experience-based knowledge of sealing methodologies gained by OPD, the PVT, and VO from working with the supply base. This knowledge captured by the Ford design community should help to greatly streamline development work on pre-production convertible vehicle programs.

In addition to poor communication at the personal level, communication problems with the supply base at the program level were also observed. In order to be responsive to emergent quality issues experienced by systems supplied by full-service suppliers, Ford's relationship with its supply base must be in-depth and positive, as Ford is dependent upon its supply base for knowledge and design capability. Unfortunately, based on discussions with supply base engineers supporting the SN-95 program, organizational issues appear to adversely affect the working relationship between Ford and its supply base at the program level. These organizational issues have developed on the SN-95 program mainly due to the experiences that the supply base has had with Ford's purchasing process. Supplier personnel related that cost estimates from Ford purchasing for components or labor typically do not match estimates made by suppliers, and at times, Ford does not even approve cost estimates after the supplier can provide actual invoices for cash payments made in support of Ford vehicle programs. Supplier engineers have concerns that there is a finite possibility that services rendered without payment in support of Ford development programs are likely to go unpaid.

The friction that has developed between the supply base and Ford purchasing at the program level has forced suppliers into adopting the position that they will not take part in any program development work without prepayment from Ford. Because the supply base is generally unwilling to work on development projects outside of existing contracts without prepayment, the cycle time for completion of performance enhancement projects can suffer. Indeed, during this project, a three-week delay was incurred because a request for payment could not quickly be pushed through the Ford purchasing process, and the convertible top supplier would not participate in conceptual brainstorming and mock-up work until proof of payment from Ford was received. In addition to preventing Ford from being able to react quickly to customer complaints with existing products/systems, the position that suppliers have adopted on the SN-95 program also prevents the free flow of new ideas and knowledge from the supply base to Ford, thus preventing development of Ford's in-house knowledge base.

8.2.2 Balance Between Corporate Cost and Quality Goals

As with any company, Ford must make a conscious decision regarding its ultimate corporate objectives, develop a cost/quality position consistent with these objectives, and maintain consistency of this cost/quality position at all levels of its product development organization. If choosing to compete on product quality, a company *must* recognize inherent trade-offs between incurred short-term costs and long term product quality that inevitably arise during program development work. An organization cannot be successful if it has ambiguous organizational goals that run contrary to one another such as cost and quality. Low-cost, high-quality production capability is something that all manufacturing organizations strive to achieve. However, there is a limit to what programs can achieve with a given budget. Knowledge of *total* program costs must be developed in order to determine the optimal balance between cost and quality. If quality drives overall program cost much more than up-front development costs, a company must be willing to accept higher development costs to realize the lower overall program cost. The concept of increased up-front program spending during development work is very difficult to push through management that is judged mainly on performance against budget. This issue again demonstrates how poor alignment of metrics can drive detrimental behavior within the overall product development process.

In the author's opinion, the organizational alignment issues raised in Section 7.5.3 are driven primarily by a single factor – inconsistency of corporate objectives toward achieving a single, balanced cost/quality position on which the company intends to compete. The pennies per vehicle saved through small design modifications or removal of existing features may be far outweighed by the money paid out to resolve warranty claims resulting from such activities, and the potential loss of repeat customers due to dissatisfaction with vehicle quality. The potential impact on overall profitability due to the loss of repeat buyers cannot be easily quantified, but it is clear that the impact could be significant. Ford needs to move from the traditional mindset of taking up-front cost out of vehicle programs to a new mindset of taking cost out of the overall program life cycle.

This mindset shift can be achieved in part by restructuring metrics such that the design community tasked with ongoing production program support (OPD) is judged on progress toward warranty reduction targets *and* cost reduction targets in a proportion consistent with the cost/quality position set at the corporate level. Since Ford has chosen to compete on cost *and* quality, OPD needs to be proactively involved in design efforts aimed at improving design robustness and attacking warranty claim drivers to ensure successful continuous design evolution of existing systems. As discussed in Chapter 7, OPD is judged heavily on progress toward cost reduction targets. However, these metrics do not account for actions taken that reduce overall program costs (e.g. warranty costs, cost of redesign projects necessary to address quality issues). For Ford to better align the overall product development community, OPD should be judged mainly on progress toward *total* program cost targets, which include up-front development costs *and* warranty costs. Unfortunately, since warranty costs are not observed immediately, the rapid rotation of engineers through various functional positions will continue to be a large barrier that prevents incorporation of warranty costs into metrics measuring progress toward *total cost* targets, which take product quality and robustness into account. The author believes that a focus on total cost targets will greatly improve the overall quality of ongoing program support.

The water seal project is a perfect example of design activity that increases per unit vehicle cost while ultimately reducing overall program costs. The program savings expected to result from warranty cost reduction are expected to exceed the additional cost of the proposed system. Also, customer satisfaction should be greatly improved, raising the possibility that an existing customer may repurchase another Ford vehicle based on perceived vehicle quality. Active OPD participation on quality improvement projects such as the SN-95 water seal system redesign should be encouraged by organizational metrics.

Unfortunately, based on the author's observations, SN-95 OPD does not have incentives in place to ensure proactive participation in projects initiated to improve program quality levels. The metrics by which OPD is judged (specifically the strong focus on cost reduction activity) are not aligned with the PVT's goal of improving product quality. Consistent with metrics against which it is judged, the SN-95 OPD focuses the majority of its efforts toward achieving cost reduction targets and as a result, PVT support on quality improvement projects suffers. In the author's opinion, the SN-95 program's strong focus on cost reduction efforts actually runs counter to the goal of consistently high product quality. A consistent corporate position on the cost/quality position at which each specific vehicle program will compete should help prevent conflicts similar to those observed on the SN-95 program from arising, in which the cost reduction efforts of one group unknowingly works against the quality improvement efforts of other groups.

One final issue with the cost/quality position at which Ford chooses to compete is the effect this position has on supply base performance. The author believes that supplier performance is adversely impacted by the tremendous compression of new vehicle program introduction cycles. Engineers from the supply base indicate that system quality delivered to Ford would likely be much higher if the 36-month development period was stretched to a 48-month development period, thereby allowing for more pre-production builds. Such pre-production builds help to identify issues before they get to the customer. However, Ford ties up tremendous capital in new programs and demands payback on its investment in the near term. Unfortunately, the relationship between the compressed development cycle and the resulting warranty costs related to poor supply base performance is not well understood. The time value of money may, in fact, be less valuable to Ford than reduced profit margins that result from warranty claims against the company's products due to quality defects. Consequently, compression of the overall product development cycle may not be consistent with the ultimate goal of delivering consistently high quality product to customers, and may actually add more cost to Ford's product development organization than it saves. Some understanding of the trade-off between program profitability (including the cost of poor quality from an overstretched supply base) and overall duration of the product design cycle needs to be developed.

8.2.3 Abandonment of Organizational Support Roles

The successful introduction/support of new/ongoing vehicle programs requires each of the functional groups within Ford's overall product development organization to fulfill their support roles. The PVT is responsible for assembly plant and supply base support while both RVT and OPD are responsible for supporting PVT. Based on the author's observations, OPD and RVT did not fulfill their ongoing production support roles adequately on the SN-95 program. It is noted that the previous statement is specific to support of the vehicle seal system, and may not be representative of SN-95 program support in general. However, the lack of design community support for the PVT is considered one of the main contributing factors to the inadequate performance of the SN-95 water seal system. The SN-95 PVT is currently overwhelmed with responsibilities and does not receive adequate support from the design community. Dearborn Assembly Plant's reliance on PVT engineers to assume responsibilities formerly fulfilled by DAP process engineers has created a resource drain on the PVT. This prevents the PVT from engaging in proactive initiation of quality improvement projects. Compounding this situation is the fact that the SN-95 PVT does not have the resources or manpower necessary to complete intensive system redesign projects without significant support from OPD and RVT. Because RVT is mainly responsible for forward model (next generation) design support, OPD is the main source of design community support for the PVT.

Because its primary role is support of ongoing production, OPD is the primary design organization responsible for working to resolve design-related failures experienced on existing systems. OPD support is especially critical for projects that involve significant design activity/testing such as the water seal system project. At the time the author arrived at Ford, little (if any) project support from OPD was observed. The strengths of VO and the PVT lie mainly in manufacturing process design. These organizations are not well suited for projects requiring intensive conceptual design activity. Significant progress on the water seal system project was not observed until OPD began to adequately support the VO, PVT, and supply base engineers who were already working on the project. OPD had access to much needed funding for prototype development as well as insight into historical design activity that was useful during the conceptual design phase of the project. If OPD had driven this performance enhancement project from its inception, the author believes that the overall duration of the performance enhancement project would have been compressed significantly.

Whereas OPD can fulfill its PVT support role by participating in PVT-initiated performance enhancement projects, RVT generally fulfills its support role through creation/modification of SDS design requirements. Both OPD and the PVT use the guidance provided by SDS design requirements to direct their design activity. Unfortunately, available RVT resources are used inefficiently if the SDS design requirements do not add value in helping OPD and the PVT focus their design activity. The usefulness of existing SDS requirements is questionable regarding design guidance for the convertible top sealing methodologies. In this author's opinion, the SDS requirements regarding seal system performance and characteristics are vague and confusing. The only information that the author could find regarding convertible top sealing methodologies in this SDS noted that no leaks shall be observed in the seal system. During work on the SN-95 water seal system project, the SDS requirements were not promptly updated to reflect lessons learned.

It is noted that the M205 (next-generation Thunderbird) currently in development is a convertible model, and will utilize guidance from its relevant SDS design specifications. Because the SN-95 lessons-learned were not quickly pushed back to the greater product development community in the form of revised SDS requirements, it is unclear whether the M205 program would have benefited from the experience-based knowledge developed in the SN-95 program without direct communication between the SN-95 water leak 'quarterback team' and M205 design engineers. It is noted that such direct communication was developed specifically for the purpose of preventing the loss of experience-based knowledge developed by the SN-95 seal redesign project.

The need for direct program-to-program communication of lessons-learned points to a weakness in the process RVT uses to continuously update SDS requirements to reflect the most current experience-based knowledge of the overall product development community. Any weakness on the part of RVT in actively developing and pushing lessons-learned throughout the greater product development community will certainly impact knowledge flow, and will reduce the organizational learning that occurs from the growing experience-based knowledge base that is developed from ongoing operations within specific vehicle programs.

8.2.4 Development of Environment that Promotes Proactive Design Activity

Ford's 'quarterback team' process is developed to address the top-ten warranty drivers experienced by ongoing production programs. However, the mindset of developing action items to address the top ten warranty drivers at any point in time may result in unintended consequences. Hypothetically, exponential growth of the eleventh greatest warranty driver could result in significant warranty costs and damage to the reputation of brand quality before it is even identified as a problem. Furthermore, a focus on the top ten warranty drivers further reinforces the *reactive* nature of Ford's ongoing program design activity. The top ten warranty drivers clearly result in significant costs to the company, but *all* warranty claims should be of concern to engineers supporting ongoing program work. All component owners should be in touch with warranty data, and be looking for opportunities to adjust design to improve system performance on an ongoing basis.

However, changing the underlying nature of ongoing program design activity requires development of a strong knowledge base in the individual engineers who own the various systems on a vehicle. As discussed earlier, the author believes that Ford rotates engineers through functional assignments much too rapidly. This personnel rotation prevents engineers from quickly developing the in-depth knowledge needed to proactively search for innovative ways to improve system performance on an ongoing basis. Slowing the rate of engineer rotation through various functional roles may help develop the in-depth knowledge base that is required to help engineers understand where to focus limited proactive resources to realize the most benefit.

For systems that have quality issues but are not ‘top ten’ warranty drivers, it is imperative that someone within OPD assume responsibility for overall system performance. Currently, there is no structure at Ford that encourages the owners of system components to assume responsibility for the overall system-level performance. There are issues with who should assume this system-level responsibility, and what authority they have to direct the efforts of peers who own other system components. However, in order to develop a truly effective product development process, it is critical that engineers within OPD are proactive in attacking what they believe to be non-optimal designs - even if the system with which they are working is not a top-ten warranty driver.

8.3 Engineering/Technology Issues

In addition to the organizational issues that hamper system-level ownership from developing within the product development community, there are also issues regarding the effectiveness of processes currently used at Ford to facilitate engineering activities needed to combat known design inefficiencies.

Ford currently uses 'quarterback teams' to address emergent quality issues experienced on ongoing production programs. The 'quarterback teams' follow a ninety-day process that has been developed at Ford to provide guidance for both diagnostic and redesign activities for systems that experience emergent quality issues. The methodology presented in this study is an embodiment of Ford's ninety-day process in its idealized state. Unfortunately, personnel resource constraints within Ford's product development community prevent management from assigning engineers solely to the support of these quarterback teams. Since the engineers on 'quarterback teams' have other daily duties associated with their positions, it is difficult for them to dedicate enough time to rigorously follow the overall ninety-day process. Indeed, for the SN-95 project, this author was dedicated completely to water leak 'quarterback team' support, and the results of this project presented herein are the result of over six months of full-time work. It is noted that the validation test period for the proposed conceptual design of the new seal system is still ongoing at the time of the writing of this document (May 2000).

The result of the SN-95 water seal system project proves that Ford's diagnostic/redesign process for systems experiencing inadequate performance levels can be very effective *if* it is followed rigorously. To ensure that the 'quarterback team' process is as effective as possible, Ford should continue to establish teams that have cross-functional expertise in both applied technology and technical methodologies associated with the process, and provide engineers supporting these teams with adequate time that allows rigorous system analysis and design activity.

8.4 Broader Implications

It is important to note that the overall system redesign methodology proposed in this study is not specific to a particular system or product. Individual process steps within the overall methodology such as the baseline characterization of target system(s) performance, analysis of failure modes and effects, and completion of internal/external benchmarking and conceptual redesign activity can be performed in a manner similar to that presented in this study. The methodology is therefore valuable, in that while the application of the methodology will certainly be different than that presented herein, the methodology itself can be generalized to address inadequate performance levels of *any* system within *any* complex, technical product.

While the proposed methodology can help companies continuously improve the quality of their products, the methodology itself does not offer any inherent competitive advantage for any specific company. However, the author believes that the efficiency with which companies execute the system redesign methodology *can* be a competitive advantage. This is because companies can differentiate themselves on quality if they can respond to customer demands faster than their competitors. Therefore, companies can develop a competitive advantage by differentiating their product development organizations along two lines. First, product development organizations need to be capable of supporting both new product introduction *and* ongoing production programs. Second, they need to aggressively leverage lessons-learned from both types of programs to improve their overall product development processes on a continuous basis. By developing these characteristics in their product development communities, the author believes that companies can realize a sustainable competitive advantage within quality sensitive marketplaces.

Chapter 9 - Summary

This study asserts that development of organizational competencies in new product introduction (NPI) and ongoing production program support can result in a competitive advantage for companies operating within a quality sensitive marketplace. However, for a manufacturing entity to realize such a competitive advantage, effective NPI *and* ongoing program support processes must exist within the entity's overall product development organization. Without adequate design community support of ongoing production programs, initial quality levels of complex, technical products will likely degrade as programs mature following their initial introduction. It is therefore critical for an organization to understand what 'adequate' design community support of ongoing production entails. For the purposes of this study, 'adequate' support of ongoing production programs requires that the organization's design community:

- develop an awareness of the identity of 'critical' systems embedded within the product they are assigned to support;
- actively monitor performance of these 'critical' systems; and
- understand the effect that 'critical' system performance has on customer perception of overall product quality.

When the aforementioned support activities identify inadequate performance levels of critical systems, organizational processes must exist that facilitate evaluation of system design, identification of root causes of system failure, and system redesign, if necessary. This study has presented a general methodology that can be utilized to help improve the efficiency of ongoing production program support. This methodology consists of the following individual process steps:

1) identification of what system(s) to target for improvement
2) failure mode analysis of targeted system(s)
3) performance benchmarking study
4) assembly process variability study
5) conceptual design brainstorming activity
6) prototype generation
7) feasibility study

The project details associated with each individual process step as presented in previous chapters of this study can be used as a case study as to how to structure evaluation/redesign activities for a critical system embedded within a complex, technical product. The aforementioned methodology was utilized herein on a performance enhancement project that was undertaken by Ford Motor Company to improve inadequate performance levels of the Mustang convertible water seal system. The project culminated in a new, prototype design that is expected to reach actual production in the summer of 2000, provided a foundation on which additional development work can be performed, and helped develop an in-house knowledge base for seal system design methodologies.

The project also demonstrated that the simple existence of organizational processes does not ensure effective support for ongoing production programs or consistently high product quality levels unless these processes are utilized within an environment that promotes consistency with overall corporate objectives and organizational learning. The support of programs that produce complex, technical products requires extensive interaction between various functional specialists within the overall product development community. Therefore, organizations that use a functional product development community structure to develop specific, in-house functional expertise must develop and manage efficient knowledge transfer mechanisms in order to facilitate the cross-functional product development environment needed to successfully support complex products. During work on the Ford-sponsored performance enhancement project, organizational barriers were observed within Ford's product development community that ranged from inefficiencies in formal documentation of organizational lessons-learned to poor coordination of the extended enterprise (internal design/manufacturing community and external supply base). These barriers were observed to prevent efficient knowledge transfer within the design community, and consequently, hinder organizational learning.

The experiences that the author gained while working on the SN-95 water seal system project are summarized and used to draw generalizations that may be useful to other organizations that are struggling to improve the efficiency of their product development processes. The following lessons-learned involve both technical *and* organizational issues, and should be considered as generalizations that were taken from the author's experiences on a specific program within Ford Motor Company:

- Establishing organizational learning as a priority within product development communities is critical in improving design robustness resulting product quality.
- Knowledge transfer mechanisms are critical in establishing a learning organization, and must be *developed and actively managed.*

- There is a clear relationship between the speed of personnel rotation through various functional roles and the effectiveness of organizational learning. This relationship is specific to individual companies and functionalities, and must be consistent with corporate objectives (broad personnel development vs. specific personnel competence).
- Active management of supply base relations becomes more critical as companies begin to fully outsource design responsibility, and consequently relinquish some control of knowledge flow and management to their external supply bases.
- A cost/quality position should be clearly established at the corporate level, and should be consistent throughout all levels of the product development organization.
- Alignment of design/manufacturing groups is critical when cross-functional teams are required during product development, and is facilitated by a consistent corporate cost/quality position.
- Management can develop organizational alignment through periodic performance appraisals that provide positive reinforcement for subordinate behavior that is consistent with overall corporate objectives.
- Aggressive benchmarking should be pursued on an ongoing basis to continuously maintain/grow the in-house knowledge base.
- Internal processes should exist within the product development organization to trigger an appropriate response to inadequate product/system performance.

Careful consideration of the aforementioned generalizations should help companies tailor organizational and technical processes to improve the efficiency of their overall product development communities. A company can realize this improved product development efficiency in two ways. First, increasing the effectiveness of organizational learning from experience-based lessons-learned (generated from ongoing production programs *and* new program introductions) will grow a company's in-house product development knowledge base. Second, developing effective knowledge transfer mechanisms can be used to promulgate these lessons-learned (captured in the company's growing knowledge base) throughout the company's entire product development community. By effectively transferring lessons-learned from new programs to ongoing production programs and vice-versa, design communities can thereby provide strong support for both newly introduced programs *and* ongoing production programs. In this manner, companies that are successful in developing highly efficient product development processes and organizations should realize a competitive advantage in the marketplace through product differentiation based on consistently high quality levels.

(This page intentionally left blank)

References

1. Cartin, Thomas J. (1999). Principles and Practices of Organizational Performance Excellence, ASQ Quality Press.
2. Chang, Richard Y. / Kelly, Keith P. (1994). Improving Through Benchmarking - A Practical Guide To Achieving Peak Process Performance, Richard Chang Associates, Inc.
3. Conway, William E. (1992). The Quality Secret: The Right Way to Manage, Conway Quality, Inc.
4. Fortune, Joyce / Peters, Geoff. (1995). Learning from Failure - The Systems Approach, John Wiley & Sons.
5. Graham, Alan / Shiba, Shoji / Walden, David (1993). A New American TQM: Four Practical Revolutions in Management, The Center for Quality Management.
6. Guest, P.G. (1961). Numerical Methods of Curve Fitting, Cambridge University Press.
7. Matthews, Clifford. (1998). Case Studies in Engineering Design, John Wiley and Sons, Inc.
8. Rosenau Jr, Milton D. (1982). Innovation: Managing the Development of Profitable New Products, Lifetime Learning Publications.
9. Vedin, Bengt-Arne. (1980). Large Company Organization and Radical Product Innovation, Institute for Management of Innovation and Technology.

(This page intentionally blank)

Appendix A - Supporting Figures

Figure A.1: Behavior of the convertible top assembly during roof retraction.

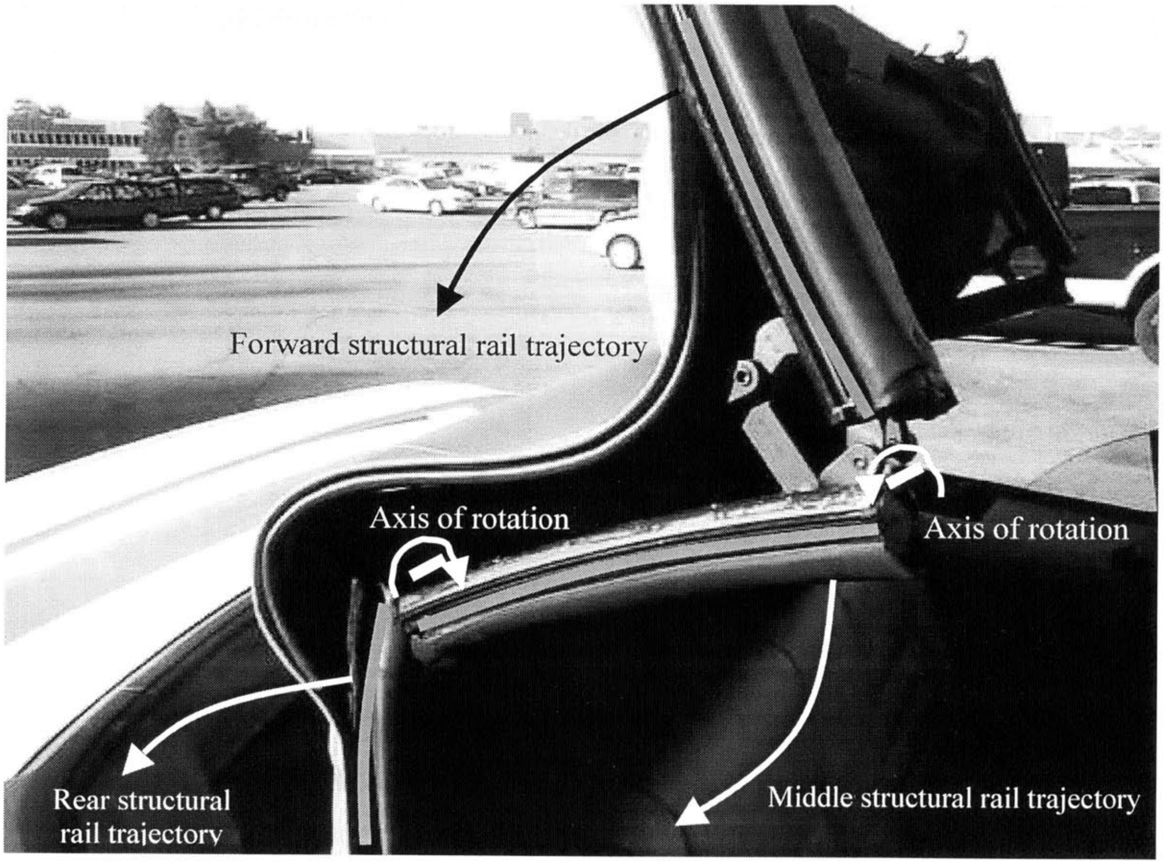
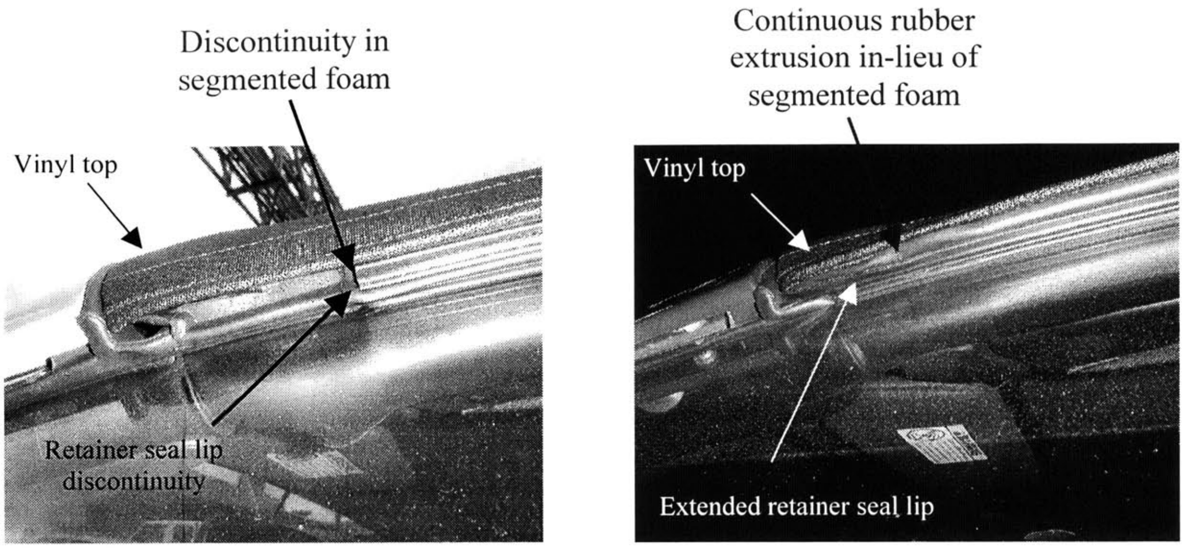
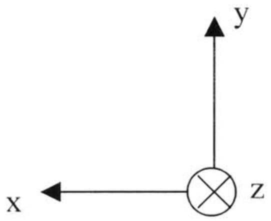


Figure A.2: Comparison of the ‘A-Pivot’ Region of the SN-95 Convertible Water Seal System in its Current Configuration and in its Prototype State.



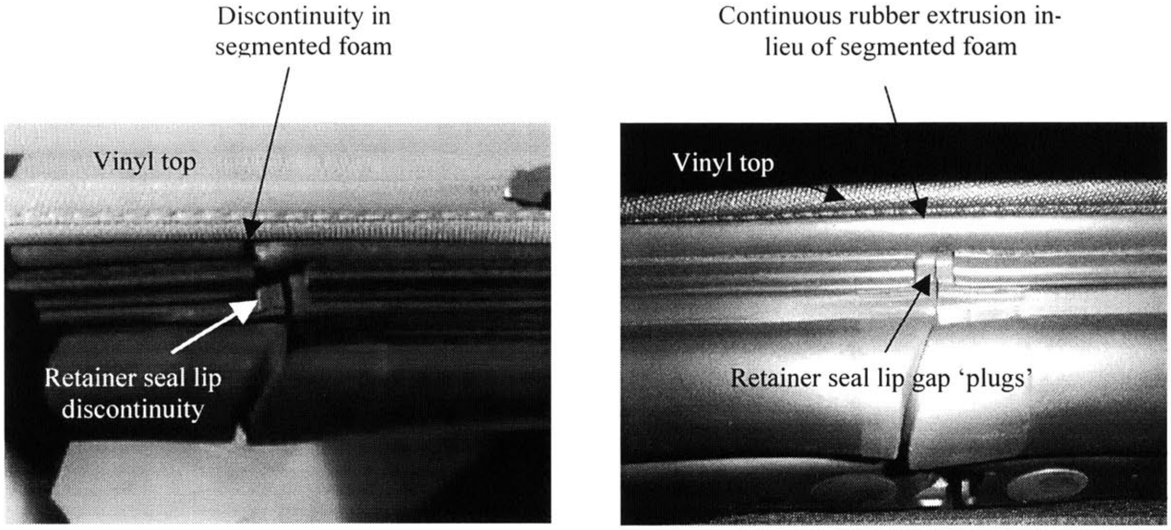
Current Production Design

Proposed Design

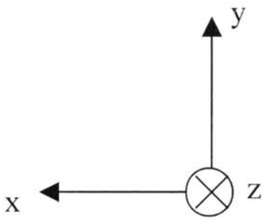


(relative to axes in Figure 2.1)

Figure A.3: Comparisons of the ‘B-Pivot’ Region of the SN-95 Convertible Water Seal System in its Current Configuration and in its Prototype State.

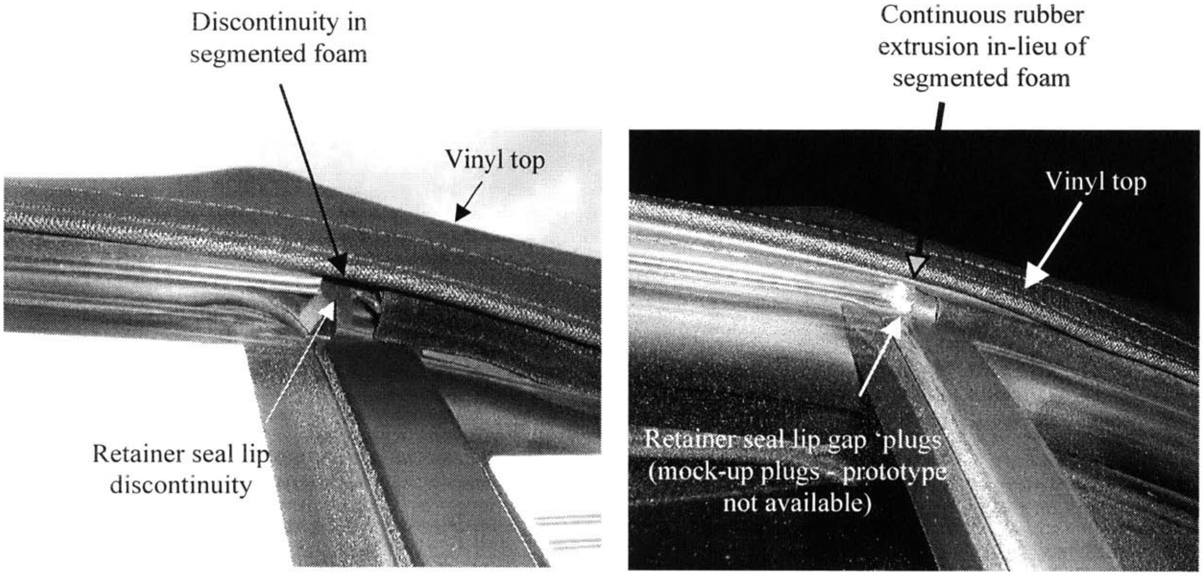


Current Production Design **Proposed Design**



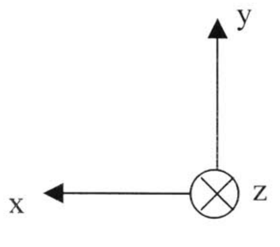
(relative to axes in Figure 2.1)

Figure A.4: Comparisons of the 'C-Pivot' Region of the SN-95 Convertible Water Seal System in its Current Configuration and in its Prototype State.



Current Production Design

Proposed Design



(relative to axes in Figure 2.1)

Appendix B – Grid Search Analysis Details

The following steps are included to augment the grid search methodology utilized for the data analysis performed in Chapter 4.3. The reader should refer to Chapter 4.3 for more details.

1. *Measurement phase*: Each fundamental variable included in the analysis is measured and recorded for each system included in the trial. Note that the measurements and values presented in this Appendix are for illustrative purposes only, and are not representative of the actual data recorded.

Fundamental Variables	Fore/aft (1)	Fore/aft (2)	In/out (3)		Leak Volume	Seal Performance Ranking
Vehicle 1	4.2	5.2	2.4		50 mL	1
Vehicle 2	5.6	3.6	5.5		460 mL	4
Vehicle 3	7.5	8.9	2.4		700 mL	5
Vehicle 4	6.4	6.9	4.7		420 mL	3
Vehicle 5	7.2	7.3	4.8		230 mL	2
	*gap dimensions in mm					

2. *Development of rank scores*, based on scaling factor permutations.

Scaling Factor Permutation	Variable 1 Scaling Factor	Variable 2 Scaling Factor	Variable 3 Scaling Factor	Vehicle 1 Rank Score	Vehicle 2 Rank Score	Vehicle 3 Rank Score	Vehicle 4 Rank Score	Vehicle 5 Rank Score
1	0	0	1	2.4	5.5	2.4	4.7	4.8
2	0	0.02	0.98	2.456	5.462	2.53	4.744	4.85
3	0	0.04	0.96	2.512*	5.424	2.66	4.788	4.9
...	...	...	...	...	...	...	...	...
1326	1	0	0	4.2	5.6	7.5	6.4	7.2

* 'Vehicle 1 rank score' for 'Scaling factor permutation 3' is calculated by:

$$[w_{13}*v_1 + w_{23}*v_2 + w_{33}*v_3] = [0*4.2 + 0.04*5.2 + 0.96*2.4] = 2.512$$

(where w_{ij} is the scaling factor for variable i from permutation j, and v_i is the measured value of parameter i)

3. *Ranking of vehicle scores* (from lowest to highest). For an assumption that minimum seal gaps produces optimal seal performance, systems with low ranked scores are expected to have the best performance.

Scaling Factor Permutation	Vehicle 1 Predicted Performance	Vehicle 2 Predicted Performance	Vehicle 3 Predicted Performance	Vehicle 4 Predicted Performance	Vehicle 5 Predicted Performance
1	1	5	1	3	4
2	1	5	2	3	4
3	1	5	2	3	4
...	...	...	...	...	...
1326	1	2	5	3	4

* Rankings based on rank scores developed in Step 2.

4. *Comparison of predicted performance ranks versus actual performance ranks.* The sum of squared error difference between the two sets of ranks are taken as a measure of the predictive ability that each particular scaling factor permutation has in determining the relative effect of each fundamental variable on the output function.

	Scaling Factor Permutation 1 Ranking	Scaling Factor Permutation 2 Ranking	Scaling Factor Permutation 3 Ranking	...	Scaling Factor Permutation 1326 Ranking	Actual Ranking
Vehicle 1	1	1	1		1	1
Vehicle 2	5	5	5		2	4
Vehicle 3	1	2	2		5	5
Vehicle 4	3	3	3		3	3
Vehicle 5	4	4	4		4	2
SSE*	21	14	14		8	

* Sum of squared error between the performance rank prediction of each scaling factor permutation and the actual performance rank based on test results. For example:

$$\text{SSE (permutation 1)} = (1-1)^2 + (5-4)^2 + (1-5)^2 + (3-3)^2 + (4-2)^2 = 21$$

5. *Interpretation of results.* The minimum sum of squared error indicates the scaling factor permutation that has the best predictive ability for performance ranking of systems, based on fundamental variable values. For the previous step, only the first three and last scaling permutations are presented. There are over 1300 permutations that are not presented in the previous step (due to a lack of space). Assuming that the four permutations examined are the only permutations used in the analysis, the grid search would suggest that permutation 1326 (1,0,0) would best predict the performance rank of various systems. This result indicates that the first fundamental variable alone drives the leakage output function. Design activity would then focus on control of the first fundamental variable (in this illustrative case, the fore/aft seal gap at the top of the division bar).

It is critical to note the difference between the minimum sum of squared error, and the worst case sum of squared error. Note that for the illustrative case herein, barring any rank score ties, the worst case sum of squared error is:

$$(5-1)^2 + (4-2)^2 = 20$$

This indicates that the best sum of squared error is only a factor of two better than the worst case scenario. Generally, an improvement of an order of magnitude indicates significant predictive ability of a particular scaling factor permutation. Improvements less than this must be used with caution, but may still suggest trends that can be useful in understanding the root cause mechanisms that drive a particular failure mode.

(This page intentionally blank)

Appendix C - Spearman Rank Test Results

Table C.1: Driver Side Spearman Rank Test for Original Thirty-Vehicle Test Sample

Driver original thirty-vehicle test sample

	X1	rank X1	X2	X3	rank X3	X4	rank X4	X5	X1 + X4	rank (X1 + X4)	X3 * X4	rank (X3*X4)	Leak volume	Leakage rank
Trial 1	7.2	12	7.43	6.05	21	4.17	15	15.62	11.37	13	25.2285	18	270	10
Trial 2	6.29	8	8.02	5.12	15	3.3	6	18.1	9.59	6	16.896	9	345	15
Trial 3	7.28	13	8.09	6.05	21	4.08	14	22.34	11.36	11	24.684	17	550	20
Trial 4	7.68	16	7.48	5.72	19	4.68	20	21.4	12.36	20	26.7696	21	340	12
Trial 5	8.21	22	8.51	4.51	6	3.18	5	20.41	11.39	14	14.3418	5	200	6
Trial 6	7.9	20	8.21	4.98	14	3.46	7	21.49	11.36	11	17.2308	11	230	9
Trial 7	8.4	25	8.85	3.7	2	3.15	4	18.86	11.55	17	11.655	3	45	3
Trial 8	10.12	29	9.68	5.65	17	4.7	21	17.7	14.82	30	26.555	20	920	28
Trial 9	8.25	23	8.79	4.55	7	3.01	3	16.92	11.26	10	13.6955	4	300	11
Trial 10	4.12	1	9.78	6.51	25	4.91	24	19.4	9.03	3	31.9641	25	375	16
Trial 11	10.4	30	10.2	2.7	1	2.48	2	16.65	12.88	24	6.696	1	40	1
Trial 12	8.92	27	9.06	4.12	3	3.5	8	17.91	12.42	21	14.42	6	60	4
Trial 13	7.78	17	8.05	6.26	23	5	25	22.09	12.78	22	31.3	24	1150	30
Trial 14	7.8	18	8.02	8.2	27	6.68	28	12.82	14.48	29	54.776	28	605	22
Trial 15	7.36	14	7.2	8.65	28	6.72	29	17	14.08	28	58.128	29	1130	29
Trial 16	6.82	11	7.5	4.88	11	4.63	19	15.7	11.45	15	22.5944	16	40	1
Trial 17	4.19	2	5.05	6.28	24	4.9	23	20.82	9.09	4	30.772	23	510	19
Trial 18	9.55	28	9.42	4.89	12	4.5	17	21.55	14.05	27	22.005	15	340	12
Trial 19	8.2	21	9.35	5.51	16	4.61	18	15.05	12.81	23	25.4011	19	735	26
Trial 20	8.35	24	9.4	5.79	20	4.78	22	15.02	13.13	25	27.6762	22	580	21
Trial 21	7.85	19	7.8	4.58	8	3.67	11	15.08	11.52	16	16.8086	8	625	24
Trial 22	5.89	6	7.36	5.68	18	3.68	12	22	9.57	5	20.9024	13	225	8
Trial 23	6.75	10	8	4.29	4	3.86	13	19.1	10.61	8	16.5594	7	110	5
Trial 24	7.48	15	7.8	7.04	26	5.95	27	18.63	13.43	26	41.888	26	340	12
Trial 25	4.63	4	5	9.87	30	7.48	30	12.97	12.11	19	73.8276	30	770	27
Trial 26	6.31	9	7.02	8.65	28	5.66	26	17.91	11.97	18	48.959	27	690	25
Trial 27	6.11	7	6.9	4.89	12	4.4	16	17.79	10.51	7	21.516	14	617	23
Trial 28	4.7	5	5.79	4.78	9	3.63	10	18.47	8.33	2	17.3514	12	205	7
Trial 29	8.6	26	8.26	4.4	5	2.17	1	20.08	10.77	9	9.548	2	375	16
Trial 30	4.52	3	6.45	4.78	9	3.55	9	15.79	8.07	1	16.969	10	440	18

Driver side rank differences (original thirty-vehicle sample)					Squared rank differences				
X1 vs. Actual	X3 vs. Actual	X4 vs. Actual	(X1+ X4) vs. Actual	(X3*X4) vs. Actual	X1 vs. Actual	X3 vs. Actual	X4 vs. Actual	(X1 + X4) vs. Actual	(X3*X4) vs. Actual
2	11	5	3	8	4	121	25	9	64
-7	0	-9	-9	-6	49	0	81	81	36
-7	1	-6	-9	-3	49	1	36	81	9
4	7	8	8	9	16	49	64	64	81
16	0	-1	8	-1	256	0	1	64	1
11	5	-2	2	2	121	25	4	4	4
22	-1	1	14	0	484	1	1	196	0
1	-11	-7	2	-8	1	121	49	4	64
12	-4	-8	-1	-7	144	16	64	1	49
-15	9	8	-13	9	225	81	64	169	81
29	0	1	23	0	841	0	1	529	0
23	-1	4	17	2	529	1	16	289	4
-13	-7	-5	-8	-6	169	49	25	64	36
-4	5	6	7	6	16	25	36	49	36
-15	-1	0	-1	0	225	1	0	1	0
10	10	18	14	15	100	100	324	196	225
-17	5	4	-15	4	289	25	16	225	16
16	0	5	15	3	256	0	25	225	9
-5	-10	-8	-3	-7	25	100	64	9	49
3	-1	1	4	1	9	1	1	16	1
-5	-16	-13	-8	-16	25	256	169	64	256
-2	10	4	-3	5	4	100	16	9	25
5	-1	8	3	2	25	1	64	9	4
3	14	15	14	14	9	196	225	196	196
-23	3	3	-8	3	529	9	9	64	9
-16	3	1	-7	2	256	9	1	49	4
-16	-11	-7	-16	-9	256	121	49	256	81
-2	2	3	-5	5	4	4	9	25	25
10	-11	-15	-7	-14	100	121	225	49	196
-15	-9	-9	-17	-8	225	81	81	289	64
				sum	5241	1615	1745	3286	1625

Table C.2: Passenger Side Spearman Rank Test for Original Thirty-Vehicle Test Sample

Passenger side original thirty-vehicle sample

	X1	X2	X2 rank	X3	X3 rank	X4	X4 rank	X5	X2 + X4	Rank (X2 + X4)	X3*X4	Rank (X3*X4)	Leak volume	Leak rank
Trial 1	9.22	9.3	8	5.4	26	3.99	18	19	13.29	10	21.55	23	440	27
Trial 2	14.3	12.9	30	2.73	4	3.98	16	18.55	16.88	30	10.87	8	0	1
Trial 3	7.82	8.3	4	6.58	29	5.42	29	20.4	13.72	13	35.66	29	435	26
Trial 4	10.79	10.1	15	4.99	21	4.5	24	18.8	14.6	20	22.46	24	245	21
Trial 5	11.21	11.94	28	4.02	14	3.32	8	19.45	15.26	24	13.35	13	265	24
Trial 6	11.61	11.4	25	5.31	24	3.94	15	16.79	15.34	26	20.92	21	745	30
Trial 7	11.31	11.15	23	5.79	28	4.32	23	19.45	15.47	27	25.01	26	465	29
Trial 8	11.8	12.21	29	3.8	10	2.79	4	19.3	15	23	10.60	6	25	11
Trial 9	9.82	10.95	20	5.05	22	4.95	27	16.96	15.9	29	25.00	25	35	13
Trial 10	9.1	8.91	6	3.81	11	3.45	11	22.06	12.36	3	13.14	12	35	13
Trial 11	10.19	10.4	19	3.09	5	3.5	13	18.16	13.9	16	10.82	7	0	1
Trial 12	8.77	9.31	9	3.51	8	4	19	20.28	13.31	11	14.04	14	25	11
Trial 13	10.68	11.05	22	3.98	13	3.08	6	22.74	14.13	18	12.26	10	15	9
Trial 14	9.63	9.93	13	6.82	30	5.91	30	21.61	15.84	28	40.31	30	255	22
Trial 15	9.82	10.31	17	4.4	17	4.61	25	18.48	14.92	22	20.28	20	202	20
Trial 16	10.59	11.01	21	2.2	1	3.02	5	13.65	14.03	17	6.64	3	90	16
Trial 17	8.68	9.58	11	4.39	16	4.1	20	18.69	13.68	12	18.00	17	20	10
Trial 18	9.58	9.59	12	5.36	25	5.22	28	21	14.81	21	27.98	28	255	22
Trial 19	10.25	11.15	23	5.21	23	4.12	21	13.51	15.27	25	21.47	22	165	18
Trial 20	7.55	8.59	5	4.16	15	3.8	14	15.63	12.39	4	15.81	16	10	7
Trial 21	8.61	9.34	10	3.6	9	3.34	9	14.5	12.68	7	12.02	9	10	7
Trial 22	11.85	11.74	27	3.49	7	2.72	3	20.29	14.46	19	9.49	4	0	1
Trial 23	9.02	10.01	14	3.2	6	3.16	7	17.39	13.17	9	10.11	5	8	6
Trial 24	8.71	9.17	7	3.89	12	3.34	9	18.09	12.51	6	12.99	11	180	19
Trial 25	6.62	7.47	2	4.78	20	4.18	22	15.29	11.65	2	19.98	19	95	17
Trial 26	10.39	10.38	18	4.41	18	3.47	12	18.8	13.85	14	15.30	15	305	25
Trial 27	7.46	7.98	3	5.71	27	4.9	26	11.85	12.88	8	27.98	27	460	28
Trial 28	12.2	11.71	26	2.6	3	2.16	1	18.4	13.87	15	5.62	2	0	1
Trial 29	10.5	10.22	16	2.24	2	2.25	2	18.68	12.47	5	5.04	1	0	1
Trial 30	5.76	7.43	1	4.55	19	3.98	16	14.42	11.41	1	18.11	18	50	15

Passenger side rank differences					Squared rank differences				
X2 vs. Actual	X3 vs. Actual	X4 vs. Actual	(X2 + X4) vs. Actual	(X3*X4) vs. Actual	X2 vs. Actual	X3 vs. Actual	X4 vs. Actual	(X2 + X4) vs. Actual	(X3*X4) vs. Actual
-19	-1	-9	-17	-4	361	1	81	289	16
29	3	15	29	7	841	9	225	841	49
-22	3	3	-13	3	484	9	9	169	9
-6	0	3	-1	3	36	0	9	1	9
4	-10	-16	0	-11	16	100	256	0	121
-5	-6	-15	-4	-9	25	36	225	16	81
-6	-1	-6	-2	-3	36	1	36	4	9
18	-1	-7	12	-5	324	1	49	144	25
7	9	14	16	12	49	81	196	256	144
-7	-2	-2	-10	-1	49	4	4	100	1
18	4	12	15	6	324	16	144	225	36
-2	-3	8	0	3	4	9	64	0	9
13	4	-3	9	1	169	16	9	81	1
-9	8	8	6	8	81	64	64	36	64
-3	-3	5	2	0	9	9	25	4	0
5	-15	-11	1	-13	25	225	121	1	169
1	6	10	2	7	1	36	100	4	49
-10	3	6	-1	6	100	9	36	1	36
5	5	3	7	4	25	25	9	49	16
-2	8	7	-3	9	4	64	49	9	81
3	2	2	0	2	9	4	4	0	4
26	6	2	18	3	676	36	4	324	9
8	0	1	3	-1	64	0	1	9	1
-12	-7	-10	-13	-8	144	49	100	169	64
-15	3	5	-15	2	225	9	25	225	4
-7	-7	-13	-11	-10	49	49	169	121	100
-25	-1	-2	-20	-1	625	1	4	400	1
25	2	0	14	1	625	4	0	196	1
15	1	1	4	0	225	1	1	16	0
-14	4	1	-14	3	196	16	1	196	9
				sum	5801	884	2020	3886	1118

Test criterion

n = 30

95% Confidence Interval for Sum of Squared Errors				$n*(n^2-1)/6 \pm 2*(n^2*(n-1)*(n+1)^2)/6)^{1/2}$
95% CI for holdout sample	4495	$\pm$	1669	
	range			
2826	$\leq$	ΣD^2	$\leq$ 6164	do not reject H_o

Table C.3: Driver Side Spearman Rank Test for Holdout Test Sample

Driver side twenty-vehicle holdout sample

	X1	X2	X3	Rank X3	X4	Rank X4	X5	X3 + X4	Rank (X3+X4)	Leak volume	Leakage rank
Trial 31	6.75	7.85	4.6	6	2.6	3	20.15	7.20	3	385	11
Trial 32	5.85	7.25	6.8	19	5.25	18	21.55	12.05	19	485	14
Trial 33	4.65	5.68	6.72	17	5.25	18	14.8	11.97	18	565	18
Trial 34	9.38	9.78	2.59	1	1.42	1	19.25	4.01	1	130	2
Trial 35	7.5	8.21	5.31	12	4.32	12	25.49	9.63	12	330	7
Trial 36	5.82	7.18	6.28	15	4.15	10	19.25	10.43	13	205	4
Trial 37	8.15	8.75	5.9	13	4.82	14	15.88	10.72	14	1200	20
Trial 38	5.83	7.2	4.3	3	3.48	6	18.6	7.78	4	460	13
Trial 39	7.59	7.79	5.19	11	3.6	7	23.85	8.79	9	550	17
Trial 40	5.05	6.01	4.09	2	2.01	2	16.81	6.10	2	135	3
Trial 41	4.21	4.82	6.79	18	4.82	14	15.22	11.61	17	350	10
Trial 42	6.62	7.11	5	9	4.4	13	13.1	9.40	11	65	1
Trial 43	5.65	6.01	6.57	16	4.82	14	24	11.39	16	290	5
Trial 44	5.4	6.76	5.09	10	4.08	9	23.2	9.17	10	340	8
Trial 45	5.19	6.39	4.95	8	3.43	5	25.65	8.38	6	340	8
Trial 46	5.4	6.09	4.78	7	3.39	4	14.9	8.17	5	510	15
Trial 47	5.71	6.72	8.73	20	6.9	20	17.38	15.63	20	565	18
Trial 48	7.27	8.69	4.52	4	4.01	8	14.95	8.53	7	310	6
Trial 49	6.99	7.79	4.55	5	4.2	11	11.89	8.75	8	450	12
Trial 50	6.2	6.91	5.93	14	5.11	17	13.19	11.04	15	515	16

Rank differences			Squared rank differences		
X3 vs. Actual	X4 vs. Actual	(X3*X4) vs. Actual	X3 vs. Actual	X4 vs. Actual	(X3*X4) vs. Actual
-5	-8	-8	25	64	64
5	4	5	25	16	25
-1	0	0	1	0	0
-1	-1	-1	1	1	1
5	5	5	25	25	25
11	6	9	121	36	81
-7	-6	-6	49	36	36
-10	-7	-9	100	49	81
-6	-10	-9	36	100	81
-1	-1	-1	1	1	1
8	4	7	64	16	49
8	12	10	64	144	100
11	9	11	121	81	121
2	1	2	4	1	4
0	-3	-2	0	9	4
-8	-11	-10	64	121	100
2	2	2	4	4	4
-2	2	1	4	4	1
-7	-1	-3	49	1	9
-2	1	-1	4	1	1
		Sum	762	710	788

Table C.4: Passenger Side Spearman Rank Test for Holdout Test Sample

Passenger side twenty-vehicle holdout sample

	X1	X2	X3	Rank X3	X4	Rank X4	X5	X3*X4	Rank (X3*X4)	Leak volume	Leakage rank
Trial 31	10.7	9.9	4.45	8	4.2	7	7.5	18.69	8	0	1
Trial 32	7.85	8.3	4.95	11	5.1	13	23.5	25.25	12	40	7
Trial 33	7.85	9.25	3.8	3	2.75	2	16.5	10.45	2	215	13
Trial 34	11.51	11.41	6.1	17	4.9	12	23.52	29.89	16	260	15
Trial 35	11.95	12.42	3.92	4	3.7	4	20.15	14.50	4	10	3
Trial 36	5	5.62	4.98	14	4.71	10	19.59	23.46	11	25	6
Trial 37	7.11	8.6	2.91	1	2.71	1	20.51	7.89	1	8	2
Trial 38	6.2	7.79	4.1	5	4.09	6	19.91	16.77	6	180	12
Trial 39	10.89	11.45	3.31	2	4.21	8	20.45	13.94	3	15	4
Trial 40	10.49	11.09	4.25	6	3.68	3	17.05	15.64	5	815	19
Trial 41	9.34	9.98	4.61	10	3.89	5	16.61	17.93	7	135	10
Trial 42	6.71	8.21	4.95	11	5.26	15	17.57	26.04	13	420	16
Trial 43	7.82	8.75	7.28	18	6.06	18	19.62	44.12	18	510	18
Trial 44	9.66	10.31	4.32	7	4.65	9	23.92	20.09	9	20	5
Trial 45	9.16	10.11	9.29	20	7.41	19	16.26	68.84	20	860	20
Trial 46	6.6	7.9	4.6	9	4.78	11	14.65	21.99	10	60	8
Trial 47	9.25	10.65	8.65	19	7.89	20	13.42	68.25	19	145	11
Trial 48	4.95	6.01	5.75	16	5.69	17	16.45	32.72	17	225	14
Trial 49	9.14	9.99	4.95	11	5.59	16	16.62	27.67	14	465	17
Trial 50	7.31	8.2	5.33	15	5.2	14	18.45	27.72	15	110	9

Rank differences			Squared rank differences		
X3 vs. Actual	X4 vs. Actual	(X3*X4) vs. Actual	X3 vs. Actual	X4 vs. Actual	(X3*X4) vs. Actual
7	6	7	49	36	49
4	6	5	16	36	25
-10	-11	-11	100	121	121
2	-3	1	4	9	1
1	1	1	1	1	1
8	4	5	64	16	25
-1	-1	-1	1	1	1
-7	-6	-6	49	36	36
-2	4	-1	4	16	1
-13	-16	-14	169	256	196
0	-5	-3	0	25	9
-5	-1	-3	25	1	9
0	0	0	0	0	0
2	4	4	4	16	16
0	-1	0	0	1	0
1	3	2	1	9	4
8	9	8	64	81	64
2	3	3	4	9	9
-6	-1	-3	36	1	9
6	5	6	36	25	36
		Sum	627	696	612

Test Criterion					
n =	20				
95% Confidence Interval for Sum of Squared Errors					$n*(n^2-1)/6 \pm 2*(n^2*(n-1)*(n+1)^2)/6)^{1/2}$
95% CI for holdout sample	1330	±	610		
	range				
720	≤	ΣD^2	≤	1940	do not reject H_o

Appendix D - Grid Search Source Code

The following source code was developed for application in the grid search analysis of the SN-95 seal system division bar failure mode. However, it is a generalized code that can be utilized in any grid search analysis.

Note: If use of this code is desired, the code must be entered in the exact format in which it is presented herein, including worksheet names within Microsoft Excel. This is required because named pages are embedded within the source code, and the code will not work unless consistency is maintained.

The following worksheets must be created within a Microsoft Excel document:

- Sheet 1 (calcs)
- Sheet 2 (Start code)
- Sheet 4 (Output)
- Sheet 5 (Input)
- Start (Sheet 1)

Source code for 'Sheet 2 (Start code)'

```
Sub startcode_Click()
   start1

End Sub
```

Source code for 'Sheet 4 (Output)'

```
Private Sub RANKTRIALS_Click()
   Rank
```

```
End Sub
```

Source code for 'Sheet 5 (Input)'

```
Private Sub btnGenerateWeight_Click()
   If Sheets("Sheet1").Cells(4, 2) = 3 Then generateWeight3
   If Sheets("Sheet1").Cells(4, 2) = 4 Then generateWeight4
   If Sheets("Sheet1").Cells(4, 2) = 5 Then generateWeight5
   If Sheets("Sheet1").Cells(4, 2) = 6 Then generateWeight6
   If Sheets("Sheet1").Cells(4, 2) = 7 Then generateWeight7
   If Sheets("Sheet1").Cells(4, 2) = 8 Then generateWeight8

End Sub

Private Sub btnScalePara_Click()
   ScalePara

End Sub
```

Source code for 'Start (Sheet1)'

```
Private Sub btnGenerateMatrix_Click()
   Call GenMatrix
End Sub

Private Sub scorearray_Click()
   actualscore
   a = Sheets("Sheet1").Cells(4, 2).Value
   If a < 3 Or a > 8 Then MsgBox "Number of parameters must be between 3 and 8.  Restart
algorithm."
   If 3 <= a <= 8 Then MsgBox "Enter actual rank score of trials, from best to worst in blue
fields, then click 'Generate Matrix' button."

End Sub
```

The following modules are required to execute the grid search analysis algorithm:

- Module_generic
- Module_3_parameter
- Module_4_parameter
- Module_5_parameter
- Module_6_parameter

- Module_7_parameter
- Module_8_parameter

Source code for 'Module_generic':

```
Sub GenMatrix()

   Dim i As Integer
   Dim x As Integer

   lnumPar = Range("numPar")
   ltrials = Range("trials")
   lscale = Range("scale")
   ReDim matrix(ltrials, lnumPar)
      Sheets("Input").Cells(1, (lnumPar / 2) + 2).Value = "Parameters"

   For i = 1 To lnumPar
     Sheets("Input").Cells(2, i + 2).Value = "X" & i
   Next i

   For x = 1 To ltrials
      Sheets("Input").Cells(x + 2, 2).Value = "Trial " & x
   Next x

   Sheets("Input").Activate
   MsgBox "Enter discretization scale, then click on 'Generate Weighting Factors' button."

End Sub

Public Sub actualscore()

   ltrials = Sheets("Sheet1").Range("trials")
   Cells((ltrials + 3), 5).Value = "Worst performance"
'   blu = Range(Cells(4, 4), Cells((3 + ltrials), 4))
'   Set blu = Range(Cells(4, 4), Cells((3 + ltrials), 4))
'   blu.Interior.ColorIndex = 45

End Sub

Public Sub ScalePara()

   Dim x As Integer
   Dim y As Integer
   Dim z As Integer
   Dim e As Integer
   Dim a As Integer
   Dim m As Double
```

```
    Dim n As Double
    Dim o As Double
    Dim p As Double
    Dim q As Double

    lnumPar = Sheets("Sheet1").Range("numPar")
    ltrials = Sheets("Sheet1").Range("trials")
    localnum = Sheets("Sheet1").Range("numPar")
    totalnum = Sheets("Input").Range("totalnum")

    e = 1
    For z = 2 To (totalnum + 1)
        For y = 3 To (ltrials + 2)
            For x = 3 To (lnumPar + 2)
            m = Sheets("Input").Cells(y, x).Value
            n = Sheets("Input").Cells(z, (localnum + (x + 3))).Value
            o = m * n
            Sheets("calcs").Cells(y, x).Value = o
            Next x
            Sheets("Output").Cells(e + 1, y).Value = (Sheets("calcs").Cells(y, 3) +
Sheets("calcs").Cells(y, 4) + Sheets("calcs").Cells(y, 5) + Sheets("calcs").Cells(y, 6) +
Sheets("calcs").Cells(y, 7) + Sheets("calcs").Cells(y, 8) + Sheets("calcs").Cells(y, 9) +
Sheets("calcs").Cells(y, 10))
        Sheets("Output").Cells(1, y).Value = "Trial " & (y - 2)
        Next y
        Sheets("Output").Cells(e + 1, 2).Value = "Permutation " & (e)
        e = e + 1

    Next z
    Sheets("Output").Activate
    MsgBox "Click 'Rank trials' button to perform ranking function."

End Sub

Public Sub Rank()

    Dim a As Integer
    Dim b As Integer
    Dim p As Integer
    Dim q As Integer
    Dim r As Integer
    Dim c As Integer
    Dim x As Integer
    lnumPar = Range("numPar")
    totalnum = Sheets("Input").Range("totalnum")
    ltrials = Sheets("Sheet1").Range("trials")
    Sheets("Output").Cells(1, (ltrials + (ltrials / 2) + 3)).Value = "Trial Rank"
    Sheets("Output").Cells(1, ((2 * ltrials) + 5)).Value = "Sum of Squared Error"

    For b = 2 To (totalnum + 1)
        For a = 3 To (ltrials + 2)
```

```
            Sheets("Output").Cells(b, (ltrials + a + 1)).Value = _
            Application.Rank(Cells(b, a), Range(Cells(b, 3), Cells(b, (2 + ltrials))), 1)
        Next a
    Next b

'Sum square error subroutine

    For s = 2 To (totalnum + 1)
        For r = 4 To (ltrials + 3)
            p = Sheets("Sheet1").Cells(r, 4)
            q = Sheets("Output").Cells(s, (ltrials + r))
            Sheets("calcs").Cells(1, 1).Value = "p"
            Sheets("calcs").Cells(1, 2).Value = "q"
            Sheets("calcs").Cells(r - 2, 1).Value = p
            Sheets("calcs").Cells((r - 2), 2).Value = q
            Sheets("calcs").Cells((r - 2), 3).Value = (p - q) ^ 2
        Next r

        Sheets("Output").Cells(s, (2 * ltrials + 5)).Value =
Application.Sum(Range(Sheets("calcs").Cells(2, 3), Sheets("calcs").Cells((ltrials + 1), 3)))
    Next s
    Sheets("Output").Cells((s + 2), (2 * ltrials + 6)).Value = "Minimum sum of squared errors"
    Sheets("Output").Cells((s + 2), (2 * ltrials + 5)).Value =
Application.Min(Range(Sheets("Output").Cells(2, (2 * ltrials + 5)), Sheets("Output").Cells((b
+ 1), (2 * ltrials + 5))))
    Sheets("Output").Cells((s + 3), (2 * ltrials + 6)).Value = "Worst case sum of squared errors
possible"
    For c = 0 To (ltrials - 1)
        Sheets("calcs").Cells((c + 1), 20).Value = (((ltrials - c) - (c + 1)) ^ 2)
    Next c
    Sheets("Output").Cells((s + 3), (2 * ltrials + 5)).Value =
Application.Sum(Range(Sheets("calcs").Cells(1, 20), Sheets("calcs").Cells(ltrials, 20)))

'Location of optimal weighting factors

    For x = 1 To lnumPar
        Sheets("Output").Cells((s + 6), ((2 * ltrials) + x)).Value = "Parameter " & x
    Next x
    Sheets("Output").Cells((s + 7), (2 * ltrials - 2)).Value = "Optimal weighting factor
combination"
End Sub
Public Sub start1()
'   MsgBox "Click 'Start algorithm' button to begin."
    Sheets("Sheet1").Activate
    MsgBox "Enter number of parameters, and number of trials, then click 'Generate score
array' button."
End Sub
```

```
'Public Sub storeobject()
'   blu = Range(Cells(4, 4), Cells((3 + ltrials), 4))
'   Set blu = Range(Cells(4, 4), Cells((3 + ltrials), 4))
'   blu.Interior.ColorIndex = 45
'End Sub
'Public Sub setobject()
'   Set blu = Range(Cells(4, 4), Cells((3 + ltrials), 4)).Interior
'
'End Sub
```

Source code for 'Module_3_parameter':

```
Dim lnumPar As Integer
Dim lscale As Double
Dim ltrials As Integer
Dim matrix()
Sub fillmatrix3()
Sheets("Output").Activate
End Sub
Public Sub generateWeight3()
   Dim a As Integer
   Dim a1 As Double
   Dim b As Integer
   Dim b1 As Double
   Dim c As Integer
   Dim c1 As Double
   Dim d As Integer
   Dim d1 As Double
   Dim e As Integer
   Dim e1 As Double
   Dim f As Integer
   Dim f1 As Double
   Dim g As Integer
   Dim totalnum As Integer
   localScale = Range("scale")
   localnum = Range("numPar")
   e = 0
   d1 = 1
   For a = 0 To 1 / localScale
      a1 = localScale * a
      For b = 0 To (1 / localScale)
         b1 = localScale * b
            d1 = 1 - (a1 + b1)
            If d1 < -0.001 Then Exit For
               Sheets("Input").Cells((e + 2), localnum + 6).Value = a1
               Sheets("Input").Cells((e + 2), localnum + 7).Value = b1
               Sheets("Input").Cells((e + 2), localnum + 8).Value = d1
            e = e + 1
      Next b
```

```
    Next a
    Sheets("Input").Cells(1, 10).Value = e
    MsgBox "Enter parameter values, then click on 'Scale Parameters' button."
End Sub
```

Source code for 'Module_4_parameter':

```
Dim lnumPar As Integer
Dim lscale As Double
Dim ltrials As Integer
Dim matrix()
Sub fillmatrix4()
Sheets("Output").Activate
End Sub
Public Sub generateWeight4()
    Dim a As Integer
    Dim a1 As Double
    Dim b As Integer
    Dim b1 As Double
    Dim c As Integer
    Dim c1 As Double
    Dim d As Integer
    Dim d1 As Double
    Dim e As Integer
    Dim e1 As Double
    Dim f As Integer
    Dim f1 As Double
    Dim g As Integer
    Dim totalnum As Integer
    localScale = Range("scale")
    localnum = Range("numPar")
    e = 0
    d1 = 1
    For a = 0 To 1 / localScale
        a1 = localScale * a
        For b = 0 To (1 / localScale)
            b1 = localScale * b
                For c = 0 To (1 / localScale)
                c1 = localScale * c
                d1 = 1 - (a1 + b1 + c1)
                If d1 < -0.001 Then Exit For
                    Sheets("Input").Cells((e + 2), localnum + 6).Value = a1
                    Sheets("Input").Cells((e + 2), localnum + 7).Value = b1
                    Sheets("Input").Cells((e + 2), localnum + 8).Value = c1
                    Sheets("Input").Cells((e + 2), localnum + 9).Value = d1
                e = e + 1
                Next c
        Next b
    Next a
```

```
    Sheets("Input").Cells(1, 10).Value = e
    MsgBox "Enter parameter values, then click on 'Scale Parameters' button."
End Sub
```

Source code for 'Module_5_parameter':

```
Public Sub generateWeight5()

    Dim a As Integer
    Dim a1 As Double
    Dim b As Integer
    Dim b1 As Double
    Dim c As Integer
    Dim c1 As Double
    Dim d As Integer
    Dim d1 As Double
    Dim e As Integer
    Dim e1 As Double
    Dim f As Integer
    Dim f1 As Double
    Dim g As Integer
    Dim totalnum As Integer

    localScale = Range("scale")
    localnum = Range("numPar")

    e = 0
    e1 = 1

    For a = 0 To 1 / localScale
        a1 = localScale * a
        For b = 0 To (1 / localScale)
            b1 = localScale * b
                For c = 0 To (1 / localScale)
                c1 = localScale * c
                    For d = 0 To (1 / localScale)
                    d1 = localScale * d
                    e1 = 1 - (a1 + b1 + c1 + d1)
                    If e1 < -0.001 Then Exit For

                    Sheets("Input").Cells((e + 2), localnum + 6).Value = a1
                    Sheets("Input").Cells((e + 2), localnum + 7).Value = b1
                    Sheets("Input").Cells((e + 2), localnum + 8).Value = c1
                    Sheets("Input").Cells((e + 2), localnum + 9).Value = d1
                    Sheets("Input").Cells((e + 2), localnum + 10).Value = e1

                    e = e + 1

                Next d
```

```
        Next c
      Next b
    Next a

    Sheets("Input").Cells(1, 10).Value = e
    MsgBox "Enter parameter values, then click on 'Scale Parameters' button."
End Sub
```

Source code for 'Module_6_parameter':

```
Public Sub generateWeight6()

    Dim a As Integer
    Dim a1 As Double
    Dim b As Integer
    Dim b1 As Double
    Dim c As Integer
    Dim c1 As Double
    Dim d As Integer
    Dim d1 As Double
    Dim e As Integer
    Dim e1 As Double
    Dim f As Integer
    Dim f1 As Double
    Dim g As Integer
    Dim g1 As Double
    Dim h As Integer
    Dim h1 As Double
    Dim i As Integer
    Dim i1 As Double

    Dim totalnum As Integer

    localScale = Range("scale")
    localnum = Range("numPar")

    e = 0
    e1 = 1

    For a = 0 To 1 / localScale
      a1 = localScale * a
      For b = 0 To (1 / localScale)
        b1 = localScale * b
          For c = 0 To (1 / localScale)
          c1 = localScale * c
            For d = 0 To (1 / localScale)
            d1 = localScale * d
              For f = 0 To (1 / localScale)
              f1 = localScale * f
```

```
                    e1 = 1 - (a1 + b1 + c1 + d1 + f1)
                    If e1 < -0.001 Then Exit For

                    Sheets("Input").Cells((e + 2), localnum + 6).Value = a1
                    Sheets("Input").Cells((e + 2), localnum + 7).Value = b1
                    Sheets("Input").Cells((e + 2), localnum + 8).Value = c1
                    Sheets("Input").Cells((e + 2), localnum + 9).Value = d1
                    Sheets("Input").Cells((e + 2), localnum + 10).Value = f1
                    Sheets("Input").Cells((e + 2), localnum + 11).Value = e1

                    e = e + 1

                Next f
            Next d
        Next c
    Next b
Next a

Sheets("Input").Cells(1, 10).Value = e
MsgBox "Enter parameter values, then click on 'Scale Parameters' button."

End Sub
```

Source code for 'Module_7_parameter':

```
Public Sub generateWeight7()

    Dim a As Integer
    Dim a1 As Double
    Dim b As Integer
    Dim b1 As Double
    Dim c As Integer
    Dim c1 As Double
    Dim d As Integer
    Dim d1 As Double
    Dim e As Integer
    Dim e1 As Double
    Dim f As Integer
    Dim f1 As Double
    Dim g As Integer
    Dim g1 As Double
    Dim h As Integer
    Dim h1 As Double
    Dim i As Integer
    Dim i1 As Double

    Dim totalnum As Integer

    localScale = Range("scale")
```

```
    localnum = Range("numPar")

    e = 0
    e1 = 1

    For a = 0 To 1 / localScale
      a1 = localScale * a
      For b = 0 To (1 / localScale)
        b1 = localScale * b
          For c = 0 To (1 / localScale)
          c1 = localScale * c
            For d = 0 To (1 / localScale)
            d1 = localScale * d
              For f = 0 To (1 / localScale)
              f1 = localScale * f
              For g = 0 To (1 / localScale)
              g1 = localScale * g
              e1 = 1 - (a1 + b1 + c1 + d1 + f1 + g1)
              If e1 < -0.001 Then Exit For

              Sheets("Input").Cells((e + 2), localnum + 6).Value = a1
              Sheets("Input").Cells((e + 2), localnum + 7).Value = b1
              Sheets("Input").Cells((e + 2), localnum + 8).Value = c1
              Sheets("Input").Cells((e + 2), localnum + 9).Value = d1
              Sheets("Input").Cells((e + 2), localnum + 10).Value = f1
              Sheets("Input").Cells((e + 2), localnum + 11).Value = g1
              Sheets("Input").Cells((e + 2), localnum + 12).Value = e1

              e = e + 1

            Next g
            Next f
          Next d
        Next c
      Next b
    Next a

    Sheets("Input").Cells(1, 10).Value = e

    MsgBox "Enter parameter values, then click on 'Scale Parameters' button."

  End Sub
```

Source code for 'Module_8_parameter':

```
  Public Sub generateWeight8()

    Dim a As Integer
```

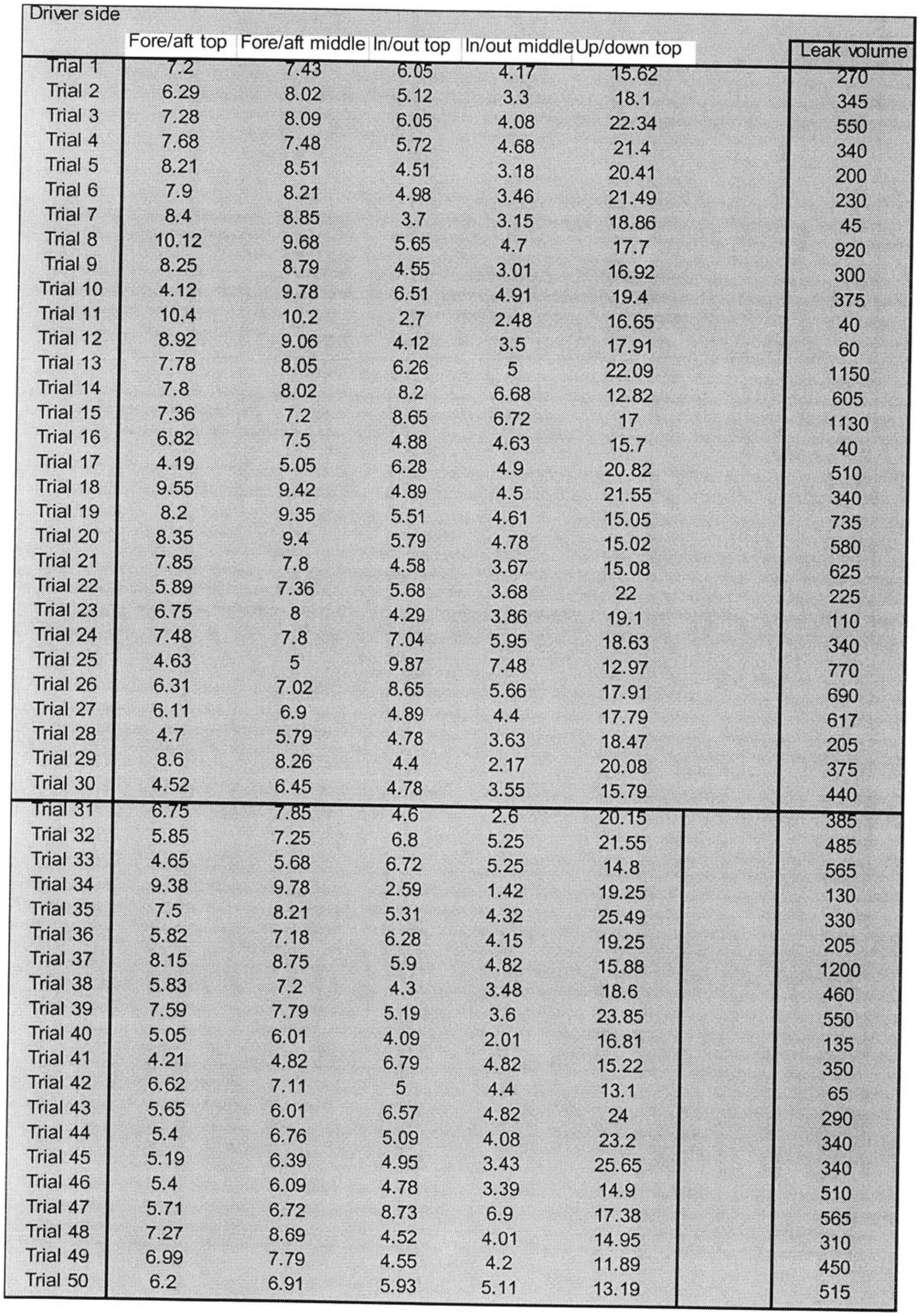
```
Dim a1 As Double
Dim b As Integer
Dim b1 As Double
Dim c As Integer
Dim c1 As Double
Dim d As Integer
Dim d1 As Double
Dim e As Integer
Dim e1 As Double
Dim f As Integer
Dim f1 As Double
Dim g As Integer
Dim g1 As Double
Dim h As Integer
Dim h1 As Double
Dim i As Integer
Dim i1 As Double

Dim totalnum As Integer

localScale = Range("scale")
localnum = Range("numPar")

e = 0
e1 = 1

For a = 0 To 1 / localScale
   a1 = localScale * a
   For b = 0 To (1 / localScale)
      b1 = localScale * b
         For c = 0 To (1 / localScale)
         c1 = localScale * c
            For d = 0 To (1 / localScale)
            d1 = localScale * d
               For f = 0 To (1 / localScale)
               f1 = localScale * f
               For g = 0 To (1 / localScale)
               g1 = localScale * g
               For h = 0 To (1 / localScale)
               h1 = localScale * h
               e1 = 1 - (a1 + b1 + c1 + d1 + f1 + g1 + h1)
               If e1 < -0.001 Then Exit For

               Sheets("Input").Cells((e + 2), localnum + 6).Value = a1
               Sheets("Input").Cells((e + 2), localnum + 7).Value = b1
               Sheets("Input").Cells((e + 2), localnum + 8).Value = c1
               Sheets("Input").Cells((e + 2), localnum + 9).Value = d1
               Sheets("Input").Cells((e + 2), localnum + 10).Value = f1
               Sheets("Input").Cells((e + 2), localnum + 11).Value = g1
               Sheets("Input").Cells((e + 2), localnum + 12).Value = h1
               Sheets("Input").Cells((e + 2), localnum + 13).Value = e1
```

```
                e = e + 1

              Next h
              Next g
              Next f
            Next d
          Next c
        Next b
      Next a

      Sheets("Input").Cells(1, 10).Value = e

      MsgBox "Enter parameter values, then click on 'Scale Parameters' button."

    End Sub
```

(This page intentionally blank)

Appendix E - Raw Data Utilized in Grid Search Analysis

Driver side data - first 30 data points used for model calibration, remaining 20 data points used as 'hold out' verification sample.



Driver side

	Fore/aft top	Fore/aft middle	In/out top	In/out middle	Up/down top	Leak volume
Trial 1	7.2	7.43	6.05	4.17	15.62	270
Trial 2	6.29	8.02	5.12	3.3	18.1	345
Trial 3	7.28	8.09	6.05	4.08	22.34	550
Trial 4	7.68	7.48	5.72	4.68	21.4	340
Trial 5	8.21	8.51	4.51	3.18	20.41	200
Trial 6	7.9	8.21	4.98	3.46	21.49	230
Trial 7	8.4	8.85	3.7	3.15	18.86	45
Trial 8	10.12	9.68	5.65	4.7	17.7	920
Trial 9	8.25	8.79	4.55	3.01	16.92	300
Trial 10	4.12	9.78	6.51	4.91	19.4	375
Trial 11	10.4	10.2	2.7	2.48	16.65	40
Trial 12	8.92	9.06	4.12	3.5	17.91	60
Trial 13	7.78	8.05	6.26	5	22.09	1150
Trial 14	7.8	8.02	8.2	6.68	12.82	605
Trial 15	7.36	7.2	8.65	6.72	17	1130
Trial 16	6.82	7.5	4.88	4.63	15.7	40
Trial 17	4.19	5.05	6.28	4.9	20.82	510
Trial 18	9.55	9.42	4.89	4.5	21.55	340
Trial 19	8.2	9.35	5.51	4.61	15.05	735
Trial 20	8.35	9.4	5.79	4.78	15.02	580
Trial 21	7.85	7.8	4.58	3.67	15.08	625
Trial 22	5.89	7.36	5.68	3.68	22	225
Trial 23	6.75	8	4.29	3.86	19.1	110
Trial 24	7.48	7.8	7.04	5.95	18.63	340
Trial 25	4.63	5	9.87	7.48	12.97	770
Trial 26	6.31	7.02	8.65	5.66	17.91	690
Trial 27	6.11	6.9	4.89	4.4	17.79	617
Trial 28	4.7	5.79	4.78	3.63	18.47	205
Trial 29	8.6	8.26	4.4	2.17	20.08	375
Trial 30	4.52	6.45	4.78	3.55	15.79	440
Trial 31	6.75	7.85	4.6	2.6	20.15	385
Trial 32	5.85	7.25	6.8	5.25	21.55	485
Trial 33	4.65	5.68	6.72	5.25	14.8	565
Trial 34	9.38	9.78	2.59	1.42	19.25	130
Trial 35	7.5	8.21	5.31	4.32	25.49	330
Trial 36	5.82	7.18	6.28	4.15	19.25	205
Trial 37	8.15	8.75	5.9	4.82	15.88	1200
Trial 38	5.83	7.2	4.3	3.48	18.6	460
Trial 39	7.59	7.79	5.19	3.6	23.85	550
Trial 40	5.05	6.01	4.09	2.01	16.81	135
Trial 41	4.21	4.82	6.79	4.82	15.22	350
Trial 42	6.62	7.11	5	4.4	13.1	65
Trial 43	5.65	6.01	6.57	4.82	24	290
Trial 44	5.4	6.76	5.09	4.08	23.2	340
Trial 45	5.19	6.39	4.95	3.43	25.65	340
Trial 46	5.4	6.09	4.78	3.39	14.9	510
Trial 47	5.71	6.72	8.73	6.9	17.38	565
Trial 48	7.27	8.69	4.52	4.01	14.95	310
Trial 49	6.99	7.79	4.55	4.2	11.89	450
Trial 50	6.2	6.91	5.93	5.11	13.19	515

Passenger side data - first 30 data points used for model calibration, remaining 20 data points used as 'hold out' verification sample.

Passenger side	X1	X2	X3	X4	X5		Leak volume
Trial 1	9.22	9.3	5.4	3.99	19		440
Trial 2	14.3	12.9	2.73	3.98	18.55		0
Trial 3	7.82	8.3	6.58	5.42	20.4		435
Trial 4	10.79	10.1	4.99	4.5	18.8		245
Trial 5	11.21	11.94	4.02	3.32	19.45		265
Trial 6	11.61	11.4	5.31	3.94	16.79		745
Trial 7	11.31	11.15	5.79	4.32	19.45		465
Trial 8	11.8	12.21	3.8	2.79	19.3		25
Trial 9	9.82	10.95	5.05	4.95	16.96		35
Trial 10	9.1	8.91	3.81	3.45	22.06		35
Trial 11	10.19	10.4	3.09	3.5	18.16		0
Trial 12	8.77	9.31	3.51	4	20.28		25
Trial 13	10.68	11.05	3.98	3.08	22.74		15
Trial 14	9.63	9.93	6.82	5.91	21.61		255
Trial 15	9.82	10.31	4.4	4.61	18.48		202
Trial 16	10.59	11.01	2.2	3.02	13.65		90
Trial 17	8.68	9.58	4.39	4.1	18.69		20
Trial 18	9.58	9.59	5.36	5.22	21		255
Trial 19	10.25	11.15	5.21	4.12	13.51		165
Trial 20	7.55	8.59	4.16	3.8	15.63		10
Trial 21	8.61	9.34	3.6	3.34	14.5		10
Trial 22	11.85	11.74	3.49	2.72	20.29		0
Trial 23	9.02	10.01	3.2	3.16	17.39		8
Trial 24	8.71	9.17	3.89	3.34	18.09		180
Trial 25	6.62	7.47	4.78	4.18	15.29		95
Trial 26	10.39	10.38	4.41	3.47	18.8		305
Trial 27	7.46	7.98	5.71	4.9	11.85		460
Trial 28	12.2	11.71	2.6	2.16	18.4		0
Trial 29	10.5	10.22	2.24	2.25	18.68		0
Trial 30	5.76	7.43	4.55	3.98	14.42		50
Trial 31	10.7	9.9	4.45	4.2	7.5		0
Trial 32	7.85	8.3	4.95	5.1	23.5		40
Trial 33	7.85	9.25	3.8	2.75	16.5		215
Trial 34	11.51	11.41	6.1	4.9	23.52		260
Trial 35	11.95	12.42	3.92	3.7	20.15		10
Trial 36	5	5.62	4.98	4.71	19.59		25
Trial 37	7.11	8.6	2.91	2.71	20.51		8
Trial 38	6.2	7.79	4.1	4.09	19.91		180
Trial 39	10.89	11.45	3.31	4.21	20.45		15
Trial 40	10.49	11.09	4.25	3.68	17.05		815
Trial 41	9.34	9.98	4.61	3.89	16.61		135
Trial 42	6.71	8.21	4.95	5.26	17.57		420
Trial 43	7.82	8.75	7.28	6.06	19.62		510
Trial 44	9.66	10.31	4.32	4.65	23.92		20
Trial 45	9.16	10.11	9.29	7.41	16.26		860
Trial 46	6.6	7.9	4.6	4.78	14.65		60
Trial 47	9.25	10.65	8.65	7.89	13.42		145
Trial 48	4.95	6.01	5.75	5.69	16.45		225
Trial 49	9.14	9.99	4.95	5.59	16.62		465
Trial 50	7.31	8.2	5.33	5.2	18.45		110