

Uncovering and Avoiding Failure Modes in Driveline and Tire/Wheel NVH using a Computational Meta-Model

by

Paul R. Braunwart

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

Master of Science in Engineering and Management


at the
Massachusetts Institute of Technology

February 2007

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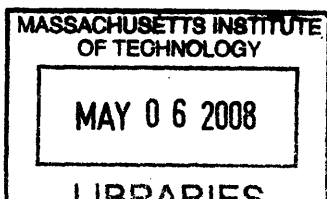

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Abstract

The automotive industry has undergone significant changes in recent years with increased competition and the introduction of new manufacturers into the market. With this changing market, a more efficient approach to Noise Vibration and Harshness (NVH) development is needed to foster better decisions and support the compressed product development timing required by the market.

To address this, the “Slider Bar” process and meta-model are presented. Based on the failure mode avoidance approach, the process and model allow the engineering teams to uncover and avoid potential tire/wheel and driveline NVH failure modes. Therefore, early in the product development process, development teams can identify control and noise factor limits and system level effects, avoid potential NVH failure modes, and develop appropriate countermeasures.

Using insights from innovation diffusion theory, the process and tool were deployed systematically to NVH community, with user insights used to adapt and improve the process and tools. Based on this work, a strategy is introduced for the development and adoption of a failure mode avoidance initiative.

Thesis Supervisor:

Dan Frey

Assistant Professor of Mechanical Engineering & Engineering Systems

Acknowledgements

Ford Motor Company

I would like to thank the management of Ford Motor Company for sponsoring me for the program. In particular, I would like to thank Mike Haffey, Chun Wu and Dave Payne for suggesting the program and then championing my nomination.

Additionally, I am grateful to my direct management team for encouraging me in my class studies and research. Both of my managers, Mike Haffey and Tom Lahvic, have been extremely supportive of my studies and this project, and my supervisors, Chun Wu and Joe Mark, were extremely accommodating of my schedule and provided me with the time and support to complete this project.

For my co-workers – Mark Daly, Pat Moore and Nae-Ming Shiau, I thank you for your continued support of this project and for the section business. Without your support, this would not have been possible, and I am forever grateful.

I am particularly indebted to the “Slider Bar” Team. I would like to thank Mark Clapper and Bob Thomas for their technical leadership in NVH and applied statistics respectively. Additionally, I am grateful to Steve Borders for his expertise in CAE and willingness to try new models, John Huber for his willingness to develop the necessary computer interfaces and enablers, Chris Billman for establishing the statistical foundation and Mounir Blichebe for piloting the process from start to finish on the SUV test case.

MIT

First, I would like to thank Professor Dan Frey of his support for this project and for providing the system engineering foundation. In particular, your review and comments were crucial to framing this work.

While at MIT, I had the pleasure to study with a group of amazing professors, all of which have influenced my education. In particular, I would to thank Professors Jim Utterback, Eric von Hippel and Tom Allen for providing new perspectives on innovation and the diffusion of technology. Additionally, Professor Oliver de Weck and Jim Lyneis established the program management foundation and introduced me to systems dynamics, which has changed my perspective and understanding of systems. Finally, I need to thank Professor Nancy Leveson and Michael Cusumano for expanding my scope beyond mechanical systems into the software domain as well.

In addition, I need to thank the ESD community and entire SDM staff for their support and guidance throughout my time at MIT. In particular, I would like to thank Pat Hale, SDM Director, for all of his help and support during the program. Additionally, I am grateful to Ted

Hoppe and Bill Foley for their help coordinating the logistics of the program, ensuring my completion.

During my time at MIT, I have been fortunate to have met, worked with and learned from my SDM friends and project teammates. In particular, I would like to thank Kevin Baughey, Jason Slagle and Jeff Lloyd to for their work on making our many assignment together interesting, challenging and enlightening.

Family

I have been blessed with a supportive family, and without them, none of this would have been possible. In particular, I am eternally indebted to Karen, my loving wife, for her continued support through the classes, projects and thesis work. Secondly, I would like to thank my parents for encouraging me to learn from an early age. Finally, I would like to thank Kevin, Sean and Kiera – my wonderful children and the true joys of my life. Your curiosity in the world and sense of adventure continue to spark my own.

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Chapter 1: Introduction

The North American automotive industry has undergone significant changes in recent years, including increased competition and the introduction of new manufacturers into the market. The traditional Big 3 automotive manufacturers have expanded to the new Big 6, and the average showroom age is declining from nearly four years to three years for a vehicle.

Given the competitive market, the current approach to Noise Vibration and Harshness (NVH) development is no longer appropriate. A quick, cost-effective process is needed to allow NVH development engineers to make better up-front decisions and support the compressed product development timing required by the market.

To accomplish this, Ford NVH must establish a failure mode free driveline and tire/wheel NVH design process, which enables program NVH teams to make informed hardware decisions with respect to driveline and tire/wheel NVH. Additionally, appropriate analytical tools must be developed to facilitate the NVH development process.

1.1 Hypothesis

A robust process must be developed and adopted to avoid failure modes and meet the critical customer-level NVH metrics for sound and vibration. Specifically, a computational meta-model based on failure mode avoidance uncovers the same failure modes as physical testing earlier in the product development cycle, allowing automotive NVH engineers to make appropriate design decision earlier in the product development timeline. Additionally, this work presents a

systematic strategy based on failure mode avoidance and diffusion of innovation theory for developing and diffusing a failure mode avoidance process to eliminate systemic failure modes.

To examine these propositions, this work will focus on developing an appropriate process, determining realistic control and noise factor ranging, establishing robust analytical and test procedures, and developing the appropriate tools to support the process. Additionally, key aspects of innovation diffusion theory are used to foster the adoption among the NVH community.

1.2 Scope

Over the last several years, failure mode avoidance has emerged as a powerful approach to improving system reliability and robustness. While researchers such as Tim Davis and Don Clausing are further developing and redefining the methodology, there are many opportunities for investigation, and this thesis focuses the application of the failure mode avoidance approach to tire/wheel and driveline NVH. Spherically, this work examines the development and spread of a meta-model for uncovering and avoiding failure modes.

1.3 Thesis Structure

This thesis consists of seven chapters, beginning with this introductory chapter, which presents of the motivation, hypothesis and thesis structure. The remaining chapters examine applicable literature, establish the background, present the results and provide conclusions and next steps.

Chapter 2 is a review of relevant literature of pertaining to both the failure mode avoidance philosophy and innovation diffusion approaches. Specifically, the chapter first examines robustness from classical experimental design through the Taguchi robust design method to the

emergence of failure mode avoidance. Then literature related to the innovation diffusion is reviewed, beginning with innovation aspects through factors affecting its adoption over time.

The third chapter discusses the failure mode avoidance approach. First, the emerging definition of reliability as failure mode avoidance definition is presented, along with its applicability to NVH. The types of failure modes and robustness improvement strategies to address these are examined. Next, the traditional experimental design approaches to robustness are discussed, as well as supporting tools such as the parameter diagram (P-diagram). Newer response surface methods, including design types, are examined. Two approaches to avoiding failure modes are presented – the operating window and distance to failure mode. Finally, the “Slider Bar” meta-model, which allows the engineer to assess graphically the distance to failure modes and sensitivity to noise, is introduced.

In Chapter 4, the diffusion of innovation is discussed, beginning with examination of innovation types and the characteristics of innovations that spread quickly. Then the source and receiver attributes are examined with respect to diffusion. Next contextual and organizational issues affecting diffusion are discussed, including institutional and environmental factors, cultural issues, managerial factors, and training. Finally, adoption rate and strategies for promoting diffusion are presented.

The fifth chapter discusses the method used for the “Slider Bar” development and subsequent diffusion among the NVH community. First, the objective measurements are determined, the P-diagram developed, and the appropriate control and noise factors are established. The CAE

modeling and processing are then discussed, along with the statistical analysis needed to generate the parameters for the meta-model. The analysis and verification of the “Slider Bar” model is presented. With the model developed, the chapter concludes with a discussion of the techniques used to spread the model.

The research results and discussion are presented in Chapter 6, beginning with an examination of the experimental design findings. Next, the verification analysis is examined, and the “Slider Bar” results are then presented for the three vehicles – a truck, sports utility vehicle, and a car. The diffusion results are then presented, especially the valuable insight provided by members of the community. Finally, a resultant strategy is introduced to address the development and adoption of a failure mode avoidance initiative.

Finally, Chapter 7 draws conclusions from the experimental and diffusion results. Then, potential next steps are recommended for continuing research in NVH and other closely related attributes.

Chapter 2: Literature Review

With the motivation and objectives established, this chapter presents a review of relevant literature of pertaining to both the failure mode avoidance and innovation diffusion approaches. Specifically, the chapter first will examine robustness from classical experimental design through the Taguchi robust design method to the emergence of failure mode avoidance. Then literature on innovations and diffusion is examined, beginning with innovation aspects through factors affecting its adoption over time.

2.1 Robustness

Design of Experiments (DOE) is a statistical method to assess the cause-effect relationship between multiple factors (inputs) and response (output). Developed in the 1920's and 1930's, the method was introduced by Sir R.A. Fisher, who used DOE to study the factors affecting crop yield in agriculture. Additionally, Fisher developed and introduced the analysis of variance (ANOVA) as the standard analysis technique for the experimental design. A leader in the field, Fisher published several papers regarding the subject, including his seminal work, *Design of Experiments*, in 1935. The first commercial applications were in the British textile industry, with the method expanding to the Western Europe and the United States after the Second World War.

While traditional DOE focused on adjusting the mean, Taguchi (1986 and 1987) emphasized reducing variability and then adjusting to target, encouraging engineers to subject the system to realistic noise conditions. Additionally, Taguchi categorized the five sources of noise affecting a system and introduced the *Quality Loss Function (QLF)* to quantify the effects of variation around the target and the potential loss to society.

To detect failure modes, Taguchi uses the concept of signal-to-noise ratio (S/N) – ideal output divided by the undesired output due to the error status. Since the S/N ratio is simply a measure of output, it can be determined experimentally and does not require the formulation of transfer functions, and Taguchi suggests increasing this ratio will yield system improvement and lead to failure mode avoidance.

However, further analysis by Leon, Shoemaker and Kacher (1987) demonstrates the S/N (closeness to target) was appropriate only when the variation was proportional to the mean response. Box (1988) argues only in this case does the signal-to-noise ratio reliably predict a failure mode is present and suggests “data analytic methods” are better at revealing information in experimental data than techniques like Taguchi’s S/N ratio.

Nair, Taam and Ye (2002), meanwhile, examine a more general and flexible for analyzing the location and dispersion effects for robustness studies. The authors argue the type of design used and nature of the data should guide the choice of analysis method, rather than trying to “force-fit” a single method like Taguchi’s S/N ratio analysis to all situations.” (Nair, Taam and Ye, 2002)

In addition, Davis (2004b) notes formulating the TF correctly and embedding the robustness in it can overcome the limitations of the S/N approach. Accordingly, he proposes measuring robustness as a function of the system transfer function, rather than the signal-to-noise ratio.

2.2 Failure Mode Avoidance and Operating Windows

While traditional reliability has focused on the probability a product will perform its intended function, Clausing (2004) offers a simpler definition – “reliability is failure-mode avoidance”, where a failure mode is any customer-perceived deviation from the desired function of the product.

Clausing (2004) describes the concept of *Operating Window* (OW), which is a metric for measuring and improving the system robustness. Initially developed during his tenure at Xerox in the 1970’s, the OW represents a range where the system functions without failure, with goal of expanding the window as broad as possible.

Building on the Operating Window concept, Clausing and Frey (2005) discuss the method’s use for failure mode avoidance, proposing four strategies to expand the operating window for single-sided failure modes. Additionally, the authors argue the failure-mode avoidance method leads to improvements with minimum data, which is particularly useful in the early stages of development where data may be limited. Further, Clausing and Frey (2005) suggest probabilistic formulations may be too quantitative and “imply a level of precision in modeling the scenario that is often unwarranted, especially during early development.” The OW method, meanwhile, exposes robustness issues early in the development cycle by employing large magnitudes of noise to the system.

Expanding on the concept from Clausing, Joseph and Wu (2002) provide a rigorous statistical foundation for the operating window method and propose a new modeling and optimization strategy to improve the method.

Davis (2004a) notes science is governed by three fundamental principles- symmetry, parsimony and unification. Symmetry implies certain things look the same before and after the system has undergone a sequence of operations. Parsimony is the concept of “making things as simple as possible (but not simpler)”, while unification is the idea of combining different concepts into the same framework. Related to these principles, Davis notes the parsimony of the reliability definition offered by Clausing (2004), argues a failure mode is anything that disrupts symmetry and introduces failure mode avoidance concept to unify the concepts into a single framework.

For the framework, Davis (2004a) introduces a universal metric for assessing the propensity for a design to fail – *distance to failure mode*. Based on the physics, geometry and physical properties, the fundamental idea is to move the system response as far from failure mode as possible. The concept can be expanded to variability due to noise, degradation due to time and degradation over a range of input, and the variability has the same units as the nominal response.

Additionally, Davis (2004b) argues failure mode avoidance requires uncovering failure modes early and adopting a counter measure. Uncovering the failure modes later in process causes “late engineering changes, inflated design costs, poor launches, excessive warranty, low customer satisfaction and significantly reduced owner loyalty.” Accordingly, Davis (2004b) suggests there are two ways to uncover failure modes early in the product development process – testing

and analysis. Testing is important; however, it is limited by the engineer's ability to apply the noise factors encountered during operation. Analysis, meanwhile, uses the transfer function to relate the system output to the prescribed inputs.

In conjunction with Davis, Brown (2004) notes the emergence of failure mode avoidance as a definition of reliability. Additionally, Zhou (2005) expands on the failure mode avoidance work of Davis, noting the potential failure modes may differ for each unique market, and for global product development, engineers must consider this.

2.3 Robustness and Failure Mode Avoidance in automotive NVH

Mahajan, Surella and Single (2003) used a *Design for Six Sigma* (DfSS) approach to examine which vehicle mounts affect the customer level vibration response and assess the effects of mount stiffness variability on the response. For the study, Mahajan, Surella and Single (2005) used a CAE-based DOE and an *Enhanced Multivariable Adaptive Regression Spline* (E-Mars) technique to build the predictive model. The model considered several noise and control factors; however, the authors considered the plane imbalance and run-outs as control factors, rather than noise factors, even though controlling these factors is often difficult and expensive.

Jomaa, Thubault and Mars (2006) applied DfSS and Taguchi robustness techniques to optimize the NVH performance of an active engine mount system for vehicles with cylinder deactivation. Meanwhile, Sun, Ranck, Voight and Steyer (2005) used a DfSS approach to examine robustness axle system NVH performance. Using a Matlab® and Simulink® lumped parameter model, Sun et al first performed a 2-level (minimum and maximum of range) screening DOE for each

parameter to determine several significant factors, which then was examined in a three level full-factorial design.

Thomas, Soderberg and Borders (2005) note CAE robustness studies must include noise factors to uncover the potential system failure modes and subsequently to develop the appropriate countermeasures. In their study, the 500 noise factor combination was intended to elicit possible – not necessarily probable – responses, which a significant departure from tradition reliability theory. Perhaps more importantly, the authors show note the cumulative improvement was not realized until the method was “spread” to other programs.

Meanwhile, Huber and Thomas (2006) examine the use of computer experiments for failure mode assessment and avoidance. Specifically, the authors discuss the use of both the inner and outer factors for computer analysis of nibble failure modes. Again, spreading the practice was crucial, leading to a four-fold reduction in customer complaints for nibble.

2.4 Diffusion of Innovation

As Szulanski (1996) notes, the ability of a firm to transfer practices is crucial to building a competitive advantage; however, transferring practices internally “is far from easy.” This transfer, or diffusion, occurs over time through communication among social networks. (Rogers, 2003) While critical, Berwick (2003) notes the diffusion of innovation is a significant challenge in most industries and is often harder than the invention.

2.4.1 Innovation

Schumpeter (1934) provides the first definition, characterizing innovation as: 1) Introduction of a new good or new quality of a good; 2) Introduction of new production method; 3) Opening of a

new market; 4) Conquest of a new source of raw material or partially manufactured goods; and 5) Creating a new organization of an industry. Utterback (1974) offered a simpler and more usable definition, stating innovation “refers to a technology actually being used or applied for the first time.”

Types of Innovation

In addition, work by various researchers (Henderson and Clark, 1990; Christensen, 1993; and Christensen, Suarez and Utterback, 1998) suggests firm survival is dependent on the type of innovation introduced into the marketplace. Some forms of innovation fall within the core competencies of and skills of the organization, while others require competencies foreign to the firm.

Robertson (1967) and Tushman and Nadler (1986) classify innovation based on the effects on established patterns, ranging from *continuous*, or incremental, improvements that follow established trajectories to *discontinuous* innovations that establish new patterns. Meanwhile, Sahal (1985) and Henderson and Clark (1990) also examine the architectural aspects of innovations, classifying innovation based on the change in system architecture.

Taking a broader view, Christensen (1997) examines two categories, which he classifies as sustaining and disruptive, and the challenges each present an organization. Sustaining technologies, whether incremental or discontinuous, improve the performance of established products along traditionally valued trajectories. Disruptive technologies, meanwhile, generally have lower traditional performance, are lower cost, yet provide ancillary benefits valued by the users. (Christensen, 1997)

Trajectories

In terms of patterns, Sahal (1985), Dosi (1988), Christensen (1997), and Silverberg et al (1988) suggest innovations proceed along defined trajectories, often shaped by changing needs or paradigms, and these *innovation avenues*, or trajectories, vary in width. Further, Sahal (1985) suggests a pattern of design serves as a *technological guidepost* that steers the course of further technological development within a given field. Additionally, Silverberg, Dosi and Orsenigo (1988) note new technology is preferred over older technology when the productivity is higher and it is cheaper per unit of capacity or its price difference can be recovered within a given period.

2.4.2 Source-Receiver Attributes

Simard and Rice (2001) and Szulanski (1996) note the importance of the source-recipient relationships on the successful adoption of an innovation. This relationship is contingent on the characteristics of the adopter and source.

Types of adopters

Regarding adopters, Rogers first introduced the prevailing ideal adopter categories in his influential work, *Diffusion of Innovation* (1962), based on the early diffusion research, classifying population of adopters into five groups – *innovators*, *early adopters*, *early majority*, *late majority* and *laggards*. *Innovators* launch the innovation, *early adopters* are opinion leaders and crucial to the spread, and the *early majority* is more conservative and more deliberate than *early adopters*. The *late majority* adopt once an innovation becomes standard, while *laggards* represent the final adopters of the population.

In terms of innovators, Von Hippel (1976, 1977, and 1986) and others show the user rather than the manufacturers develop a number of important innovations. To characterize these users, Von Hippel (1986) introduced the concept of *lead users* – innovative users who encounter the needs of a market months or years before the majority and expect to benefit from a solution to their needs.

As previously noted the early adopters are critical for the adoption and often serve as opinion leaders for the community. These early adopters typically are driven by the goal of improving performance (DiMaggio and Powell, 1983), and the research by Valente and Davis (1999) suggests the diffusion accelerates rapidly if the first adopters are opinion leaders, particularly when matched to the community. Further, Robertson (1967) notes the “two-step flow of communication” suggests media influences the opinion leaders, who then influence the others within the group.

As Rice and Rogers (1983) note, transfer of knowledge includes reinvention, or adaptability, after the innovation is transferred. Often, the knowledge is *sticky* in nature – i.e. difficult or costly to transfer explicitly within an organization (Von Hippel, 1994), and Szulanski (1996) identified the three most important sources of *stickiness* and potential knowledge barriers – absorptive capacity, casual ambiguity, and relationship between the source and receiver. To address this barrier, Allen (1986) and others (Argote, 1999) suggest the best technique for transferring sticky information is to move knowledgeable employees to a new organization.

Abrahamson and Rosenkopf (1997) also look at the effects of social networks, noting innovation diffusion theories “could be enriched by a focus on social networks.” Specifically, they propose the number and structure of the network links may influence the extent of diffusion within a social network. To bridge these networks, Allen (1984) suggests teams should be staffed with *technological gatekeepers*, who have contact with various external sources of information.

Since communication is essential, Allen (1986) suggests innovation requires three forms of communication – communication for coordination, communication for information, and communication for inspiration. Fraser (2000 and 2001) among others recommends using multiple communication channels should be used, including general publications, interactive sessions and direct personal communication, and the communication should be targeted to the audience and explicitly convey the benefits of the change.

2.4.3 Contextual and Organizational

Further, organizational and contextual factors present are potential facilitators or impediments to the spread of an innovation. Accordingly, O’Neill, Poudier and Buckholtz (1998) note effective *organizational learning* is critical for survival, and *organizational memory* affects the adoption performance, influencing the adoption rate and “characteristics of the efficiency gap for those strategies.” In addition, Simard and Rice (2001) note realistic training expectations must be established in support of change effort, with the training tailored to the audience, directly applicable to the work of the employee, and not perceived as overly complex.

While research by O’Dell and Grayson (1998), Astebro (1995) and others suggest management involvement is essential, Molinsky (1999) suggests there needs to be a balance, noting three

management paradoxes affecting change within an organization. 1) Change depends on management, but management makes change less likely. 2) Change depends on the commitment of management, but the commitment of change leaders makes change less likely to occur. 3) Change depends on rhetoric, but rhetoric makes change less likely to occur.

2.4.4 Time

The innovation spreads among the adopter community, from an awareness of the new product or process to adoption. This spread takes various times, with the cumulative adoption rate of new users generally following an S-shaped curve.

Stages of Diffusion

In their work, Gort and Klepper (1982) examine the diffusion of products, noting product innovation is composed of two fundamental steps – the technical development and the introduction into the marketplace. Once in the market, potential adopters first must recognize the innovation and then form an opinion of the product or process. Then adopters must decide whether to make the change, and “external support may be helpful.” (Fraser, 2002)

Implementation, the final phase, involves executing the change as well as measuring the progress of the change.

S-shape adoption Curve

Based the examination of the diffusion of hybrid seed corn in two Iowa communities, the work of Ryan and Gross (1943) data suggests the adoption rate resembles a normal distribution, with Rogers (1995) noting the cumulative number adopters resembles an S-shaped curve over time.

Further, Silverberg, Dosi and Orsenigo (1998) note diffusion of new products and processes take

numerous lengths of time. Additionally, their dynamic diffusion model suggests, “the S-shaped form of the equation ... stands-out.” (Silverberg, Dosi, and Orsenigo, 1988)

The 1961 study by Mansfield examines the spread of innovations across several industries, generally confirming the Rogers model. (Mansfield, 1961) Noting the limited previous research on the topic, Jensen (2001) focuses on intrafirm diffusion of a process innovation using a differential game mode, and the results of the model align previous empirical research by Mansfield (1961). Additionally, several analytical models (Iwai, 1984, Silverberg et al, 1988 and Jensen, 2001 among others) generally confirm the S-shape adoption curve.

2.4.5 Diffusion Strategies

To foster diffusion, several authors have proposed strategies to assist the spread. O’Dell and Grayson (1998) also note strategies for diffusing best practice in an organization, including the use of both benchmarking and best practice teams, knowledge and practice networks and internal audits.

Meanwhile, Simard and Rice recommend several strategies for diffusing best practices. The first is to identify translators to frame the knowledge transfer, opinion leaders to lead the charge and knowledge brokers to bridge communities. Additional strategies include providing incentives for knowledge sharing among groups, and focusing on external rather than internal competition.

Berwick (2003) proposes several rules, or strategies, to foster the spread of innovation. First, sources of innovation must be identified, then management must foster innovative individuals, and senior leadership must provide the time and resources to test innovation. Next, management

must promote interaction and communication between among the adopters. Leaders then must encourage reinvention, must create slack for adopters to discover and adopt the innovation, and finally, champions must lead by example.

2.5 Summary

This chapter presents a literature review of both the failure mode avoidance and innovation diffusion approaches relevant to this thesis. Specifically, the chapter first will examine robustness from classical experimental design through the Taguchi robust design method to the emergence of failure mode avoidance. Then literature on the innovations and the diffusion is examined, beginning with innovation aspects through factors affecting its adoption over time.

Chapter 3: Failure Mode Avoidance

This chapter examines the failure mode avoidance approach, beginning with the failure mode avoidance definition of reliability and its applicability to NVH. Then the failure modes types are then and robustness improvement strategies are discussed. Next, the traditional techniques to assess and improve to robustness are examined, as well as supporting tools, and then newer response surface methods are presented. Then, two approaches to avoiding failure modes are presented – the operating window and distance to failure mode. Finally, the “Slider Bar” meta-model is introduced.

3.1 Reliability as Failure Mode Avoidance

Traditionally, reliability is defined as “the probability a product will perform its intended function for a specified period of time under specified environmental conditions.” (Roush and Webb, 2006) Unfortunately, the definition fails to capture the true essence of reliability, particularly with respect to automotive NVH.

Clausing (2004) offers a more applicable definition – “reliability is failure-mode avoidance”, where a failure mode is any customer-perceived deviation from the intended function of the product. This new definition of reliability is the basis for the work and examined in the subsequent sections.

3.2 Failure Modes

As note previously, it is important to eliminate potential failure modes during the early stages of product development rather than during the testing or production phases. To accomplish this, the

two general cause of failure modes must be addressed – mistakes and lack of robustness.

Mistakes results from an error in judgment or the failure to take action for a particular failure mode. Accordingly, the counter measure is avoiding the mistake through careful planning and awareness, which can be enhanced through training, guidelines, and health charts. Robustness, meanwhile, is the system sensitivity to variability, especially noise in the environment, and the countermeasures are changing the system sensitivity to noise through the techniques of robust design. (Clausing, 2004 and Davis, 2004)

While mistake prevention is important to any engineering effort, the focus of this work is robustness failures, their discovery and the development of appropriate countermeasures. The next sections will outline robustness.

3.3 Types of Failure Modes

Failure modes can be categorized in two main groups – *hard failures* where the system breaks or ceases functioning and *soft failures* where system function is less than ideal, often eliciting customer complaints.

Hard failures

1. **No function:** In this case, the system breaks, failing to deliver intended function and must be repaired or replaced to meet the desired function.

Soft failures

2. **Partial function or over-function:** Here, the system performance is lower or higher than the intended function, and failure may occur during any point of the life cycle. Again, the system must be repaired or replaced for the system to operate as intended.
3. **Degraded function:** Similar to the previous the failure mode, degraded function is characterized by deviation (higher or lower performance) than intended, and the system must be repaired or replaced to recover intended function. The difference, however, is the deviation occurs with respect to a usage parameter, such as time, cycles or miles for the automotive industry.

4. **Intermittent function:** In this case, the system fails (higher or lower performance) sporadically and subsequently recovers when conditions allow.
5. **Unintended Function:** Here, the system functions even though the required operating conditions are not present.

The engineer then must address these failures to improve the robustness of the system.

3.4 Robustness Improvement Strategies

As Davis (2004) notes, there are five strategies for improving robustness:

1. **Alter the design concept or technology.** In this case, change the technology or decouple the functions.
2. **Make the design insensitive to noise factors.** Here, use parameter design to reduce the system sensitivity, upgrade the design specifications, or employ redundancy.
3. **Remove or reduce the noise factors.** For this strategy, components are moved to mitigate the effect from neighboring systems, or manufacturing variations are reduced for critical parameters, such as imbalance.
4. **Use a compensation device.** Here, a device, such as a tuned absorber, is used to shield the component from noises.
5. **Move the failure mode to another area where it will cause less harm.** In this case, the error state is sent elsewhere where it has a less harmful effect.

Then testing is performed to assess the effectiveness of these strategies.

3.5 Design of Experiments

DOE is a statistical method to assess the effect of multiple factors simultaneously and economically, with the goal of distinguishing the best factor combination. First developed in the 1920's, classical design of experiments was pioneered by Sir Ronald A. (R.A.) Fisher, who used DOE to study the factors affecting crop yield in agriculture.

Traditionally, DOE focused on the adjusting mean; however, variability is often a concern in many applications including automotive NVH. To address this, Taguchi (1986 and 1987) introduced the *Robust Design Method*, which emphasized reducing variability and then adjusting

to target. Specifically, the method focused on the ability of a system to perform its desired function in the presence of noise, with engineers encouraged to subject the system to realistic conditions. Additionally, Taguchi categorized the five sources of noise affecting a system and introduced the *Quality Loss Function (QLF)* to quantify the effects of variation around the target and the potential loss to society.

To detect failure modes, Taguchi uses the concept of *signal-to-noise ratio (S/N)* – ideal output divided by the undesired output due to the error status. Specifically, S/N is the desired response over the response variance, with a common maximizing formulation expressed as:

$$s/N = 10 \log \left(\frac{\mu^2}{\sigma^2} \right) \quad \text{Equation 1}$$

Where, μ is the mean response, and σ^2 is the variance of the response. Thus, the objective in this case is to increase the mean response and minimize the variation.

Since the S/N ratio is simply a measure of output relative to input, it can be determined experimentally and does not require the formulation of transfer functions. Therefore, using only an experimental approach, an engineer can determine the factor settings that produce low noise relative to the average response. Further, Taguchi (1987) suggests increasing this ratio will yield improvement and help avoid failure modes, and Taguchi and Clausing (1990) argue significant improvement in any component will improve the robustness of the system.

To increase system robustness, the traditional Taguchi approach follows five¹ basic steps (Roy, 2001):

1. **Plan the experiment.** In this step, the project objectives, measurement method and factors are determined.
2. **Design or identify the experimental design.** With the factors and levels determined, an appropriate experimental design is established.
3. **Conduct the experiment.** The experiments then are run according to design and data collected.
4. **Analyze the results to obtain information about the design.** The collected data are examined according to standard statistical techniques to determine the appropriate factor settings.
5. **Confirm the best design.** In this step, the factors settings are verified.

These steps form the foundation modern experimental design methods, including DfSS, and are the basis for the approach in this work.

3.6 System P-Diagram

To facilitate robustness initiatives, the system product or process parameter diagram (P-diagram) depicted in Figure 3.1 often is used, helping the engineer characterize the system inputs, factors and outputs.

¹ Ulrich and Eppinger (2004) suggest an alternative seven-step process, which divides the first step into two – identifying factors and metrics and then formulating the objective function. Additionally, a seventh step, reflect and repeat, is added.

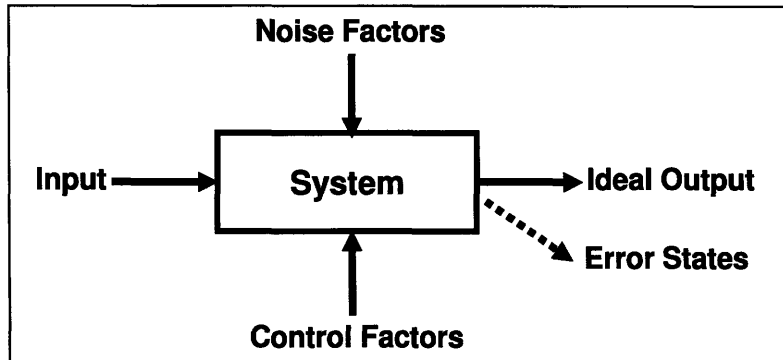


Figure 3.1 – System P-diagram
 The parameter diagram (P-diagram) depicts the factors associated with a product or process.

Here, the *input* is primary signal (i.e. energy, material, or information) supplied by the customer, or a neighboring system, that causes the system to function, and as Clausing (2004) notes may not be printed specifications. The *ideal output (function)* is the primary intended function of the system and is typically expressed as a transformation of energy. Meanwhile, the *error state*² is the undesirable output of the system that can lead to system failure modes, which are characterized by the soft or hard failures described previously.

In experimental design, *Factors* are the independent variables, and *levels* are the factor values evaluated in the experiment. For example, body mounts (factors) are evaluated at different stiffnesses (levels) to assess the effect on the system. *Interaction* is the effect of one factor change on the response due to varying another factor, such as the influence of temperature on the stiffness of elastomeric mounts. As my colleague Bob Thomas notes, it is important to establish “*rich and realistic*” values for the factors. That is, the factor levels must be rich enough to excite the failure mode, yet realistic enough to be encountered in production or customer use.

² While not traditional, Ford typically includes error states in the P-diagram, since they closely align with failure modes in the system and thus provide a link between traditional robustness and failure mode avoidance approaches.

3.7 Control & Noise Factors

Control factors are the parameters related to the physics of the design, which can be adjusted by engineer to affect the system response and used for potential countermeasures to system failure modes. Alternatively, *noise factors* are those parameters the engineer cannot directly control that potentially influence the ideal system response, leading to the system error states.

3.7.1 Types of noise

As noted previously, Taguchi (1986 and 1987) classified the five types of noise affecting a system. These five types fall into the two main categories – *inner noises* related to capacity and *outer noises* related to demand.

Inner Noises (Capacity Noises)

1. ***Piece-to-Piece variation***: These noises represent the variability between products supposedly created under the same manufacturing conditions, such as the residual imbalance at the ends of a driveshaft.
2. ***Changes over time***: These factors are internal to the design, which vary in performance over time.

Outer Noises (Demand Noises)

3. ***Customer usage and duty cycle***: The system use, including unintended use, can introduce noise into the system.
4. ***Customer operating environments***: Environmental factors, such as temperature, may influence the system response.
5. ***System Interactions***: The error states from neighboring systems may be noise factors in the examined system, or there may be unresolved design issues with the neighboring systems and the subsequent interaction with system of interest.

These noises affect the system response, and the engineer must select an experimental design strategy to address them.

3.8 Experimental Designs

To perform an experiment, a number of designs exist to examine the effects of the various factors and levels. Though Frey et al (2003) have demonstrated an adaptive *one factor at a time*

(OFAT) design can be effective in certain circumstances, typically *factorial designs* are used to explore the design space simultaneously and efficiently and are used in this research.

3.8.1 Factorial Design

In factorial design, the system factors are evaluated at different levels to determine the influence on the response. In a *full factorial* design, every factor and level combination is evaluated, allowing the identification of all main effects and multifactor interactions affecting the response. While this may provide valuable insight into the system, this approach is only feasible for a limited number of factors and levels such as the two-factor and-level design in Table 3.1.

Table 3.1 – Full Factorial design for two factors at two levels

	X ₁	X ₂
Trial 1	1	1
Trial 2	1	2
Trial 3	2	1
Trial 4	2	2

Since the number of trials for k factors at n levels is n^k , the runs needed for a *full factorial* experiment greatly increases when more factors and levels are considered.

To improve efficiency, *fractional factorial* designs are used to evaluate a portion of the combinations in the full factorial design, with some interactions confounded with main effects and other interactions. Since, the effects of higher-order interactions are typically insignificant, many fractional factorial designs provide estimates the main effects and two-factor interactions only. Popularized by Taguchi, the *orthogonal array* is the simplest fractional factorial that assesses the main effects, and these designs are often named according to the number of trials, such as the L4 in Table 3.2.

Table 3.2 – L4 design for three factors at two levels

	x_1	x_2	x_3
Trial 1	1	1	1
Trial 2	1	2	2
Trial 3	2	1	2
Trial 4	2	2	1

While, columns for x_1 and x_2 are similar to the full factorial, this design includes a third factor (x_3) which is confounded with the interaction between x_1 and x_2 . To examine the main effects of three factors without confounding, an L8 array such as Table 3.3 must be used.

Table 3.3 – L8 design for seven factors at two levels

	A	B	C	D	E	F	G
Trial 1	1	1	2	1	2	2	1
Trial 2	2	1	1	1	1	2	2
Trial 3	1	2	1	1	2	1	2
Trial 4	2	2	2	1	1	1	1
Trial 5	1	1	2	2	1	1	2
Trial 6	2	1	1	2	2	1	1
Trial 7	1	2	1	2	1	2	1
Trial 8	2	2	2	2	2	2	2

Here, the main effects for A, B and D are determined without confounding, while C, E and F estimate the interaction for AB, AC and BC respectively.

Several methods are used to evaluate the effects of noise on the system response. In the simple case, noise factors may be compounded, with each trial replicated such as the design in Table 3.4.

Table 3.4 – L4 design including noise

	x_1	x_2	x_3	N+	N-
Trial 1	1	1	1		
Trial 2	1	2	2		
Trial 3	2	1	2		
Trial 4	2	2	1		

When there are several noise factors of interest, two arrays are typically employed – an inner array for the control factors to explore the design and an outer array for range of noise encountered in operation. For example, the design in Table 3.5 includes an L8 inner orthogonal array for the control factors and an L4 outer array to assess noise.

Table 3.5 – L8 inner array with an L4 outer array

	A	B	C	D	E	F	G	1	1	2	2	Na
								1	2	1	2	Nb
								1	2	2	1	Nc
Trial 1	1	1	2	1	2	2	1					
Trial 2	2	1	1	1	1	2	2					
Trial 3	1	2	1	1	2	1	2					
Trial 4	2	2	2	1	1	1	1					
Trial 5	1	1	2	2	1	1	2					
Trial 6	2	1	1	2	2	1	1					
Trial 7	1	2	1	2	1	2	1					
Trial 8	2	2	2	2	2	2	2					

Thus, the resulting response the effects of both control factors and noise on the system.

3.9 Response Surface Methods

Introduced by Box and Wilson (1951), *Response Surface Methodology* (RSM) is a combination of statistical and optimization methods for improving designs used to model the transfer functions between a given set of factors and the response of the system. In addition, response surfaces are used to optimize the settings and when curvature is suspected in the surface. Given these advantages, this work uses response surface designs to evaluate the design space and build the response surface.

Selection is contingent on the system knowledge of the engineers. That is, factorial designs are useful when the statistical model is known, while space-filling designs are helpful when the engineer does not know the model.

3.9.1 Factorial Designs

Factorial designs, such as the full-factorial design depicted in Figure 3.2, are used when the system factors, factor levels and statistical model are well known.

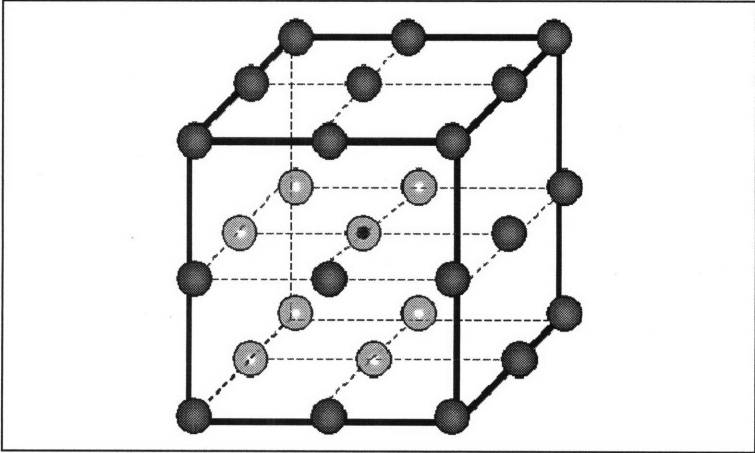


Figure 3.2 – Full-factorial experiment for 3 factors and 3 levels.
In a full factorial design, every factor and level combination is evaluated. This design allows the estimation of second order terms.

In contrast to the full factorial design, fractional factorial design, such as the *Central Concept Design* (CCD) and the *Box-Benhken* design (Figure 3.3), explore the design space more economically – i.e. use fewer factor levels to assess the system design space.

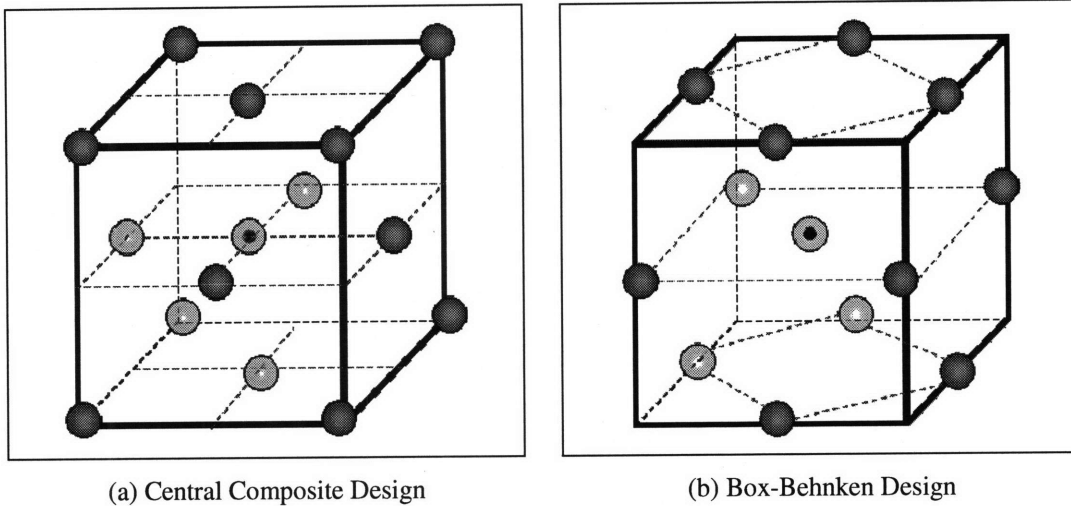


Figure 3.3 – Typical fractional factorial design in RSM

These fractional factorial designs explore the design space more economically, evaluating a portion of the combinations in the full factorial design.

Therefore, these fractional factorial designs often are used when the statistical model is identified, with the CCD and Box-Behnken among the most commonly used.

Central Composite Design (CCD)

Central Composite Design (Figure 3.3 (a)) includes center points to assess the effects of curvature on the response and allows for efficient estimation of the second order terms. However, this design tests the system at the extreme (corner points) of the design space, which may not be in the operating range for the system.

Box-Behnken

The Box-Behnken design (Figure 3.3 (b)) is a complement to the Central Composite Design, testing the points not included in the CCD. This design is the most efficient three-level design and is useful when the operating range of the factors is well known, since the design does not test the extreme points like the CCD. In addition, this design ensures all factors are not tested to the high level at once.

3.9.2 Space-filling

Space-filling designs, as the name implies, spread points throughout the desired design space, allowing the full range of the design to be modeled without biasing the importance of any factors. (See Figure 3.4.) Space-filling designs are particularly helpful when the system knowledge is low and wide design space is considered. This improves interpretation capability for building the meta-model and helps provide the best estimate of the mean system response.

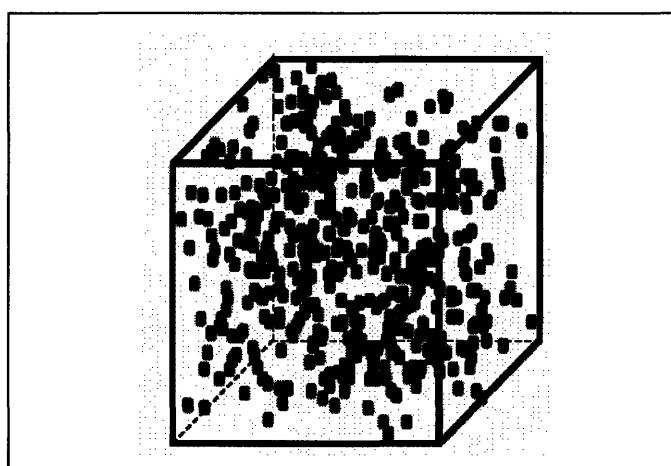


Figure 3.4 – Space-filling Design Example
Space-filling designs distribute points throughout the desired design space.

While varieties of space-filling designs are used, the *Latin Hypercube*, *Uniform Designs*, and *Low Discrepancy Sequences* are among the most common.

Latin Hypercube

Latin Hypercube designs are relatively computationally efficient to generate and allow a large number of runs and factors at many levels. However, the design space may not be optimally filled, and the number of runs is equal to the number of levels, which may be computationally prohibitive as the number of factors and levels increases.

Uniform Designs

In these designs, points are distributed uniformly throughout the design space, and any number of levels and factors per level may be used. However, uniform designs assume an equal importance of factors, and the computation increases proportionally with the number of runs, factors, and levels.

Low Discrepancy Sequence

Low Discrepancy Sequence (LDS) refers to quasi-random, deterministic sequence that seeks to minimize the deviation from uniformity, or discrepancy, for a given set of points. Efficient to generate, LDS are often employed when a space-filling design is required; however, the user must be careful the points are adequately distributed within the design space and patterns are avoided. While several types of LDS are used, the Halton and Sobol LDS are among the most common.

Halton

The Halton sequence is among the simplest and most efficient low discrepancy sequence to implement. However, patterns tend to emerge as the number of dimension increase, and other sequences, such as Sobol sequence, are preferred for increased dimensions. (Krykova, 2003)

Sobol

The Sobol sequence is the most efficient LDS, producing good uniformity and yielding the least standard error of any low discrepancy of any LDS method. This sequence has been used successfully up to 260 dimensions with little or no degradation (Krykova 2003), making the design particularly useful when simpler low discrepancy sequences are not sufficient.

3.9.3 Regression Analysis

With the trials run, regression model is used to predict the response for different combinations of parameters. The regression model for at two-level typically is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \dots + \varepsilon \quad \text{Equation 2}$$

Where, β_0 is the average response; $\beta_1, \beta_2, \dots, \beta_n$ are regression coefficients; x_1, x_2, \dots, x_n are the factors; and ε is the error in modeling.

Thus, the system response for various factors is expressed as an equation, which is useful for developing models of the system. In this work, the resulting equation is used to develop the meta-model, which is used to uncover and avoid system failure modes.

3.10 Failure Mode Avoidance

As noted previously, failure mode avoidance has emerged as the definition of reliability, where a failure mode is any customer-perceived deviation from the intended function of the product.

To quantify this deviation, the metric must have the following characteristics (Davis, 2004):

1. ***Can be represented graphically.*** It visually depicts the response and failure mode relationship.
2. ***Is sensitive to noise.*** That is, the metric captures the effects of noise on the system response.
3. ***Measures distance to failure mode.*** It provides information about the system response relative to potential failure modes.

To accomplish this, two analogous approaches are used – *operating window* and *distance to failure mode*.

3.10.1 Operating Window

In the traditional approach to robustness, smaller magnitudes of noises typically are applied early in development, with increased levels applied late in the development process. Thus, robustness issues are not found until late in the development process, when changes are difficult and expensive to implement.

The *Operating Window* (OW) method, meanwhile, is a metric for measuring and improving the system robustness and exposes robustness issues early in the development cycle by employing large magnitudes of noise to the system. (Clausing, 2004) The OW represents a range where the system functions without failure, and the goal is to expand the window as broad as possible early in the development phase. (See Figure 3.5.)

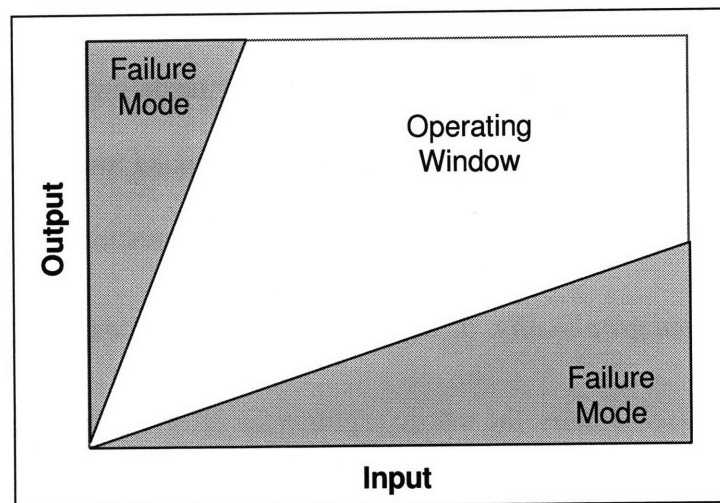


Figure 3.5 – Operating Window
The Operating Window represents the range where the system functions without failure. (Adapted from Clausing, 2004)

Thus, the failure mode region is away from the performance of the system.

3.10.2 Distance to Failure Mode

Similar to the OW method, the *distance to failure mode* is a metric for assessing robustness of a system. Based on the physics, geometry and properties of the system, the objective is to move the response as far from failure mode as possible, and this can be represented graphically four ways – *probabilistic, dispersion, functional output* and *signal-to-noise ratio*.

In the probabilistic view, either the Weibull probability plot or probability density function (PDF) is used to examine the distance to failure mode, and the objective is moving the system away from failure mode, such as the distribution to the left (blue square) in Figure 3.6.

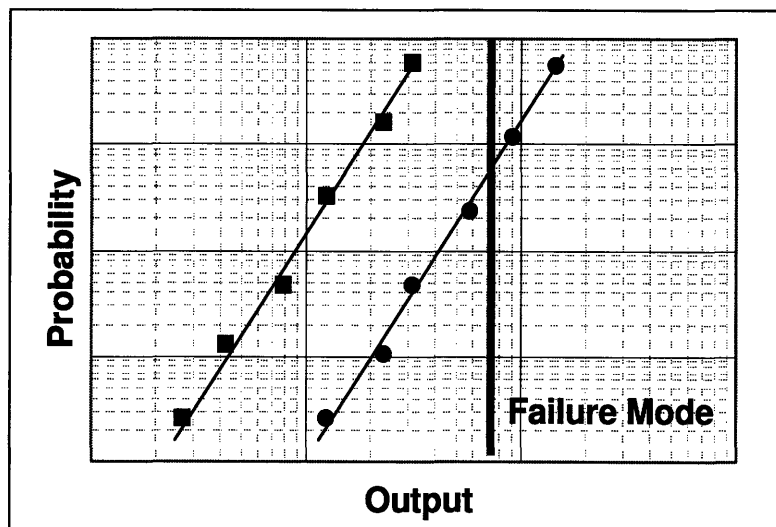


Figure 3.6 – Probabilistic representation

In the probabilistic view, the Weibull probability plot can be used to examine the distance to failure mode. The distribution represented by the blue squares is further from the failure mode. (Adapted from Davis, 2004a)

In this case, the engineer concentrates on moving the output away from the failure mode (x-axis), while the statistician focuses on the probability of failure (y-axis).

Alternatively, the distance to failure mode can be viewed with respect to the dispersion of a particular system response, such as Figure 3.7.

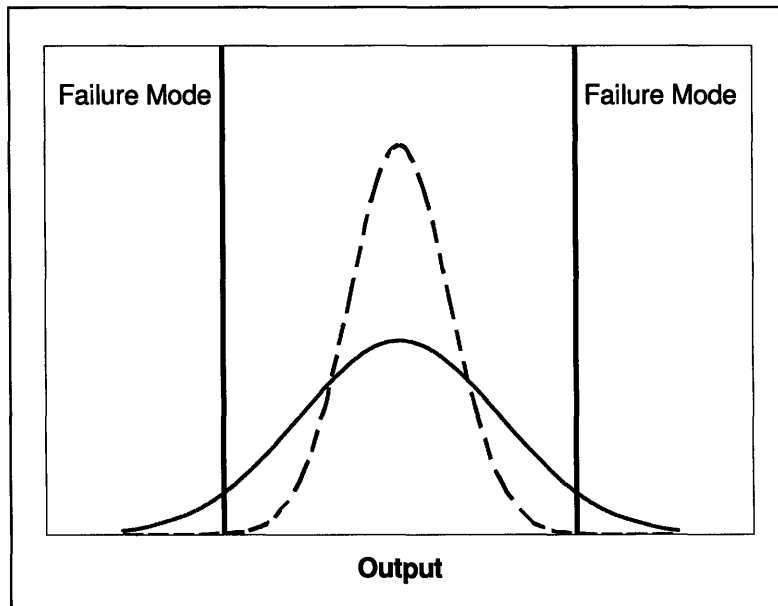


Figure 3.7 – Dispersion Representation
The distance to failure can be viewed with respect to the variation. The response represented by the blue dotted line has less spread than and is farther from failure modes. (Adapted from Davis, 2004a)

Here, the response represented by the blue dotted line has less dispersion and is farther from the potential system failure modes.

The functional attribute representation provides the additional feature of evaluating the degradation over time, such as the example in Figure 3.9.

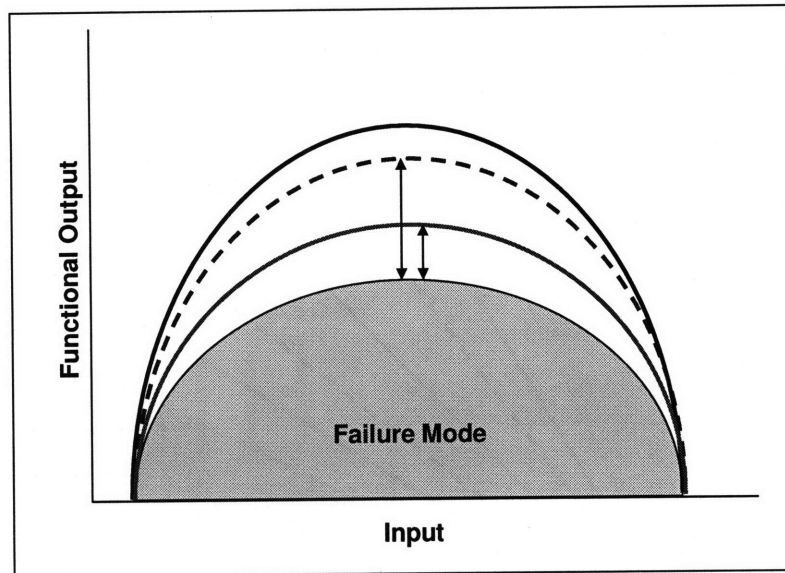


Figure 3.8 – Functional Output

The functional attribute representation provides the additional feature of evaluating the degradation over time. The response depicted by the dotted blue line is further from the failure mode and has less degradation over time (Adapted from Davis, 2004a)

For this example, the response depicted by the dotted blue line is further from the failure mode, having less degradation over time than the response represented by the solid red line.

Finally, the metric can be expressed in terms of the signal-to-noise ratio advocated by Taguchi, which is a subset of the distance to failure mode. (Davis, 2004)

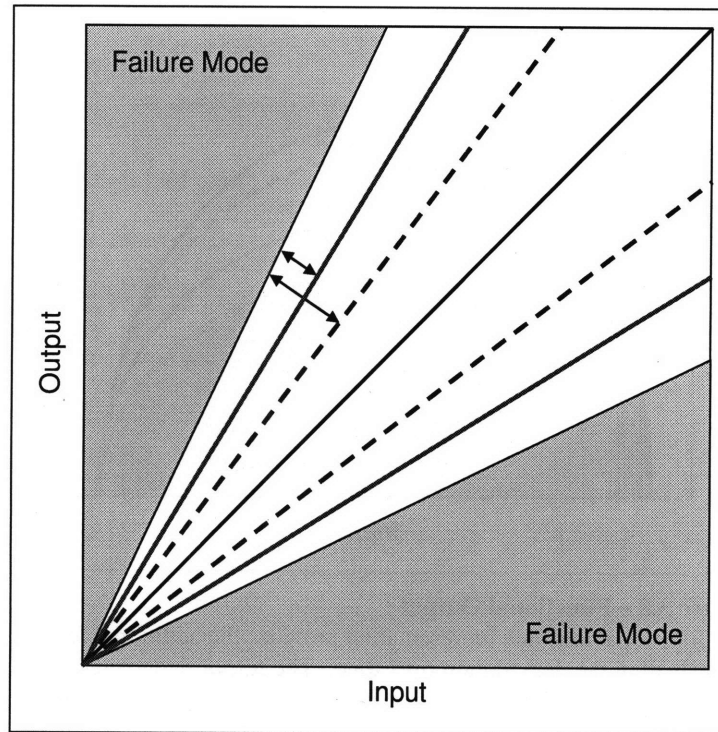


Figure 3.9 – Signal-to-Noise Representation

The distance to failure mode metric can be expressed in terms of the signal-to-noise ratio. Here, the system represented by the dotted blue line has better S/N and is further from the potential failure of the system. (Adapted from Davis, 2004a)

Here, the system represented by the dotted blue-line in Figure 3.9 has better S/N, thus further from the failure modes of the system.

Although each representation is used, NVH failures are typically related to random failures and functional degradation over time, so the probabilistic and functional representations typically are used to evaluate the distance to failure mode. In the case of tire/wheel and driveline NVH, the engineer often is more concerned with random failure, rather than the degradation over time. Therefore, this work focuses on the probabilistic representation for the distance failure mode.

In the probabilistic representation, the failure modes for engineering activities are double-sided – i.e. failures occur when the response moves beyond the lower specification limit (LSL) or upper specification limit (USL) as depicted in Figure 3.10 (a).

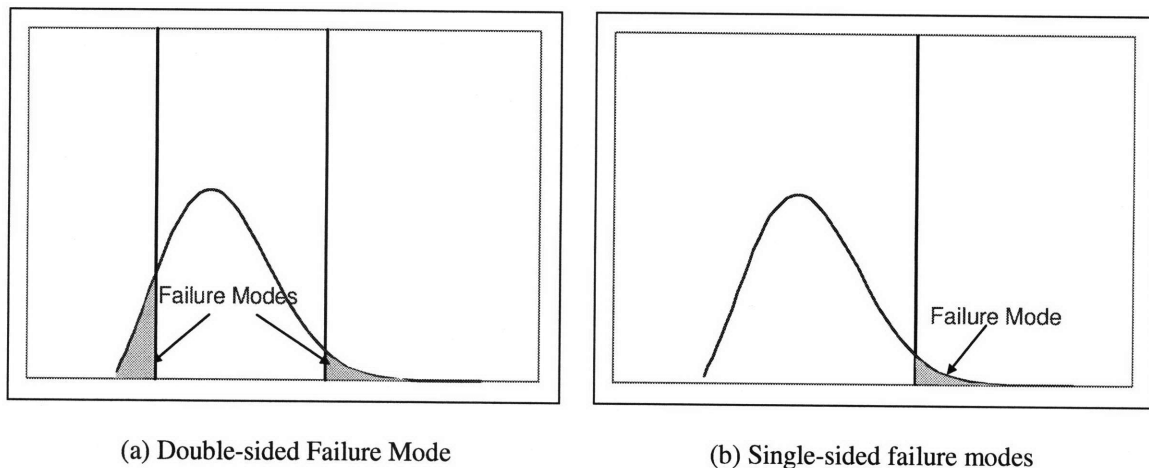


Figure 3.10 – Failure Modes

The failure modes for engineering activities exhibit are often double-sided; however, in NVH, are generally single-sided, since generally less vibration and sound are desirable at the customer response points.

However, in NVH, the failure modes are generally single-sided, or associated only with the USL as illustrated in Figure 3.10 (b). That is, the NVH engineer is generally concerned with ensuring the vehicle level customer response (e.g. interior quietness or seat track vibration) is below an upper specification limit, which is set by customer demand since lower (less sound or vibration) is desired³.

³ In general, less sound and vibration is desirable at the customer response points. However, in certain instances, such as sound quality or tonal masking, the sound or vibration level is increased to affect a certain characteristic such as *sporty* in sound quality or provide a masking level to hide (mask) other sounds (e.g. gear whine) or vibrations (e.g. buzz) from customer detection.

3.11 “Slider Bar”

Named for the method of adjusting parameters in the meta-model, the “Slider Bar” approach integrates the failure mode avoidance philosophy. Specifically, the “Slider Bar” allows the engineer to assess graphically the distance to failure mode and the sensitivity to noise for a particular system.

The “Slider Bar” approach differs from typical meta-models in several areas. In particular, most meta-models use random input distributions to produce probabilistic output, while the “Slider Bar” uses a uniform distribution of input to assess the possibility a system will fail, which is the essence of failure mode avoidance. Additionally, the dynamic interface allows real-time assessment of distance to failure mode and sensitivity to noise. Thus, engineers can perform parameter design to move the response, and then perform tolerance design to tighten tolerance on critical factors identified in the analysis.

3.12 Summary

Failure mode avoidance is emerging as the definition of reliability, particularly in fields such as automotive NVH. To address the failure modes and improve robustness, DOE techniques and newer response surface traditionally have been used. However, two new approaches (Operating Window and Distance to Failure Mode) have been developed to address failure modes and characterize the distance between the system and potential failures. While analogous, this work focuses on the distance to failure mode approach, introducing the “Slider Bar” process.

Chapter 4: Diffusion of Innovation Background

As noted previously, the innovation process is composed of two fundamental steps – the development of the new product or process and the subsequent spread through the community.

While the previous chapter presented the background for the new process – failure mode avoidance, this chapter focuses on diffusion of the innovation through the community. The next sections will present innovation diffusion background, beginning with a definition of diffusion. Innovation types and the characteristics of innovations that spread quickly are examined. Then the source and receiver characteristics are discussed with respect to diffusion, followed by the contextual and organizational factors that affect the adoption of a new product or process. Finally, adoption rate and strategies for promoting diffusion are examined.

4.1 Diffusion

Diffusion is the spread of the innovation over time through the exchange of information and knowledge among social networks. (Rogers, 2003 and Fraser, 2001) In this context, this work focuses on the innovation characteristics, the attributes of the source and receiver, the contextual and organizational factors, and the adoption over time.

4.2 Innovation

Innovation refers to the initial application of a technology, and often the type of innovation is critical to the success of the firm. Some innovations are compatible with the core competencies of and skills of the organization; while others require competencies the firm does not possess. In addition, some innovations diffuse quickly, while others spread slowly among the adopters.

4.2.1 Types of Innovation

Since the majority of innovations tend to be sustaining rather than disruptive (Tushman and Nadler, 1986 and Christensen, 1997), this work will focus on the three main types of sustaining innovations – *continuous*, *dynamically continuous*, or *discontinuous* innovations. (Robertson, 1967) *Continuous*, or incremental, innovation involves alteration of a product or process and typically reinforces the competitive position of the established firms. *Dynamically Continuous* innovations may include developments of new products or alterations of existing products but do not alter the established patterns or trajectories. *Discontinuous*, or radical, innovations establish new products and new patterns, often requiring new skills, core competencies, organizational structures, management methods, and support systems. (Robertson, 1967, Tushman and Nadler, 1986, and Henderson and Clark, 1990)

4.2.2 Characteristics of Rapidly Diffused Innovations

Regardless of type, some innovations diffuse rapidly through the community, while other are adopted more slowly. Rogers (2003) identified the characteristics of innovation that diffuse rapidly:

1. **Relative Advantage.** That is, the amount of benefit (e.g. economical or social) compared to current product or process.
2. **Compatibility.** The amount a new product or process fits with current system, values and needs of the potential users.
3. **Complexity.** That is, whether the innovation is perceived as easier to understand or implement than the current way, with simple ideas adopted more rapidly than those requiring new skills or knowledge.
4. **Trialability.** This refers to ease of testing a product or process before making a full commitment by the individual user.
5. **Observability.** The amount the innovation and its impact are visible to others.

These perceptions of the innovation predict 49% to 87% of the variance in the dissemination rate with relative advantage as the most influential factor. (Rogers, 2003)

4.3 Source and Receiver Attributes

For successful diffusion, knowledge of the innovation must be transferred from the source to the various adopter groups. This transfer is dependent on the characteristics of the various adopters and relationship between the source and recipient.

4.3.1 Adopter Types

Based on the early diffusion work, Rogers (2003) classified the population of adopters into five ideal groups depicted in Figure 4.1.

- *Innovators* represent 2.5% of the population and adopt greater than two standard deviations (SD) faster than the mean adoption rate. Members of this group have the ability to comprehend and apply technical knowledge, tend to be venturesome, and introduce the new product or process into the system.
- *Early adopters* represent 13% of the population and adopt between one and two SD faster than the mean adoption rate. These individuals are respected opinion leaders amongst their peers and are crucial to the spread of an innovation, often triggering the critical mass for adoption.
- *Early Majority* adopt before the mean, though they tend to be more conservative and deliberate in their decisions than early adopters. Members of this group engage in frequent peer interactions but are not opinion leaders among the community. Additionally, they are more likely focused on local application of innovations rather than global improvement. (Berwick, 2003)
- *Late Majority* adopters are more conservative, risk averse, and tend to adopt once most of the uncertainty has been eliminated – in other words, once a product or process once it becomes standard.
- *Laggards* represent the final 16% of the population – the last members of a community to adopt. Berwick (2003) notes the term laggard underestimates the “value and wisdom” of the group, suggesting the terms “traditionalists, sea anchors, or archivists” better describes their work.

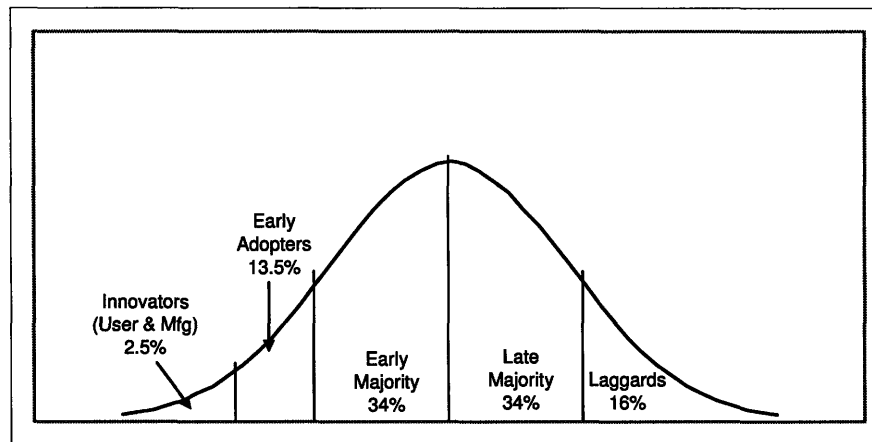


Figure 4.1 – Adopter categories

The population of adopters is classified into five groups based on innovativeness and adoption rate. While manufacturers develop a number of innovations, *lead users* are sources innovations and often encounter the needs of a market months or years before the majority. (Adapted from Rogers, 2003, and Von Hippel, 1986.)

While manufacturers develop a number of innovations, *lead users*, a particular type of innovator, are important sources of new products and processes and can be vital sources of information on the needs of market, since they encounter the needs of a market months or years before the majority. (Von Hippel, 1986)

The transfer of knowledge from the source to the various adopter categories is essential, and three potential knowledge barriers are *absorptive capacity*, *causal ambiguity*, and relationship between the source and receiver. Absorptive capacity is the ability of an organization to recognize and apply new practices, organizations with higher absorptive capacity will tend to be more proactive and use the opportunities present in the environment. (Cohen and Levinthal, 1990) Causal ambiguity results when the cause and effect relationship is difficult to define. That is, members of the recipient group are more likely to adopt when the benefits are defined clearly and are more likely to support subsequent ambiguous transfers after an initial successful transfer. (Szulanski, 1996 and Simard and Rice, 2001)

The relationship between the source and recipient is also an important factor in the diffusion of an innovation. For successful transfer, the source should be a successful organization, and trust between the source and the recipient is important for knowledge transfer. (Simard and Rice, 2001) Additionally, the relationship must be fostered to avoid the “*not invented here* (NIH)” syndrome, the aversion of some individuals to using external knowledge noted by Katz and Allen (1982) among others.

The number and structure of the network links may influence the diffusion within a social network. Thus, effective communication among networks is essential to diffusion of an innovation, and communication should be targeted to the audience, explicitly conveying the benefits of the change. To accomplish this, multiple communication channels should be used, including general publications, interactive sessions and direct personal communication. (Fraser, 2001)

4.4 Contextual and Organizational Related Issues

In addition to the characteristics of the innovation and adopters, contextual and organizational issues may foster or impede the spread of a new product or process. In particular, institutional and environmental factors, cultural issues, managerial factors, and training present potential barriers for spread.

4.4.1 Institutional Factors

Institutional factors may work as barriers to the spread of best practices. First, legitimacy is a critical factor in the diffusion, and some internal groups may reject an innovation if not recognized as “best” within the industry. Second, the spread may be difficult if the practice is

viewed as competitor of an institutionalized practice.⁴ Finally, management must balance corporate standardization of practice and flexibility for the local units. (Simard and Rice, 2001)

4.4.2 Environmental Factors

Environmental factors are significant, since the diffusion tends to correlate with the amount of environmental uncertainty for a firm. (Simard and Rice, 2001) That is, organizations in highly certain environment tend to maintain current practice, while those in highly uncertain must recognize and adopt new practices to survive. Additionally, prior success may present a barrier since firms are reluctant to try the new practices over established, successful ones. (Van de Van, 1986)

4.4.3 Organizational Culture Identity

The product or process also must be aligned with the culture of the source, recipient and interconnected organizations and resulting organizations identity of the unit. In particular, “extreme changes will be more difficult to implement as they will be prejudged as irrelevant for lack of fit with the organizational identity.” (Simard and Rice, 2001) Further, the size of a firm may be a factor, since increased size tends to provide more finance and knowledge, yet the increased size may foster bureaucracy that impedes the diffusion.

4.4.4 Management Related Factors

Managerial commitment is an important facilitator for diffusion of innovation; however, there needs to be a balance to avoid compartmentalizing a change, overextending management champions and disenchanting potential adopters.

⁴ Several researchers have examined the multi-mode interaction of technologies, including pure competition, symbiotic and predator-prey relationships. Interested readers are encouraged to read Pistorius and Utterback (1996 and 1997) for additional details.

The first paradox is “change depends on management, but management makes change less likely to occur.” (Molinsky, 1999) That is, management is necessary for change; but must avoid “compartmentalizing” changes to a particular organization. The second paradox is “change depends on the commitment of change leaders, but the commitment of the change leaders makes change less likely to occur.” In essence, committed change leaders are required to secure the necessary personnel and financial resources, yet overcommitted leaders often cannot dedicate the appropriate attention. The final paradox is “change depends on rhetoric, but rhetoric makes change less likely to occur.” In other words, rhetoric is necessary to inspire and motivate the team, yet may disillusion those members instituting the change. (Molinsky, 1999)

4.4.5 Organizational Learning and Training

As noted previously, *organizational learning* is essential for product or process adoption and for the ultimate survival of a firm. Therefore, realistic training expectations must be established, with training tailored to the needs of the target audience. To accomplish this, successful firms focus on fostering knowledge sharing and recognizing employees for their work. (O’Dell and Grayson, 1998).

4.4.6 Reward System

In particular, the organization must weigh team versus individual rewards as well as balancing between “extrinsic and intrinsic rewards.” (Simard and Rice, 2001) Further, O’Dell and Grayson (1998) note successful firms focus on culture for knowledge sharing and recognize, yet Simard and Rice (2001) note the difficulty in establishing reward system for knowledge sharing, especially with respect to measuring the “quality and impact” of the shared knowledge.

4.5 Time

Although the adoption takes various times, the cumulative adoption rate of new users generally results in a S-shaped distribution, with some quickly adopted innovations having a steep curve (solid blue) and slowly adopted ones exhibiting more gradual curves (dashed magenta) as depicted in Figure 4.2.

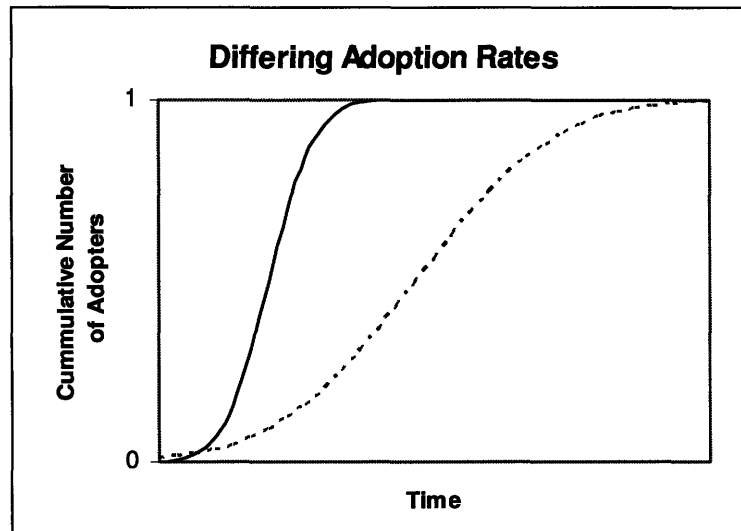


Figure 4.2 – Adoption Rates

The cumulative adoption rate for an innovation generally follows an S-shaped curve. Some quickly adopted innovations have a steep curve (solid blue), while slowly adopted ones exhibit a more gradual curve (dashed magenta).

The development or identification of the innovation is the first step in the process. Once the process has been identified, there are generally two stages to diffusion. In the first stage, a group of innovators adopts the innovation, and in the second stage, early adopters act as opinion leaders for the innovation, which then spreads throughout the organization. (Rogers, 2003) Further, this process can be accelerated by soliciting appropriate opinion leaders and matching them to the members of the user community. (Valente and Davis (1999).

For each adopter, there are four primary stages to the adoption process – *awareness*, *persuasion*, *decision-making* and *implementation*. In the awareness step, potential adopters first must recognize the potential for improvement. Then they must be cognizant of innovations, understanding the function and potential advantages and disadvantages. Adopters then form favorable or unfavorable impression of the innovation in the persuasion stage, and then accept or reject the new product or process in the decision-making step. Implementation, the final phase, involves executing the change as well as measuring the progress of the change. (Rogers, 2003 and Fraser, 2002)

4.6 Diffusion Strategies

For diffusing best practice, O'Dell and Grayson (1998) recommend the use of both benchmarking and best practice teams, knowledge and practice networks, and internal audits. Meanwhile, Kostava (1999) recommends using a *transfer coalition* composed of a core group of managers who are in charge of the transfer and a *flexible* expert group from the appropriate functional areas.

Simard and Rice recommend several strategies for diffusing best practices. The first is to identify translators to frame the knowledge transfer, opinion leaders to lead the charge and knowledge brokers to bridge communities. Additional strategies include providing incentives for knowledge sharing among groups, and focusing on external rather than internal competition.

Berwick (2003) proposes seven rules, or strategies, to foster the dissemination of innovation. First, sources of innovation must be found, through networking, attending conferences or perusing scientific journals for example. Second, senior leadership must identify foster

innovative individuals. Third, management must invest in early adopters, providing them the time and resources to try innovations on a small scale. Next, senior leadership must make early adopter activity observable by fostering the social interaction and the resulting social channels of communication between early adopters and the early majority. Then, leaders must trust and enable reinvention of an innovation, highlighting individuals who have adopted outside innovations for their work. The sixth rule is create slack time for every adopter to discover, use and adopt the innovation. Finally, champions must lead by example, prepared to initiate change themselves like Captain James Cook.⁵

4.7 Summary

There are several critical factors for the adoption of an innovation within a network, including the aspects of innovation, characteristics of the source and receivers, contextual issues and time. Specifically, some innovations are compatible with the skills and knowledge of the firm, while others require competencies that are foreign to the group. Further, some innovations spread quickly due to their clear advantage, compatibility with the adopters, and lower complexity.

The successful transfer of knowledge also is dependent on the characteristics of the source and adopters. In addition, organizational and contextual issues may provide potential barriers, especially institutional factors, cultural issues and managerial factors. Further, the transfer occurs over time, beginning with awareness of the innovation to adoption, and there are several strategies for facilitating the diffusion of a new product or process.

⁵ Berwick (2003) recounts the story of the slow adoption of scurvy fighting techniques beginning with James Lancaster's experiment in 1601 to a universal British policy in 1865. Unlike others, the explorer James Cook instituted a combination of hygiene and dietary practices to prevent scurvy and required his officers to lead by example and eat the diet as well. Thus, Cook lost only three men on his three voyages, while other captains lost scores of sailors to scurvy.

Chapter 5: Method Development and Diffusion

With the background established, the next stage of the research was development of “Slider Bar” process and its spread among the NVH community. First, the objectives and targets are established, the P-diagram developed, and the appropriate control and noise factors are identified. Next, the CAE modeling and processing are discussed, along with the statistical analysis needed to generate the parameters for the meta-model. The analysis and verification of the “Slider Bar” model are then presented. With the model developed, the chapter concludes with a discussion of the techniques used to spread the model.

5.1 “Slider Bar” Development

The first stage of the innovation process is the development of the new process or product. In this case, the “Slider Bar” process was established, including the following:

1. Establish objectives, including motivation and performance targets.
2. Develop the P-diagram, including ideal function and error states.
3. Determine “rich and realistic” noise and control factors.
4. Update the CAE model and load cases for the computational analysis.
5. Perform CAE/VSIGN runs, including the multiplying transfer functions (TFs) to by Monte Carlo Loads and the post-process of results to develop histograms.
6. Analyze histograms and perform step-wise regression to determine Weibull shape & scale.
7. Input equations to response surface generator utility to develop “Slider Bar” model.
8. Analyze and verify the model versus the CAE.

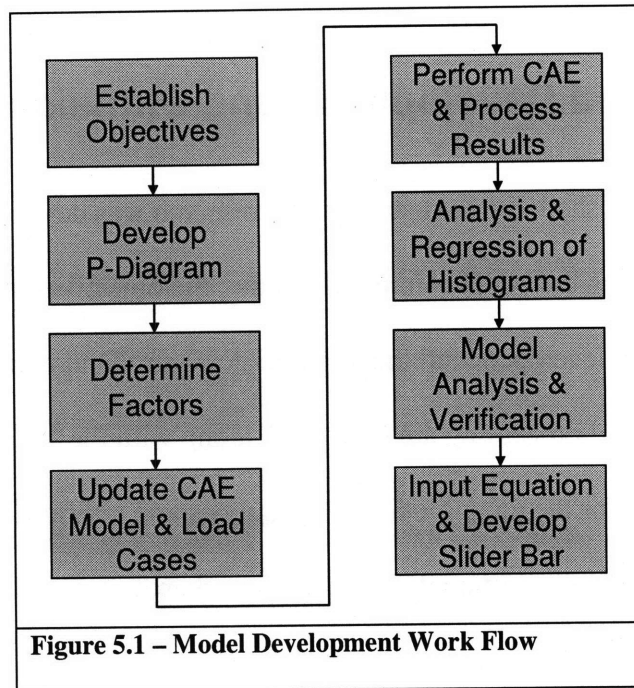


Figure 5.1 – Model Development Work Flow

The subsequent sections present each step in the “Slider Bar” development, highlighting the critical aspects.

5.2 Establish Objectives

The first step in the process was establishing project motivation and objectives. In this case, the motivation was to support corporate quality initiatives and the new global product development system, which includes reduced development time and limited hardware prototypes. Therefore, the primary objective was to develop a process and accompanying tools to uncover failure modes early in the product development to cycle, where countermeasures are more feasible and cost effective.

For the customer response metrics, both internal and external vehicle were benchmarked according to established corporate best practices (Clapper and Braunwart, 2001), and the targets

were established through customer and NVH expert subjective evaluations, which were correlated with objective vibration and sound metrics.

5.3 Vehicle System P-Diagram

The next step of the model development was to build the vehicle system P-diagram for tire and wheel shake and driveline roughness, including the subsystem inputs, the noise and control factors, the ideal function and potential error states encountered. (See Figure 5.2)

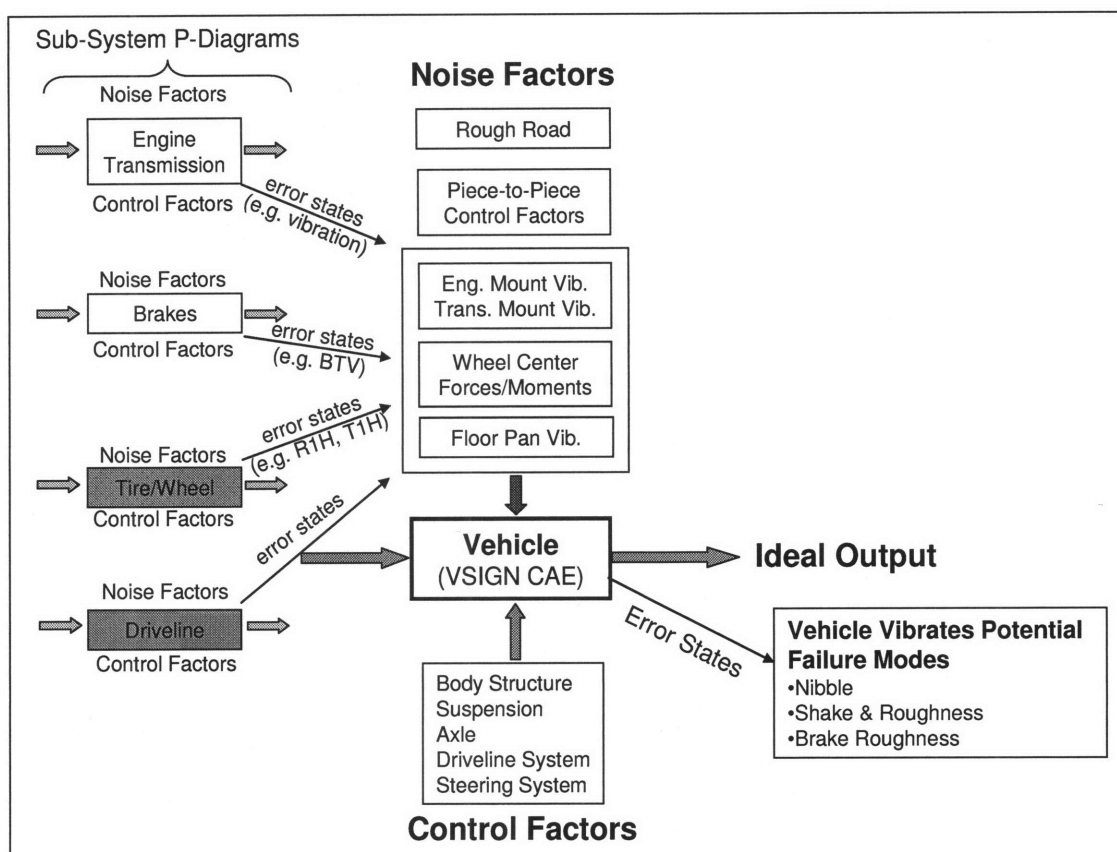


Figure 5.2 – Vehicle level P-diagram

In this case, the subsystems are the input for the system, with a quiet and smooth ride the ideal output. The failure modes are tire/wheel shake, driveline roughness and driveline-induced boom. Meanwhile, the control and noise factors include the body structure, mounts, driveline system and steering system

In this case, the tire/wheel and driveline subsystems are the input for the system, with a quiet and smooth (low vibration level) ride the ideal output. The failure modes, or error states, in this case are tire/wheel shake, driveline roughness and driveline-induced boom at the customer response

points. Meanwhile, the control and noise factors include the body structure⁶, driveline components and steering components, and these are examined in the subsequent section.

5.4 Control and Noise Factors

With the vehicle P-diagram established, the potential control and noise factors were examined for the various vehicle configurations. These include traditional body-on-frame (BOF) trucks and sport utility vehicles (SUV) that use a solid rear axle or an independent rear suspension (IRS), unibody all-wheel drive SUVs and crossover utility vehicles (CUV), and rear wheel drive (RWD) sedans and coupes. (See Figure 5.3 through Figure 5.6.)

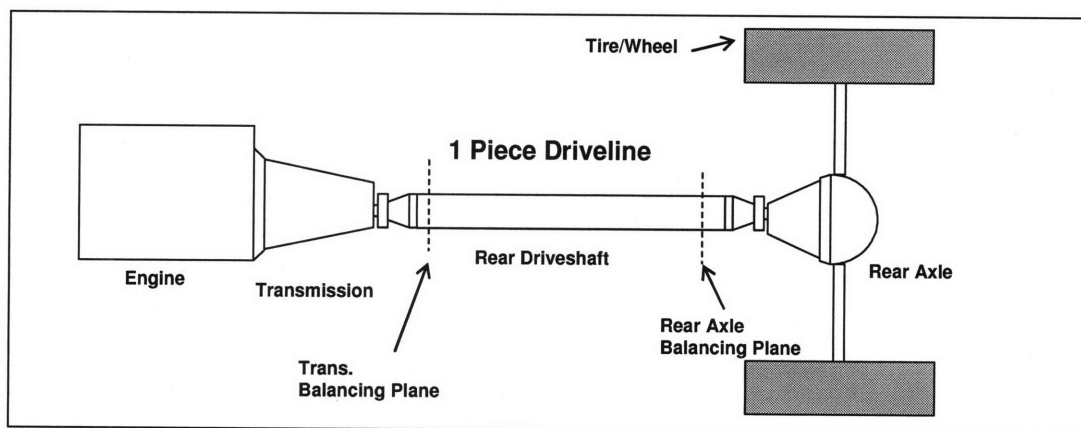


Figure 5.3 – 1-Piece driveline system

For traditional body-on-frame trucks and sport utility vehicles, the driveline typically consists of a single driveshaft is coupled to either use a solid rear axle or an independent rear suspension. (Adapted from Clapper and Braunwart, 2001)

⁶ Body structures are often difficult to adjust especially later in the development process and typically are examined only when there is a coupling issue between a component and the body – e.g. steering column and the cross-car beam of the body structure.

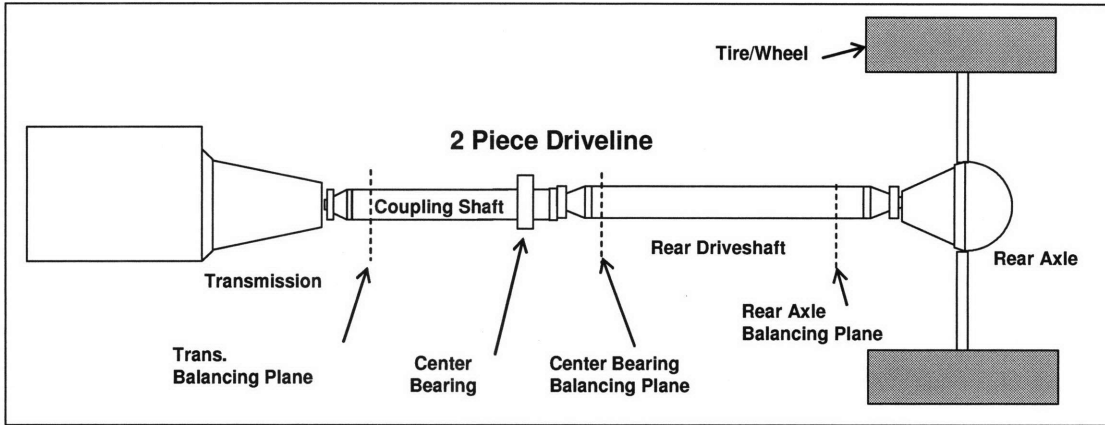


Figure 5.4 – 2-piece driveline system

More vehicles are using a 2-piece driveline, which includes center-bearing linking the two shafts. (Adapted from Clapper and Braunwart, 2001)

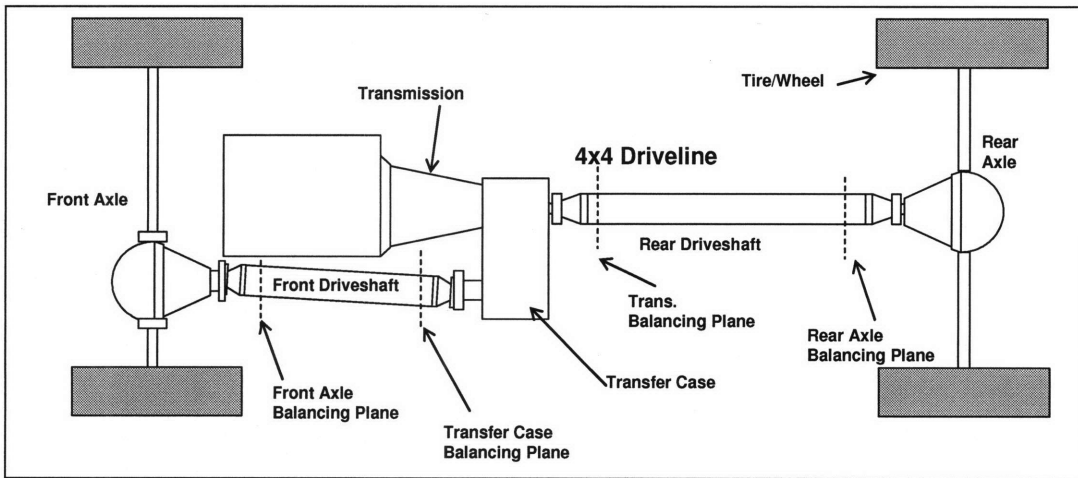


Figure 5.5 – 4x4 driveline system

The traditional 4x4 driveline system utilizes a transfer case to transmit torque to the rear and front driveshafts. (Adapted from Clapper and Braunwart, 2001)

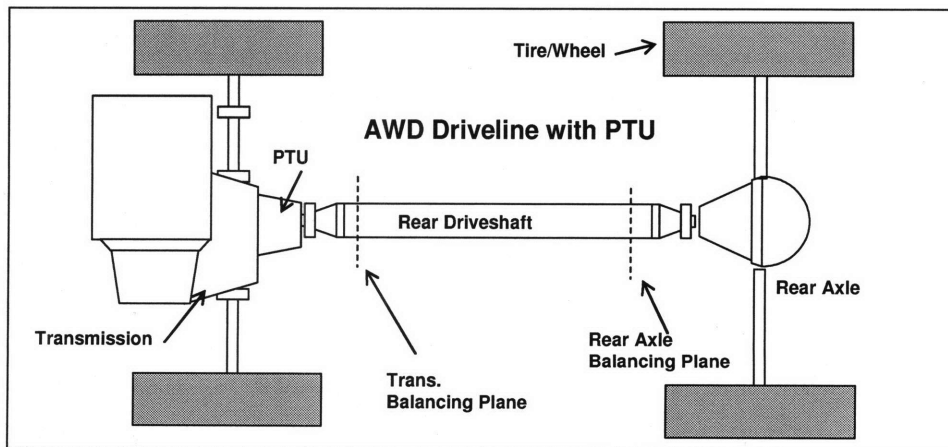


Figure 5.6 – AWD drive system with powertrain take-off unit (PTU)

Many AWD drive cars and crossover vehicle use a transverse mounted powertrains with a PTU mated to driveshaft. (Adapted from Clapper and Braunwart, 2001)

For each vehicle configuration, the common and unique control factors were determined and documented in Table 5.1 below, though individual programs may have additional control factors that influence the system response.

Table 5.1 – Typical Control Factors

	Driveline	Common	Tire/Wheel
Truck (BoF w/ solid axle)	Leaf Spr Bushing Leaf Spr Modes CB Mnt Rates Axle Gear Ratio D/S-Slip Slide Res D/S Bend Modes P/T Bend Modes	Body Mnt Bushing Rates Frame Modes Trans Mnt Rates Engine Mnt Rates Hydrobushing Parameters	Suspension Bushing Rates Suspension Geometry Shock Rates
SUV (BoF w/ IRS)	Axle Mnt Rates CB Mnt Rates Axle Gear Ratio D/S-Slip Slide Res Axle Mnt Locations D/S Bend Modes P/T Bend Modes	Body Mnt Bushing Rates Frame/Subframe Modes Trans Mnt Rates Engine Mnt Rates	Suspension Bushing Rates Suspension Geometry Shock Rates
Car (E/W & AWD)	RDU Mnt Rates CB Mnt Rates Axle Gear Ratio D/S-Slip Slide Res	Subframe Mnt Bushing Rates Frame Modes P/T Mnt Rates	Suspension Bushing Rates Suspension Geometry Shock Rates

For BOF vehicles with a solid rear axle, the distinctive control factors include the leaf spring bushings and modes, while axle mount rates and locations among the factors for body-on-frame vehicle with IRS. For unibody SUVs, CUVs and cars, the unique control factor include axle and RDU mount rates.

While a number of control factors are common, the unique noise factors for each system are captured in Table 5.2 for both the driveline and tire/wheel systems.

Table 5.2 – Noise Factors

Driveline	Tire/Wheel
D/L Plane Imbalance	Static Imbalance
Axle Front/Rear PLRO	Dynamic Imbalance
PTU PLRO (E/W AWD only)	Longitudinal Force
	Vertical Force

For driveline, the noise factors primarily are related to the piece-to-piece variation in the system components at the planes in the system. These include the imbalances and composite flange run-outs (CFRO) at each plane, the pitch-line run-out (PLRO) at each axle, and the PLRO at the PTU plane in east-west (e/w) applications. For the tire/wheel, the noises are the static and dynamic imbalance and the longitudinal and vertical forces at each tire/wheel plane.

As noted earlier, the ranges for each control and noise factor must be “rich and realistic” to excite the failure mode, yet occur in use. To accomplish this, control factor values for the powertrain (engine and transmission) and body mounts were obtained from an internal database, containing the stiffness values for various internal and competitor mounts. Rates for the remaining mounts, bushings and leaf springs represented typical values for vehicles produced for the North American market and were determined through benchmarking or supplier capability analysis.

The bending mode ranges were determined by analyzing the standard driveshafts used on a typical program including tube length, tube thickness and material selection. Meanwhile, the slide-resistances were based on analytical approximation of experimental measurements. Finally, the suspension geometry values represent the range allowed by package constraints, while maintaining the required vehicle dynamics and safety functionality.

For the noise factors, the driveline planar imbalance and pitch-line run-out ranges again were based on standard values, determined using benchmarking and supplier capability analysis. Meanwhile, the values for the tire and wheel imbalances and forces are the result of extensive benchmarking, tire analysis, and historical data.

5.4.1 Distribution Selection – Uniform vs. Normal

Both the normal and uniform distributions often are employed in the automotive industry; however, the selection of one is often a contentious issue among the engineering community. While Thomas, Soderberg and Borders (2005) successfully used the uniform distribution in their nibble NVH work, there was some belief among the NVH community that the normal distribution better represents the factors and is understood better by the NVH development engineers. Therefore, the truck model first was run using uniform distributions for each of the control and noise factors, and then run again using normal distributions for the factors. The results were compared to determine the effect of the distribution choice.

5.5 Update Model and Loads

Before the model is run, the experimental loads and model are updated. First, the loads are established for the system control and noise factors, and then the computer model is adjusted to improve computational efficiency.

5.5.1 Design of Experiments

For the DOE runs, the Box-Benhken design initially was used, given its success in the previous nibble studies. (Thomas, Soderberg, and Borders, 2005) Specifically, this design was selected given its efficiency as a second order model, with the second order response surface generated using the regression analysis discussed in a subsequent section.

After the initial results, a space-filling design was considered to explore the design space. Given its simplicity and efficiency, the Halton Low Discrepancy Sequence (LDS) was selected for the subsequent computer runs over other designs such as Latin Hypercube, which would have been more computationally intensive and expensive given the required number of runs.

Additionally, a separate set of the test runs are performed using a *Plackett-Burman*⁷ design.

These runs are not part of the regression analysis and subsequent response generation and are used as an assessment of the model.

5.5.2 Update Model

With the DOE established, a computer simulation is performed using an internally developed modal solver package, which includes a graphical user interface as well preprocessing and post-

⁷ Plackett-Burman designs are fractional factorial designs and are typically used to investigate main effects.

processing capabilities. In preparation for the simulation, the CAE model is simplified and the number of degrees of freedom reduced for efficiency.

5.6 Run Model & Process Results

Using the DOE parameters, the vehicle model is run N -times in the modal solver to generate a set of transfer functions (TFs) between each factor and the customer response point – i.e. seat track vibration, steering wheel vibration and sound at the outboard ear of the driver. (See Figure 5.7 below)

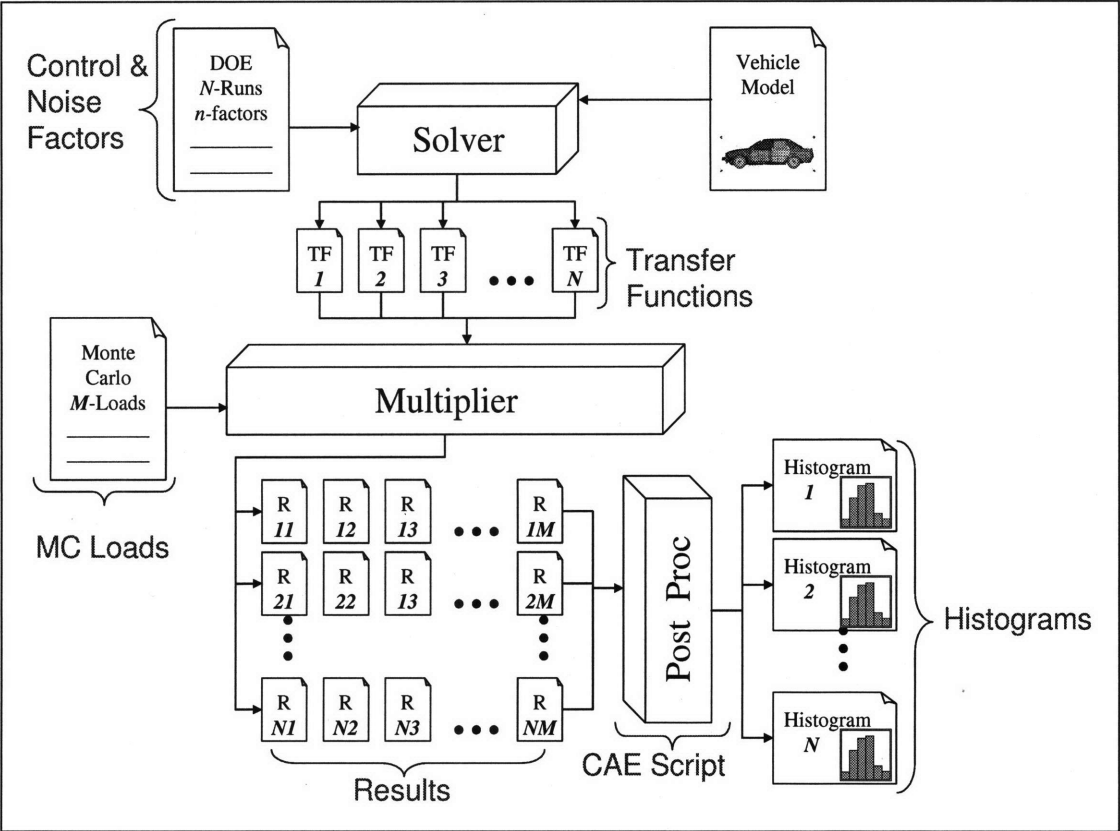


Figure 5.7 – Computer Simulation to generate transfer functions
 Using the DOE parameters and the vehicle CAE model, the modal solver is run to generate a set of transfer functions. A separate software tool multiplies the transfer functions by the Monte Carlo loads, and the results are then post-processed to yield a set of histograms. (Adapted from Braunwart, Thomas, Clapper, Borders, Huber and Blibeche, 2006a)

This results in a set of N transfer functions, which are then multiplied by the Monte Carlo loads using a separate, more computationally economic software package. The N by M results are then

post-processed using a CAE script to generate a set of N histograms for subsequent analysis using either commercially or internally developed software packages.

5.7 Analysis and Regression of histograms

The histograms are then analyzed using a statistical software analysis package and fit to a particular distribution. For this work, the Weibull distribution is used, given its flexibility, extensive use in accelerated life testing, and previous success in modeling NVH phenomena. (See Figure 5.8 below.)

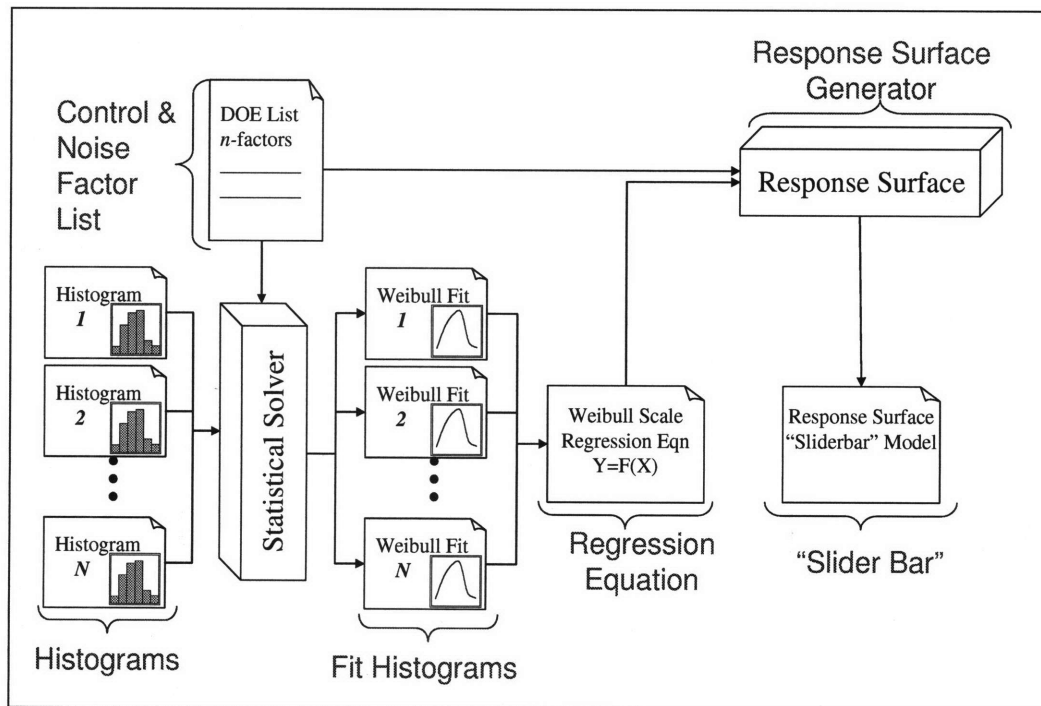


Figure 5.8 – Determination of Weibull parameters and generation of the meta-model
 Using a statistical software package, the set of histograms is then analyzed and fit to Weibull distribution. The constant shape and modeled scale parameters are then entered into response surface generator utility to produce the “Slider Bar” meta-model. (Adapted from Braunwart, Thomas, Clapper, Borders, Huber and Blichebe, 2006a)

In this case, the Weibull shape parameter is held constant (not modeled) and the median value from the histogram results is used. This approach is used since a common assumption of accelerated life testing, called the *Failure Mode Conservation Principle*, is the shape parameter

remains constant for a given failure mode – i.e. each failure mode has distinct shape parameter and sufficiently different shape parameters suggest different failure modes are present.

It is important to note this principle differs from the *Conservation of Failure Modes Principle* discussed by Davis (2004a), which states the number of failure modes is finite and must be uncovered. Rather than contradictory, the *Failure Mode Conservation Principle* used here can be viewed as complementary to Davis’ principle – i.e. there are a finite number of failure modes to be uncovered, each with a unique shape.

For example, the probability density function and probability plots are shown for various shape parameters in Figure 5.9.

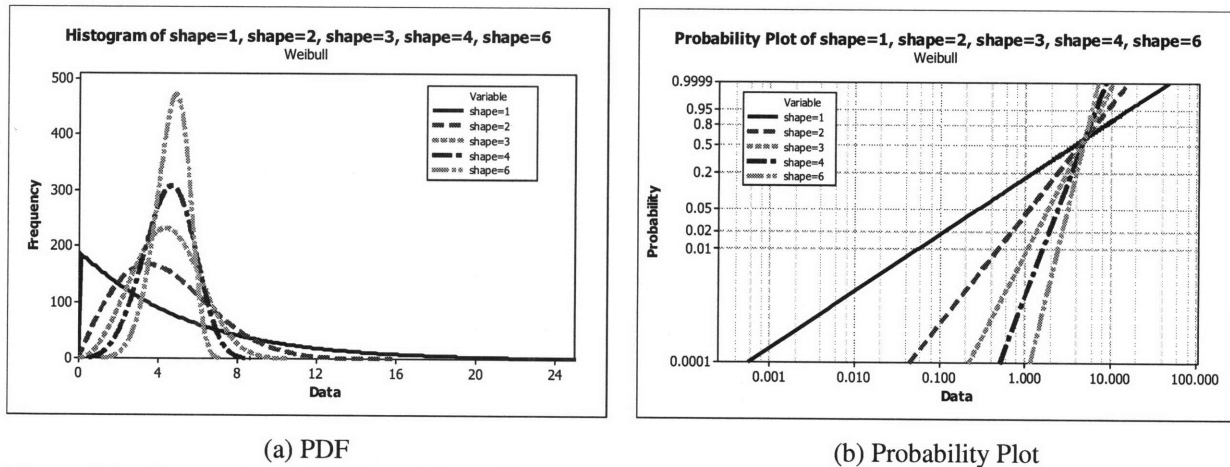


Figure 5.9 – Comparison of different shape for constant scale parameter

The probability density function (PDF) and probability plots are shown for various shape parameters with a constant scale. The curve for shape of 1 is significantly different from the others, while the distributions with shapes of 3 or 4 were sufficiently similar, suggesting the same failure mode is present.

Here, the curve for shape of 1 (solid black curve) is significantly different from the others, while the distributions with shapes of 3 or 4 were sufficiently similar, suggesting the same failure mode is present.

While the shape parameter is constant, the scale parameter is statistically modeled, using a stepwise linear regression technique. Here, main effects, all second order interactions, and pure quadratic terms are included, with the standard stepwise regression method used to identify the useful subset of predictors by adding and eliminating variables for *p-values* greater than an *α-value* of 0.05.⁸

With the analysis and regression complete, the median shape parameter and modeled scale parameter are determined for each of the customer responses. Therefore, all the necessary information for developing the “Slider Bar” meta-model is available.

5.8 Input Equation and Develop “Slider Bar”

With the regression analysis output, the “Slider Bar” is generated using an internally developed software packed for response surface analysis. The DOE factor list and resulting Weibull shape and scale parameters are entered to yield a meta-model for further exploratory analysis; however, the model is first verified against the CAE.

5.9 Analysis and Verification

To verify the meta-model, the next step is to inspect the shape and scale histograms to confirm the fit, which is accomplished through both visual inspection and by comparing the R^2 values⁹.

⁸ Used in hypothesis testing, the p-value is the probability of obtaining a test statistic that is at least as extreme as the observed value, assuming the null hypothesis is true – i.e., the finding was the result of chance alone. Typically, the null hypothesis is rejected if the p-value is equal to or smaller than the significance level, or *α-value*, which is commonly 0.05 (5%).

⁹ R^2 , the coefficient of determination, represents the percentage of total variation in the response explained by factors in the model, and generally, the higher the R^2 , the better the model fits the data.

For the visual inspection, the histogram first is examined to determine if there is one mode for the shape parameter.

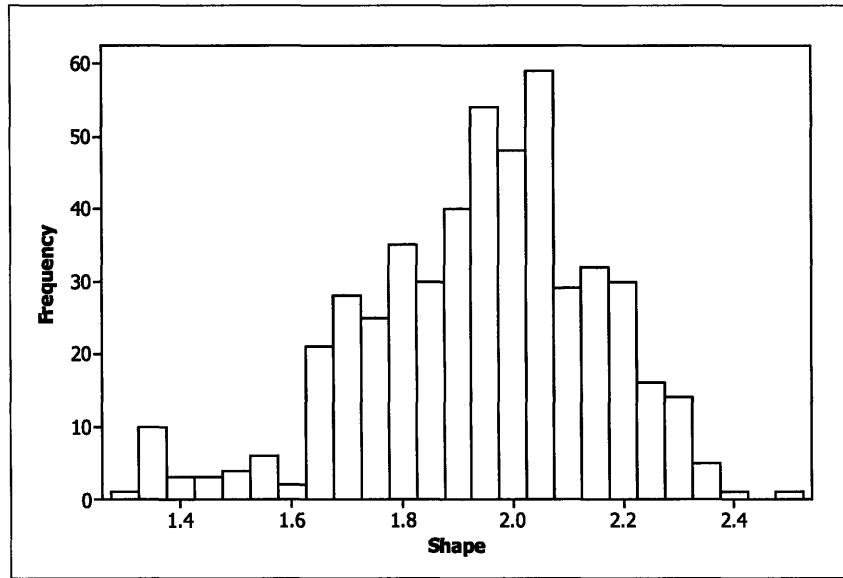


Figure 5.10 – Shape Histogram Example
The histogram should resemble the theoretical Weibull distribution, though individual bins may be higher or lower than expected.

The histogram preferably would have a single mode and resemble the theoretical Weibull distribution. In practice, the histograms resemble Figure 5.10 – i.e. the overall trend is similar to the Weibull distribution, though individual histogram bins may be higher than expected.

In addition, a probability plot is generated to assess the fit of the Weibull distribution to the response. (See Figure 5.11.)

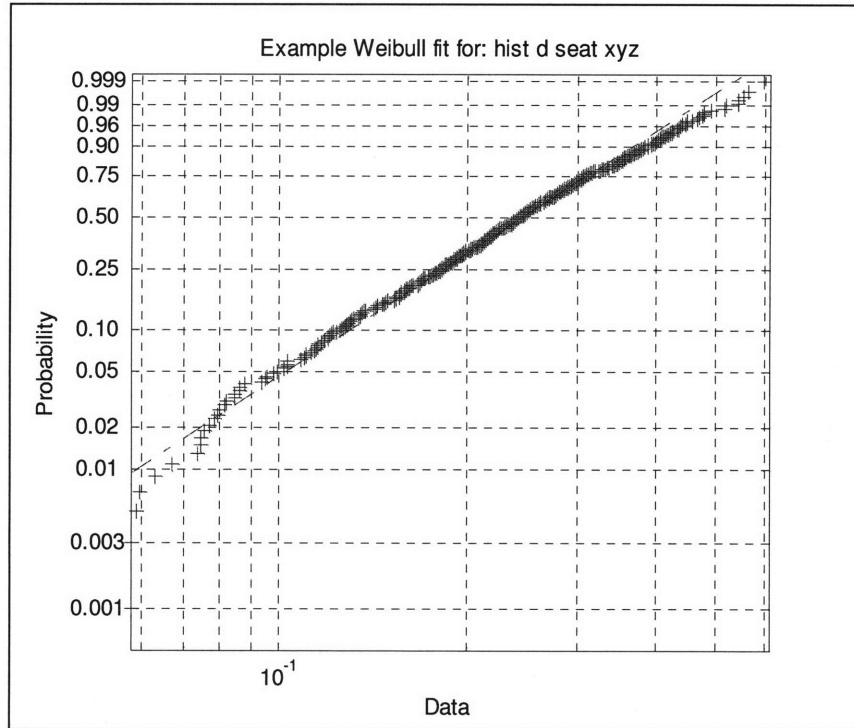


Figure 5.11 – Weibull probability plot example
 The distribution fits through the majority of the range and the Anderson-Darling (AD), suggests a sufficient fit.

In this case, the distribution fits through the majority of the range and the Anderson-Darling (AD)¹⁰ value suggests a sufficient fit.

Next, the results of the statistical solver and resulting “Slider Bar” meta-model are compared with the CAE model for validation.

¹⁰ The Anderson-Darling test is used to determine whether a sample comes from a specified distribution, and smaller values indicate the distribution fits the data better.

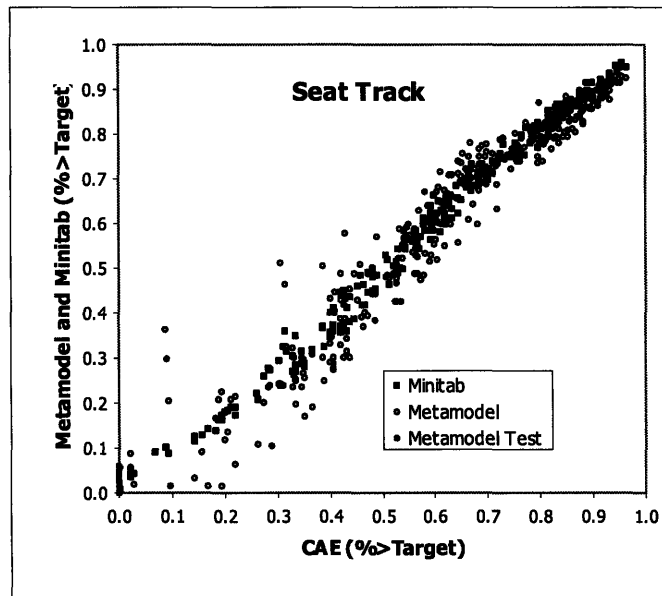


Figure 5.12 – Comparison of meta-model and CAE
 Ideally, there results from the statistical package and meta-model should match the percent exceeding from the CAE model throughout most of the range. In this case, the statistical package and the meta-model runs exhibit some scatter from the CAE.

Ideally, there should be little scatter from the diagonal – i.e. results from the statistical package and meta-model match the percent exceeding from the CAE model throughout most of the range. In the case depicted in Figure 3.10, the statistical package (Minitab™), the meta-model runs, and the meta-model test runs exhibit some scatter from the CAE, and one possible reason for the scatter is the need for different experimental design to improve the meta-model prediction of the CAE.

5.10 NVH Process

A limited number of CAE-based DOE investigations have been performed with control factors, although these are generally done later in the development process to “find and fix” problems noted by the experimental development team and management. (See Figure 5.13.) At this point in the development process, limited mounted tuning is generally the only opportunity to improve the NVH performance since the body structure and system components are complete.

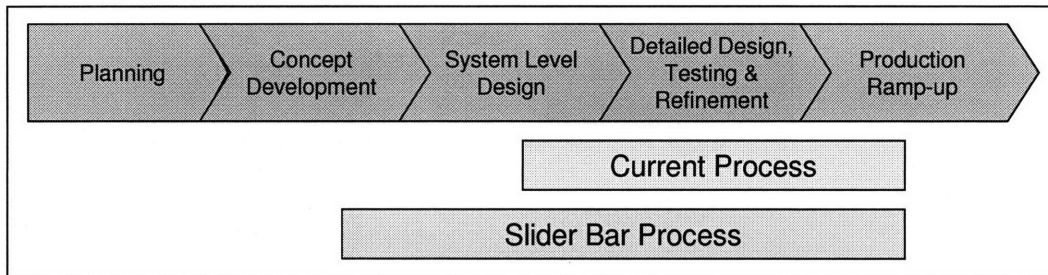


Figure 5.13 – Process Timing Comparison

The current process generally is performed later in the development process, while the “Slider Bar” process can be used from the concept development to production. (Adapted from Ulrich and Eppinger, 2003)

The new “Slider Bar” process, meanwhile, examines both the control and noise factors affecting the system, and can be used from the concept development stage through production.

Additionally, the process can be expanded to the early stages of concept development if an appropriate surrogate model is available.

5.10.1 Current Process

In process currently used, development NVH engineers request a particular set of control factors for the model, such as body mounts and engine mounts. The CAE NVH engineers then update the particular components in the model, run the full vehicle model, and analyze the data with respect to the customer response point metrics. Once the analysis is complete, the CAE NVH and development NVH engineers meet to review the results and determine what subsequent analytical and experimental testing must be done. Unfortunately, this is a single iteration, which may be repeated several to dozens of times during the product development cycle for a particular vehicle program.

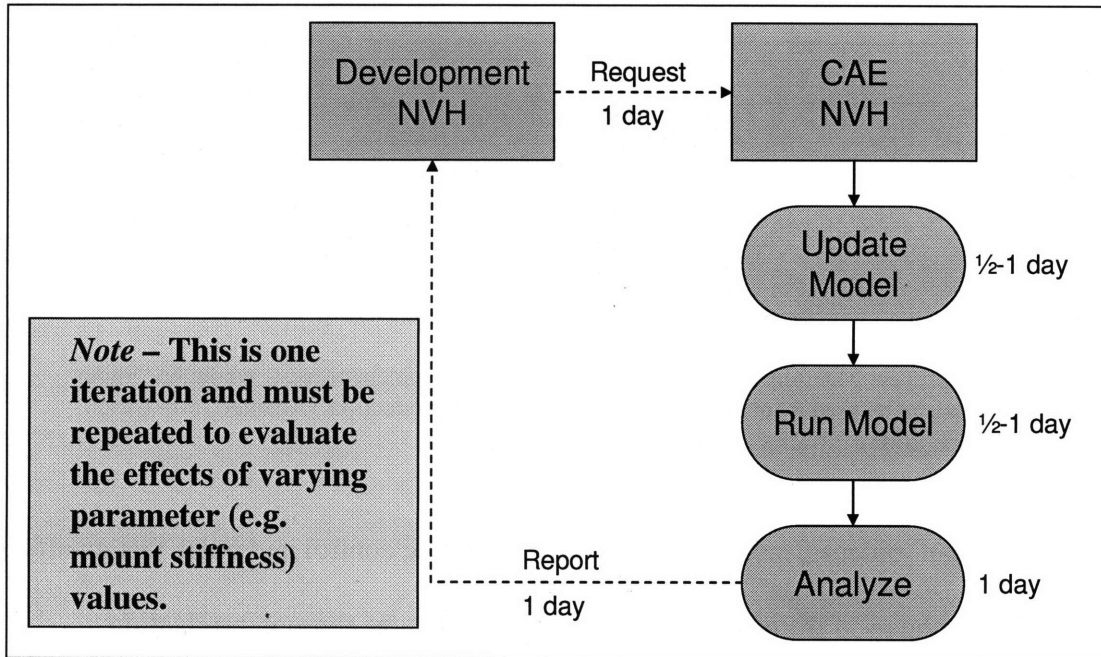


Figure 5.14 – Current Process

In the current process, the development engineers request CAE NVH to examine a particular set of parameters – e.g. body mounts. The CAE NVH then updates the parameters, runs the model, analyzes the results and reports the findings to the development team.

5.10.2 “Slider Bar” Process

With the “Slider Bar”, the process requires more interaction between the development engineers and the CAE engineers, particularly in determining the appropriate control and noise factors for evaluation and establishing the corresponding “rich and realistic” ranges for each factor.

Additionally, the post-processing, statistical data analysis and regression, and response surface generation increase the time. However, this process will be run only at specific milestones in the product development cycle, rather than the several dozens times in the current process.

Therefore, the cumulative time will be reduced, while allowing the engineers to consider more factors and the possible operating ranges for each factor.

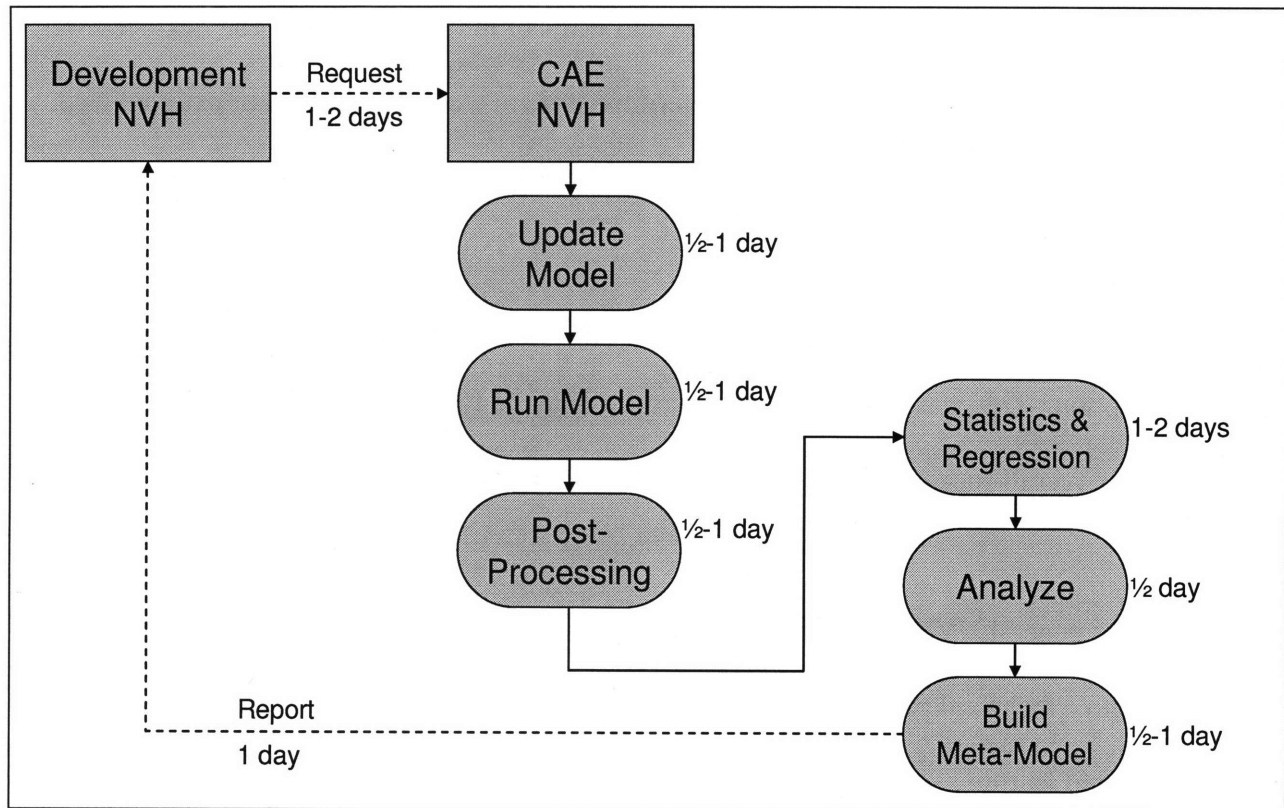


Figure 5.15 – “Slider Bar” process

The “Slider Bar” process requires greater interaction between the development and CAE to establish factors and levels. The CAE NVH engineer then updates the models, runs the models, and post-processes the results. Statistical and regression analysis then is performed, the results analyzed and verified, and the meta-model generated.

5.11 Diffusion

During the development of the failure mode approach, the product attributes identified by Rogers (1995) were used to ensure the team was focused on a process and corresponding suite of tools that readily were adopted by the user community. In particular, the development focused on providing a clear relative advantage for the user over the current process and tools. An additional objective was to ensure the process and tool complexity were reduced, could be easily tested and produced an observable change for the user.

Once the process development was complete, the first step in the diffusion was to determine type of process innovation – continuous, dynamically continuous, or discontinuous – and the potential

alignment issues with the culture, competencies and skills of the organization. The next step was to identify the potential adopter groups and determine if there were any internal or external lead users, who could be leveraged as sources of knowledge and innovation.

The focus then shifted to working with the identified opinion leaders within the communities to speed adoption. This was important particularly within the CAE community, where adoption was critical to overall success of the process and the majority of the changes would occur.

To address the general NVH community, a multi-channel communication approach was used, beginning with a technical presentation at an internal NVH conference and continuing through a series of tailored learning sessions for the CAE NVH and program development NVH engineers. For the CAE engineers, training content was focused on the experimental designs and the process for building, updating, and exercising the vehicle model to support the slider bar process. Meanwhile, the training for the development NVH engineers concentrate on using the resulting meta-model to examine the potential design space. This is useful particularly early in the product development process when the design is not frozen and it is more cost effective to change. Additionally, the meta-model helps the test engineer determine the appropriate range for "tunable" parts, such as body, axle and engine mounts.

The development then focused on improving the relative advantage and promoting adaptability to help increase adoption. The final step was to elicit feedback from the users to improve the process and associated tools.

5.12 Summary

Given the competitive nature of the automotive industry, the “Slider Bar” process is needed to uncover and avoid failure modes early in the product development process, where countermeasures are more effective. To accomplish this, the process objectives first are identified, including determination of metrics and failure modes. Next, control and noise factors, including “rich and realistic ranges”, are identified for each vehicle program. The CAE modeling and processing are then discussed, including the statistical analysis needed to generate the parameters for the meta-model, and the steps for analysis and verification of the “Slider Bar” model are presented. The chapter then concludes with a discussion of the techniques used to spread the model among the potential adopters, and the results are discussed in the next chapter.

Chapter 6: Results & Discussion

With process background established, this chapter presents the results and discussion, beginning with an examination of the experimental design findings. The verification analysis is examined, including a comparison with experimental results, and the “Slider Bar” meta-models are then presented for the three vehicles used to develop and pilot the process. The diffusion results are presented, and finally, a resultant strategy is introduced to address the development and adoption of a failure mode avoidance initiative.

6.1 DOE Results

Based on the previous work for nibble, a Box-Behnken design initially was used for the computer runs. However, the resulting shape parameter histogram appeared bimodal for the steering wheel vector velocity, suggesting potentially two failure modes. (See Figure 6.1.)

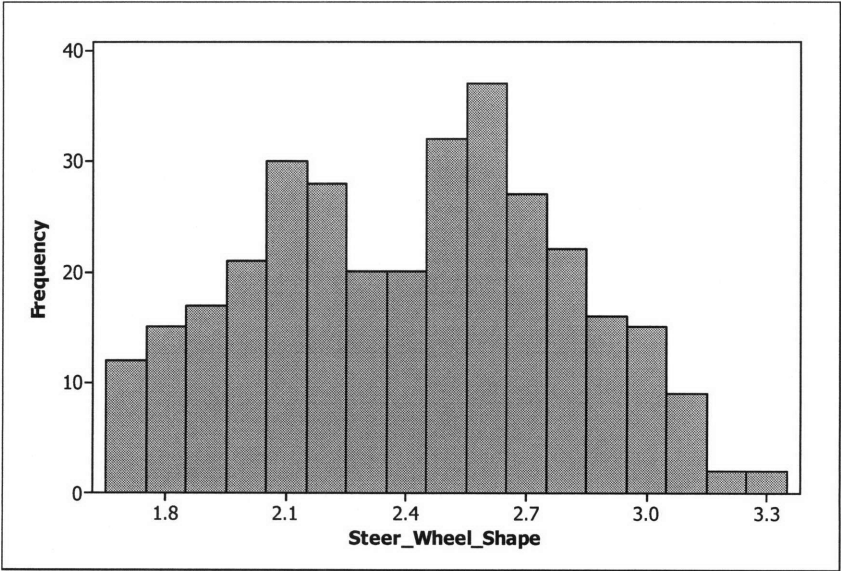
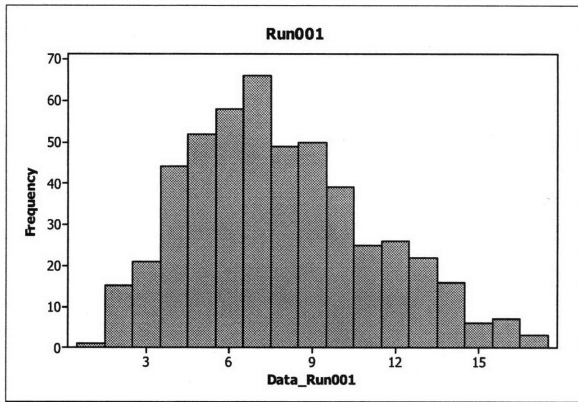
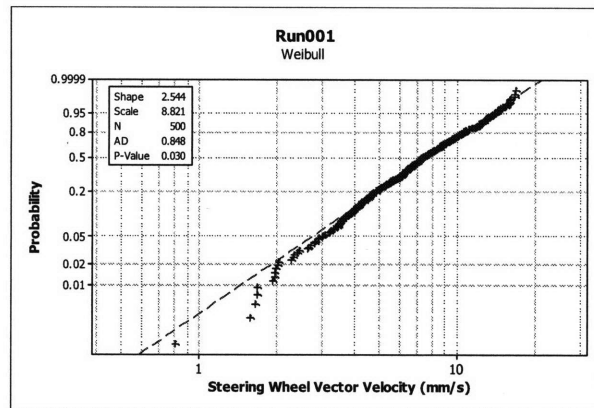


Figure 6.1 – Steering Wheel Shape parameter
The steering wheel shape parameter histogram appeared bimodal, requiring further analysis to determine whether two failure modes were present or whether the possible bimodality was the result of experimental design and analysis.

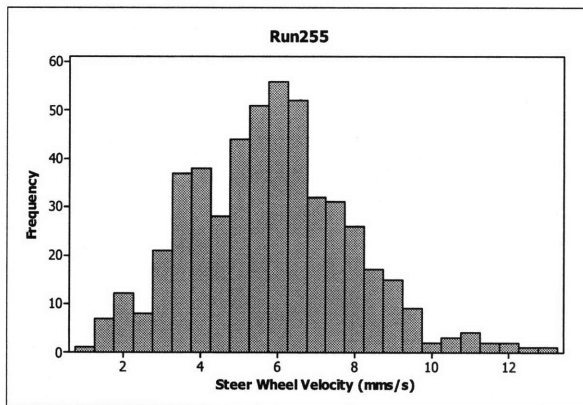
Since a single failure mode was expected, further analysis was performed to determine whether two failure modes were present or whether the possible bimodality was the result of experimental design and analysis. To determine this, the histograms and probability plots for the steering wheel response were examined. (See Figure 6.2 below.)



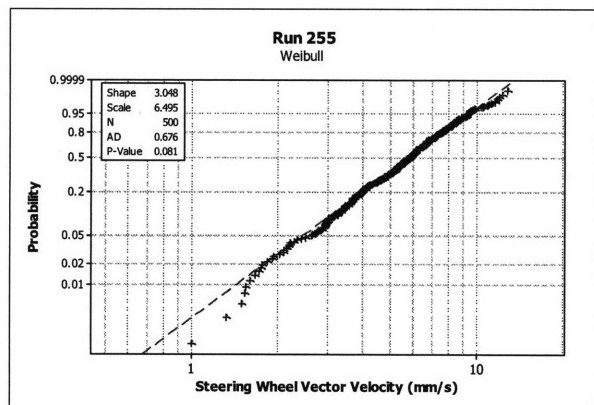
(a) Histogram



(b) Weibull Probability Plot



(a) Histogram



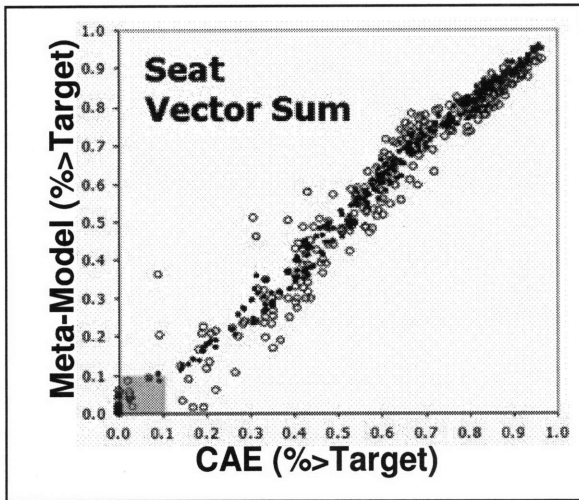
(b) Weibull Probability Plot

Figure 6.2 – Example Histograms

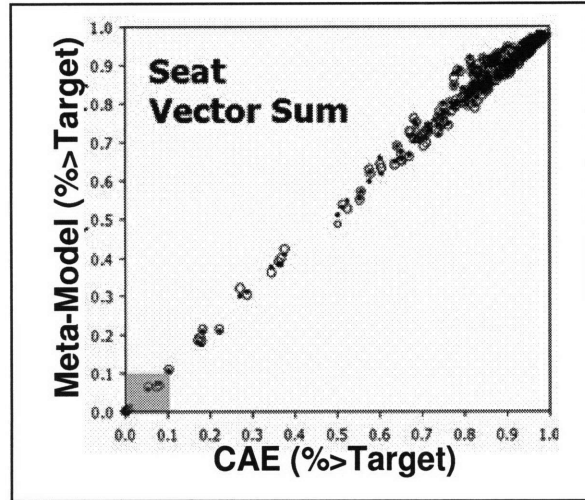
From the various histograms and probability plots, there appeared to be a single mode and the shapes were sufficiently similar.

Examining the various histograms and probability plots, there appeared to be a single mode and shapes were sufficiently similar. Therefore, the apparent bimodality exhibited in Figure 6.1 was merely a *red herring*.

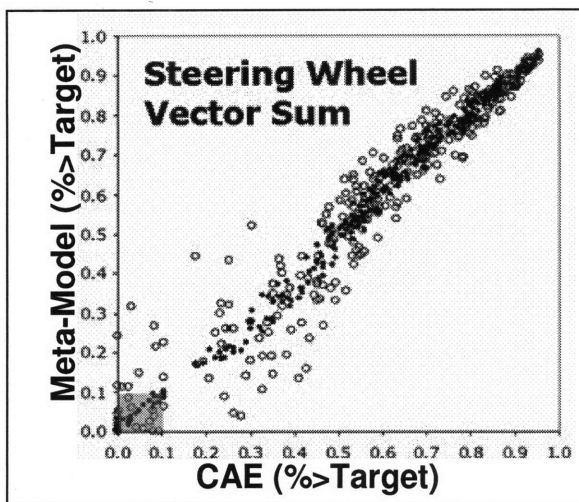
The meta-model fits were then compared with the original CAE for validation; however, the meta-model runs and test runs exhibit some scatter from the CAE. Since it was possible the design was not eliciting the system the response, the process was repeated using a Halton low discrepancy sequence for the experimental design, with the results depicted in Figure 6.3 below.



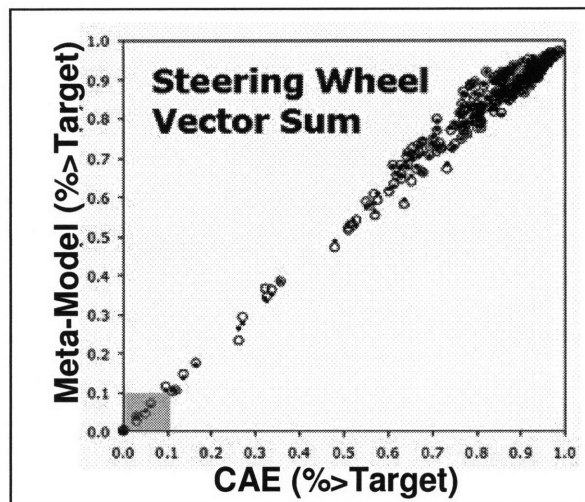
(a) Box-Behnken design



(b) Halton Low Discrepancy Sequence



(c) Box-Behnken



(d) Halton Low discrepancy Sequence

Figure 6.3 – Meta-model results for truck program.

The Box-Behnken designs exhibit greater scatter throughout the range than the Halton LDS designs. (Adapted from Braunwart, Thomas, Clapper, Borders, Huber and Blicheche, 2006a)

Here, the Box-Behnken designs (Figure 6.3 a and c) have greater scatter around the diagonal than the corresponding results determined using the Halton LDS designs, suggesting the LDS design better matched the CAE and may be a more appropriate design for the tire/wheel and driveline investigations.

For nibble, Box-Behnken designs work well since the response is monotonic and typically in one frequency band. More precisely, the response is monotonic relative to the control factors – e.g. more damping is always better. However, for tire/wheel shake and driveline roughness, the response is modal dependent and in multiple frequency bands. (See Figure 6.4)

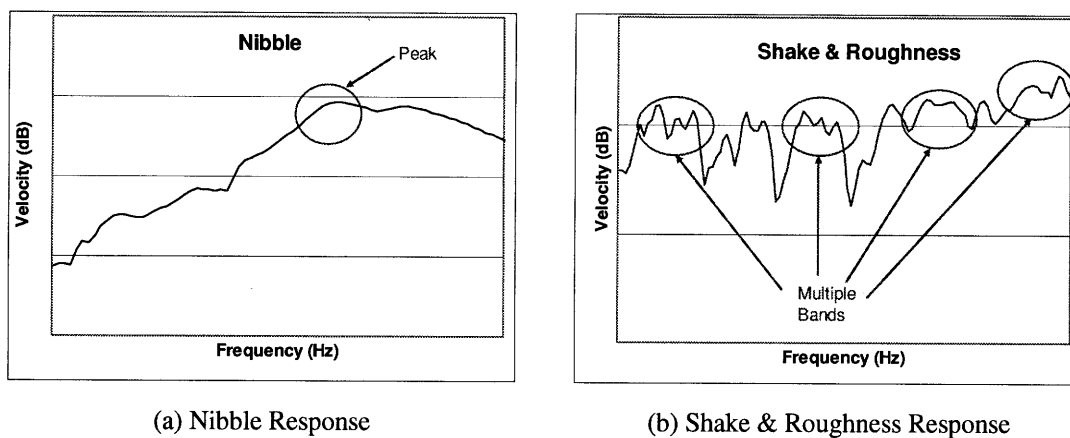


Figure 6.4 – Comparison of Nibble and Shake a Roughness responses

For nibble, the response is monotonic, while the tire/wheel shake and driveline roughness response is modal dependent and is multiple frequency bands.

In the case of nibble, both the dispersion and discrepancy of the Box-Behnken design were not concerns, since the peak was always selected. For driveline roughness and tire/wheel shake, the Box-Behnken might skip a peak, whereas lower discrepancy and dispersion of the Halton LDS captured the failure modes. (See Figure 6.5.)

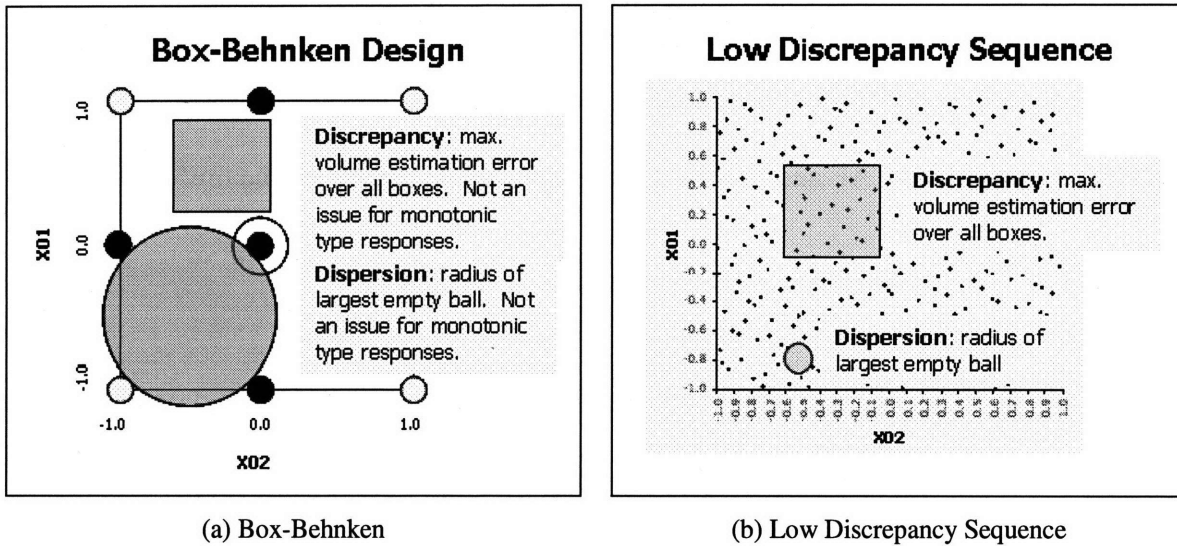


Figure 6.5 – Discrepancy and Dispersion comparison.
 For nibble, the response is monotonic and typically in one frequency band, therefore both the dispersion and discrepancy of the Box-Behnken design were not concerns. However, for tire/wheel shake and driveline roughness, the response is modal dependent and in multiple frequency bands, and the lower discrepancy and dispersion of the Halton LDS was needed. (Adapted from Braunwart, Thomas, Clapper, Borders, Huber and Blichebe, 2006a)

Based on these reasons, a space-filling design is required to explore the entire design space for driveline roughness and tire/wheel shake.

6.2 Distribution Results

While the normal and uniform distributions are often used in automotive engineering, there was the belief that normal distributions better represent the control and noise factors for tire/wheel and driveline NVH. To examine this assertion, the model was run for both normal and uniform distributions, and the expected values of the scale parameters were compared for each customer response point using the Central Limit Theorem. (The Central Limit Theory suggests the distribution of averages approaches normal as depicted in Figure 6.6 – i.e. the cumulative effect of adding distributions approaches a normal distribution regardless of the parent distributions.)

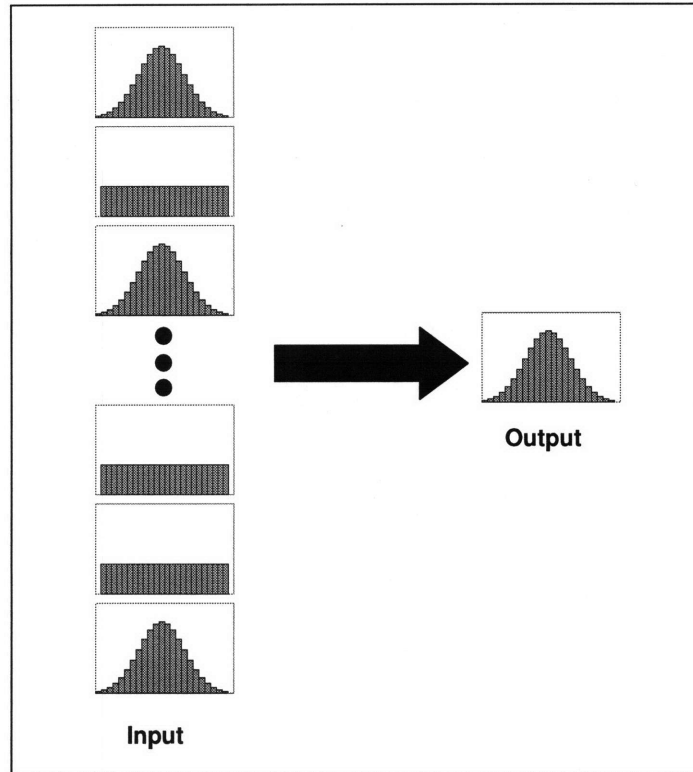


Figure 6.6 – Central Limit Theorem
 The Central Limit Theorem suggests the distribution of averages approaches normal regardless of the parent distributions.

In this case, the DOE results using uniform and normal distributions displayed similar results for the scale factors, with less than 10% difference between the two.

Based on these factors, the uniform distribution was used in this research and resulting standard process within the company. In addition, the uniform distribution makes more sense in the context of failure mode avoidance, allowing the engineer to examine the possible design space, which is particularly important early in the development process when component and system process capability may not be well known. Further, for the driveline and tire/wheel components, the plus and minus 3-sigma limits used for the normal distribution generally are close to the minimum and maximum values for the uniform distribution.

6.3 Additional Verification

For further verification, the slider bar Weibull fits were compared with the results from a Monte Carlo simulation tool, which uses test-based or CAE-based transfer function to determine the customer level response point. (See Figure 6.7 and Figure 6.8) For the seat track (Figure 6.7 (a)), the slider bar and CAE-based Monte Carlo runs have similar scale factors – less than 10% difference, while the test-based run is sufficiently different – nearly 40 %.

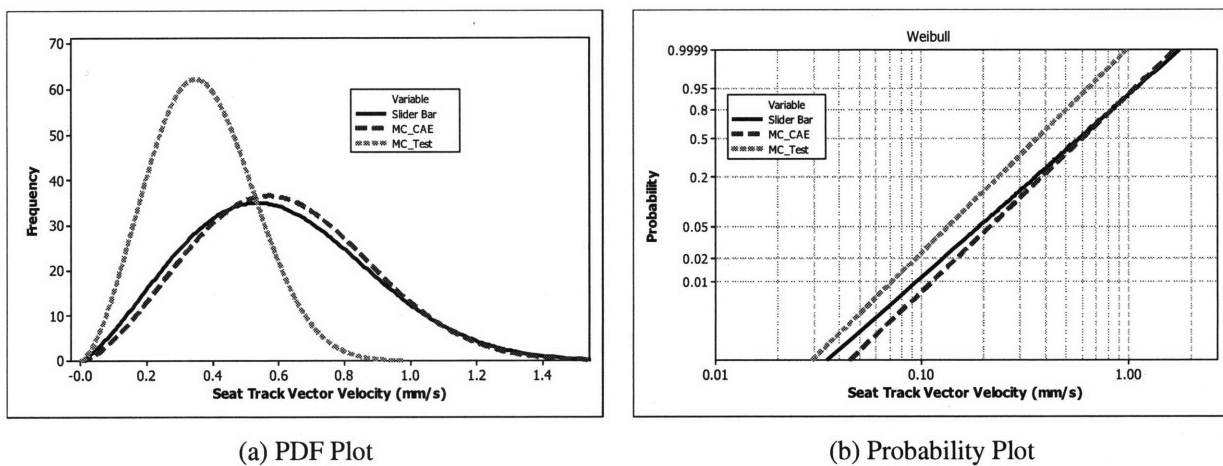


Figure 6.7 – Comparison of the Seat Track response

Although the scale parameters are different, the “Slider Bar” and the Monte Carlo have similar shape factors, and therefore uncover the same vehicle failure modes.

While this may appear a potential issue, it is important to note for the test vehicle, the exact values for several control and noise factors were unknown including the frame bending modes, driveshaft slide resistance, and PLRO. Thus, using the appropriate values likely would decrease the difference among the three.

More importantly, however, the shape parameters are sufficiently similar among the three runs – less than 14% difference. Therefore, applying the *Conservation of Failure Mode Principle* discussed previously, the slider bar and the Monte Carlo runs uncover the same failure modes for the vehicle.

The Weibull fits for the steering wheel are similar among the three (See Figure 6.8), with the percent difference is less than 13% and 10% for the shape and scale parameters, respectively.

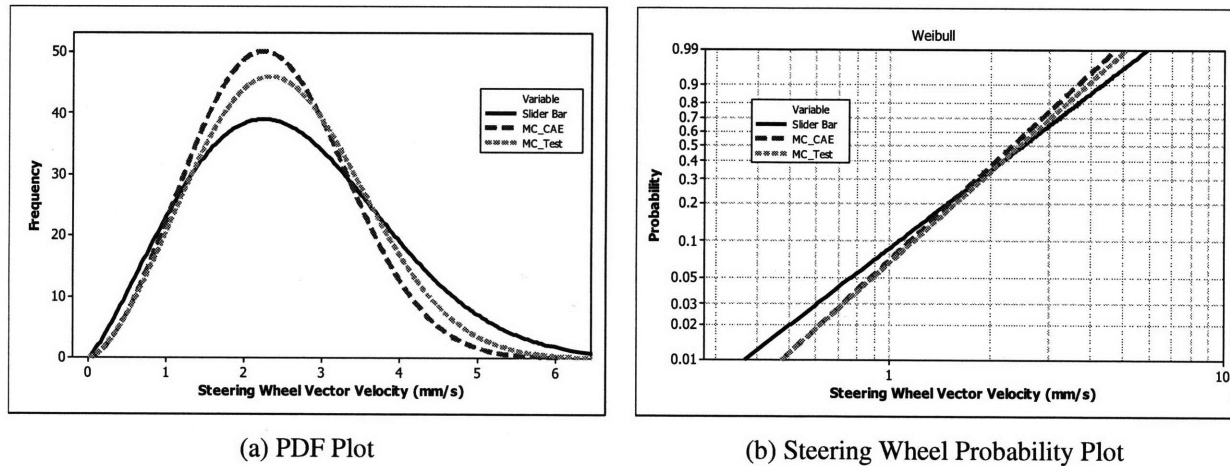


Figure 6.8 – Comparison of the Steering Wheel responses
 The “Slider Bar” and the Monte Carlo have similar shape factors, and therefore uncover the same failure modes for the steering wheel response.

Again, the three runs uncover the same failure modes for the steering wheel.

6.4 Slider Bar Results

With the verification complete, the Slider Bar then was used to explore the design space for the program, allowing the engineer to examine effects of varying factors and determine an optimized factor set for the vehicle. Here, the process was developed and piloted on three vehicles – Truck, SUV, and Car, each at a different stage in the product development process. (See Figure 6.9.)

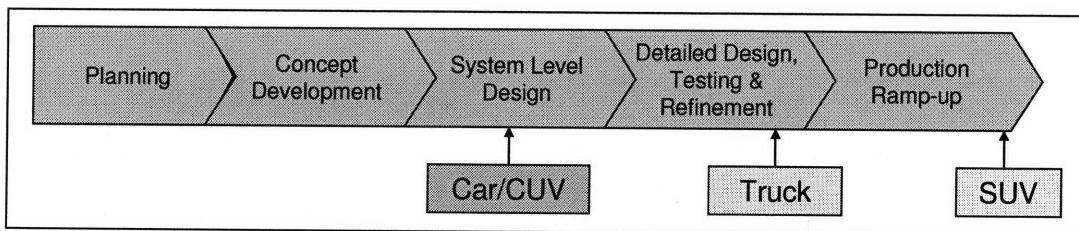


Figure 6.9 – Vehicle Timing in the generic product development process
 The “Slider Bar” was piloted on three different vehicles programs at different stages in the development process. (Adapted from Ulrich and Eppinger, 2004)

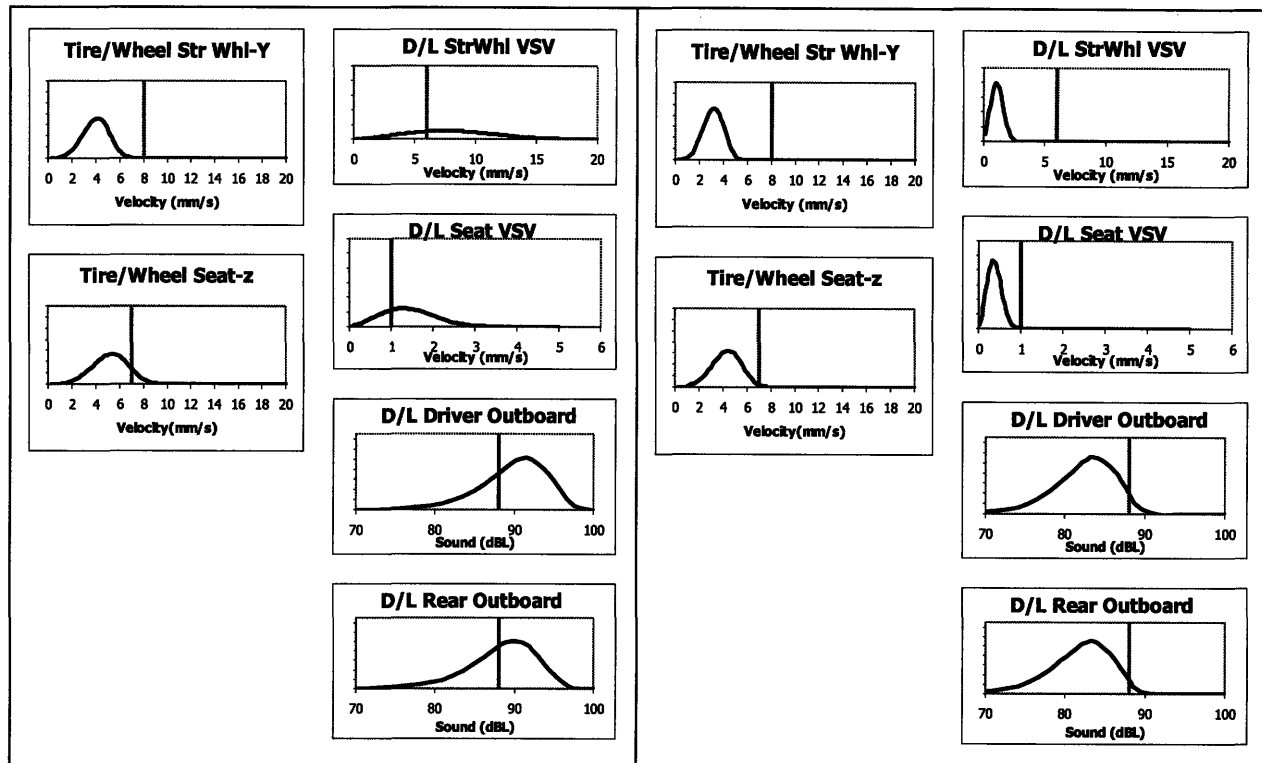
The truck was just over one year from production, using a hybrid of the former Ford production system and the new global production system. The primary objectives for the truck were to determine critical factors affecting the system response and establish the mount tuning ranges for experimental testing. Just launched, the SUV was used for process validation and to determine opportunities for additional vehicle improvements, such as optimizing the mount stiffness for both NVH and vehicle dynamic performance. The Car, meanwhile, was in the system level design stage, where more opportunities exist to modify the design.

6.4.1 Truck Model Results

As noted above, the truck objectives were to determine critical factors and establish the mount tuning ranges. To accomplish this, the “Slider Bar” meta-model was run for the initial parameter values, and the results showed a high percentage of possible vehicles exceeding the established objective targets, thus resulting in an NVH failure. To determine which factors were critical, an optimization was performed, and the following three control factors had a significant effect on the overall tactile and audible system level:

- Body Mount #2
- Leaf Spring Bush
- Leaf Spring Mode

By adjusting these factors, the response was moved further from the failure mode, and the percentage of vehicles exceeding target was reduced. (See Figure 6.10. below)



(a) Initial Design

(b) Optimal Design

Figure 6.10 – Initial Design versus Optimal Design

For initial parameter values, and the “Slider Bar” results showed a high percentage of possible vehicles exceeding the established objective targets, thus resulting in an NVH failure. The meta-model was then used to identify critical factors affecting the response. (Adapted from Braunwart, Thomas, Clapper, Borders, Huber and Blibeche, 2006a)

For Body Mount #2, the corresponding design actions included exploring potential design trade-offs with the vehicle dynamics and durability engineers to lower the nominal value for the mounts. Additionally, the supplier design and manufacturing processes could be explored to shift the mean lower and tighten the distribution. For the leaf spring modes and bushing, different spring stiffness values and bushing locations were examined to shift the response outside the region of interest.

In addition to the critical factors, the truck was sensitive to driveline imbalance at the front plane of transfer-case. Since the transfer-case was already sourced to a supplier, the available options were to address supplier capability, including examining the process to ensure planar imbalance

is lower and the dispersion is smaller. For future programs, the team could work with the supplier to change the design (e.g. change flange design), or may consider different supplier sources for the transfer-case.

Additionally, the “Slider Bar” was particularly useful in determining the tuning range for the experimental testing. Using the “Slider Bar”, development engineers could perform a real-time assessment of different mount values and establish a realistic range of parts for mount tuning exercise, saving valuable test time and financial resources.

6.4.2 SUV Model Results

The SUV had just launched, with the vehicle response near or better than the driveline and tire/wheel targets. (See Figure 6.11.) Therefore, the “Slider Bar” was used to determine additional improvement opportunities, including potential cross-attribute optimization.

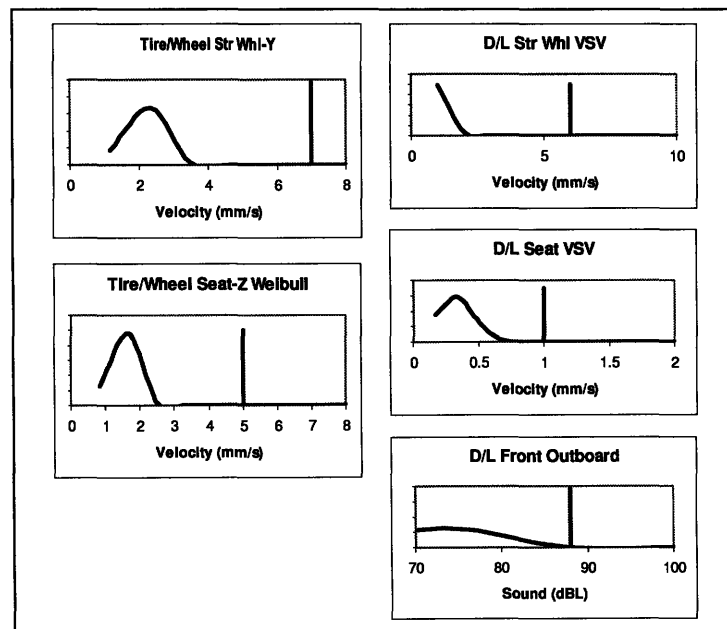


Figure 6.11 – SUV results

The SUV results were near or better than the targets. Therefore, the meta-model was used to determine additional improvement opportunities. (Adapted from Braunwart, Thomas, Clapper, Borders, Huber and Blibeche 2006b)

Since the response is relatively insensitive to engine and transmission mounts, the team could consider changing the stiffness to improve other attributes – i.e. softer for idle NVH performance or stiffer for vehicle durability. While there is some sensitivity to rear axle plane imbalance, the team may consider relaxing specifications for other planes, possibly realizing a cost save in the manufacturing process.

6.4.3 Car Model Results

The Car was earlier in the product development process, where more opportunities exist to modify the design, and the objective again was to determine the critical parameters affecting the system response. To accomplish this, the “Slider Bar” was run for the initial parameter values, with the results suggesting few vehicles would exceed the vehicle level targets.

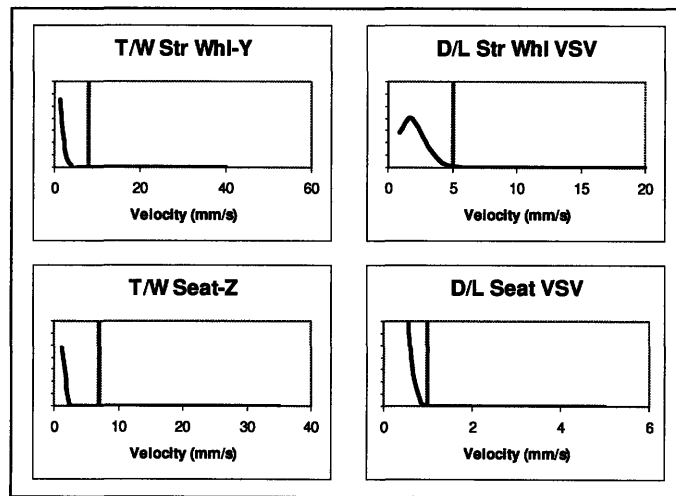


Figure 6.12 – Car Results

For the initial parameter values, with the Car results suggest few vehicles would exceed the vehicle level targets.

Therefore, the “Slider Bar” was used to determine sensitive parameters for possible cross-attributes trade-offs.

Using the “Slider Bar”, the sensitive parameters in the design space were uncovered. Here, the vehicle was sensitive to rear subframe bending mode and imbalance at the RDU plane. To address these, the rear subframe mode must be moved higher in frequency, possibly by

increasing the stiffness, while the driveline imbalance at the RDU must be controlled, since higher imbalance levels adversely affect the system response.

The vehicle response also appeared insensitive to RDU gear ratio, providing opportunities for further cross-attribute optimization. In particular, the gear ratio could be lowered to improve fuel economy, which has become a pressing customer and corporate concern.

6.5 Diffusion of Innovation

As noted previously, the innovation involves two basic steps – the technical innovation and its subsequent diffusion of the innovation through the system. With the basic process, established the focus shifted to the diffusion of the “Slider Bar” among the CAE and development NVH communities.

The first step was to determine the type of innovation and potential managerial and organizational effects. In this case, the slider bar process is clearly a *dynamically continuous* innovation, requiring some new core skills and competencies in addition to those currently employed. Thus, the focus was on expanding the skill set of the recipients, while using the current organizational and managerial structure.

The “Slider Bar” process was then evaluated against the characteristics of rapidly diffusing innovations – relative advantage, compatibility, complexity, trialability and observability. The initial review suggested the “Slider Bar” presented a clear advantage over the current process, was compatible with adopters, and had the same or lower complexity than the current process. However, an impartial evaluation from the potential users was necessary.

To accomplish this, the next step was to identify lead users and opinion leaders, who could be leveraged for their knowledge of the collective user community, providing valuable insight for the “Slider Bar”. Here, the leader users identified different experimental designs, which were integrated into the process to improve computational efficiency.

Opinion leaders identified the primary issue facing the adoption of the slider bar process within the CAE community – the perceived relative advantage of the “Slider Bar”. Specifically, the perceived advantage of the initial process was limited compared with the current procedures. While the process considered more factors and the corresponding factor ranges, the initial “Slider Bar” required more time, and the statistical and regression involved a fair amount of manual manipulation between several distinct software packages. Thus, the new process did not provide the CAE NVH engineer a distinct advantage in his or her daily routine.

With this information, the work focused on strengthening the characteristics of the innovation valued by the user. Specifically, the statistical and regression analysis was automated to reduce the amount of manual manipulation required. (See Figure 6.13)

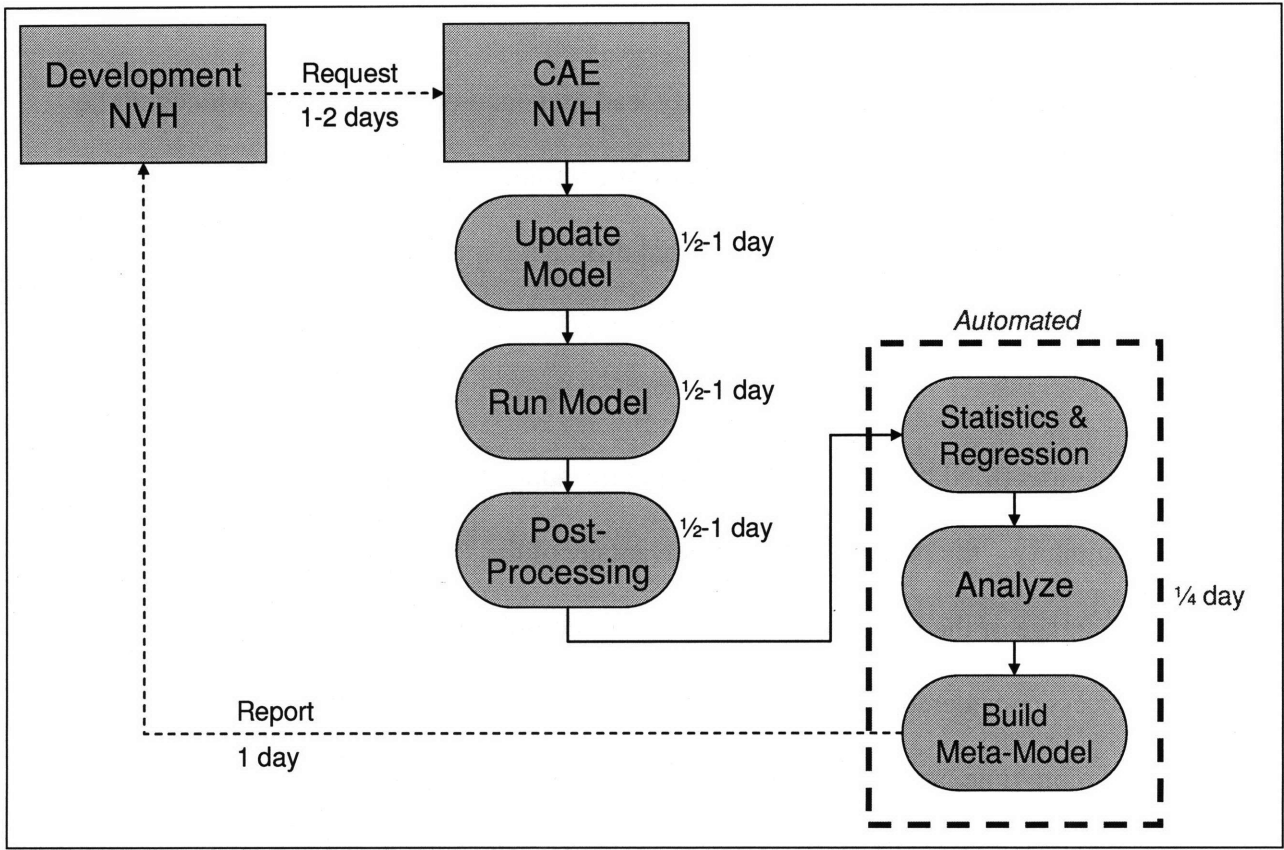


Figure 6.13 – Automated Slider Bar process

Based on feedback from the user community, the regression, analysis and model building steps were automated, reducing the cumulative time and increasing the relative advantage of the “Slider Bar” process.

This process adjustment is an example of the adaptation, or reinvention, that is critical for the adoption of an innovation.

With the automation, the time required for the “Slider Bar” was reduced significantly and now was competitive with a single iteration of the current process. Therefore, the “Slider Bar” now provided distinct advantages for the users over the current process, which are summarized in Table 6.1.

Table 6.1 – Process Comparison

Current Process	Slider Bar Process	Automated Slider Bar Process
Single Iteration	Multiple (500+) Iterations	Multiple (500+) Iterations
Tuning Parts	Tuning & Development	Tuning & Development
Late in Development	Early & Late in Development	Early & Late in Development
Limited Parameter & Tolerance Design	Real-time Parameter & Tolerance Design	Real-time Parameter & Tolerance Design
1 to 3 per iteration	4 to 5 for all runs	1.5 to 4 days for all runs

In particular, the new process examined more of the design space for the engineer and allowed real-time assessment of the effects of varying that design space. Thus, the engineer could perform parameter design to adjust the design, and then tighten the tolerances on noises using tolerance design.

With the relative advantage established, the objective now was to create awareness in the NVH community. To accomplish this, multiple communications were used, beginning with an internal NVH conference presentation followed by a general learning session. After addressing the general community, a series of tailored learning sessions were conducted for the CAE and development NVH engineers. For the CAE engineers, training content was focused on the DOE and CAE model development for the process, while the training for the development NVH engineers concentrate on using the meta-model to explore the potential design space.

While the process adoption in Figure 6.14 is due to multiple factors, anecdotal evidence suggested the tailored training session and automated processing helped the adoption, highlighting the relative advantage the “Slider Bar” provided over the current process.

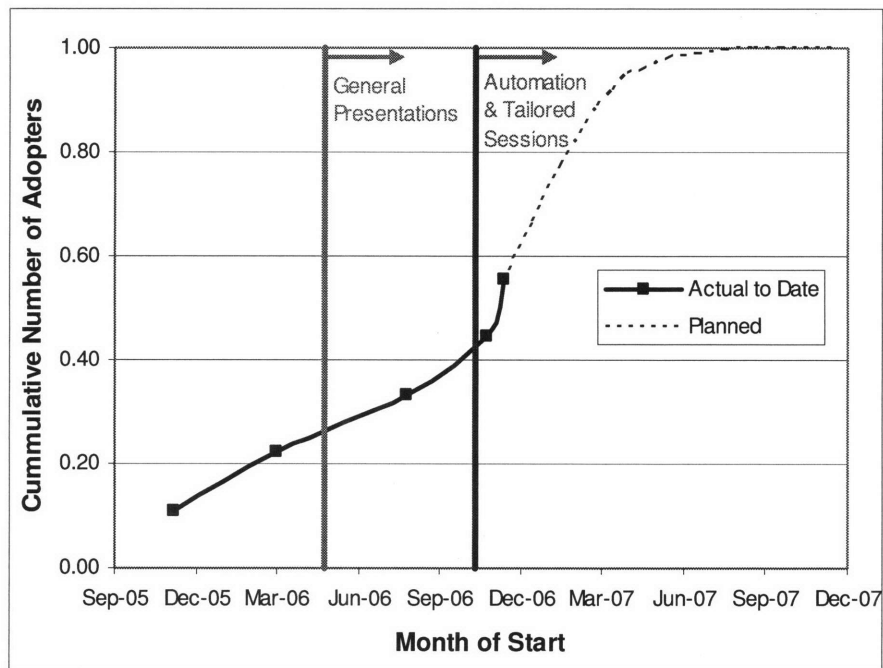


Figure 6.14 – Adoption of the “Slider Bar” process

Here, the pilot programs are represented by the first three squares in the curve, with two additional programs added before the end of 2006. Based on the programming timing, additional vehicle programs are planned, with the planned adoption for North American operations by the third quarter of 2007.

6.6 Strategy

Integrating the failure mode and diffusion approaches, the resulting strategy was developed to address the development and adoption of the failure mode avoidance initiatives:

Table 6.2 – Strategies for development and diffusion

<u>Strategy</u>	<u>Responsibility</u>
1. Establish motivation and objectives for the process change.	Management/ Technical Leader
2. Determine failure modes and ideal function, including level and the required distance to failure mode.	Technical Development Team
3. Develop system P-Diagram, including determination of noise and control factors.	Technical Development Team
4. Develop and perform the experimental design and subsequent analysis.	Technical Development Team
5. Determine type of innovation, whether it is continuous, dynamically continuous, or discontinuous.	Management/ Technical Leader
6. Identify recipient group, including potential lead users and opinion leaders, and focus on the characteristics they value.	Management/Technical Leader
7. Identify and remove organizational, managerial or contextual factor, which may present potential barriers.	Management/ Implementation Team
8. Employ multiple communication channels to reach recipients, while tailoring the message to each group.	Management/ Implementation Team
9. Focus on improving the perceived and relative advantage and promote adaptability.	Team
10. Elicit feedback, verify the change and adjust as necessary.	Team

While each member of the team should be aware of the entire process, each strategy requires particular knowledge, skills and authority to perform.

First, management or the technical leader would establish the motivation and objectives for the innovation, through internal and external benchmarking and market analysis. The technical development team, consisting of the technical leader and development engineers, then characterizes the system, including determining ideal function, potential failure modes and required distance to failure mode. The next step is the development of system P-diagram, including the determination of control and noise factor and “rich and realistic” ranges for each. Under the guidance of the technical leader, the technical development team then identifies the experimental design analysis appropriate for the system.

With the technical portion complete, the management and technical leaders must determine whether the process change is continuous, dynamically continuous or discontinuous and assess the compatibility with the knowledge and skills of the organization. The management, or technical leader if appropriate, then identifies the recipient group, especially leader user innovators and opinion leaders who can provide insight into the user community and the product or process characteristic they value.

The management and implementation team, which may include the development engineers or new personnel, then identifies potential organizational, managerial or contextual issues and removes or mitigates potential barriers to the adoption. To foster adoption, the implementation team must use multiple communications to reach the various recipient groups, with the message tailored for each particular group.

The final two steps represent the necessary continuous improvement for the process. The entire team must focus on improving the perceived and relative advantages of the change, while promoting adaptation and reinvention. Finally, the team must verify the system change, gather feedback from adopters and non-adopters, and adjust the process as necessary to meet changing needs.

6.7 Summary

With the model complete, the results were examined and discussed, starting with the experimental design. For tire/wheel and driveline NVH, the response is modal dependent and is multiple frequency bands, and a space-filling design is required to excite the response in the design space. Additionally, the Design of Experiment results were similar for control and noise factors with uniform and normal distributions. Therefore, uniform distribution was selected for the process, since it better aligns with the failure mode avoidance approach and allows the engineer to explore the possible design space.

The meta-model then was compared with the results from Monte Carlo simulation, using both CAE-based and test-based transfer functions. Although the scale parameters are different, the “Slider Bar” and the Monte Carlo have similar shape factors, and therefore uncover the same vehicle failure modes in the vehicle system.

The “Slider Bar” meta-models are then presented for the three vehicles used to develop and pilot the process. For the Truck, the “Slider Bar” identified critical factors to reduce the potential number of vehicles exceeding target, and the meta-model was used to identify the stiffness

ranges for the experimental mount tuning exercises. Meanwhile, the meta-model identified critical factors

Next, the diffusion results are presented for the process, especially the insight provided by the lead users and early adopters. These groups were critical for the adoption, providing crucial insight that led to the automation of the process. Finally, a resultant strategy is introduced to address the development and adoption of a failure mode avoidance initiative.

Chapter 7: Conclusions & Recommendations

With the increasingly competitive market, the current approach to NVH development is no longer appropriate. A quick, cost-effective process is needed to allow NVH development engineers to make better up-front decisions and support the compressed product development timing required in the new Ford production system. Additionally, appropriate analytical tools must be developed to facilitate the NVH development process.

7.1 Conclusions

The “Slider Bar” process and tools uncover are critical for establishing NVH failure mode free systems, ensuring appropriate up-front design considerations. Thus, early in the product development timeframe, development teams can define the design space by identifying control and noise factor limits and system level effects, avoid potential NVH failure modes, and develop appropriate countermeasures. Additionally, the process and tools are critical to achieving corporate targets for driveline and tire/wheel NVH and systemic failure mode reductions.

Further, the “Slider Bar” process supports the long-term objective of performing cross-attribute optimization, particularly early in the program. With this process, NVH engineers can perform a real-time assessment of parameter changes required by other functional areas such durability and vehicle NVH dynamics. Thus, design changes and necessary counter-measures can be made with respect to improving total vehicle performance early in the design process and at the lowest total cost.

To accomplish this, vibration and sound failure modes limits were established, the vehicle system P-diagram was developed, and the “rich and realistic” ranges for the control noise factors were determined. The appropriate experimental designs required to explore the design spaces were created, with the low discrepancy sequence Halton and Sobol designs archived in a corporate online library for future access by the program teams. Using the experimental designs, the CAE runs were then performed, transfer functions multiplied by Monte Carlo loads, and the results post-processed to generate histograms. The histograms were then analyzed to determine the shape and scale parameters, which are then entered in a response surface generator utility to develop “Slider Bar” meta-model.

Using insights from innovation diffusion theory, the tool and process were deployed systematically to CAE and development NVH engineers using a multiple communication channels to facilitate diffusion to all programs. Opinion leaders and lead users were identified to foster the spread of the innovation through the respective communities. Training was tailored directly for each group to convey the relative advantages of process, and the lessons learned from these training sessions were incorporated into the process and tool.

The tool was piloted on three programs (SUV, Truck, Car), with two additional programs added by the end of 2006. Based on the programming timing, additional vehicle programs are planned, with the planned adoption for North American operations by the third quarter of 2007.

7.2 Recommendations & Next Steps

Opportunities exist for future work in driveline and tire/wheel NVH as well as other areas. In particular, there are several near-term and long-term recommendations, which need to be addressed.

In the short-term, the process must be expanded to the remaining program teams, with the goal of eliminating systemic driveline and tire/wheel NVH failure modes. Specifically, high volume and high leverage vehicles must be targeted to maximize the effect, with the remaining vehicles completed by the end of the third quarter 2007. Additionally, the further process improvements, including additional automation, should be explored to increase the efficiency.

For the future, the process also must be extended to other NVH phenomena, starting with idle NVH since it is a significant customer concern, which results in customer complaints, dissatisfaction and warranty costs. After Idle NVH, the “Slider Bar” process must be spread to other high-leverage NVH concerns as well as attributes such as Vehicle Dynamics that share some common control and noise factors. This way, the engineer can perform cross-attribute failure mode avoidance and assess the implications of potential design actions on the various responses in the vehicle.

In addition, the previously discussed strategy was helpful in focusing the “Slider Bar” process development and the subsequent diffusion. Therefore, it should be evaluated on other failure mode avoidance efforts, with feedback used to improve and adjust the strategy.

Glossary

Boom is a low frequency (below 100 Hz) audible response.

Composite Flange Run-out (CFRO) is the out of plane variation at the axle composite flange.

Computer Aided Engineering (CAE) is the use of information technology, both software and hardware, to assist engineers in modeling, simulating and analyzing a component, subsystem or system.

Driveline refers to the components used to transmit power from the transmission to the wheels, including driveshafts, center-bearing, axle, and half shafts.

Harmonics refer to the integral multiples (i.e. $1f, 2f, 3f \dots nf$) of a given frequency.

Harshness refers to the low frequency (25 – 100 Hz) vibration of a structure or component, which may be perceived tactically or audibly by the customer.

Noise Vibration Harshness (NVH) is the tactile or audible response perceived by the customer, which potentially detracts from their driving experience.

Noise is the unwanted audible response due to the transfer of vibrational energy in a structure to air pressure waves.

Orders refer to the rotational harmonics of a rotating object, such as a driveshaft or crankshaft in automobiles.

Pitch Line Run-out (PLRO) refers to the out of plane variation with respect to the pitch-line of the pinion gear.

Powertrain refers to the components used to generate and transmit power in an automobile, including the engine, transmission, driveshafts, and axle.

Roughness refers to low frequency (below 80 Hz) vibration response, which has a noticeable time variation.

Shake is low frequency (5 – 40 Hz) vibration.

Vibration is the oscillatory motion about a reference point, occurring at a given frequency or set of frequencies.

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