Chassis Flexibility: Assessing Architectural Differences and Their Effect on Managing Derivative Product Development

by

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ABSTRACT

A theoretically cost-efficient and time-efficient strategy for reacting to emerging automobile consumer needs is to derive new vehicle products from in-development designs. In practice, however, vehicle designs can be difficult to change quickly or easily during the development process without affecting the base product quality. This inability to "flex" is usually attributed to vehicle architecture and organizational complexity. Further complications are caused by the demands of multiple projects occurring simultaneously within the organizational environment.

The chassis chunk (the subframe, suspension, steering, mounts, wheels and tires) is one whose architecture limits product flexibility. The complex design of these systems is dictated by the desired performance, the interactions within the chassis, and the interactions with the body, engine, and transmission. In addition, the team organization, communication paths, and interactions are equally complex. This tangled web of system, team, and information interactions leads to largely integral, specialized, inflexible designs that hamper the development of concurrent derivative products.

A method based on systems engineering and systems architecture tools, including Design Structure Matrix (DSM), was developed and used to identify chassis design drivers and evaluate the degree to which they provide flexibility potential. The method is qualitative and uses and a set of heuristics for evaluating design drivers and flexibility potential. A case study is developed, using a typical front-wheel drive architecture, to demonstrate a holistic approach for evaluating flexibility potential. The tools are also used to understand the current chassis engineering organization and chassis development process.

The method was found to be cumbersome and yielded qualitative but non-definitive results when applied to the complicated chassis architecture. From these results, recommendations for improvements to chassis development processes and team structures to support multi-project management and the development of derivative products were developed.

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At the top of the list, I need to thank my wife, Julie Coleman Daleiden, who gave her husband to this effort. This thesis, and the course of studies of which it was a part, took time and energy, and caused anxiety and frustration. It took me away from home, for weeks and months, and caused me to work late into the night, for work and school. Still, she hung in there, encouraged me when I needed it, made fun of me when I deserved it, and told to stop whining and get to work. While I was busy with Ford and MIT, she finished a one year medical residency rotation, managed the construction of our new house, and took care of our dogs. In return, I have promised not to work on any more degrees for five years. Now, if I could only get her to stop going to school, we might be able to see each other.

This thesis was supported by Ford Motor Company, through its participation as a Partner in the System Design and Management Program at MIT, and particularly by the Large and Luxury Car Vehicle Center Quality Office. I am grateful to Bob Matulka, Bill Powers, and Ken Dabrowski, who have championed Ford's association with SDM. I am indebted to Don F. Nelson, my manager, Joe A. White, my director, and Mary Ann Wright for my nomination into the SDM program. I am especially thankful to Joe and Don for their continued support over the last two years as I disappeared to Cambridge at what seemed to be the worst possible times. I also need to thank Don for taking time on his vacation to review this paper.

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Though they had never met me before, Ford manager Paul Giltinan, technical specialist Paul Davis, and supervisor Jeff Lippa willingly provided technical expertise on chassis design that was crucial to the thesis. Paul Giltinan was especially helpful in providing descriptions of the process and reviewing key chapters. Paul Davis spent consideratble time in discussions with me, understanding my goals, directing me towards some extremely valuable resources, and reviewing the key technical chapters of this paper. Thanks also to George Nicols of Rapid Global Business Solutions, for providing the example of a systems dynamics chassis model.

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Finally, on the academic side, Dr. Dan Whitney and Dr. Ali Yassine have been excellent professionals with which to work. Dan's MIT contacts, breadth and depth of knowledge, and critical eye for details were essential to defining and developing the research effort. Huge debt is owed Ali, who questioned everything and then directed me towards a potential answer, who read everything no matter how simple-minded, and who never seemed to tire of my tendency towards vagueness. Together, they made me a better researcher and a clearer thinker.

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CHAPTER

1 Derivative Products and Multi- Project Management

1.1 Introduction

My fascination with cars and the auto industry comes from my father, who was an executive at Chrysler, one of the finance guys, a "bean" counter. The automotive industry was his first and only career choice when he graduated from college, because he enjoyed competition and liked cars. He really liked the big, powerful, heavy-metal dinosaurs of the sixties and seventies, disliked the cookie-cutter, econo-boxes of the late-seventies and early eighties, and was surprisingly enthusiastic about the utilitarian mini-van. He changed as the industry changed, and I think he learned that, in a competitive environment, a company's existence depended on understanding the needs of the consumer and developing products to meet those needs. Although it seems obvious today, the history of the domestic automotive companies shows that it was a poorly addressed truth for decades.

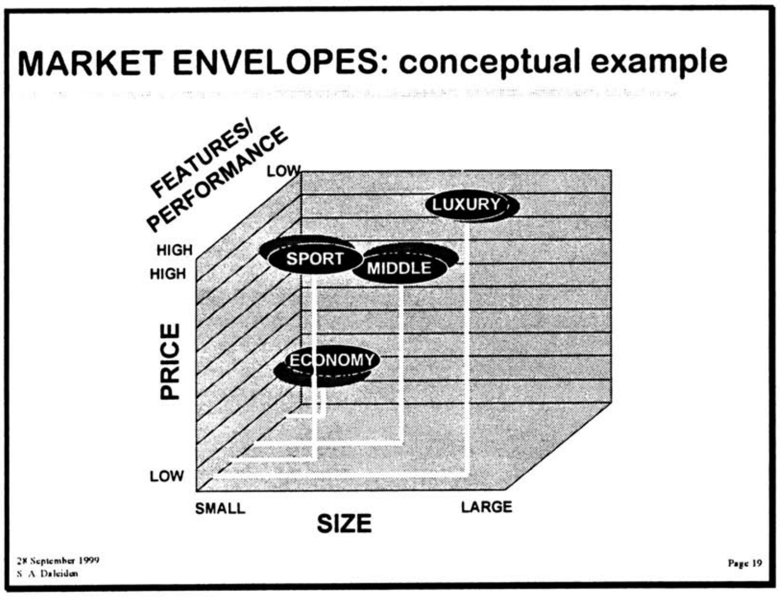
As an engineer at Ford Motor Company working on quality and reliability, my work puts me in the competitive environment of new product development. Although I used to work for NASA (on the space shuttle), at a university gas dynamics research lab, and for TRW (on ballistic missiles, not automotive components), studying automobiles and the auto industry was a passion. In my eyes, cars are integral to modern society and a source of freedom. They are also fun to look at, fun to sit in, and fun to drive (maybe I would have stayed in the aerospace industry if I had been able to fly the space shuttle). However, product consumers expect a lot from their vehicles. They expect the comfort and support of a good chair or couch, the quietness of a church, and all the conveniences of their homes and offices. They expect a ride that is as smooth as a puck on clean ice, the safety and security of a bomb shelter, and the reliability and durability of good hammer.

These high expectations cause automobile purchase to get more scrutiny than most consumer purchases. High price is also a factor. Next to a home purchase, an automobile is the single most expensive product on which most people will spend their money, and most consumers make this purchase knowing that, in all likelihood, they will replace it in about six years. Few consumer purchases generate as much passion and emotion as an automobile. Unlike a computer, clothes washer, or a chain saw, an automobile purchase is not just about technical performance and reliability. Self-image, what the car says about the owner, is equally important, and this is one of the toughest attributes to build into a car, because it is unique and changes as styles and technology changes. Aesthetics, "feel", and brand image all play a role in the effect an automobile has on the owner's self-image.

There is some thought in the automotive industry that consumer's attitudes towards cars and trucks are unfair. Consider commuter rails and subways, like those in Boston, Washington DC, New York, Chicago, San Francisco, Los Angeles, Tokyo, Paris, and London. The users of these transportation products accept and tolerate the noise, the bumpy ride, and the lack of cupholders or good audio systems. Your average household appliance or furniture is typically purchased to fulfill a single function, and is not expected to tolerate continued exposure to harsh, unfriendly environments. Yet, to be successful, the modern automobile must be multi-functional, be excellent at every function imaginable (and some not imagined by the designers), and perform those functions under all conditions, regardless. To some in the industry, that seems like a lot to ask from a man-made product. However, because there are automotive companies whose products do fulfill those requirements, the expectations of the consumer are justified.

To attract consumers and appeal to their personal self-images, automobile developers try to differentiate their products along several dimensions that the consumer will notice. Figure 1.1 provides a conceptual example of what the dimensions of a "market envelope" could be. One dimension could be features and performance, like horsepower or power sliding doors (on mini-vans), practicality or reliability. Another dimension could be price, while a third could be vehicle size or interior space. Extending the concept, the market envelope is an n-dimensional space whose dimensions are defined by consumer-perceived attributes. The ranges of the dimensions are also defined by the consumer, in terms of needs or desired performance. However, regardless of the dimension or the achievable range, a company's success along any dimension can usually be quickly and easily mimicked by the competition (or at least some of the competition), making any product-specific uniqueness a temporary advantage. Competition can match on quality, on price, on cost reduction. Improvements in manufacturing can be matched. Styling and features can eventually be mimicked, approximated, copied, and surpassed.

Figure 1.1 Conceptual Example of Market Envelopes



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This intense search for maintainable advantages has led automobile developers to look at everything they do. They study how they design and develop assembly processes and assembly plants. They consider where they locate their people and how they treat and educate their people. They also study the strategies behind organization structures, product architecture, and product development. This has led to the consideration of derivative products as a strategic advantage for continued automobile development success.

1.2 Key Concepts: Derivatives, Design Drivers, and Flexibility

In discussing derivative products at a conference recently, a person whose work focused on mathematics (as opposed to consumer products) thought that the discussion was about mathematical derivatives. Hence, at this point, It would be helpful if some key concepts were defined. This will allow the sections that follow to make use of these concepts, as they are the subjects of the thesis.

Using the language of systems architecture, which will be covered in Chapter 2, a derivative product is a product whose fundamental forms (physical elements, components, systems) are based on a forerunner or a contemporary form. Although it is not necessary, the "base" form and the derivative form could share physical elements. Applying this to an automobile, it usually means significant commonization of underbody, body structure, powertrain, chassis components, and interior trim elements. Derivative envelope refers to the range of derivative products that is achievable or supportable by the base product, which is the range over which key customer-perceived attributes can be varied.

Design drivers are the key parameters that push a design in one direction or another. They can come from several sources, including the customer, the corporation, engineering, manufacturing, or styling. However, not every design parameter, customer attribute, or functional requirement (these terms are also defined in Chapter 2) is a design driver. To help identify them, 4 criteria were developed that a design driver should meet:

1. they affect important customer-perceived attributes
2. they have many interactions with and drive decisions about other parameters
3. they are difficult to change or iterate, often becoming constraints.
4. they are set earlier rather than later in the product development process

Parameters that meet these criteria will force the architecture or the design in certain directions that will be difficult to change later.

There are different ways to think about flexibility. By definition, flexibility is an ability to respond or conform to changing or new situations (Webster's New Collegiate Dictionary, G&C Merriam, MA, 1979). In terms of this thesis, flexibility and flexibility potential describe the ability of a product to respond to changes in design direction and support derivative products or to act a platform for a portfolio of products. Thus, flexibility potential supports the ability of a product to increase its market envelope by increasing its achievable range along key consumer-attributes (the dimensions from Figure 1.1).

Flexibility potential is determined by the organization, the development process, and the product architecture. Relative to architecture, three "genes" that parameters can have that enable flexibility were conceived:

1. Improved-range gene enables a parameter to cause an increased range of response in an output (an attribute or some other characteristic).
2. Multi-path gene enables several parameters to achieve the same response in an output.
3. Multi-attribute gene enables one parameter to control or affect the responses of several outputs simultaneously.

In this thesis, the flexibility potential of a product describes the potential the product has for supporting a variety of different settings for key customer-perceived attributes. Although this appears to require only the Improved-range gene, it is also dependent on Multi-path and Multi-attribute genes to act as enablers for the Improved-range gene. This will be discussed in Chapter 4.

The existence of these genes would suggest a strong potential for flexibility in a product, because there would be different ways to achieve the same response, allowing more opportunities to skirt constraints, and there would be a larger range of values (larger in terms of achievable responses) that could be achieved. A parameter that cannot affect attributes significantly has little value in terms of flexibility potential. These ideas are stated here as if they are clear and obvious, but they will be substantiated in Chapter 4 and Chapter 5.

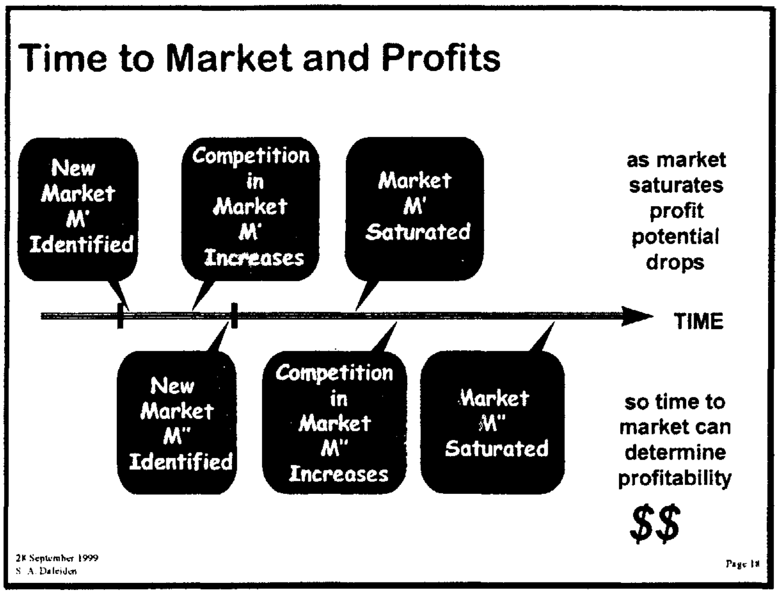
1.3 Derivative Products In Multi-project Environments

There are four key elements to a successful automobile development strategy:

- innovative products
- fast time to market
- meet consumer needs
- exceed consumer expectations

A company that can quickly change its products along these elements can maintain a competitive advantage in the market place. Consider Chrysler, whose lines have changed and morphed at a stunning rate in the last ten years. Their success at generating interest, enthusiasm, and a positive brand image is an example of how rapid product development and fast introduction and production of break-through products, at the instant the consumers want them, can be a key to success. Volkswagen is another example, as are Honda and Toyota. These companies bring together, in different ways, the four product development (PD) strategy elements in manners that allow them to rapidly respond to emerging consumer needs and wants. They may not be the first to the market, but, if the market is compatible with their corporate strategy, then they will have a product in that market quickly. Figure 1.2 shows the importance of getting to the new markets early. This is when consumers paying more for the new stuff, when profits are easier and fatter profits, as compared to later, when the market is mature, the consumer is jaded, and the competition is fierce.

Figure 1.2 The Importance of Time to Market



Time to Market and Profits

as market saturates profit potential drops

so time to market can determine profitability

$$

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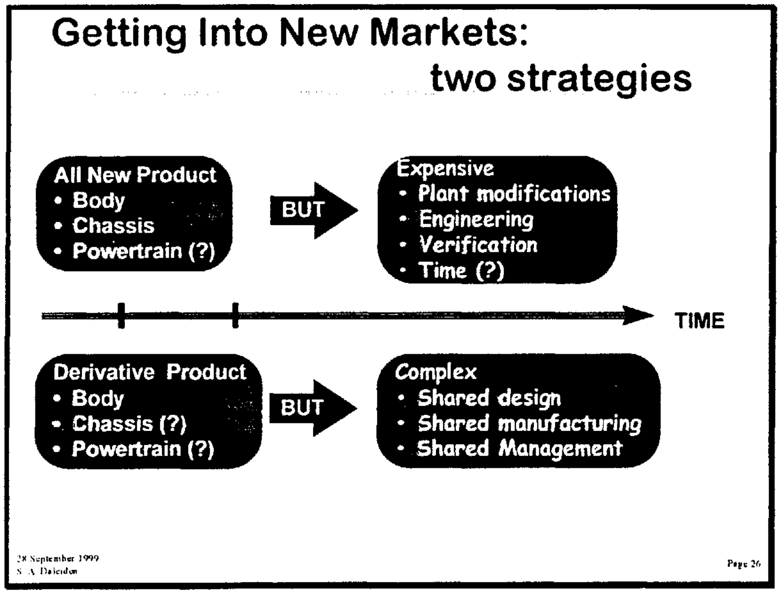
Figure 1.3 shows two strategies for responding to new markets, and a brief summary of the risks and advantage with each. The first way is to develop a unique, all-new product. The biggest risk with this approach is investment and time to market. With this approach, a company knows it will be late to market, but it can be comfortable that it will understand the market by the time the product is out the door. This may be appropriate for long-term markets with high expectations, like luxury or sports car markets. Another way companies respond rapidly and cost-effectively to newly identified consumer wants and emerging product markets is to derive new products from existing products. Developing derivative products vastly improves the time to market, but can be investment-prohibitive and can put the integrity of the design at risk, as will be discussed later.

Two strategies that are used when doing derivatives are to start from a design that is in-production or from one that is in-development. Cusumano and Noebeka [1998] have labeled these as sequential technology transfer and concurrent technology transfer. Figure 1.4 provides a visual interpretation of sequential and concurrent derivative product development. The Model A is the base product and provides the underpinning architecture for a family of derivatives that include A' and A". The vision in the sequential case is a dedicated team that stays with the program for each derivative, while concurrent envisions the same team engineering the derivatives nearly simultaneously.

Figure 1.3 Two Strategies for Responding to New Markets



Getting Into New Markets:
two strategies

All New Product
- Body
- Chassis
- Powertrain (?)

BUT

Expensive
- Plant modifications
- Engineering
- Verification
- Time (?)

TIME

Derivative Product
- Body
- Chassis (?)
- Powertrain (?)

BUT

Complex
- Shared design
- Shared manufacturing
- Shared Management

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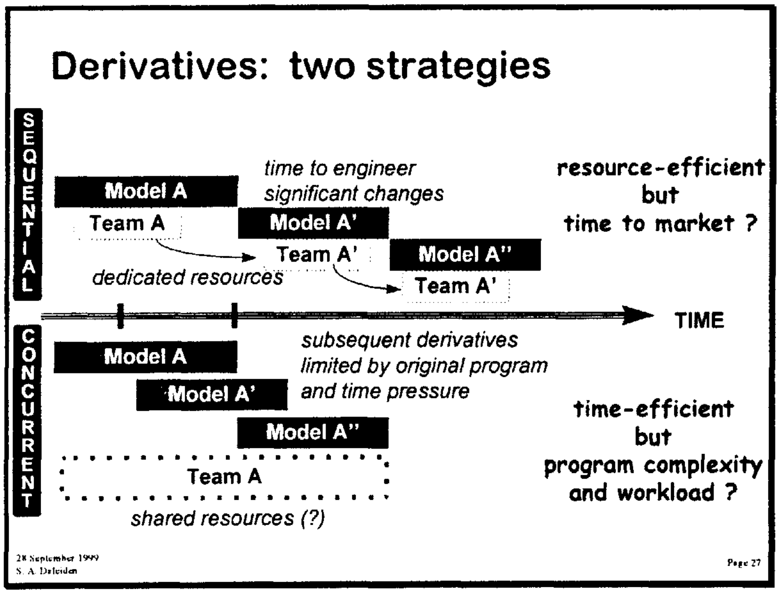
Figure 1.4 Two Strategies for Derivative Products



Derivatives: two strategies

SEQUENTIAL

Model A
Team A
time to engineer significant changes
Model A'
Team A'
Model A"
Team A'
dedicated resources

resource-efficient
but
time to market ?

TIME

CONCURRENT

Model A
Model A'
Model A"
Team A
shared resources (?)
subsequent derivatives limited by original program and time pressure

time-efficient
but
program complexity and workload ?

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Figure 1.4 captures the nature of the trade-off decision that is made in choosing between sequential and concurrent. Sequential makes good use of limited resources by allowing them to focus on the a single product at a time. This is efficient because it should reduce unintended re-work that occurs with multiple projects, excessive workloads, and overtime. However, sequential also sacrifices time to market which, as noted earlier, could reduce the profit potential in a market. Concurrent, on the other hand, improves on the time to market issue but can cause poor quality products if resources are insufficient or the engineering complexity of the product architecture is overwhelming. Properly managed, the resource issue may be overcome. The product architecture complexity issue might also be overcome with proper management of resources, provided that technological breakthroughs (whose occurances are generally unpredictable) are not required.

There are situations where time to market is not critical, such as markets where needs change slowly. Traditional luxury cars (large, rear-wheel drive) and pick-up trucks are examples of such markets. However, even these products can be asked to support derivative products if an emerging consumer trend is identified.

1.4 Concurrent Development of Derivative Products At Ford Motor Company

While Ford Motor Company has successfully used sequential development on derivative vehicles such as the Mercury Cougar and the Lincoln Navigator, it has been less successful at concurrent development. There are two typical scenarios that I have witnessed at Ford where derivative products are proposed. The first is a situation where a derivative product is planned for concurrent development with a base product, both to be handled by a single team. The second situation is one in which management or marketing, in response to recently identified consumer wants or purchasing trend, requests a program team, which is in the middle of the product development process, to investigate the feasibility of delivering a substantially different product derived from their in-development product. Again, the expectation is that the team would deliver both products.

At Ford, the first scenario results in products that are not extensively different. The core reasons behind this are the desire to minimize product development and production costs (through the use of common components and system designs), maximize usage of manufacturing facilities (by having common sheetmetal), and provide both Ford and Mercury dealers with product in key market segments such sport-utility vehicles or mid-size cars. These lead to product designs that are integral, developed with a single intent, and aimed at broad, traditional markets. Examples include "sister" products such as the Ford Taurus and the Mercury Sable, the Ford Crown Victoria and the Mercury Grand Marquis, and the Ford Explorer and Mercury Mountaineer.

In the second scenario, the proposals are evaluated by the base project team and then rejected for one or more of the following reasons:

- The team cannot contain the proper development of the derivative product and associated manufacturing processes, and resolve engineering issues, with the main product within the time allocated for the main project.
- The variable and investment costs needed to incorporate necessary architecture or manufacturing changes are beyond the scope of the targeted budget.
- The engineering and support resources needed to properly develop both the derivative product and the main product are not available or are beyond the scope of the levels allocated to the base project.
- The level of complexity caused by the derivative is unacceptable to manufacturing.

Each of these reasons is supported by financial considerations and cost impacts that affect the company's profits, its shareholder value, and its ability to continue to provide customer value. Improper development of either the product or the process causes in-plant repairs (and high manufacturing costs), higher field warranty, and recalls. These last two are particularly destructive, since they directly damage consumer confidence and brand loyalty.

There are physical mechanisms behind the rationale for rejection, and they are usually lumped together and called "complexity". Because of the time it takes to analyze, engineer, design, tool, manufacture, and test new components and systems, changes identified less than 2 years before launch will not be fully validated prior to launch. Also, all product development teams at Ford work in a "multi-project environment" [Cusumano, 1998], which means there are different products at different stages of development throughout the company. Typically, the pools of limited resources needed to engineer those vehicles are spread as thin as can be while providing the minimum necessary coverage and support. Thus, once a program is kicked-off, getting resources becomes politically difficult. As the number of tasks and the complexity of the product increases, the team will be stretched. Proper management of limited resources, particularly people, will become extremely critical, because there will be little relief available. This puts the integrity (particularly quality) and the focus of the main program at risk. In addition to resources and product complexity, team complexity also plays a role in hindering the development of derivative products in this multi-project environment, by increasing the need for clear communication and causing confusion over ownership of issues and product attributes.

However, in identifying complexity as an issue, two points must be acknowledged. First, as observed by Crawley, complexity, is neither good nor bad. It can be useful and possibly critical for achieving an optimum functional design. In that regard, it is simply something to be created or avoided to meet a goal [Crawley, 1998]. Certain levels of complexity cannot be avoided, and often work to provide optimal performance. While it is true that optimal designs are difficult to modify, due to interactions, it should also be recognized that those interactions are what allow the design to be optimal. The second point is that Ford is not the only automobile developer and manufacturer that is dealing with these complexities. They are common across the industries, and the best companies are finding the best ways to manage them and use them to their advantage.

1.5 Thesis Problem Statement (or What is Wrong with What ?)

The challenge to Ford, then, is to get better at managing concurrent product derivatives and developing coherent and compatible multi-project strategies. To do so, the company must identify and satisfy a set of technical and organizational requirements and constraints. Among the technical constraints to concurrent derivative products is the inability of the product development teams and the products to quickly change focus and direction during the development process without affecting the quality of the base product. The technical requirements include visioning a coherent, compatible family of products whose architecture is flexible enough to meet current and future consumer wants and needs, and engineering derivatives that are compatible with cost, timing, and manufacturability constraints. The organizational constraints include limited resources, unavoidable variation in the product development process, the process's insatiable appetite for resources, and the need to manage communication across multiple products simultaneously, efficiently, and effectively. The organizational requirements include a structure that encourages cross-product and cross-functional interactions, and a resource efficient strategy for managing the development of derivative products.

One approach to the technical requirements is to develop a map that captures the flexibility potential of the vehicle architecture, and ensures that the potential is compatible with the total product strategy of the company. The flexibility potential will indicate what derivatives are possible (a derivative envelope), while making the envelope align with corporate strategy will set up a coherent product portfolio strategy. The other piece is identifying an organization structure that supports the development of derivatives in a multi-project setting by mechanizing, as much as possible, cross-product and cross-functional communication.

Developing a thesis around an entire vehicle would be a major undertaking. However, based on my experience, I identified one group of systems whose integrality tends to limit flexibility, and whose team complexity hinders multi-project management. This group is the chassis chunk, which includes the subframe, suspension, brakes, and steering. The complex design of these systems is dictated by packaging and desired performance, and they interact with each other as well as with the body, the engine, and the transmission. The team structure also has its complexities. While the component engineering is carried out by the chassis team, and requires interaction with powertrain and body engineers, certain performance attributes of the chassis are coordinated and managed by the Vehicle Engineering group.

The consequences of both product and organizational complexity is that chassis development is a tangled web of system, team, and information interactions, tied to an investment intensive manufacturing base. These lead to designs that are specialized, inflexible, and integral. That is, consumer-desired attributes result from the interaction between many physical elements, the physical elements are unique to the product and are designed to provide a particular attribute target value, and the elements mutually constrain each other. Together, they hamper the development of concurrent derivative products.

The goal of this thesis is to improve Ford's ability to do derivative products, by providing a methodology for assessing the flexibility potential of an architecture and by identifying an organizational structure and other enhancements that would surmount some of the current organizational and process constraints. The results of the thesis are intended to provide product planners and engineering teams with guidance on how to respond to customer needs in chassis design through proper architecture selection, and to help management teams understand how to improve the cross-project and cross-functional interactions necessary for concurrent projects. Together, this will allow Ford to take in-process products and develop derivatives faster and better.

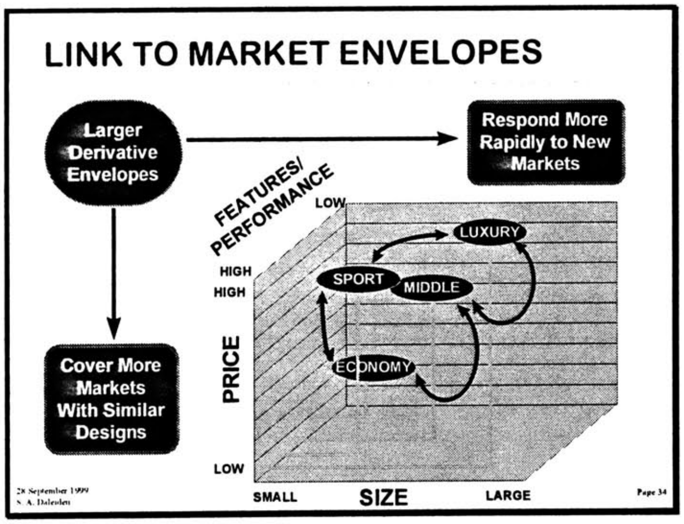
1.6 Thesis Objectives

The primary objectives and deliverables of this thesis are to:

- explore the potential for capturing and assessing the potential flexibility (or the derivative envelope) of different design representation methods.
- capture and analyze the case for chassis flexibility, from the consumer's perspective.
- identify and analyze the chassis design drivers, which are the key design decisions and parameters that provide or inhibit architectural flexibility in the chassis system.
- evaluate different strategies for organizing and managing concurrent projects and cross-project and cross-functional interactions, in the context of Ford's current organization and product development process.
- propose improvements to chassis development processes and team structures to support multi-project management, based on smoother information flows and task dependencies
- learn more about vehicle and chassis architecture development.

Figure 1.5 is a vision of one possible outcome of the objectives: a understood linkage between the derivative envelope of an architecture and the potential markets over which it can be flexed.

Figure 1.5 Link Between Derivative Products and Market Envelopes



LINK TO MARKET ENVELOPES

Larger Derivative Envelopes

Respond More Rapidly to New Markets

Cover More Markets With Similar Designs

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1.7 Personal Relevance (or Why This Subject Matters to Me)

I started in engineering as a co-op engineering trainee at Marshall Space Flight Center, doing structural loads analysis and loads verification for the space shuttle. During graduate school, my research assistantship had me working in the gas dynamics lab, doing research in fluid dynamics and building CFD models. After receiving my M.S.E in Aerospace Engineering, I worked for TRW as a systems engineer doing trajectory analysis and reconstruction for ICBMs and developing dynamic motion analysis software. This introduced me to the roots of systems engineering and especially the verification and validation process. The technical challenges were interesting at first, but I began to sense a lack of urgency, excitement, and new challenges in the industry. In the early 90's, the aerospace and defense industries were shrinking and my wife and I were tired of California. She decided to go to medical school and I decided to jump to the automotive industry. It was natural, given my automotive roots. Also, during my years in the aerospace industry, my interest in the automotive industry never waned. I read about the new products and kept up with industry changes. Whenever a co-worker was thinking of buying a new car, they inevitably talked to me, because I was constantly talking about cars.

In February, 1994, I began working at Ford as a product design engineer handling window mechanisms and latching systems. The title was a little misleading, because the suppliers did most of the designing, while I handled the internal logistics of releasing the design into Ford's database, coordinating between suppliers, and fighting for packaging space. I also spent a lot of time chasing quality issues on current models, identifying root cause, and working with suppliers to develop fixes that could be immediately implemented in production. This taught me a lot about manufacturing automobiles and the mis-communication and lack of trust that exists between the engineering community and the manufacturing and assembly plants. My second job at Ford, started in 1995, was implementing reliability improvement methods on a modified platform that was to support three very different derivative vehicles and that could be manufactured at any of three assembly plants. The program was exciting and ambitious. So ambitious that the financial analysis could not justify the investment. The program was canceled after one year of development.

This assignment taught me a lot. It provided my first high-level experience with Ford's product development processes. My job required extensive cross-functional communication and effort, and had me working with people from manufacturing, body engineering, chassis engineering, vehicle engineering, and project management. I also had ample opportunities to meet with and observe the Chief Program

Engineer, the Vehicle Line Director, and even the Vehicle Center Vice-president, and I began to see how complex, confusing, and frustrating, regardless of position, product development could be. It was during this assignment that I read "The Machine That Changed The World" and began to think more about processes, organizations, and management. This program also presented me with my first example of derivative products being developed in a multi-project environment. From a product and manufacturing strategy perspective, it seemed to make perfect sense. The platform was to be partially carry-over, and the chassis components were planned to be carry-over and commonized. Thus, it also provide me a first instance of how the design history of a chassis architecture can limit flexibility and make a derivative too expensive to pursue. (although the reader might wish to know more about the particulars of this project, its details are considered confidential and proprietary and thus not appropriate for this forum.)

As this project closed up shop in December 1995, I was asked to work on a corporate re-engineering effort focused on developing a new product development process. I was fairly unique on the team, being relatively new to the company with little knowledge of how the company's process had evolved. The working group, which consisted primarily of supervisors, managers, and chief engineers, was split into six function/organization teams. However, in the midst of the six teams, there were two primary "attitude" camps. The first camp was skeptical, and simply wanted to get this process re-engineering done and get back to the job of developing the new vehicles. The other camp was optimistic and saw an opportunity to improve how Ford works. Consequently, the team struggled for focus and agreement, because everybody recognized that they would have to execute whatever was developed. The conclusion was to maintain the traditional structure. Again, it was an educational experience for me, as I refined my skills at communication and negotiation, became more comfortable challenging management, and learned a lot about Ford's culture, processes, and people. By summer, 1996, the process development group was declaring victory and going back to develop vehicles, while I helped develop training materials and led training sessions.

In July, 1996, I was assigned to the 2000 Taurus Team, to implement some of the processes I had developed. Again, I was struck about how exciting developing a new product can be. By January, 1999, as the team approached engineering sign-off, I was struck by how wearing and tiring a long-term development process can be. It is tough for a team and its leaders to maintain enthusiasm and focus for three years. Twice during the course of the Taurus program the team was requested to develop concepts for derivative products that could compete in markets substantially different from Taurus's target market. Management wanted to deliver but was not willing to risk the integrity of the core product. In both cases, the team responded with packaging, cost data, and resource and timing estimates that demonstrated the limitations of the current chassis architecture and the inadequacy of the budgeted resources. (Again, I apologize for the lack of details but this example also involves confidential and proprietary information that is not appropriate for this paper.)

My experience in the aerospace and automotive engineering industries has taught me that competition for a discriminating consumer or client is important for pushing an industry forward, for making it hungry and willing to change. I have also found a special, unexpected joy in developing consumer products, things that anybody and everybody can use, and a particular interest in the attributes that the chassis systems influence. I have seen that team processes and attitudes affect outcomes as much as technical challenges, and that solutions to technical challenges are sometimes developed without a long-term strategy for future product growth. My desire in this thesis is to clarify these issues and possibly point to a method that will help improve long-term thinking about flexible architecture that supports generations of products.

1.8 Methodology Overview

Before starting on this research, the author had no real tools for accomplishing the stated goals, only a desire to capture, understand, and frame the issues. In the end, the thesis used concepts and tools from literature on systems architecture, systems engineering, and organizational processes as frameworks for mapping and analyzing chassis architecture and the chassis development process. Primary among the engineering tools was the Design Structure Matrix (DSM) approach, which was applied in an atypical fashion, and a series of parameter comparison matrices that traces the flow of information. This will be covered in Chapter 4. The key tools for evaluating the organizational issues were the "three lenses" from the SDM Organizational Processes course (Anacona, Kochen, et. al) along with multi-project heuristics from Cusumano. The background of these tools will be the focus of subsequent chapters.

To demonstrate the approach, a case study was developed for a front-wheel drive chassis. The chosen architecture was evaluated by focusing the tools mentioned above on vehicle dynamics parameters. These were chosen because they most strongly represented the customer-perceived attributes that are controlled by the function of the chassis system, and yet they are affected by body and powertrain design. From a high-level perspective, they can be considered one the drivers of chassis architecture.

The primary sources of engineering data included interviews with Ford engineers and managers, engineering documentation (packaging layouts, System Design Specifications, installation drawings), and benchmarking data.

1.9 Research Setting

This research opportunity was provided and supported by the author's employer, Ford Motor Company, and particularly by the Large Vehicle Center and the Large Vehicle Center Quality Office, as part of the company's on-going commitment to employee education and the development future technical leaders. The research effort was carried out at Ford's Research and Engineering Center in Dearborn, Michigan, with assistance and input from Chassis and Vehicle Engineering engineers and managers from the Large and Luxury Vehicle Center and Research and Vehicle Technology center.

As part of the System Design and Management Program, the author spent five months on-campus at MIT taking courses (including Product Design and Development) and doing basic literature research to refine the thesis concept and the problem statement. In this effort, Dr. Ali Yassine and Dr. Dan Whitney provided critical input on direction and sources.

1.10 Thesis Outline

Chapter 2 outlines generic product development processes and their linkages to systems architecture, systems engineering, and design principles. These are intended to ground the reader in the language and concepts that will be used to evaluate.

Chapter 3 provides an overview of chassis architecture and the systems that will be encompassed in the chassis chunk discussions. Again, these provide a basic grounding for the reader.

Chapter 4 describes the various methodologies that could have been used in the development thesis and then details the method and approach chosen. A step-by-step description of the method and the analysis process is provided, along with examples and a set of heuristics for use in analysis.

Chapter 5 applies the methodology to a simple vehicle architecture example, to show how it can be used and suggests other insights than can be gained. Chapter 6 presents the primary case study. It documents the application of the methodology and the heuristics to a specific chassis architecture and details the analysis and conclusions. Observations based on the mappings developed are presented and tied to ideas presented in Chapters 2 and 3. Recommendations regarding strategies around chassis flexibility are complete the chapter.

Chapter 7 pulls together different thinking on management strategies, and applies them to the case of a derivative product in a multi-project environment. This chapter contains recommendations on management strategies, based on the application of the methodology presented in Chapter 4, and suggestions on organizing for derivative products.

Finally, Chapter 8 summarizes the findings and recommendations of the research. Possible research directions are also outlined.

CHAPTER

2 Vehicle Architecture and Systems Engineering

In December of 1995, near the completion of my second year with Ford Motor Company, I was selected to work on the company's new product development process. The company was trying to bring together the latest engineering thinking and tools in a comprehensive and cohesive process that took an idea from consumer wants to consumer product faster than anything Ford had done before. Among the tools and concepts was an approach called systems engineering. As a refugee from the aerospace industry, and from TRW (the company that invented systems engineering), I was surprised to learn that engineering at Ford was heavily component-focused, and that system interaction issues continually bedeviled the company. The component-thinking and the cultural attitudes that support it still exist at the company, but they are being worn away through education, new processes and tools, and continuing management pressure.

An idea that followed closely on the heels of systems engineering was to evaluate and standardize vehicle architecture throughout the company. This supported and strengthened the concepts behind systems engineering. Again, the component-mentality has provided substantial barriers to implementation and, again, education, perseverance and upper management commitment to a vision (a vision that includes improved shareholder value) is a critical part of that vision.

Because product architecture and systems engineering concepts and tools are applied and discussed in subsequent chapter, this chapter lays out the theoretical background needed to understand and implement the concepts behind these methods, and to introduce the terminology and associated definitions that will be used. Applications to automobile development are provided. This chapter also introduces concepts and tools used later in this thesis. The chapter starts with a short description of the product development process and how product architecture and systems engineering are incorporated. Product architecture concepts and applications are discussed. This is followed by an outline of systems engineering fundamentals.

2.1 Product Development Process Overview

The goal of this section is to briefly compare some of the literature on product development processes, outline common themes, and identify a model which will serve as back drop for the discussions later in this chapter and other chapters. There are whole books, whole chapters of books, and many articles devoted to describing generic and industry-specific product development processes. Ford Motor Company has an entire organization devoted to improving, maintaining, and assisting the implementation of its product development process. The Ford process has five primary steps:

- Define and Translate Customer Wants
- Cascade and Balance Requirements
- Design for Robustness
- Integrate and Verify
- Confirm Production Capability and Launch.

Each process step is supported by sub-processes and specific milestones and deliverables for each organization.

The product development process described by Ulrich and Eppinger [1995] is very generic and provides an excellent starting point. Their five phases consist of:

- Concept Development
- System-Level Design
- Detail Design
- Testing and Refinement
- Production Ramp-up

Each of their phases has detailed sub-phases that clarify the work that is done. Of the sub-phases, the concept development phase, being first, is the most critical. It includes:

- identifying customer needs
- benchmarking competitive products and establishing target specifications
- generating and selecting product concepts
- refining specifications

Revelle, Moran, and Cox [1998] present seven steps in their step-by-step Quality Function Deployment (QFD) process:

- Identify the Market
- Select a Product Concept
- Design Product
- Confirm Product Design
- Design Manufacturing
- Confirm Design Manufacturing
- Manufacture Product

As will be noted later, the primary tool for QFD is a series of matrices that capture and cascade information.

Rechtin and Maier [1997] focus on the activities of the "system architect", and provides a model that consists of:

- Client Need And Resources
- Conception And Model Building
- Interface Description And Systems Engineering
- Engineering And Detailed Design
- Development And Production
- Testing, Certification, And Acceptance
- Operation And Diagnosis
- Evaluation And Adaptation

Fowlkes and Creveling [1995] focus on a "robust engineering" process that embraces Taguchi methods. Their three phases in "off-line quality engineering" are:

- Concept Design
- Parameter Design
- Tolerance Design

The names of the phases and steps indicate how very close are the processes. It is generally common that establishing some understanding of the customer is where the process must start. In the Ford model, the customer includes the corporation and the government, as well as the purchaser of the product. The models also move from high-level concepts to lower-level design, and incorporate verification and validation of the product function and the process capability. The processes have much in common in their details and differ primarily on how the authors chose to group different efforts. Since I took Professor Eppinger's class on product development, I admit to a bias towards his material. For the purposes of discussion, this thesis will use the Ulrich/Eppinger model (henceforth referred to as the PD model) as a framework within which the concepts of product architecture and systems engineering will be placed.

2.2 Product Architecture and The Automobile

Architecture brings to most people's minds thoughts of buildings and bridges. However, architectural concepts apply to all objects, and especially those created by humans. Ulrich and Eppinger [1995] define product architecture as

> 'the scheme by which the functional elements of the product are arranged into physical chunks and by which the chunks interact."

This is very close to the more familiar definition of architecture relating form and function. Boppe [1998] defines systems architecture as :

> "the structure, arrangement, or configuration of system elements and relationships required to satisfy both constraints and a set of functional, performance, reliability, maintainability, and extensibility requirements".

This definition, although narrow from the perspective of architecture (but broad from a systems engineering perspective), brings in important issues of constraints and requirements. Rechtin and Maier [1997] define system architecture as

> "the art and science of creating and building complex systems"

and that it is the

> "part of system development most concerned with scoping, structuring, and certification."

Recognizing the relation between scope, function, concept, and form is critical to understanding architecture. Scope addresses the boundaries, what will be encompassed and what will be ignored. Function describes the desired behavior or operations, and is form-free. That is, the functions should be able to be described without including a description of the form of the solution. Applying these concepts to a product such as an automobile means understanding the functions that are desired by the consumer. Concept describes a specific vision of how the function can be fulfilled, or maps function to form [Crawley, 1998], and is technology-specific. Form describes the physical embodiment of the function. Concepts and forms can be proprietary and patentable. However, the highest praise for a form is to call it elegant, which says the solution generated is unique, efficient, original, and aesthetically interesting.

In terms of an automobile, providing personal, flexible transportation could be the function. From that function, several concepts can be envisioned that used non-powered and powered ground-based implementations, air-borne implementations, or molecular rearrangement implementations. These implementations could lead to forms such as bicycles, mopeds, airplanes, or the "transporter" on Star Trek™. An automobile is just another possible form in a vast universe of potentials.

Another critical role for architecture and those that practice it, as suggested by Rechtin and Maier [1997], is to reduce "complexity, uncertainty, and ambiguity to workable concepts" that the engineers can make work. Architecture, according to Rechtin and Maier, focuses on the "critical few details", which generally involve connections, linkages, and interfaces.

Interfaces, the linkage between physical elements, are created by the architecture decisions made about functional decomposition and interactions during the pre-concept, technology-independent phase [Crawley, 1998]. Like concepts, the number of functional decomposition potentialities is limited only by the imagination of the architect, and is one of the challenges that make architecting a product as much an art as a science, as much "synthesis as analysis, induction and deduction" (Rechtin and Maier). Like most arts, architecting requires experience, which implies failure and success. To improve the odds of success, Rechtin and Maier (1997) list four architecting methodologies:

- Normative or solution-based
- Rational or method-based
- Participative or stakeholder
- Heuristic or lessons learned

These methodologies are guidelines to and through abstraction and feasibility, not cookbooks or precise analytical or optimization tools. Success will not come without thoughtful effort. To support these methodologies, Rechtin and Maier provide what they consider the "foundations of modern systems architecting":

- Systems approach
- Purpose orientation driven by the client
- Modeling methodology
- Quality so demanding it is impractical to measure defects or certify prior to use ("ultraquality implementation)
- Insight and heuristics

There is enough background at this point to discuss the concepts of modularity and integrality. Ulrich and Eppinger [1995] specify two "properties" of a modular product":

- Systems or "chunks" are responsible for one or a few functional elements in their entirety.
- Interactions and interfaces between systems or chunks are well-defined and are fundamental to the primary function of the product.

They have also specified three properties that a integral product might have:

- Functions are the responsibility of more than one chunk or system
- A single chunk or system is responsible for many functional elements
- Interactions and interfaces between chunks or between systems are ill-defined and may be incidental to the primary function of the product.

In an integral architecture functions would "emerge" [Crawley, 1998] as properties of the interfaces. An example of integral architecture is a Personal Digital Assistant like the Palm Pilot ®, which uses single screen for data input and for visual transfer of information. Modern desktop personal computers, with their self-contained CD-ROM drives, modem cards, and hard drives, are examples of modular architecture in a product. Another example is the jet engine on modern aircraft, which is primarily responsible for propulsion. The human brain is an example of both integral and modular architecture. It has specific regions being largely responsible for specific functions yet the whole article is so interconnected that certain levels of redundancy are exhibited for some functions [Damasio, 1994]

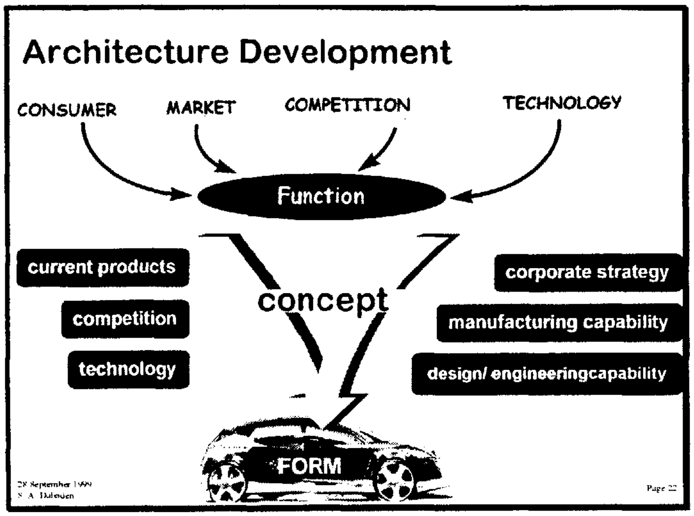
The idea of emergent properties is another critical concept in systems architecture. Flexibility potential, as defined in Chapter 1, can be considered an emergent property of architecture, since it depends on how the chunks and systems are put together. Product complexity is also an emergent property, since it is an outcome of interfaces. In general, decisions that impact and support flexibility and modularity are architecture decisions. Consequently, product architecture must occur very early in the product development process, in the "Concept Development" phase of the PD process. Table 2.1 compares Rechtin and Maier's "Foundations" with the steps inside the Concept Development phase of the PD process. Although the match is not explicitly one-to-one, the common themes are apparent. The systems approach and "ultraquality" implementation would support the development and refinement of specifications, while the insight, heuristics, and modeling methodology would support the generation of product concepts.

TABLE 2.1 Comparison of Concept Development Processes

RECHTIN/ MAIER FOUNDATION	PD CONCEPT PHASE
• Systems approach	• Identifying customer needs
• Purpose orientation driven by the client	• Benchmarking competitive products and establishing target specifications
• Modeling methodology	• Generating and selecting product concepts
• "Ultraquality Implementation	• Refining specifications
• Insight and heuristics	

Figure 2.1 is a vision of architecture development and the factors that influence it. The consumer, the market, competition, and technology all suggest desirable functions and undesirable conditions for the product to avoid. These functions are analyzed on the basis of known capabilities and constraints of manufacturing, design and engineering, technology, corporate strategy, and competition to propose a concept and a form to provide those functions.

Figure 2.1 **Architecture Development**



Consider again the personal, flexible transportation function. There are many ways the function could possibly be decomposed, including the following:

- transport five human passengers over long distances quickly
- protect and contain human passengers in a comfortable, controlled environment
- can be operated safely with minimal training, skill and intelligence.
- isolate human passengers from outside disturbances
- allow for instantaneous direction changes in response to human commands
- facilitate feedback on system performance and external conditions
- allow for travel over a variety of surfaces in all weather conditions
- allow for instantaneous acceleration changes in response to human commands
    - acceleration
    - deceleration

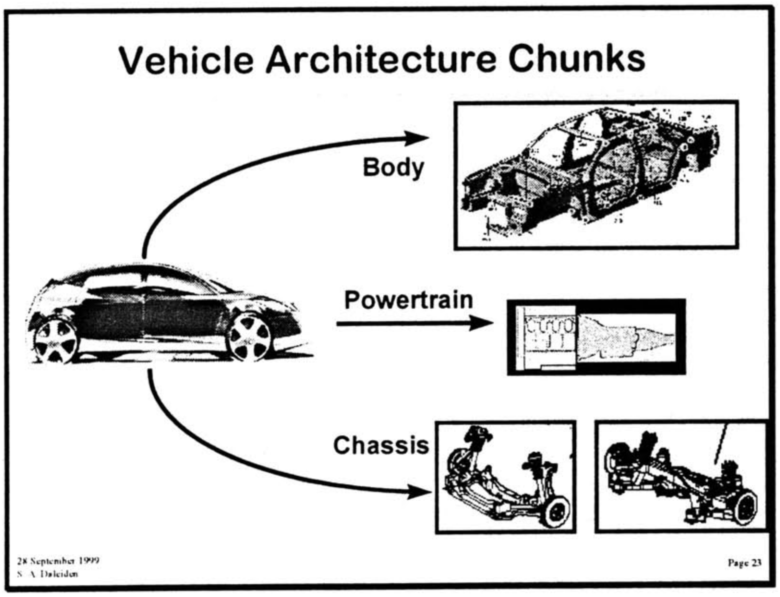
Government requirements, corporate strategy, consumer preferences or abilities, and technology cost factors might drive additional functions:

- ground based
- impact resistant.
- maximum attainable speed of 100 KPH
- manufacturable on an assembly line

From these functions, one can begin to envision a conceptual chunks and forms:

- body shell to house, isolate, and protect passengers
- body structure to support shell and provide crash protection
- engine and transmission to provide controllable speed and acceleration
- brakes to provide controllable deceleration
- steering to provide direction control
- suspension to isolate body and passengers

Figure 2.2 Vehicle Architecture Chunks



Vehicle Architecture Chunks

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This vehicle architecture is shown in Figure 2.2. The functions presented above represent an extremely simplified case, making it look like the automobile's functions separate cleanly into modular chunks. As will be discussed later, some of the functions end up being shared among systems. Also, there concept gets modified by the addition of a subframe system and mounts. As noted in Chapter one, one way companies respond rapidly and cost-effectively to newly identified consumer wants and emerging product markets is to derive new products from existing products. In terms of architecture, that could mean using similar strategies or concepts to allocate or partition functions to physical forms, so that there is little engineering re-work. This could mean actual sharing of component between the base design and the derivative design, or it could be that the same conceptual approach is used.

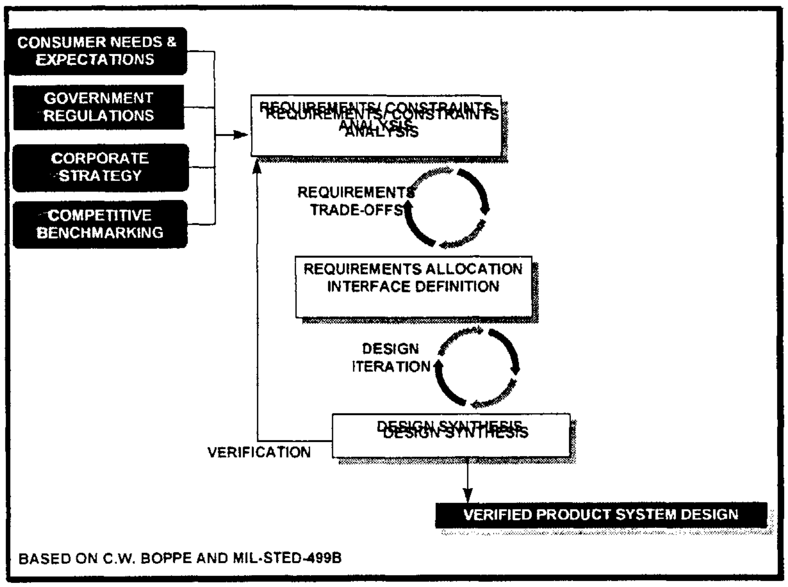
2.3 Systems Engineering and The Automobile

Like product development architecture, systems engineering means pretty much the same thing to those who understand it, but each interpreter has some nuance that they want to emphasize. For Rechtin and Maier [1997], systems engineering is a "multi-disciplinary engineering discipline in which decisions and designs are based on their effect on the system as a whole." Boppe [1998] defines systems engineering as "an engineering discipline that addresses requirements analysis and the design, development ,and operation of complex products." Boppe also defines the objectives of systems engineering as :

- to ensure that customer needs and expectations are met
- to manage the inherent complexity of large-scale, sophisticated products
- to integrate the technical and management processes required to design robust products within performance, cost, and schedule constraints.

Figure 2.3 is a derivation of the systems engineering process presented by Boppe [1998], which is based on a draft of MIL-STD-499B. The process includes iterations to allow trade-offs and balancing around requirements and then design concept trade-offs, requirement re-allocation, and interface refinement.

Figure 2.3 Systems Engineering Process



BASED ON C.W. BOPPE AND MIL-STED-499B

Ford has its own version of systems engineering, which is taught in a special course. In the Ford model, the key idea is the proper cascade of targets and requirements to specifications and the integration and verification of systems. In general, the flow goes as follows:

- consumer wants are identified based on marketing research of lead users, target consumers, and competition
- other wants are determined from corporate strategy and government regulations, current and pending
- wants are translated into objective engineering metrics at the highest level possible.

Generally, the following ideas are contained within systems engineering:

- Identify consumer, Corporate, and Regulatory wants and constraints
- Translate wants and constraints into vehicle attributes
- Develop and analyze objective requirements at vehicle level using vehicle attributes
- Develop alternative chunk concepts and interfaces that support vehicle requirements
- Select preferred concept based on requirements, constraints, and design principles.
- Cascade and allocate vehicle requirements to system level specifications
- Develop alternative system concepts and configurations.

- Select and refine preferred solution.
- Integrate and validate system designs.

The primary idea is to translate higher-level attributes (wants, constraints, mandates) to specifications (metrics and values) to which an engineer can design. An important point that relates systems engineering to systems architecture is that requirements cascading cannot proceed to the next lower level without a concept and an associated functional decomposition.

In implementing systems engineering in the automotive industry, each step has its own special difficulties. For instance, identifying and prioritizing consumer wants is difficult because people often do not know how they will use something or if they will want it until they have it and can use it. The right-hand sliding door on the mini-van, and the mini-van itself, are examples of products that received tepid results in marketing studies but that, when executed and placed in the consumer's hands, were blistering successes. On the other hand, the styling of the 1996 Taurus tested well in initial marketing studies but did not fare well in the market place, partially due to its "far-out" look.

Government regulation is another input that is somewhat unpredictable, particularly regarding safety. There are lawsuits on-going that are intended to hold old model vehicles to more modern safety standards that did not exist when the models were developed. In essence, they want to change the requirements for the product after the product is in produced and sold.

One useful systems engineering tool is Quality Function Deployment (QFD) or the "House of Quality". QFD can be described as "a set of planning and communication routines" that "focuses and coordinates skills within an organization" [Hauser and Clausing, 1988]. More specifically, according to Revelle, Moran, and Cox [1998], QFD has the following objectives"

- translate consumer, stakeholder, and regulator wants into "substitute quality characteristics at the design stage."
- cascade and communicate the substitute quality characteristics to the production activities.

The typical understanding and usage of QFD in automobile development is to facilitate and communicate the selection and cascading of customer wants to vehicle attributes, vehicle targets, system requirements, and design parameters and specifications. This is accomplished by

- relating higher-level attributes to lower-level attributes and rating the strength of the relation
- rating the performance of competitive designs with respect to the higher-level attributes
- evaluating the strength of inter-correlation among the lower-level attributes
- establishing target values and metrics for the lower-level attributes.

The tool takes the form of a house-shaped matrix, as shown in Figure 2.4. The cascading is carried out by using a series of the houses that is as long as required to cascade information to the lowest useful level.

Figure 2.4 House of Quality and Requirements Cascade

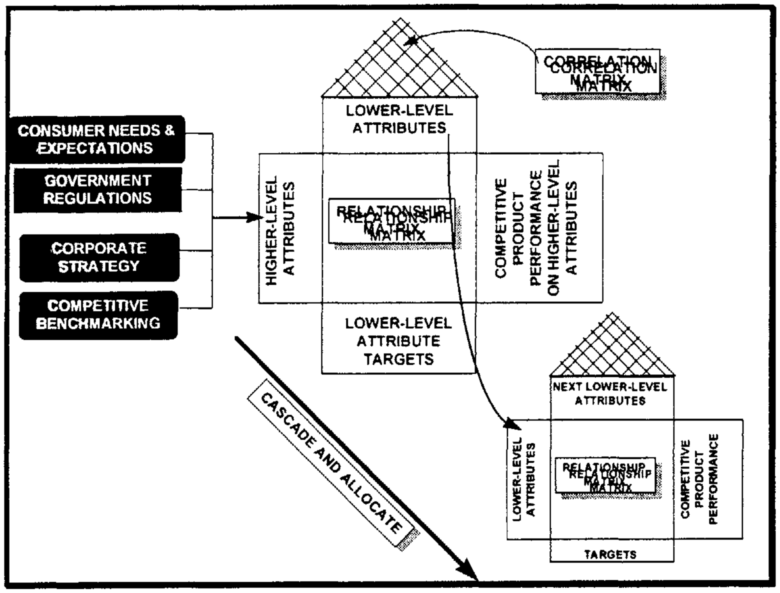


Table 2.2 shows the levels that would be cascaded through for a total vehicle QFD.

TABLE 2.2 TYPICAL MATRIX COMPARISONS FOR VEHICLE QFD

LEVEL	HIGHER-LEVEL ATTRIBUTE	LOWER-LEVEL ATTRIBUTE
1	consumer want	vehicle attribute
2	vehicle attribute	vehicle requirement
3	objective vehicle requirement	system specification
4	system specification	sub-system/component specifications

Ulrich and Eppinger [1995] also suggest starting with customer wants and using matrices in the development of product specifications. One of their tools is the "needs-metrics" matrix, an example of which appears in Table 2.3. This is used a basis for developing other matrices which capture competitive benchmarking data and eventually target specifications

Table 2.3 Needs-Metric Matrix Example (based on Ulrich and Eppinger)

METRIC NEEDS	wheel travel	shock absorber stiffness/ length	control arm position/ geometry	maximum steering angle	steering rack position/ stiffness	subframe stiffness/ geometry	anti-roll bar stiffness/ compliance	Spring Stiffnesses
smooth ride on smooth and rough road	◆		◆		◆		◆	◆
straight ahead stability		◆	◆		◆			
cornering stability			◆	◆	◆	◆	◆	◆
cornering controllability			◆		◆		◆	
straight ahead controllability			◆					
ease of slow-speed maneuvering			◆	◆	◆	◆		
minimal fore/aft pitch			◆					◆

Robust design methods are useful in refining design concepts once requirements are defined. They can be used in conjunction with any of the tools previously described, but are best applied at a sub-system or component level, due to the reliance on physical experiments or accurate, correlated CAE models. The robust design approach uses Taguchi methods, designed experiments (DOE), and statistical analysis to identify optimum design parameters and tolerances [Fowlkes and Creveling, 1995]. These optimum settings should improve the ability of a design to consistently achieve its proper specification or functional requirements under normal operating conditions (noise). Application of Robust design methods require both product engineering knowledge as well experience with DOEs and statistical analysis concepts.

Another tool that is useful in the systems engineering process is Failure Mode Effects Analysis (FMEA). FMEAs are useful for exploring potential failure modes and prioritizing design actions to eliminate those failure modes. This can be very beneficial for functions that can generate potential safety concerns and can help the product anticipate and stay ahead of government safety regulations. Again, a system-level concept and initial requirements or specifications are needed for this tool to be applied.

Returning to the PD model discussed in section 2.1, the tasks inside systems engineering start during concept development, and support system-level design, detailed design, and testing and refinement. Consequently, systems engineering can be viewed as the backbone of the PD process, a perspective that Ford endorses. In general, the processes and tools are flexible, allowing them to applied to the development of a derivative product or a single core product.

2.4 Good Design Guidelines

As should be clear from the preceding discussion, system architecture and systems engineering are tied together by the PD process and by overlapping areas of concern. In particular, they especially want to ensure that the product design gets off to the best start possible by making sure the customer wants are understood and that these wants are properly translated. They are also both concerned with issues of complexity and agree that minimizing complexity leads to a design that is easier to develop and engineer.

There are a few of ways that complexity can be reduced. One is through the use of heuristics or lessons learned [Rechtin and Maiers, 1997]. Below are some of the heuristics collected by Rechtin and Maier (1997)

- In partitioning, choose the elements so that they are independent as possible, that is, elements with low external complexity and high internal cohesion
- Do not partition through areas or across elements where high rates of information exchange occur.
- Group elements that are strongly related to each other, separate elements that are unrelated.
- fewer interactions leads to simpler, less complex designs.
- Interfaces change as architecture evolves, and increase as complexity increases
- Relaxing constraints leads to new forms

- Moving to a wider purpose expands the range of solutions.
- Local optimization does not lead to global optimization.
- Modularity generally leads to compromise in functional performance.

These provide guidance but very little detail. They cannot anticipate every scenario, and thus there may be situations where they do not apply. The use of heuristics requires experience and intuition, and may be an art within an art.

Another method is systems modeling [Rechtin and Maier, 1997][Boppe, 1998]. Ford has extensive CAD/CAE capability to handle static and dynamic simulations. However, many of the interactions between chassis systems are not handled well by the tools, and there is no CAD/CAE tool that can handle all dynamic and static scenarios for the entire chassis. Currently, different models are developed for different simulations and situations. This will be discussed in Chapter 3.

Finally, an excellent source of guidance on handling complexity is Axiomatic Design developed by Nam Suh [1998]. Axiomatic design focuses on functions, functional requirements (FRs), design parameters (DPs), process variables (PVs), customer attributes (CAs), and constraints. FRs describe the functional needs or characteristics of the product, DPs are primary physical variables that characterize the design, such as specifications, while PVs are the key variables in the process domain. A design matrix relates the FRs to the DPs.

There are two axioms in Axiomatic Design:

1. Independence - maintain the independence of the funtional requirements (FRs)
2. Information - minimize the information content of the design

Whether these are actually axioms or principles of good design is debatable. Regardless, they provide a useful starting point for analyzing complexity and are backed up several theorems, which include:

- when the number of DPs is less than the number of FRs, either the FRs cannot be satisfied or a coupled design results
- When a design is coupled due to the number of DPs being less than the number of FRs, the design can be decoupled by adding new DPs until the numbers are equal.

- When there are more DPs than FRs, then the design contains redundencies or it is coupled.

The axioms and theorems provide a perspective for looking at complexity and modularity. Though they might still meet the axioms and be considered good designs, complex designs would have many FRs and many DPs across many levels of decomposition. A modular design would meet the axioms by having an equal number of FRs and DPs. An integral design would have functions shared or performed by multiple physical elements, which leads to coupled FRs , a coupled design, and an inability to meet the first axiom.

The steps in axiomatic design for a product are:

- Define the FRs of the system based on CAs.
- Map the FRs from the functional domain to the physical domain.
- Maintain the independence of the system functions.
- Minimize the information content of the system.
- define modules in terms of FR/ DP relationships.
- Decompose FRs and DPs
- Develop system architecture

The process of decomposing the FRs and DPs is described as a "zig-zag" between the functional domain (what) and the physical domain (how). This is a key distinguishing feature of axiomatic design.

The process steps of axiomatic design clearly support the work that is being done during the concept, system design, and detailed design phases. It is very much an approach that can support both system architecture and systems engineering, as evidenced by Suh's suggestion of the use of QFD to translate CAs to FRs [Suh, 1998]. The axioms also support the development of architecture that is modular, and thus flexible. Suh warns, however, that FRs must be developed in a "solution neutral environment", without a vision of what the design solution will be. In terms of automobiles, this becomes an extremely challenging task, due to the manufacturing and organizational inertia that exists around traditional architectural solutions.

Additionally, It has been suggested by several sources (Ulrich and Eppinger [1995], Rechtin and Maier [1997], to name a couple) that an integral design is usually more optimized for functional performance within constraints than a modular design. If this is true (and I think it is), then an automotive design that meets the demands of axiomatic design will result in a product that is optimized for flexibility and modularity, allowing rapid and relatively easy development of derivatives. However, the automobile architecture will not be optimized for total functional performance, or will not be feasible due to constraints such as weight, fuel economy, cost or packaging. Again, this implies that meeting the standards of axiomatic design may not be possible for an automobile.

2.5 Chapter Summary

This chapter laid the groundwork for subsequent chapters by introducing key concepts of product development, system architecture and system engineering and highlighting how the. Particularly important is understanding that the system architecture and system engineering tools and concept need to be applied early in the product development process for them to be truly useful.

The chapter introduced architecture concepts such as function, form, concept, and emergent properties. Integral and modular architecture were described using criteria from the literature. The chapter also provided guidelines for developing architecture, including heuristics and Axiomatic Design Systems engineering tools for developing and cascading requirements were introduced and described, including QFD.

Chapter

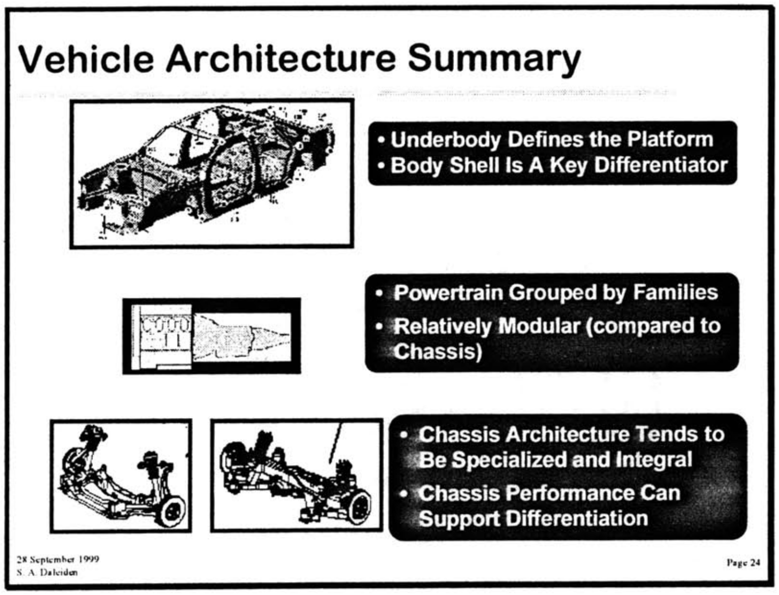
3 The Role Of The Automobile Chassis

My first awareness of product differentiation came at the age of six, when my brothers and I began collecting miniature, die-cast automobiles. Since we were living in Great Britain at the time, I favored the Corgis ™, because they were large enough to allow one to perceive design differences between models. When we returned to the United States, where my favored brand was not readily available, I began to amass a stable of Matchbox ™ and Hot Wheels™. Like most boys, I liked the wild, outlandish concept models. However, I also coveted models of the 4 -door sedans and pick-up trucks by Ford, Chrysler, and General Motors that I saw on the road everyday, because they were different. I also understood, my own simple way, that they served a special purpose: a family of five cannot travel in comfort in the Batmobile, but they can in a Chrysler Newport Custom.

The other buried lesson I learned from my small (small in stature, not in quantity) collection of miniature automobiles, and from my brothers and friends, was that, to the consumer, a product that doesn't look different isn't different. Vehicle design styling drives differentiation. Figure 2.2 in Chapter 2 presented the traditional architecture chunks for an automobile. Figure 3.1 reprises this architecture and highlights how differentiation in the chunks is perceived. The body shell, which is the most visible part of the vehicle, is considered a key differentiator. It determines vehicle size and shape, and contains virtually all exterior styling elements.

Shape, character lines, exterior size, interior space are key differentiators to consumers, and they are aware of them and respond to them. Interestingly, consumer studies done during the development of QFDs suggest that people are not aware of the influence of design styling, as evidenced by the low ranking in importance they generally accord it. However, the excitement and sales figures generated by fresh, well-styled vehicles makes it clear to the automotive industry that design styling can make or break a product, and that appearance is a key differentiator to consumers.

Figure 3.1 Vehicle Architecture Summary



Vehicle Architecture Summary

- Underbody Defines the Platform
- Body Shell Is A Key Differentiator

- Powertrain Grouped by Families
- Relatively Modular (compared to Chassis)

- Chassis Architecture Tends to Be Specialized and Integral
- Chassis Performance Can Support Differentiation

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Figure 3.1 also indicates that differences in nuances or attributes most affected by chassis design are not readily apparent to most consumers. Experience on products like Taurus SHO and Contour SVT support the idea that customers need to spend some appreciable time driving and riding in such vehicles to value the differentiated chassis. However, due to the limited visual differentiation, the chassis and powertrain differences between the specialty product and the base product attracted few consumers who were appreciably different from those attracted to the core product. Fundamentally, by themselves, changes in the sub-systems that make up the chassis cannot make a derivative vehicle successful in a market that is extensively distinct from that of the base product. People want vehicles to make a clear statement, and differentiation in the chassis by itself does not support that clarity.

That is not to say that the chassis is irrelevant to the development of a derivative product. Combined with proper changes to the body, a chassis that has flexibility potential will allow a derivative product to better meet the expectations of the target market and could allow the product to reach markets it cannot achieve with body shell changes. A chassis that supports flexibility will also allow derivatives to be developed faster can make a difference in price, quality, and functional performance, which can affect long-term success or failure in the markets.

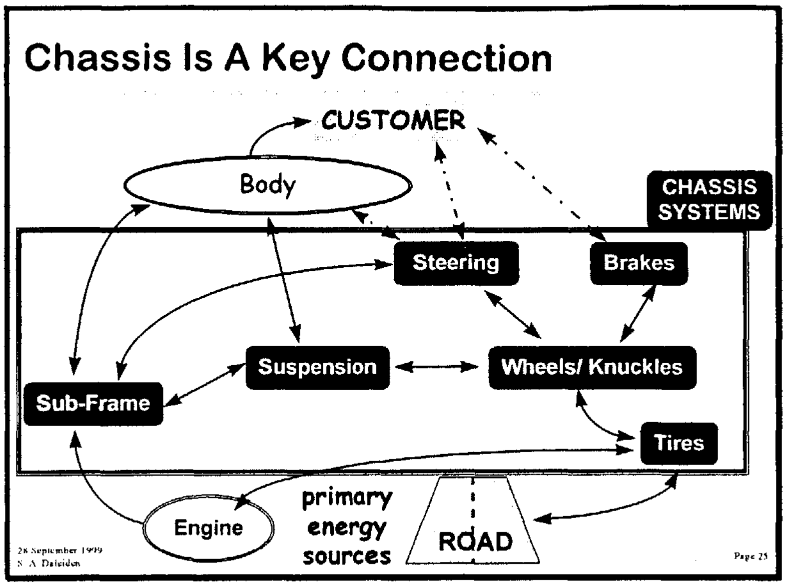
This chapter uses the language and ideas discussed in Chapter 2 to describe the architectural elements of the chassis. This will set the stage for later discussions on its flexibility potential and its ability to contribute to or hinder a successful derivative product. The key functions of the chassis sub-systems will be outlined and then the primary consumer-perceived attributes. The traditional functional partitioning will be presented and then the chassis development process will be described.

3.1 Function of Chassis

Chapter 2 presented the systems engineering approach and the high-level view of the vehicle architecture, of which the chassis was a key chunk. Typically, when applying systems engineering, the consumer comes first, followed by the development and cascading of requirements, development and refinement of a concept, and so on through component design, system integration, and product validation. However, the literature chassis design [Barstow, 1997] [Gillespie, 1992] [Milliken and Milliken, 1995] treat automobiles as pre-defined systems and sub-systems, as shown in Figure 3.2, with the chassis sub-systems providing key interfaces between the body and the road, between the body and the powertrain, and between the powertrain and the road. The primary function of the chassis is not considered in a concept-free manner. This is reasonable, given that the decomposition of the automobile changes very slowly, due to the relatively static nature of modern assembly plants and methods. However, to completely layout the chassis system, as well as provide background for some decisions regarding subject matter scope, it is beneficial to first consider the functions of the chassis without reference to a specific chassis concept, before diving into the consumer attributes.

Chapter 2 provided an example of how the architecture of a vehicle would be functionally decomposed and assigned to the body, powertrain, and chassis elements. Following the guidelines expressed by Crawley [1998], Rechtin and Maier [1997], and Ulrich and Eppinger [1995], and building from the example in Chapter 2, the fundamental functions of the chassis include:

Figure 3.2 Chassis: A Key Interface



Chassis Is A Key Connection

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- physically connect the body and the powertrain.
- support the body and the powertrain loads during static and dynamic events.
- physically support the body and powertrain on the road surface.
- support the connection of the powertrain drive mechanism to the vehicle drive mechanism.
- provide and maintain contact between the vehicle drive mechanism and the road.
- provide the driver with reliable directional control of the vehicle.
- Isolate the passengers from the vibration energy inputs of the road and powertrain
- stabilize vehicle during linear motion.
- stabilize vehicle during cornering.
- provide physical sensory feedback to driver on vehicle performance.
- manage impact energy during crashes to protect passengers.

Note that, for the most part, the braking function, which is traditionally part of the chassis chunk, has not been included. This was done because the functions performed by the braking system are noticeably different from the functions of the other sub-system, having primarily to do with the physics behind proper deceleration.

3.2 Consumer-perceived Attributes Influenced by Chassis

"A vehicle exists to carry someone or something from one place to another", according to Barstow [1997]. This is an engineering perspective, not a consumer's perspective, and not the perspective of a consumer-focused company. Modern automobiles are used as status symbols, personality reflectors, entertainment, offices, and personal sports equipment. Understanding the needs of the consumer, and understanding the prioritization of those needs, is critical to developing a product that meets those needs and can lead to product that provides attributes that consumers do not even realize they want until there is product that demonstrates those attributes.

From the perspective of the automobile user, the chassis chunk does not connect the powertrain to the body. It connects the consumer to high leverage attributes, attributes about which consumers care deeply. However, capturing, interpreting, and truly understanding consumer perceptions about vehicle chassis performance is extremely difficult because the consumer often cannot sort out what is influencing their perceptions and cannot verbalize precisely the factors driving their likes and dislikes. This is an indication that complexity is being encountered. As noted in Chapter 3, when assessing chassis performance, most developers focus on attributes that relate to vehicle dynamics. For example, while developing the 1997 Chevrolet Corvette, engineers at General Motors focused on customer comments about ride and handling [Ryan et al., 1997] with "Voice of the Customer" attributes such as:

- Car's Handling allows for fast cornering
- car handles well over poor roads
- car's handling provides a total feel of the road
- car responds well to steering wheel movement
- car has smooth ride over bumpy roads
- car does not shake or vibrate.

These subjective attributes were used in a QFD structure in which these were linked to objective metrics and prioritized. It was also reported that the QFD structure showed the strength of the relationship between the objective and the subjective

In developing the Volvo 850 GLT [Wedlin et al., 1992], Volvo engineers worked with customer-focused attributes such as

- driving pleasure

- driving safety
- ride comfort
- noise comfort
- driving comfort

Volvo tried to interpret the customer's response to vehicle dynamics at high level and then tie these customer-derived attributes directly to objective metrics which can be used in the engineering process.

Similar to Volvo, Ford [Ford - A,1996] uses high level subjective attributes (ride, steering, handling, braking, NVH) that are broken down into sub-attributes such as:

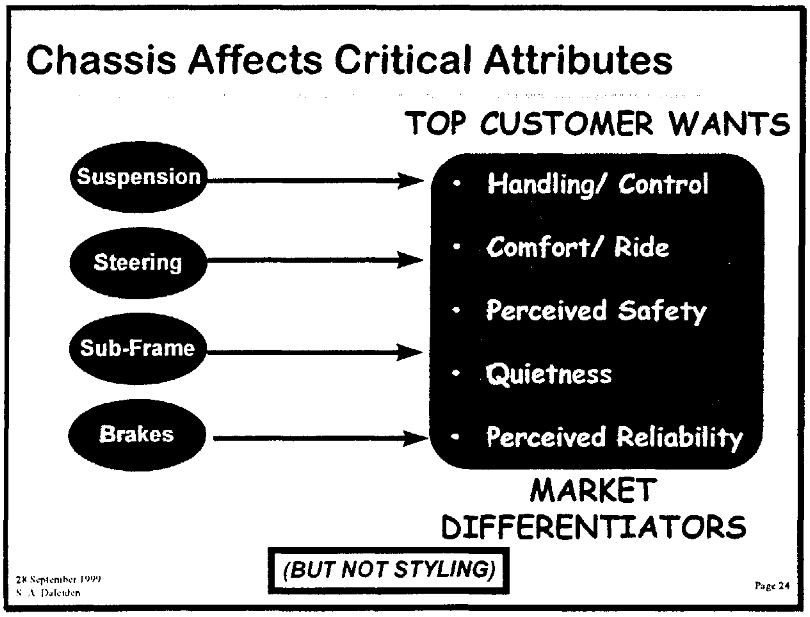
- body control
- parking and maneuvering
- straight ahead control
- cornering control
- steering disturbances
- straight ahead stability
- cornering stability

These sub-attributes can be broken down into lower-level characteristics. Apparently, neither Ford nor Volvo attempts to apply a full-blown QFD approach.

These approaches can be seen as following the systems engineering approach of top-down cascading of requirements. Also, all three can be seen to be following the basic early product development steps (identifying customer needs, establishing specification, generating compatible concepts) covered by the PD model discussed earlier. Thus, a common approach is used by industry, with similar consumer-based descriptive attributes used as a basis for setting performance requirements for objective performance metrics.

Figure 3.3 summarizes the consumer-perceived attributes that are most affected by chassis design, identified from other technical literature on chassis design [Barstow, 1997] [Gillespie, 1992] [Milliken and Milliken, 1995]. This information supports the approaches that the industry takes to characterize the consumer-perceived attributes that are influenced by chassis architecture.

Figure 3.3 Attributes Influenced By Chassis



Chassis Affects Critical Attributes

TOP CUSTOMER WANTS

- Handling/ Control
- Comfort/ Ride
- Perceived Safety
- Quietness
- Perceived Reliability

MARKET DIFFERENTIATORS

(BUT NOT STYLING)

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Table 3.1 shows how these attributes ranked in QFD studies performed at Ford [Ford- A, 1996]. In the table, the ranking number represents the relative number times a specific attribute or want was highlighted by consumers. A lower number for a particular attribute means that that attribute was considered very important. Other Ford data suggests that consumers are more sensitive to problems associated with steering, ride, and handling than they are to other types of problems, because these attributes tie to the feeling of comfort, stability, controllability, and operation safety that consumers expect from their automobiles.

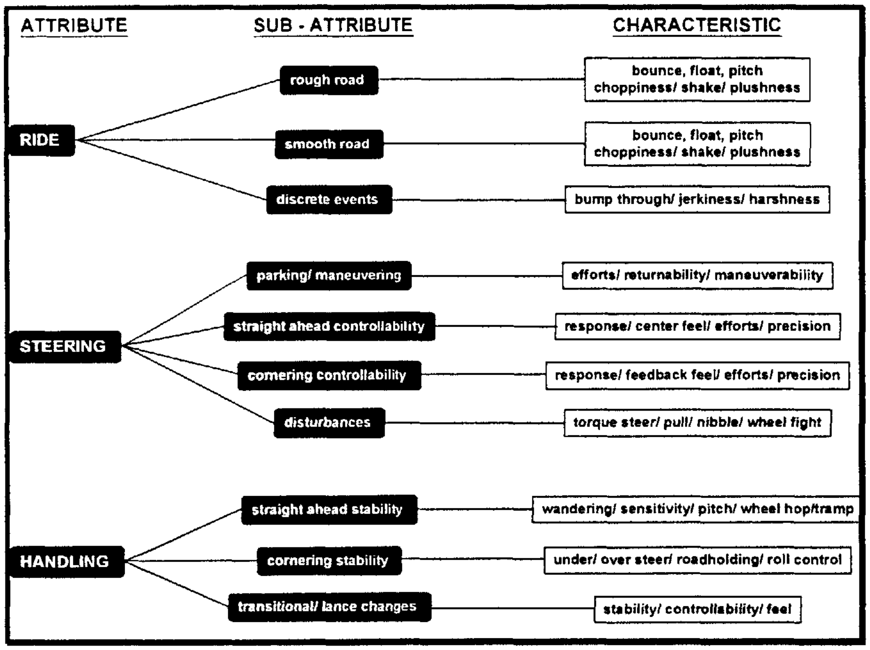
The conclusion is that consumer-perceived nuances or attributes such as ride (which includes aspects of roadholding and feel), steering (which also includes aspects of safety and feel), and handling (which includes aspects of roadholding and safety), which are influenced or determined by chassis design, are also of importance to the consumer. In the automobile design industry (including race car design) these attributes are generally lumped together and labeled “vehicle dynamics”. In general, braking is also considered as part of vehicle dynamics, due to the load transfer that occurs during braking.

TABLE 3.1 AGGREGATED QFD RESULTS

Customer Want	Rank
roadholding - secure, stable, confident	2
safety	3
feel	8
steering precision, response	9
handling	12
ride	16

The attributes associated with vehicle dynamics can be partitioned in sub-attributes and characteristics, as shown in Figure 3.4. For the purposes of this thesis, going down to the characteristic level does not provide additional information, because the objective metrics do not significantly differentiate between characteristics within a given sub-attribute. This will be discussed in Chapter 6.

Figure 3.4 Attribute Partitioning



These attributes characterize the customer's perceptions and the dimensions along which they will evaluate a vehicle against their desired performance. However, the desired performance level for each attribute is not constant across all consumers. Table 3.2 summarizes the range of performance that different vehicles were targeted to achieve [Wedlin et al., 1992] [Ryan et al., 1997] [Schmid et al.,1997]

[Neal et al., 1997], [Ford - A, 1996]. The Corvette, being a true sports car, aims to provide a stiff though not harsh ride, precise, responsive handling under high speed conditions, and accurate road feel and feedback through the steering wheel, because this what a sports car enthusiast wants. At the opposite extreme, the driver of the Lincoln Town Car is looking for a soft, isolating ride, handling that is stable and forgives errors, and steering that isolates road vibrations and requires little effort.

Table 3.2 Comparison Of Consumer Wants and Range on Vehicle Dynamics:

VEHICLE	RIDE	HANDLING	STEERING
Chevy Corvette	stiff, firm not harsh low pitch	precise responsive high g stability	good torque feel accurate road feel
Volvo 850	soft stable low pitch	secure forgiving	low effort good feel
Ford Taurus	med stiff med soft med pitch	med precise responsive stable	low effort good torque feel
Lincoln Town Car	soft isolating med pitch	forgiving stable	very low effort isolating

The words used to describe the attributes, which are qualitative and overlap in meaning, also indicate that these attributes, which are physical sensations of motion, are not cleanly separated in the perceptions of the consumer. The primary discriminator is the path through which the sensation is transmitted, manifested, and felt. Sensations that come through the seat are generally attributed to ride. Those that manifest themselves in the motion of the vehicle body are attributed to handling, and those that are felt by the consumer's hands via the steering wheel are attributed to steering. Regardless, this lack of separation, which really reflects coupling between the attributes, is a further indication of complexity and makes the functional partitioning (discussed in the next section) difficult.

3.3 Chassis Functional Partitioning and Architecture Decomposition

The primary functions for the chassis were listed in section 3.1 and the primary customer wants and attributes were listed in section 3.2. Applying systems architecture and engineering methods, the next steps would be to separate the functions and the attributes they provide and then develop concepts that provide that function. However, as noted earlier, the automotive industry has developed the functional break-down and the sub-system concepts that support that breakdown. Figure 3.2 showed the primary elements of the chassis chunk, which are the steering system, the suspension system, wheels/ tires systems, and the sub-frame system. As noted previously, the brake systems is also part of the chassis chunk but it is not being considered.

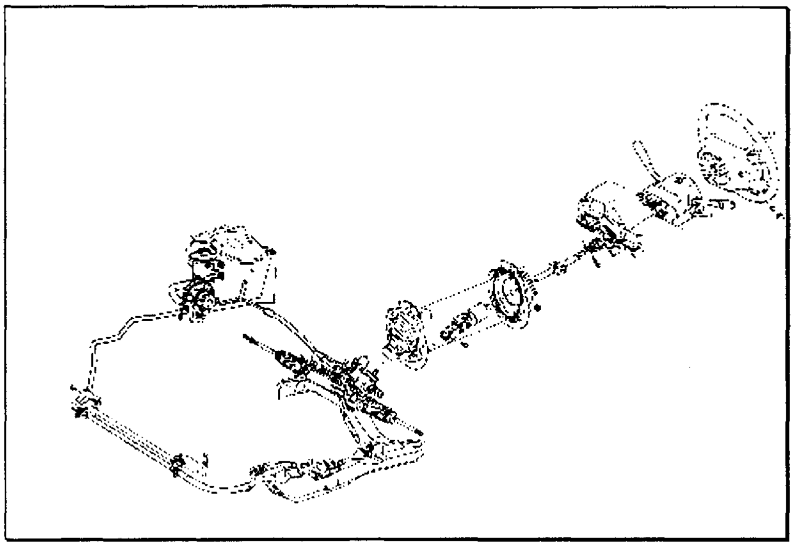
A review of the vehicle dynamics literature and Ford system design specifications provided the functional descriptions of the chassis sub-systems. These are summarized in the paragraphs below.

The steering system functions include:

- Providing reliable directional control of the vehicle to the driver
- Interfacing between the driver and the road.
- Furnishing acceptable steering efforts.
- Isolating the driver from harsh road inputs and poor vehicle responses.
- Controlling system noise and vibration.
- Furnishing the driver with acceptable steering feel and feedback
- Provide and support vehicle crash energy management

Figure 3.5 provides an example of a rack and pinion steering system.

Figure 3.5 Steering System

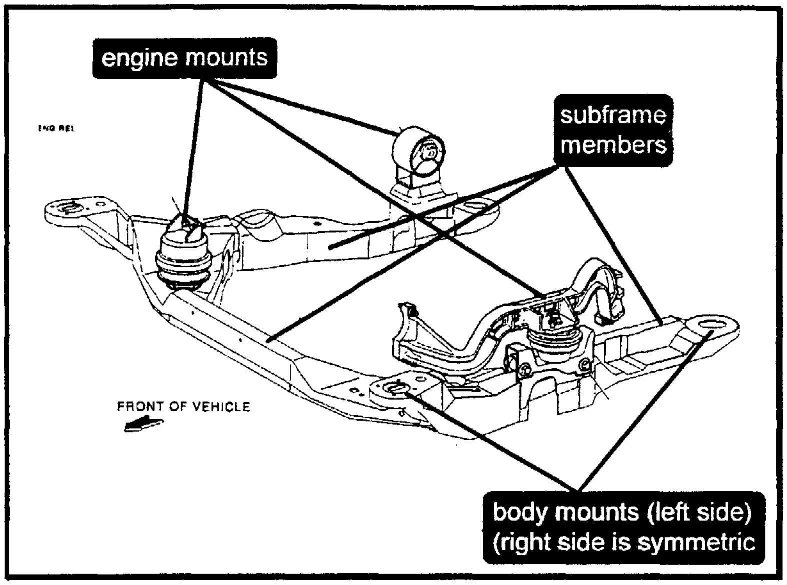


The sub-frame functions include:

- Providing physical interfaces between the suspension system and body/frame.
- Providing physical support and location for chassis components.
- Providing physical support and location for powertrain components
- Controlling suspension movement relative to body/frame.
- Managing road load and powertrain vibrational energy transmission.

Figure 3.6 is an example of a subframe for a front wheel drive vehicle. In addition to the subframe members, the engine and body mounts (left side only) have been labeled.

Figure 3.6 Subframe and Mounts

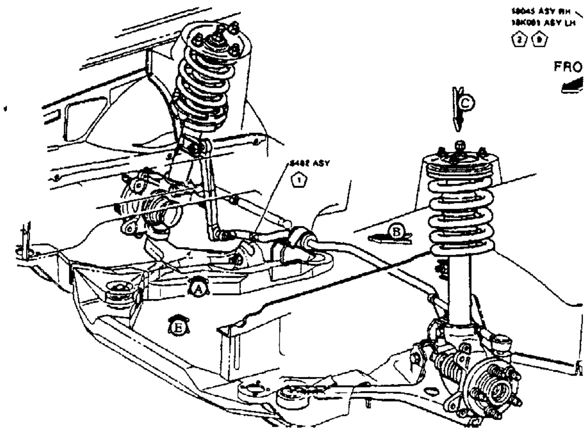


The primary suspension functions include:

- Supporting the body, chassis, and powertrain chunks under all load conditions.
- Interfacing between wheels and subframes and/ or wheels and body.
- Distributing loads to four wheels during all maneuvers.
- Stabilizing vehicle body motion during all maneuvers
- Absorbing shock and dampening loads to control vehicle response to road inputs.
- Ensuring constant tire/ road contact
- Providing and maintaining appropriate tire-to-road orientation.
- Supplying desired vehicle attitude, ride height, and appearance.
- Managing vehicle load transfer during acceleration.
- Isolating passengers from harsh road inputs.
- Providing acceptable tire wear.
- Supporting easy service, maintenance, and adjustments
- Managing steady-state and transient handling maneuvers acceptably

Figure 3.7 is an example of a front suspension. This particular architecture is a MacPherson strut suspension, named after its inventor, Earle MacPherson, a Ford suspension engineer.

Figure 3.7 Front Suspension Example



The primary functions of the wheels/ tires are:

- Supporting the total vehicle under all load conditions.
- Providing the interface between the vehicle and the road (powertrain and road, and steering system and road.)
- Providing steering forces during turning maneuvers.
- Furnishing lateral tractive capability under different environmental conditions.
- Supporting acceptable acceleration capability under various conditions.
- Supporting directional stability
- Providing a quiet, comfortable interface between ground and suspension.
- Absorbing and damping energy from road inputs.

The primary functions of the body and engine mounting subsystem are:

- Facilitating proper vehicle ride and handling.
- Isolating vehicle passengers from unacceptable noise, vibration, and harshness.
- Physically joining the body to the subframe and other chassis structure.
- Supporting loads.

- Supporting acceptable vehicle crash energy management.

Figure 3.6 included an example of the body mounting and engine mounting systems

These functions tell us something about the nature of the standard chassis architecture. First, note that each system is handling multiple functions that are not strongly related. Combing through the function descriptions once more, and reviewing Figure 3.2, reveals that the steering, suspension, body mounting, and tire/wheel systems have multiple interfaces. Next, comparing the functions assigned to each of the systems above with the original list of chassis functions provided in section 3.1 reveals that several functions are spread across or handled by more than one system. For instance, the task of isolating the passengers in the vehicle appears as a function of nearly every system. Vehicle stability, crash energy management, and load management also are handled by multiple functions.

The conclusion is that the chassis systems are integral and complex. They share functions and handle multiple functions, which violates some of the good design guidelines identified in Chapter 2. They have multiple interfaces, and the interfaces cross system boundaries as well as chunk boundaries. The suspension system is particularly complex and integral. It also has the largest variety of concepts that have been developed over the decades to optimize performance.

Race car chassis do better than passenger cars when it comes to separating out some functional aspects of chassis and particularly suspensions. They do this by eliminating or de-emphasizing some functions (such as isolation - a race car driver wants to feel the road) and providing specific suspension components to better handle specific functions. This allows them to better predict specific performance parameters (due to better correlation with CAE models) and to tune their vehicle for a specific race track or for particular conditions. For instance, they can develop a control arm geometry that de-couples lateral load management and response and longitudinal load management and response, allowing these parameters to be tuned separately. The disadvantage of this geometry is its sensitivity to build variation in the rest of the vehicle, particularly other chassis components and the body, and its inability to accommodate large ranges of wheel travel. Thus, while the component may segregate and control certain attributes, its design constrains the achievable range of other attributes.

Race cars are special, however. Each is hand-built to tight tolerances and the usage allows limited wheel travel, which simplifies the overall design. They are not cost constrained, do not have to meet federal emissions or safety requirements (though they have other requirements to meet), and can sacrifice comfort or space for improved performance. Race car suspensions are used on many high performance and luxury vehicles, particularly rear-wheel drive models. A more common architecture is the MacPherson struts suspension (Figure 3.7), which is used on most front-wheel-drive vehicles. It is extremely package-efficient, fairly insensitive to build variations, and can handle a large range of wheel movement and loads. However, it drives compromises between handling and ride due to a need for camber compensation [Wedlin et al., 1992]. This architecture will be discussed in Chapter 6.

In summary, the standard chassis architecture is, by tradition, integral and complex. Functions are shared by systems and components, and a component can impact several functions and attributes. Generally, specific implementations are developed to optimize one attribute at the expense of another.

3.4 Automobile Chassis Development Process

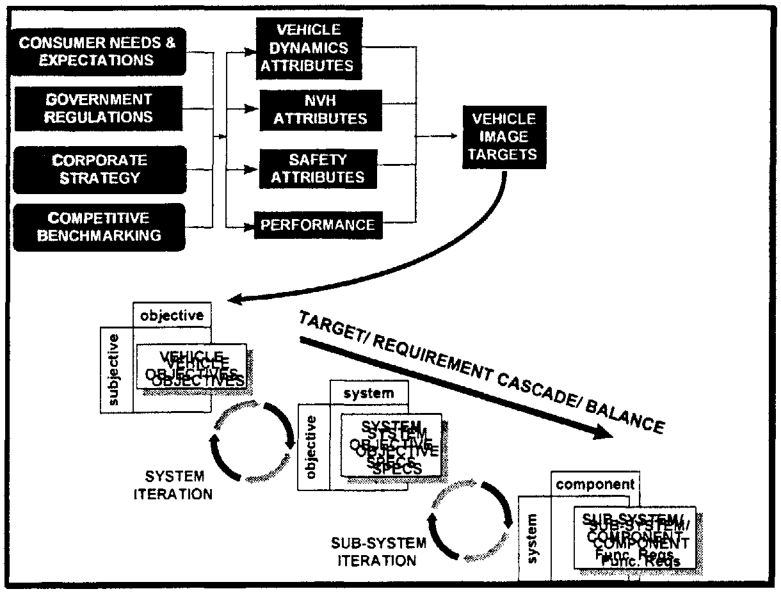
The development of the chassis chunk is nearly as complex as the product itself. The ownership of the attributes and the functions is difficult to assign on the basis of systems, components, and people. Complexity is added by the involvement of multiple organizations (this will be covered in Chapter 4).

At Ford, the theoretical development of the chassis design essentially follows the systems engineering approach using QFD-like matrices, and is captured in Figure 3.8. It evaluates the customer wants regarding the vehicle dynamics attributes (ride, steering ,handling), as well as the corporate goals, the target market, and government requirements that affect chassis design. From the wants, vehicle target images for the sub-attributes are developed. The sub-attributes are tied to vehicle dynamic metrics which in turn relate to system design specifications. It is the system design specifications that determine the design of the components.

The target and image setting are carried out by vehicle engineers, who provide the vehicle dynamic targets to the affected chassis design engineers, as well as powertrain and body engineers, as appropriate. The vehicle engineers also define the preferred kinematic axis, suspension geometry (for packaging), compliance budget, and vehicle response targets. These are also provided to the chassis engineers, who then integrate the specific targets into a set of system design specifications. In the beginning, the primary task is usually one of achieving cost, weight, and packaging requirements, because the design is changing very little (from one product cycle to the next) in terms of desired functional performance. Design engineers often lament how few opportunities they get to actually design and engineer a product.

During the process, vehicle response targets are generally achieved through iteration of component designs in response to subjective management review drives. This can occur only after full vehicles (either mules, prototype or pre-production vehicles) are available. As will be discussed and demonstrated in Chapter 6, this is the largest source of iteration, and is due to the variation between the predicted behavior of the vehicle and the actual behavior after integration of the systems and chunks has occurred.

Figure 3.8 Chassis Design Process Overview



The primary output of the design engineer is the component CAD file, the assembly CAD file, and the associated cost and weight. The correctness of their design is initially verified in testing of prototype parts, and then later using production parts. Both bench testing and full vehicle testing is done, but, again, the vehicle testing is handled through the vehicle engineer.

Table 3.3 provides a generic chassis development process [Milliken, 1995] [Giltinan, 1989] and identifies the responsible organizations. As will be shown in Chapter 6, the process is heavy with communication between organizations and people. In this regard, it reflects the complexity of the system. The steps are listed in the approximate order in which they are supposed to occur, but, according to chassis engineers, most of the tasks occur simultaneously and require iteration. Table 3.3 identifies those steps that typically require iteration or are involved in iterations. In addition, the process is flexible and is affected by the needs and directions of the program executing the process. For instance, some systems or components may be designated to be carry-over from a prior model or to be common with those used on another product. This eliminates the need to develop a design on the element but will probably cause extra effort on an interfacing component or system to design around additional constraints. The track or wheelbase of the vehicle can be determined by the assembly plant's layout and facilities, again changing the order in which steps might occur.

TABLE 3.3 Generic Chassis Development Process

Process Step	**Iterative (Y/N)**	**Responsible Organization**
Define wheelbase/ track		VE
Select Engine/ Transmission		VE
Define expected vehicle loads		VE
Develop engine layout		VE
Define CG location		VE
Design Body shell/ fenders geometry/ location	Y	BE
Design Body front structure/ rails geometry/ location/ vibrational characteristics	Y	BE
Design Body dash panel geometry/ location/ vibrational characteristics		BE
Design Body shock towers geometry/ location/ vibrational characteristics		BE
Design Body rear structure/ rails geometry/ location/ vibrational characteristics	Y	BE
Design Transaxle halfshafts geometry/ location/ vibrational characteristics		PT
Design Exhaust system geometry/ location/ vibrational characteristics		PT
Define kinematic axis	Y	VE
Define suspension geometry	Y	CE
Define compliance budget	Y	VE
Define vehicle response properties	Y	VE
Select front tyre / wheel	Y	CE
Select rear tires/ wheel	Y	CE

Process Step	Iterative (Y/N)	Responsible Organization
Design Brake system		CE
Design front subframe structure		CE
Design front hub & bearing	Y	CE
Design front knuckle	Y	CE
Design front control arms assy.	Y	CE
Design front struts/ shock absorbers		CE
Select front coil spring	Y	CE
Design ball joint - front control arm/ knuckle		CE
Design front stabilizer/torsion bars	Y	VE
Design front stabilizer bar linkage	Y	VE
Design front stabilizer bar insulator	Y	VE
Design front control arm bushings	Y	CE
Select body mounts/ isolator	Y	VE
Design engine mounts	Y	VE
Design rear tension strut bushing	Y	VE
Design rear stabilizer/torsion bars	Y	VE
Design rear stabilizer bar linkage	Y	VE
Design steering gear/ rack	Y	CE
Design steer hydraulics (pump, etc.)		CE
Design steering column		CE
Design tie rods		CE
steering linkage ball joints		CE
Design rear hub & bearing		CE
Design rear spindle		CE
Design rear upper control arm		CE
Design rear lower control arm		CE
Design rear shock absorber	Y	CE
Design tension struts (fore/aft control)	Y	VE

Process Step	**Iterative (Y/N)**	**Responsible Organization**
Design rear coil spring	Y	CE

Organizational Responsibility VE - Vehicle Engineering
BE - Body Engineering
PT - Powertrain Engineering
CE - Chassis Engineering

3.6 Chapter Summary

This chapter used some of the concepts laid out in Chapter 2 to describe the architecture of the automobile chassis. The key functions of the chassis sub-systems were outlined, and it was noted that the chassis is an interface between the powertrain, the body, and the ground. The primary consumer-perceived attributes, sub-attributes, and characteristics were identified, and it was noted that these attributes generally are grouped under the label "vehicle dynamics. The traditional functional partitioning and architectural decomposition to physical systems was described, and it was noted that there was significant function-sharing by the systems and is evidence of an integral design.

The last section reviewed the design process for a automobile chassis. The steps in the process can occur simultaneously or in sequence, and many require iterations. The process followed is dependent, to a certain extent, on the level of product pre-definition that exists when the process is started. Also, there are many organizations involved, which implies complex communication and management issues.

Chapter 2 and Chapter 3 provided an understanding of the architecture and engineering background of an automobile chassis. Chapter 4 will describe the methodology that will be used in subsequent chapters to analyze the chassis architecture and organization.

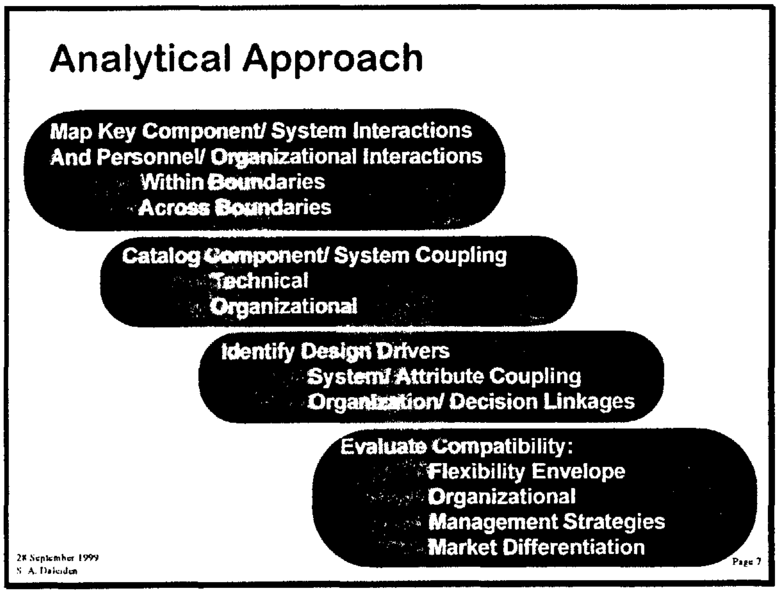
Chapter

4 Analytical Methodology

As any child will tell you, there is more than one way to slice a pizza. The good thing is that, normally, you can see the entire pizza, and, even if you cannot see the pizza, you know what a pizza looks like before and after you partition it. The analytical approach I took was a little like cutting a pizza without knowledge of what a pizza looks like and without knowledge of the proper slicing tool. I only know that I want to have sliced pizza when I am done, and I want to be able to re-assemble the pieces (before they are eaten) make sure that I have a whole pizza.

The core of my goal was to capture requirements that drive chassis design and examine the dependency of those requirements across the affected organizations, the design process, the components, and the customer attributes. Figure 4.1 below is a high-level, conceptual overview of the analytical approach.

Figure 4.1 **Analytical Approach**



Analytical Approach

Map Key Component/ System Interactions
And Personnel/ Organizational Interactions
- Within Boundaries
- Across Boundaries

Catalog Component/ System Coupling
- Technical
- Organizational

Identify Design Drivers
- System/ Attribute Coupling
- Organization/ Decision Linkages

Evaluate Compatibility:
- Flexibility Envelope
- Organizational
- Management Strategies
- Market Differentiation

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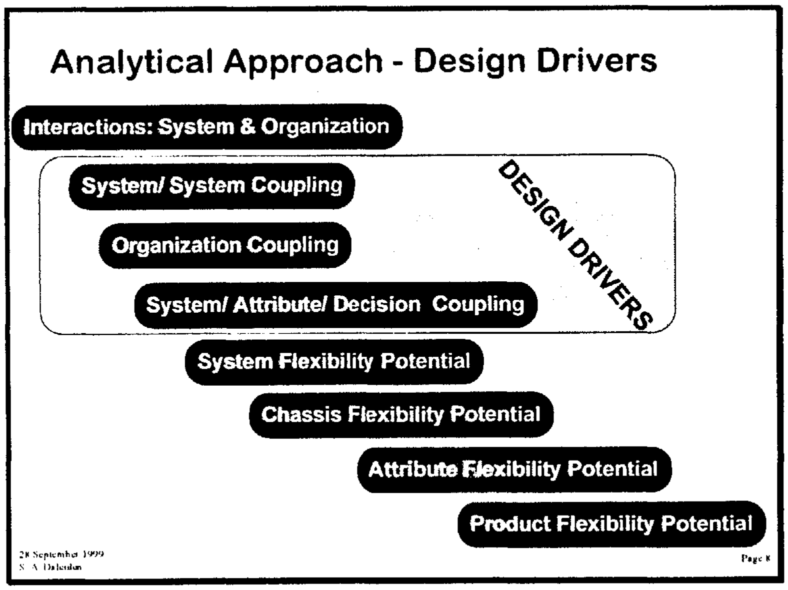
The process starts with mapping key interactions involving things (systems, components, attributes, objective metrics) and people (work groups, functional organizations, projects). The coupling or linkages between components and systems are cataloged as to whether they are technical (physical relations, such as those between a component and an attribute) or organizational (such as shared responsibility or information transfers). From the information gather, the probably design drivers are identified by understanding the linkages mapped. Then flexibility envelope (or flexibility potential) is assessed and evaluated against the organization, management strategies, and market differentiation goals.

The key challenges were going to be finding methods and tools to capture, represent, and map the interactions, identify the design drivers, and evaluate the flexibility envelope. Figure 4.2 shows conceptually how the design drivers might be identified by looking at the coupling and dependencies across systems and organizations and attributes. It was also thought that these dependencies would yield insight about the flexibility envelope. However, a mapping approach was needed.

Figure 4.2 Design Drivers



Analytical Approach - Design Drivers

Interactions: System & Organization

System/ System Coupling

Organization Coupling

System/ Attribute/ Decision Coupling

DESIGN DRIVERS

System Flexibility Potential

Chassis Flexibility Potential

Attribute Flexibility Potential

Product Flexibility Potential

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There are several approaches that could be taken, some of which have become more practical as the availability of extremely powerful personal computers has increased. The key criteria for a good approach would be the following:

- it is time-efficient (the pay-off is worth the time spent)
- it can be carried out successfully in the time allotted
- it improves understanding without misleading, add clarity without concealing

- it is compatible with an intuitive, compact, visual representation

A review of the literature revealed five potential approaches that could be used in this analysis. The following sections outline the four approaches and highlight advantages, disadvantages, and implementation barriers.

4.1 Pictorial Mapping

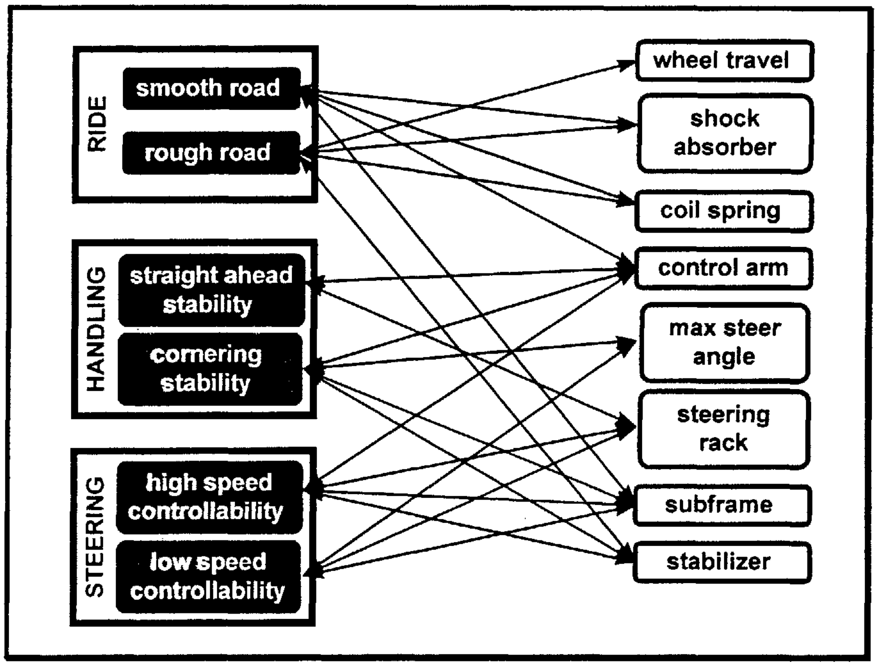
This is one of the simplest and most intuitive ways of capturing and visually representing relations and dependencies. It is also the one from which most people start. During separate interviews with different people at different organizational levels, two engineers and two managers began their descriptions of dependencies by drawing a pictorial map.

The map starts with separating elements into categories. In the example shown in Figure 4.3, the categories are attributes/ sub-attributes and design parameters. Using arrows (or some other representations such as colors) the various elements in the categories are linked to each other. The primary advantage to this approach is that it is simple and intuitively easy to comprehend. It is also visually simple, as long as the relations are simple and few

However, as the elements in the categories or the relations (arrows) between elements become more numerous, the visual simplicity of the diagram disappears. The diagram begins to look like a plate of spaghetti and, although the concept remains intuitive, understanding the diagram becomes difficult, and can cause severe eyestrain.

The other shortcoming with pictorial maps is that they represent the static case, cannot capture time-related processes, and do not provide a mechanism for gaining insight. This is the most serious weakness with them, and is one of the reasons they are often seen as having little practical value for this type of analysis.

Figure 4.3 Pictorial Mapping Example

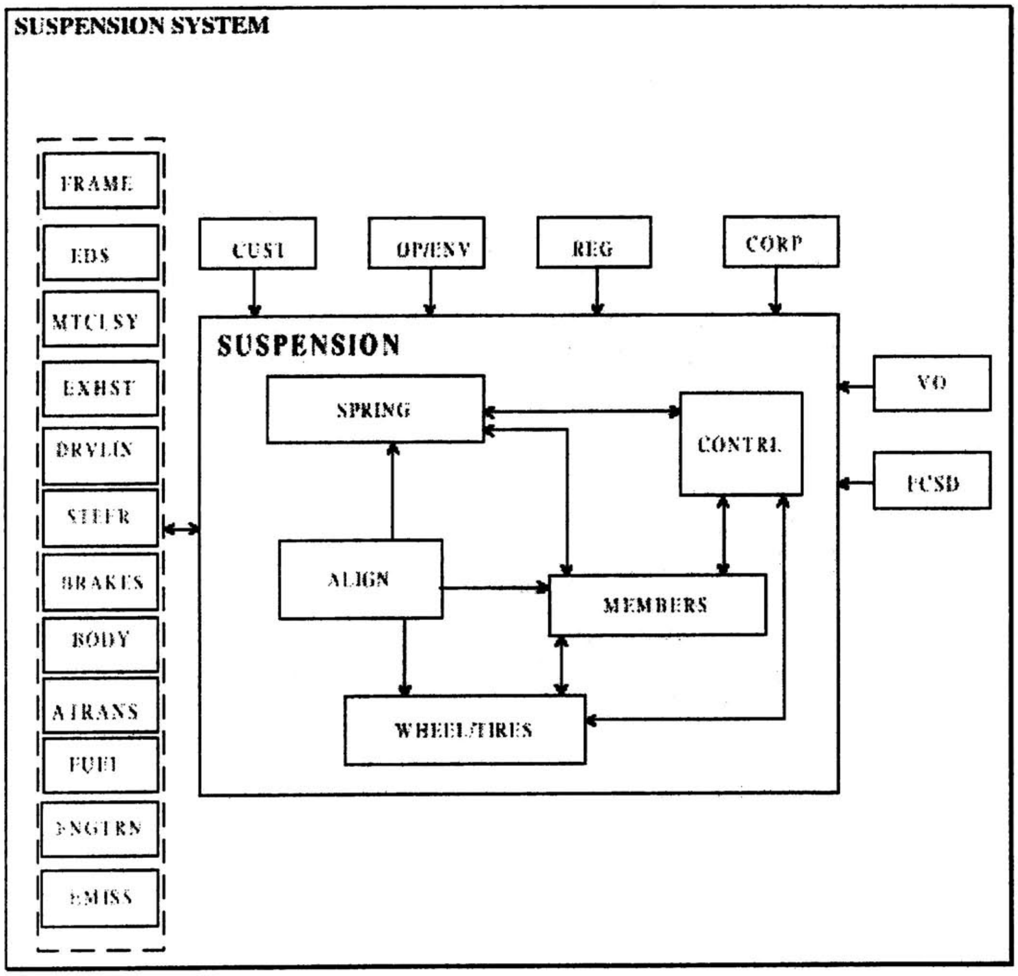


Block diagrams are conceptually very close to pictorial maps. They are extremely useful in capturing, visualizing, and understanding the relationships between elements in systems. Block diagrams are generally used to represent interactions or relations between similar types of elements. For instance, they are commonly used to develop and cascade system and component specifications. However, they can be used to capture relations with other types of elements, such attributes.

However, like pictorial maps, they suffer from the spaghetti syndrome. As the number of elements and relations increases, the visual clarity of the diagram diminishes rapidly. Adding a few elements with several relationships can quickly make the diagram illegible, rendering the diagram useless.

Also, like the pictorial map, block diagrams represent the static case and cannot capture time-related processes. Block diagrams are also not very rich in information, and do not provide a mechanism for gaining insight, other than by studying them.

Figure 4.4 Block Diagram Example



4.2 Matrices

When I first came to Ford Motor Company, it seemed as though the company was addicted to matrices. Whenever anybody had a problem to solve, a workplan to develop, and complex analysis to perform, they started by developing a matrix. I still think we are addicted to them, that they are used to obscure and sell as much as to clarify and demonstrate. However, I have a better appreciation for the usefulness and communication power of a well structured and properly informed matrix. It is particularly good at capturing relationships and structures in a compact form.

In using matrices, there are few different structures that can be developed. The choice is dependent on what is wanted.

- Type 1 - A versus B

  This is an NxM, not necessarily square matrix. Two different sets of elements appear, one on each axis of the matrix. Marks in the cells of the matrix represent relationships or dependencies between sub-elements. Numerical rankings, symbols, or colors can be used to indicate the relative strengths, direction, or significance of the relation. Most of the matrices used in QFD are of this type, although they have extra columns for special information. Figure 4.5 below shows an example of a type 1 matrix.

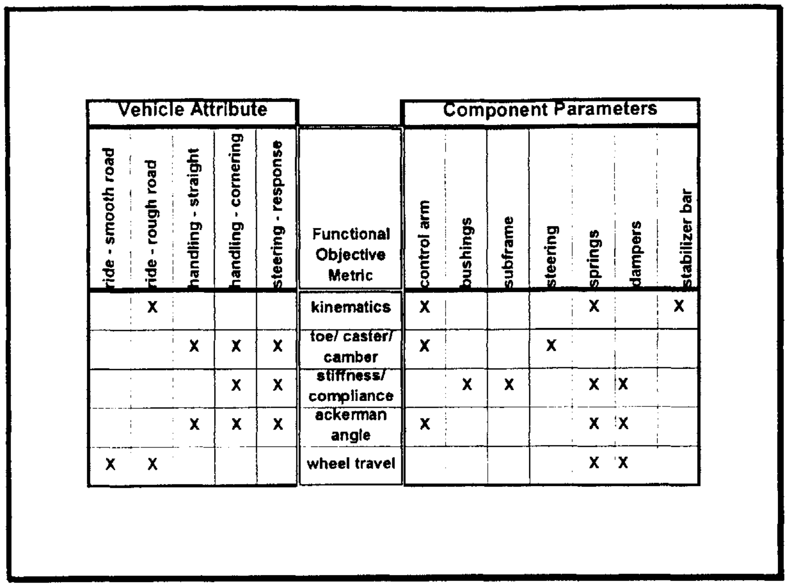
Figure 4.5 Type 1 Matrix Example

decimal code	OBJECTIVE REQUIREMENTS CUSTOMER ATTRIBUTES	FMVSS visibility	exterior surface minimum radii	requency separation	vehicle response	vehicle weight	orsepower	orque	minimum clearances	vehicle drag	package efficiency	inocular vision	eliability	vehicle height	vehicle tread	oe	wheel travel	vehicle wheelbase
256	sporty appearance		X							X				X	X			X
128	excellent visibility	X										X						
64	always starts and runs												X					
32	outstanding acceleration					X	X	X										
16	roomy interior								X		X							
8	comfortable for long drives			X	X													
4	smooth braking													X		X	X	X
2	good cornering													X	X	X		
1	stable/precise-bumpy roads			X	X				X								X	

- Type 2 - A versus B versus C

  This is a combination of two Type 1 matrices that share a common set of elements. The shared element set would make up the center vertical axis. The remaining two elements sets would sit horizontally on either side of the center vertical axis. Figure 4.6 below demonstrates a simple example.

Figure 4.6 Type 2 Matrix Example



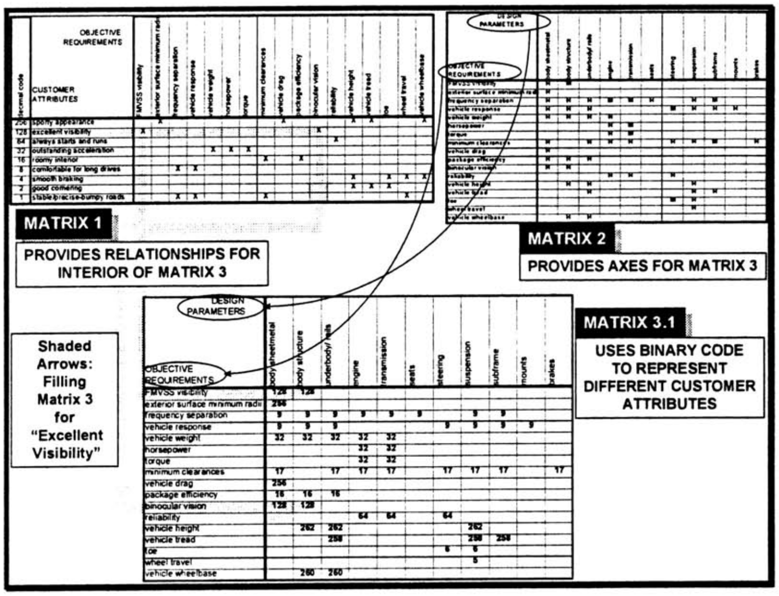
Vehicle Attribute						Component Parameters						
ride - smooth road	ride - rough road	handling - straight	handling - cornering	steering - response	Functional Objective Metric	control arm	bushings	subframe	steering	springs	dampers	stabilizer bar
	X				kinematics	X				X		X
		X	X	X	toe/ caster/ camber	X			X			
			X	X	stiffness/ compliance		X	X		X	X	
		X	X	X	ackerman angle	X				X	X	
X	X				wheel travel					X	X	

Once again, marks in the cells represent relationships or dependencies between sub-elements. Numerical rankings, symbols, or colors can be used to indicate the relative strengths, direction, or significance of the relation.

- Type 3 - A versus B via C

  This is a combination of two Type 1 matrices into a single NxM matrix. Again, sub-elements of A and B sit on each axis of the matrix, as in Type 1. Then information on C, whose dependency relationship with A (or B) may (or may not) be captured on another matrix, is inserted into the A-B matrix. Unless the A-C relation is very simple, a alpha-numeric code (or symbolic or color) will probably have to be developed for the sub-elements of C to keep the A-B-C matrix compact. If properly constructed, this matrix allows the relation between the three elements to be represented. An example of how this matrix could be assembled in shown in Figure 4.7. This example will be covered in detail in Chapter 5.

Figure 4.7 Type 3 Matrix Example



- Type 4 - A versus A

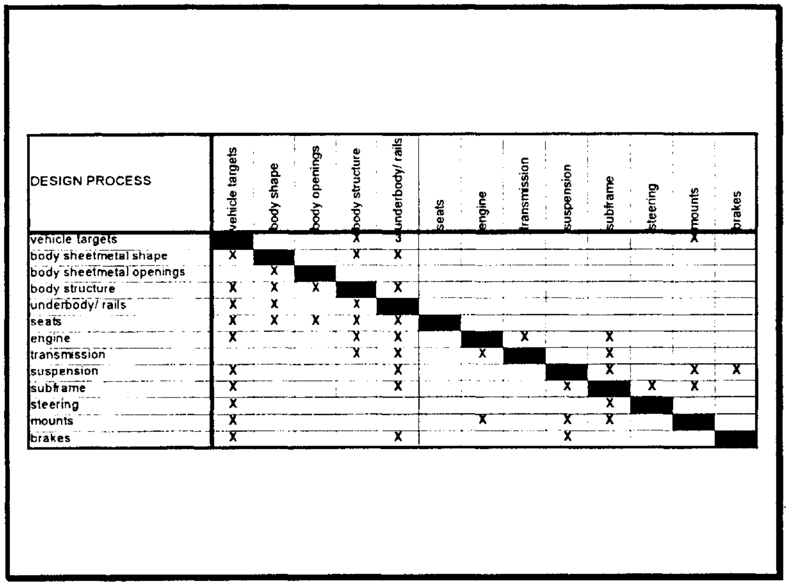
  This is an NxN (square) matrix. The goal here is to map the dependencies and relations that exist between sub-elements. Depending on the element structure, this matrix can be used to capture feedback and iteration. Again the marks in the matrix can be simply denote the existence of a relations, or a code can be developed to capture strength or source of the relation.

The roof on the "House of Quality" [Clausing, 1989] is one example of this type. It is a triangular shaped matrix which captures the correlation between the sub-elements. The matrix sub-elements sit below the triangular matrix (after all, it is the roof). Marks in the matrix capture the strength of the correlation. Note that only correlation is captured - there is no information on which direction the influence flows or whether there is information being fed back.

Another example of this type of matrix is the Design Structure Matrix (DSM). This approach, developed and evolved by Steward [1981], Eppinger and McCord [1993], and others, focuses on modeling product development processes, with the goal of improving those processes by identifying and reducing iterations by clustering around interactions, accelerating sequential tasks by structured overlap, and improving the coordination between parallel tasks. Used for these purposes, the ability to capture feedback and iteration becomes invaluable.

- The DSM is a map showing these influences and the interactions that determine the overall design structure of a system.
- If no interactions exist between two sub-systems or components, then the DSM will be empty,

Figure 4.8 Type 4 Matrix Example



DESIGN PROCESS	vehicle targets	body shape	body openings	body structure	underbody/ rails	seats	engine	transmission	suspension	subframe	steering	mounts	brakes
vehicle targets	■			X	X							X	
body sheetmetal shape	X	■		X	X								
body sheetmetal openings		X	■										
body structure	X	X	X	■	X								
underbody/ rails	X	X		X	■								
seats	X	X	X	X	X	■							
engine	X			X	X		■	X		X			
transmission				X	X		X	■		X			
suspension	X				X				■	X		X	X
subframe	X				X				X	■	X	X	
steering	X									X	■		
mounts	X						X		X	X		■	
brakes	X				X				X				■

Figure 4.8 shows a simple example of a DSM. In the DSM, the elements in the matrix represent product development tasks or deliverables from a task. The elements appear on both the horizontal axis and vertical axis, in the sequential order in which they are normally executed. The marks in the matrix represent interactions between the matrix elements, so the diagonal should be uniformly filled or not filled. Following across a row shows the tasks upon which an element is dependent upon. Following a column down shows the tasks that are dependent upon the element. If no interactions exist between two elements, then the DSM will be empty at their two row/column intersections.

Stated from a different perspective, marks below the diagonal represent information (design parameters) that is fed forward to the following elements. Marks above the diagonal represent information that is fed backward (or feedback). Feedback information is indicative of iteration, which means re-work for some part of the product development process. As shown by Eppinger et al. [1994], re-ordering the tasks optimally to reduce as many feedbacks (iterations) as possible and increasing the clustering of dependent tasks (both forward and back dependencies) to improve the overall efficiency of the process

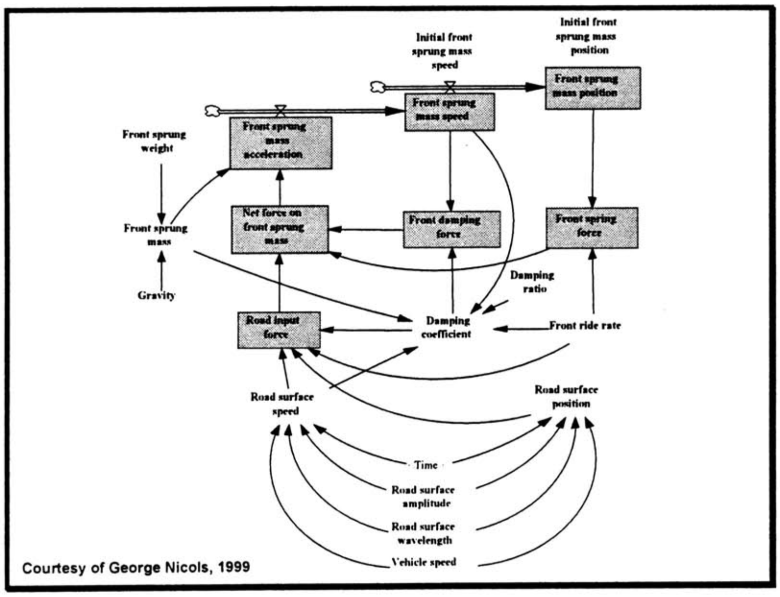
A major advantage with DSM is the existence of computerized algorithms for determining optimal or near-optimal tasks sequences. This is possible using eigenstructure analysis methods.

4.3 System Dynamics

System Dynamics is focused on representing and analyzing dynamic relationships between seemingly separate elements, with one of core concepts being feedback and the ability of small changes in place and time to have large effects at another place and time. It has been applied extensively to model organizations, and is based on systems thinking, the idea that a system is best understood by study the whole, not an individual part of the system. Clearly, the issues surrounding engineering and managing the development of an automobile, and a chassis chunk, a systems issues. Consequently, the ability to simulate and capture feedback and iterations is a strong advantage in using system dynamics

Figure 4.9 illustrates a system dynamics model that was developed for a chassis systems (in Vensim, a user-friendly software designed for use in system dynamic modeling). This model shows the power of the approach and also indicates what the primary dilemmas will be. The difficulties with a system dynamics approach are partly technical and partly logistical. While there are many aspects of the vehicle chassis systems whose vehicle dynamics dependencies can be modeled, there are many more that can only be guessed. It would also be important to understand the feedback mechanisms, since they are often different from the feed-forward mechanisms. These both can be overcome with experimentation to improve correlation with reality. Metrics would also need to be chosen to measure correlation.

Figure 4.9 Chassis System Dynamics Model Using Vensim



Courtesy of George Nicols, 1999

As implied by the intricacy of Figure 4.9, capturing the full complexity of the development process would be a significant (but very interesting) undertaking. Equations representing the relationships between steps would need to be developed. In systems dynamics, this is often the hardest step, because the subject sometimes don't lend themselves to being put into the form of an equation. This is not true for relations founded in physics. But consider the relation between the design of system and the decisions made regarding architecture. The System Dynamics model would need to be dynamic itself, able to change to capture the different physical relations and components that could result from different architectures.

Overall, a System Dynamics approach could be very rich. However, linking the management and engineering parameters appeared to be an unsure proposition and it did not seem likely that the analysis (building a correlated model) could be completed in the time allotted.

4.4 CAD/CAE

The final and most sophisticated tool is to use CAD models of the system and its components, and software capable of handling the complex static and dynamic relations, to simulate the function of the system. This approach would be excellent for doing sensitivity studies, to determine the final impact of component changes on customer attributes. However, current modeling techniques and software are not able to fully and faithfully model and simulate an entire chassis system in a single package.

Generally, CAD models are built to study specific aspects of system performance (static packaging, loading, dynamics). Separate systems may be modeled separately. For instance, brake systems may be modeled specifically to predict brake roughness. CAD/CAE is used to study the interactions and sensitivities associated with kinematic and compliance changes (using software such as ADAMS) but they cannot incorporate the static and loads analysis of a finite element analysis. All of this partitioning serves to reduces modeling complexities and run-times, and make the results faster to generate and easier to interpret..

When the models are kept small and the attribute modeled is constrained to just statics or just dynamics, the correlation to real world data is good. However, as the models are expanded and more attributes are modeled, the correlation quickly gets worse, probably due to unmodeled interactions. Normally, during the product development process, detailed vehicle dynamic modeling is not undertaken unless there is a vehicle available to which the model can be tuned. This is because the models use simplifications based on ideas such as the relative order of magnitude between factors to ignore some factors.

Like the Systems Dynamics model, this method was probably a rich approach. However, it would be require extensive access to and knowledge of the right CAD/CAE software. Also, like System Dynamics, linking the management and engineering parameters in the model appeared problematic. Thus, given the author's lack of refined CAD/CAE ability, it did not seem likely that this approach could be applied in the time allotted.

4.5 Mapping Method

As noted earlier, there are a lot of ways to cut this pizza. I chose to use matrices to do the mapping analysis. The reasons for this were:

- they are simple to do on personal computer
- they are universally understood
- they promised to provide the best pay back (in terms of insight) for the time invested
- they met the four criteria I set out at the beginning of the chapter

To carry out the analytical approach described earlier required the development of four static matrices to capture different relationships, dependencies and influences. A set of heuristics were also chosen to allow interpretation and analysis of the matrices. The heuristics are introduced and described in Section 4.7. This section presents the four matrices, which were:

- Matrix 1 (attributes-objectives), showing consumer-perceived attributes aligned against objective metrics for requirements (vehicle dynamics parameters). This is a Type 1 matrix.
- Matrix 2 (objectives - component design parameters) shows influence of chassis key suspension and steering components on the system objectives. This is also a Type 1 matrix.
- Matrix 3 (objectives - components design parameters - attributes) is a "joint matrix", in that it joins or combines information from Matrix 1 into Matrix 2. It links the influence of the components on the objectives to the influence of the objectives on the attributes. This is a Type 3 matrix.
- Matrix 4 (system design structure matrix) captures information dependency between chassis design activities, from vehicle level design decisions down to component design. This is a Type 4 matrix.

The following steps walk through the creation of the matrices:

Step 1.

Collect the information needed to create Matrix 1 and then fill in the matrix. This means identifying the relevant customer attributes (CAs) and the corresponding objective metrics that determine them or greatly influence them. The customer attributes are installed along the vertical axis and the objective metrics are placed along the horizontal axis. Marks in the cells where the attribute and objective metric intersect indicate the existence of influence of the objective metric on the attribute, and can be ranked as high or medium, if desired. This information can come from several sources, such as:

- subject matter experts
- QFD reports
- system design specifications
- technical papers or text books
- experimental data
- test plans and reports

In some respects, Matrix 1 is similar to the Product Planning or Phase I QFD matrix [Clausing, 1989]. The Product Planning matrix is the part of the "house of quality" matrix that contains the "what's" and the "how's". It contains customer wants on one axis, product requirements on another axis, and shows which requirements most strongly influence the customer-perceived attributes. The customer "what's" are prioritized to support target-setting and requirement trade-offs, and the correlation between the "how's" is assessed.

Although visually similar, Matrix 1 does differ, particularly in its goals. Matrix 1 is being used to assess potential flexibility, by capturing the objective metrics (which are functional requirements) that determine and influence the customer's perception of ride, steering, and handling. There is no prioritization, and no information about relationships between the objective metrics.

Step 2.

Collect the information needed create Matrix 2 and then fill in the matrix. This means identifying the components (or component design parameters) that greatly influence or are influenced by the corresponding objective metrics that used in Matrix 1. The organizations that are responsible for developing the components should also be identified. The component design parameters are installed along the horizontal axis and are grouped by organization. The objective metrics are placed along the vertical axis. Marks in the cells of the intersections indicate the existence of influence of the objective metric on the attribute and can also be ranked high or medium. This information can come from the same sources used for matrix 1, as well component design specifications. Note that Matrix 2 requires that a specific design concept be specified.

Matrix 2 has many of the characteristics of a Product Design or Phase II QFD matrix. A Product Design QFD matrix contains product requirements along the vertical axis, part characteristics along the top horizontal axis, and relationship information in the matrix created by the two axes. However, Matrix 2 makes no attempt to drill down to specific component design characteristics such as material selection, material properties, or geometry.

Step 3.

Use the information in Matrix 1 and Matrix 2 to create Matrix 3, the Joint Matrix. Matrix 3 has the same horizontal and vertical labels as Matrix 2. The information from Matrix 1 is used to fill in the cells. First, a code (numbers and/ or letters) must be developed to represent the customer attributes and must be capable of distinguishing between groups made up of different combinations customer attributes. An example of such a code, based on decimal representation of binary numbers, is provided in Chapter 5.

For each objective metric in Matrix 1, there are a set of customer attributes that are influenced by the objective metric and which can be represented by the code. This code is inserted in Matrix 3, at each cell where the same objective metric has a mark. In this way, the cells of Matrix 3 are filled.

Step 4.

Collect the information needed create Matrix 4, the DSM, and fill in the matrix. This means identifying the tasks needed to design the components (or component design parameters) and the types of information that are passed between the tasks. For this exercise, the order in which the tasks occur and the organization that is responsible are important and should be captured. The structure of the DSM was discussed in section 4.4. As noted, marks in the cell represent dependencies between elements on the matrix axes. In this case, the dependencies are design information that is transferred between tasks. To fill in the cells, the following information must be collected for each design task:

- What is produced and what is done.
- What design decisions are made.
- What design parameters are determined
- What vehicle performance attributes are determined or influenced
- What information is needed and where it comes from
  - ⇨ Specifications
  - ⇨ Drawings
  - ⇨ Design parameters
  - ⇨ Vehicle performance attributes
- To whom is information (or product) provided and what is done with that information.

This information can be captured from the following sources:

- design engineers and managers
- program work plans
- system and component design specifications
- corporate product development process documents

Before filling in the cells, the design information that is transferred should be grouped according to some common characteristics that are related to the objective metrics from Matrix 1. This enables the cells to capture the type of information transferred along with existence of dependency, and enables a relationship to customer attributes to be recognized. Again, a code should be developed that allows the cells of the matrix to capture the unique combinations of information types that might be transferred. A couple of examples are presented later in this paper.

Initially, the design tasks should be entered in the order in which they occur and numbered sequentially on that basis. Then the tasks should be grouped by organizational responsibility.

These steps described the creation of the matrices. The next section discusses the interpretation and analysis of the matrices.

4.6 Discussion and Analysis of Matrix 3 and Matrix 4

It should be recognized, from the previous sections, that Matrix 3 (Joint Matrix) and Matrix 4 (DSM) are the key products to be analyzed. They are visual tools that capture information qualitatively via patterns of connectivity, as opposed to quantitative tools that capture information numerically. Being visual tools, the insight that is gained from the matrices is obtained by studying the patterns and the connections reflected in the patterns. This may seem obtuse or imprecise, and may feel like art, which is not surprising, as I think architecture and engineering combine art and science. To help, this section lays out some guidelines for interpreting the patterns. First, a framework for evaluating Matrix 3 and Matrix 4 will be introduced and generally described. Then a step-by-step description of the evaluation process will be presented.

Both Matrix 3 and Matrix 4 contain information from Matrix 1 and Matrix 2. Matrix 3 explicitly captures the sets of objective metrics and component design parameters that influence specific groups of sub-attributes, and implicitly captures the way sub-attributes and components interact through one or more of the objective metrics. Matrix 4 explicitly maps the key component, system, and organizational interactions that occur during the design process and catalogs the dependencies based on the type of information. This implies three perspective to use when analyzing Matrix 3 and Matrix 4.

The first perspective is an organizational perspective. By grouping components by organization, the patterns of Matrix 3 display the organizational boundaries that customer attributes and objective metrics cross. The patterns of Matrix 4 shows the type of information (in terms of objective metrics, which can be related to customer attributes) that is crossing organization boundaries. Thus, they can both identify dependencies between organizations and implicate the attributes that will be affected.

The second perspective is that of the product development process. The concerns from this perspective are information order, iteration (as represented by feedback), opportunities for task simultaneity, and the number of different data sources for a given task. This is captured by Matrix 4 alone.

The third perspective is that of the product architecture, which is concerned with what attributes are emerging, what elements are interacting to create the attributes, what functional boundaries are being crossed by interactions, and the physics behind the interactions. This is the most difficult perspective to evaluate because it involves both Matrix 3 and Matrix 4, and an understanding of the physics of the system and the attributes. Matrix 3's patterns capture the influence relationships between components (and component design parameters), objective metrics, and customer attributes, which are determined by the product architecture. Matrix 4 captures the type of information that is transferred between component design tasks.

Another concept is that is critical to this analysis is flexibility, which was introduced in Section 1.2. To reiterate, the literal definition of flexibility is an ability to respond or conform to changing or new situations. For this thesis, flexibility and flexibility potential are used to describe the ability of a product to respond to changes in design direction and support derivative products or to act a platform for a portfolio of products. Section 1.2 also defined three genes that components can have that enable flexibility:

1. Improved-range gene is when a component can cause an increased range of response in an objective metric or attribute
2. Multi-path gene is when there are more than component that can be used to achieve the same response in an objective metric or attribute
3. Multi-attribute gene is when one component can affect or control the responses of several objective metrics or attributes simultaneously.

As noted previously, the third gene can be thought of as an efficiency gene, because changing a single parameter causes changes in several attributes simultaneously. These genes will be referenced as the assessment process is described.

To explain the process of assessing Matrix 3 and Matrix 4, four pairs of matrices have been generated to act as references. These idealized, factitious Matrix 3 / Matrix 4 pairs represent four possible scenarios for a system's architecture. These four scenarios (or architectures) are:

1. modular
2. modular improved for flexibility
3. conditional flexibility
4. pseudo-modular

Figure 4.10 represents Matrix 3 for scenario 1, a completely uncoupled (modular) architecture. The components are numbered (1, 2, 3, 4, 5), the objective metrics (OMs) are represented by the letters L, M, N, O, and the attributes (in the cells) are represented by the letters A, B, C, D.

Figure 4.10 Modular Matrix 3

	COMPONENTS			
OMs	**1**	**2**	**3**	**4**
L	A			
M		B		
N			C	
O				D

Figure 4.11 is the DSM for the modular case. It is linked to Matrix 3 through the components and the tasks. That is, the task T1 is the steps needed to develop component 1, T2 is the steps to development component 2, and so on. For Matrix 3 and Matrix 4, it is assumed that all the components are designed and released by different organizations and represent complete functional systems. Each organization would then be responsible for the corresponding component design task in Figure 4.2.

Figure 4.11 DSM - Modular

	TASKS			
	T1	T2	T3	T4
T1	■			
T2		■		
T3			■	
T4				■

Figure 4.12 is the Improved for Flexibility scenario. The system is more complex, having more components. Note that there are now two components that can act on attribute A via the objective metrics L. Figure 4.13 is the DSM for this scenario. The information type L1 in the cell is related to the objective metric L in Matrix 3 for this sceario. For this scenario, there is iteration around Task T1. Note that, because all tasks are performed by different organizations, any information that is fed forward or backward must cross an organizational boundary as well as a functional systems boundary.

Figure 4.12 Improved For Flexibility

	COMPONENTS				
OMs	1	2	3	4	5
L	A	A			
M			B		
N				C	
O					D

Figure 4.13 DSM - Improved for Flexibility

	TASKS				
	T1	**T2**	**T3**	**T4**	**T5**
T1	■	L1			
T2	L1	■			
T3			■		
T4				■	
T5					■

Extending the example into more complicated (and more realistic) space is Figure 4.14, which is Matrix 3 for the Conditional Flexibility scenario. The relationships of component 1, component 2, and attribute A are unchanged from scenario 2. Component 3 can act on attributes B and C via two different objective metrics, M and N. Component 3 and Component 4 can both influence attributes B and C through attribute N. Component 4 can also influence attributes A and D via objective metric O. Finally, the Figure 4.5 implies that attributes B and C are coupled, as are attributes A and D.

Figure 4.14 Conditional Flexibility

	COMPONENTS				
OMs	**1**	**2**	**3**	**4**	**5**
L	A	A			
M			BC		
N			BC	BC	
O				AD	AD

Figure 4.15 is the DSM for the conditional flexibility scenario. Again, the information types (L1, M1, N1, O1) are related to the objective metrics (L, M, N, O) in Matrix 3 for this scenario. This scenario has iteration around Tasks T1 and T3. Again, the information that is transferred between tasks crosses organizational and system boundaries, because each task is performed by a different organization.

Figure 4.15 DSM - Conditional Flexibility

	TASKS				
	T1	**T2**	**T3**	**T4**	**T5**
T1	■				O1
T2	L1	■			
T3			■	N1	
T4		L1	M1	■	
T5		L1		N1	■

To examine the effects of coupled attributes, consider Figure 4.16, which is a revision of the modular architecture of Figure 4.10. In the psuedo-modular scenario, the components are linked to unique attribute combinations via unique objective metrics. However, the attributes are coupled, and are no longer uniquely tied to the objective metrics and the components. Component 1 can influence attributes A and B via objective metric L, and Component 4 can also influence attribute A, along with attribute D, via objective metric O. Thus, they can influence different aspects of attribute A.

Figure 4.16 Pseudo-modular

	COMPONENTS			
OMs	**1**	**2**	**3**	**4**
L	AB			
M		BC		
N			CD	
O				AD

Figure 4.17 is the DSM for the psuedo-modular scenario. Again, tasks are linked by information types, and the information types are based on the objective metrics. There is iteration around all the tasks.

Figure 4.17 DSM - Pseudo-modular

	TASKS			
	T1	T2	T3	T4
T1	■	M1		O1
T2	L1	■	N1	
T3		M1	■	O1
T4	L1		N1	■

These four pairs will be referred to in the following description of matrix evaluation process. The process will use the three perspectives described earlier. Each perspective will have a process consisting of a series of steps that outline what features to look for in each matrix, followed by a set of heuristics that should be used to assess the features in terms of flexibility potential and design drivers. For each step, examples will be provided by applying the steps to the example matrices above. The heuristic description will be followed a summary applying the heuristics to the example matrices above. Each perspective description will finish with a discussion of the rationale behind the heuristics. The perspective descriptions will start with the organizational perspective. This will be followed by the PD perspective process, and then the architectural perspective description will complete the analysis.

ORGANIZATIONAL PERSPECTIVE

Step 1:

- In Matrix 3, identify attribute or attribute combinations (sets of coupled attributes) and that are repeated and influenced by components controlled by different organizations.

For instance, in Figure 4.10 there are no repeated attributes. In Figure 4.12 there is one repeated attribute that crosses organizational boundaries (attribute A), while in Figure 4.14 there are three repeated attribute/ attribute combinations (attribute A and attribute combinations BC and AD). In Figure 4.16 there are four attributes (A, B, C, D) that are repeated by the attribute coupling.

Step 2:

- In Matrix 3, identify objective metrics that are influenced by multiple components controlled by different organizations.

For instance, in Figure 4.12, the objective metric L is influenced by component 1 and 2, in Figure 4.14, objective metrics L, N, and O are influenced by two components each. Figure 4.16 and Figure 4.10 have no objective metrics that are influenced by multiple components.

Step 3:

- In Matrix 4, identify information types or sets of information types that are transferred between tasks executed by different organizations.

For instance, in Figure 4.11 there are no repeated attributes, in Figure 4.4 there is one repeated attribute that crosses organizational boundaries (attribute A), in Figure 4.15 there are seven transfers of information (L1 three times, N1 twice, and M1 and O1 once each) and in Figure 4.17 there are eight transfers of information (L1, M1, N1, and O1 are each transferred twice).

Step 4:

- Of the repeated by attributes and attribute combinations in Matrix 3, identify those that are influenced by powerful organizations. Also note the common OMs through which the powerful organizations influence the attributes. These attributes and OMs are potential design drivers.

For instance, in the example matrices, if it is assumed that the organization that designs and releases component 2 is very powerful, then in Figure 4.12, the attribute A and objective metric L would be noted as potential design drivers. In Figure 4.16, objective metric M and the attribute combination BC are potential design drivers which can drive the design of other components through the attributes.

Step 5:

- In Matrix 4, identify transferred information that is generated by powerful organizations. This information and the associated components and objective metrics are potential design drivers.

For instance, in Figure 4.13, Task 2 can influence Task 1 by the feed back of information L1. Task 2 and L1 would be potential design drivers if the organization responsible for Task 2 is powerful. In Figure 4.17, information M1 becomes a potential design driver.

Step 6:

- Evaluate observations from previous steps based on the following heuristics:

⇒ Attributes and objective metrics in Matrix 3 that are influenced by multiple organizations indicate more difficult management due responsibility and communication issues.

⇒ Information in Matrix 4 that fed to or determined by multiple organizations also indicates more difficult more difficult management due responsibility and communication issues.

⇒ Component designs, objective metrics, and attributes that are influenced by more powerful organizations but are shared among organizations (as shown in Matrix 3) are likely to be design drivers.

⇒ Component designs and information types that are determined or influenced by more powerful organizations and provided to other organizations (as shown in Matrix 4) are likely to be design drivers.

Using these heuristics, the Modular architecture is relatively unencumbered by management and communication issues and has no identifiable design drivers. The Improved for Flexibility architecture has slightly more difficult management caused by a single linkage, the sharing of attribute A between components (Figure 4.12) and the exchanging of information L1 (Figure 4.13). The Conditional Flexibility architecture has even more difficult management issues, due to sharing of responsibilities for attributes and objective metrics, which creates seven linkages in Figure 4.14 (between the organizations owning component 1 and component 2, component 3 and component 4, component 4 and component 5, component 4 and component 1, component 4 and component 2, component 5 and component 1, and component 5 and component 2) . It also has seven instances of information being exchanged (shown in Figure 4.15). The coupling of attributes in the Pseudo-modular architecture leads to shared responsibility for those attributes. However, the number of organizations involved appears more or less complex than in Conditional Flexibility, showing four linkages in Figure 4.16and eight information exchanges in Figure 4.17. If all organizations are equally powerful, then there will be no design drivers identified.

DISCUSSION OF ORGANIZATIONAL HEURISTICS

The analysis above suggests that a numerical rating can be developed based on the number of linkages captured in Matrix 3 and Matrix 4. This idea is not explored in this thesis, other than to note that such a rating would need to be normalized to allow comparison between systems. This normalization could be based on the number of cells in a matrix.

In the heuristics above, one accepted wisdom is that parameters that cross organizational boundaries will be more difficult manage, due to consequences such as turf wars, issue responsibility, and work distribution. It is also accepted that such situations increase demands for communication and decrease the likelihood that such communication will naturally take place, because it crosses the boundary of the normal work group. Thus, The dependencies highlighted in Matrix 3 and Matrix 4 reveal where management and communication difficulties will be likely occur and imply the points at which the management of developing derivative products (or any products) will be most troublesome. The other information drawn from these linkages relates to the relative power of specific organizations. Parameters owned or determined by more powerful organizations will become design drivers, while those determined by weaker organizations will be more liable to iteration and change. These will be discussed in Chapter 7, using the chassis case study that will presented in Chapter 6.

PD PROCESS PERSPECTIVE

Step 1:

- In Matrix 4, identify information that is determined early and that is fed into other tasks.

For instance, in Figure 4.13, information L1 is developed in Task 1 and Task 2, but the other tasks, being uncoupled, could be executed simultaneously, so L1 may not be that early. Figure 4.15, however, has L1 being developed in Task 1 and Task 2 and being passed to Task 3 and Task 4. M1 and N1 are also needed to do Task 4. However, these are developed late, relative to L1.

Step 2:

- In Matrix 4, identify information that is determined iteratively.

For instance, in Figure 4.15, information L1, M1, N1, and O1 might all be determined iteratively, due to the feedback of information N1 and O1. The same is true of Figure 4.17.

Step 3:

- In Matrix 4, identify opportunities for simultaneous execution of tasks based the absence of transferred information, which indicates an uncoupling of tasks. Such structures indicate shortened process execution time and faster time to market

For instance, as noted in Figure 4.13, Tasks 3, 4, and 5 can be executed simultaneously with Task 1 or Task 2. In Figure 4.17, there is little opportunity to improve the time to market.

Step 4:

- Evaluate observations from previous steps based on the following heuristics:

⇒ Information types that are determined early (as shown in Matrix 4) and that feed multiple design tasks are likely to be design drivers. Iteration decreases this likelihood but does not eliminate it.

⇒ Information that is determined iteratively and whose iteration is contained within a few tasks suggest flexibility potential, especially for supporting changes. The larger the number of tasks iterated over and the larger the amount of information affected, the less the flexibility potential will be

⇒ Iteration indicates a greater development time due to re-work, which is detrimental to product success.

Evaluating the example matrices based on these heuristics, the Modular architecture has no identifiable design drivers. For the Improved for Flexibility architecture (Figure 4.13), information type L1 is the only candidate for a design driver. However, it can only influence Task 2. Figure 4.15 suggests that information type L1 is a design driver for the Conditional Flexibility architecture, because it is developed early and it feeds Tasks 2, Task 4, and Task 5. Figure 4.17, Matrix 4 for the Pseudo-modular architecture indicates that L1 may be a design driver in this case also.

Regarding iteration and its effect on flexibility, the Improved for Flexibility architecture (Figure 4.13), has L1 as the only iterative information type. This suggests it could allow some flexibility potential around components 1 and 2. Figure 4.15 suggests that information type M1 and N1 could support some flexibility potential, due to the contained nature of the iterations (that is, the M1 and N1 are restricted to a few tasks, while L1 stretches across several tasks.

In terms of product development time, the Modular architecture has the shortest potential time (due to the ability to execute all tasks simultaneously), while the Pseudo-modular has the longest (because each task must wait for the previous task to finish). The other architectures fall in between these two.

DISCUSSION OF PD HEURISTICS

There is accepted wisdom, that iteration is re-work and should be reduced, that task simultaneity should be increased because doing so reduces development time, and that sources of data should be kept to a minimum, to reduce communications. This paper will not explore the reduction of iteration or increase of task simultaneity, which are explored by researchers such as Eppinger, Whitney, etc.

Regarding information order, Matrix 4 suggests that early design decisions regarding requirements, (which set specific levels for the objective metrics and component design parameters, which together encompass the transferred information) become constraints on later decisions, except where the architecture supports flexibility. This implies that some early decisions define one set of design drivers, because their specification reduces the design latitude of later design parameters and drives the design direction. Regarding iteration, there are two comments to make in the context of derivative products. First, iteration can be planned and unplanned. Unplanned derivative products usually cause unplanned iterations, which will not be captured in the normal PD process. The second comment is that for some attributes of an automobile, iteration is a normal part of the PD process. Thus, information that iterates and attributes that are affected by iterative information are not constrained by earlier decisions. This implies flexibility in the architecture. As will be noted in Chapter 6, this is true of some chassis objective metrics and many chassis attributes.

ARCHITECTURAL PERSPECTIVE

The architectural perspective is the most difficult perspective to analyze. To help the description, the evaluation of Matrix 3 and Matrix 4 will be described separately.

Architectural --- Matrix 3

Step 1:

- Identify those attributes that are very important to the customer.

Step 2:

- Identify the number of different attribute/ attribute combinations that appear in the matrix.

For instance, in Figure 4.10, there are four (A, B, C, D), in Figure 4.14 there are three (A, BC, AD), and in Figure 4.16 there are four (AB, BC, CD, AD).

Step 3:

- Identify attribute or attribute combinations (sets of coupled attributes) that are repeated in the matrix and are influenced by different components. This means evaluating across a row. Also note those attribute/ attribute combinations cross system boundaries.

In Figure 4.10 there are none, in Figure 4.12 there is one (A), and in Figure 4.14 there are three (A, BC, AD) and in Figure 4.16. there are four (A, B, C, and D, which are each repeated as part of a combination).

Step 4:

- Identify components that influence different attribute or attribute combinations via different OMs. This means evaluating down a column.

In Figure 4.10 and Figure 4.12 there are none. However, in Figure 4.14, component 3 can affect different aspects of attributes B and C through the objective metrics M and N. Component 4 in Figure 4.14 can affect four attributes (though they are coupled in pairs BC and AD) via the objective metrics N and O.

Step 5:

- Evaluate observations from previous steps based on the following heuristics:

⇒ Components and objective metrics that affect attributes that are very important to the consumer indicate design drivers.

⇒ Coupled attributes indicate more difficult engineering than uncoupled attributes. More difficult engineering inhibits flexibility potential.

⇒ More linkages that cross system boundaries in indicate more difficult engineering, due to more physical relationships to capture, analyze, and predict.

⇒ Repeated attribute or attribute combinations across a row indicate that there are attributes that can be affected by multiple components. This indicates the existence of the multi-path flexibility gene (introduced in Chapter 1), which suggests improved flexibility potential.

⇒ Multiple attribute or attribute combinations down a column indicate a component that can affect multiple attributes or combinations of attributes through different objective metrics.

This indicates the existence of the multi-attribute flexibility gene and suggests improved flexibility potential. However, the flexibility potential is reduced if attributes are coupled.

⇒ A component that influences multiple attributes or attribute combination can be considered a design driver and has the ability to greatly assist or hinder flexibility potential.

⇒ Generally, a design driver that influences an attribute will hinder the flexibility potential of that attribute.

⇒ The range of the flexibility potential is tied to the sensitivity relationship between the component, the objective metric, and the attribute.

Based on the observations above and the heuristics, consider Figure 4.10, the modular architecture scenario. Assuming that the attributes are important to the consumer, then flexibility potential is provided for each attribute by each component via each objective metrics, because the attributes are uncoupled. If component 1 is constrained to a certain design, then the attribute A is also constrained. This is simple, ideal modularity, with straight-forward relations, indicating relatively simple physical relations and flexibility potential that is limited by the range provided by each one-to-one relation.

Now consider Figure 4.12, the Improved for Flexibility scenario. There is no coupling between attributes, so the physical relations should be relatively simple. There are no components that standout as design drivers. The system has two components that can act on attribute A via the objective metrics. If the component 1 is constrained, it is still possible that component 2 could be used to change attribute A. In this way, an attribute linked across components can achieve greater flexibility potential. The issue of range is still dependent on the relative sensitivity but with two "levers" to work on the attribute A, it seems reasonable that the likely range of flexibility potential would be increased.

Next, consider Figure 4.14, the Conditional Flexibility scenario. There is coupling between attributes (BC and AD), indicating more complicated physics and reduced flexibility potential. Component 4 and possibly component 3 look like they could be design drivers, because they can influence multiple attributes. Component 3 can affect different aspects of attributes B and C through each of the objective metrics. This does not mean the effects on B and C can be separated out easily. Essentially, attributes B and C are coupled. In terms of flexibility potential for B or C, component 3 offers the multi-attribute flexibility potential gene. Given the correct conditions (sensitivity, target values), component 3 alone could provide significant flexibility potential by its ability to affect two key attributes. Realistically, component 3 also includes risk for inadvertently impacting one of the attributes negatively. Component 4 also can also multiple attributes, but, as a design driver, it has significant risks of unintended results as changes are cascaded. However, note that component 5 offers some ability to "re-tune" the combination of attributes A and D, and components 1 and 2 offer similar options for attribute A. The linkages across components and objective metrics hold the possibility increasing the flexibility potential but the more complicated physical relations detract from this potential.

Finally, consider Figure 4.16. The attributes are coupled, creating very complicated physical relations, and they are no longer uniquely tied to the objective metrics and the components. As noted earlier, component 1 can influence attributes A and B via objective metric L, and Component 4 can also influence attribute A, along with attribute D. However, because component 4 acts on attribute A via objective metric N, it is affecting A differently than component 1, which means component 4 cannot be used to tune attribute A. In this case, the lack of linkages (and thus, the lack of levers) is reducing flexibility potential, due to the coupling of the attributes.

Based on this analysis, Figure 4.12 would hold the most potential for flexibility, followed by Figure 4.10, and Figure 4.14. Figure 4.16 appears to offer little flexibility potential due to the coupling of the attributes, the number of attribute combinations, and their one-one alignment with the components and objective metrics

Architectural --- Matrix 4

Step 1:

- Identify information that is developed early, is provided to multiple tasks, and is not subject to iteration.

In Figure 4.11, there are no information elements forwarded. In Figure 4.13, Figure 4.15 and Figure 4.17 information type L1 is developed early. In each case, it could be subject to iteration, although in Figure 4.13, the iteration is contained within two tasks which could complete early in the process.

Step 2:

- Identify information that is forwarded, and information that is provided to multiple tasks. These engineering tasks (and the information and component designs developed as part of those tasks) are coupled.

In Figure 4.13, information type L1 is forwarded to only to Task 2. In Figure 4.15 and Figure 4.17 information types L1, N1, and M1 are forwarded to other tasks, with L1 being fed to multiple tasks.

Step 3:

- Identify information that is fed backward (iteration) to multiple tasks, indicating that these engineering tasks (and the information developed) are also coupled and require iteration.

In Figure 4.13, information type L1 is fed backward to Task 1. In Figure 4.15, N1 is fed backward to Task 3 and O1 is fed backward to Task 5. In Figure 4.17 information types M1 and N1 are each fed backward to a single task, while O1 is fed backward to Task 3 and Task 1.

Step 4:

- Identify information that is fed (backward or forward) into tasks that design many different systems and information that is fed into tasks that design a few systems.

For the example matrices, it is assumed that each component and each task represent an important self-contained system. Thus, in Figure 4.13, information type L1 is exchanged across two systems represented by Task 1 and Task 2. In Figure 4.15, L1 is exchanged across four systems (Task 1, Task 2, Task 4 and Task 5), M1 is exchnaged across two systems (Task 3 and Task 4), N1 is exchanged across three systems (Task 3, Task 4, and Task 5), and O1 is exchanged across two systems (Task 1 and Task 5). In Figure 4.17 information type L1 is exchanged across three systems (Task 1, Task 2, and Task 4), M1 is exchanged across three systems (Task 1, Task 2, and Task 3), N1 is exchanged across three systems (Task 2, Task 3, and Task 4), and O1 is exchanged across three systems (Task 1, Task 3, and Task 4).

Step 5:

- Evaluate observations from previous steps based on the following heuristics:

⇒ Tasks that develop information early and are not subject to iteration probably will develop information that can become constraints on the architecture.

⇒ Information that feeds multiple tasks, is developed early, and is not subject to iteration is probably a design driver.

⇒ Information that feeds multiple tasks, is developed early, and is subject to iteration may also be a design driver.

⇒ Design drivers inhibit flexibility potential, unless they themselves have flexibility potential or if they are subject to iteration.

⇒ Tasks coupled by information exchange indicates more difficult engineering than uncoupled tasks. More difficult engineering inhibits flexibility potential.

⇒ Information that is fed to a few multiple tasks that are contained within a few systems and that are developed iteratively indicate flexibility potential.

⇒ Information whose iteration causes iteration on many other information types and whose iteration crosses many system boundaries, will hinder flexibility potential. As the distance between the tasks (in terms of the development sequence) increases the flexibility potential will decrease.

Based on the observations above and the heuristics, consider Figure 4.11, the modular architecture scenario. There is no information that is exchanged, so there is no evidence of design drivers, and there is little indication of flexibility potential beyond what is supported by the one-to-one relationships between the attributes, the objective metrics, and the components.

Now consider Figure 4.13, the DSM for the Improved for Flexibility case. Information L1 could be a design driver, because it is developed early, but it can only affect the products of Task 2. L1 is iterative and feeds a few tasks, which suggests it provides flexibility potential but also increases the engineering complexity.

In Figure 4.15, the DSM for the Conditional Flexibility scenario, L1 is more likely to be a design driver, because it is early and feeds three tasks. L1 is also implicitly iterative due to the feedback of O1, so it could provide some flexibility potential but it will also complicate the physical relations. M1 and N1 are fed to a few tasks and are developed iteratively, suggesting that they provide some flexibility potential.

In Figure 4.17, the DSM for the Pseudo-modular scenario, the L1 is again a possible design driver, as is M1. However, L1 and O1 cross several system boundaries (as represented by the tasks) and together create possible iteration throughout the whole process. This suggests that there is very little flexibility potential in this architecture, compared to the other examples.

The analysis above suggests that Modular architecture and the Improved for Flexibility architecture both provide flexibility potential, with the Improved for Flexibility architecture providing more flexibility potential but also having more difficult physics with which to contend. The Conditional Flexibility architecture also provides flexibility potential but with more unknowns around the engineering challenges.

DISCUSSION OF ARCHITECTURAL HEURISTICS

When studying Matrix 3 and Matrix 4 from the perspective of architecture, one of the applicable heuristics is that more linkages between matrix elements increases the difficulty of understanding the physics involved, which makes the engineering more intricate. Along these lines, it will become more difficult to model and predict customer attributes as the number of influential components or objective metrics increases. The engineering becomes more difficult because the correlation of models, particularly those used in CAE, breakdown. The breakdown occurs because models aggregate factors, use "rules of thumb", and simplify relationships by ignoring factors.

Matrix 3 captures (through the use of a code or some other method) the components that affect multiple attributes and the attributes that are affected by multiple components. Uncoupled architecture will have the "pure" attributes, not combinations of attributes, each tied to unique objective metrics and unique components. Highly coupled architecture would all attributes being affected by all components via all objective metrics. A less coupled but still complex architecture would have unique but overlapping combinations of attributes tied to each objective metrics. Matrix 3 for an architecture between these extremes would have some "pure" attributes and some combinations (but not many.) The combinations indicate attributes are coupled, and the matrix shows which objective metrics and components can be used to affect them. This captures the second and third flexibility genes.

The marks in the DSM (Matrix 4) represent cascading of design information that is needed to determine other design information and create of the architecture of the product., and uses the objective metrics to define the categories of information that are passed. In this way, the DSM can link design information to objective metrics and attributes and can map how changes (in attributes, objective metrics, and design information) cascade and influence other types of information. The DSM also captures the type of information that is iterated. This is important, because information (and the architecture it describes) that requires iteration, which is planned for iteration, should be flexible, so that changes can be contained. Consequently, this suggests that Matrix 4 captures which architecture elements (decisions, objective metrics, and design parameters) should be flexible. That is, those linkages (information representing decisions that affect objective metrics and attributes) that cross a few system boundaries and require iteration that is restricted to a few discreet tasks indicate flexibility potential. Those that cross system boundaries but that do not iterate indicate constraints. Those that iterate across large numbers of task will cause significant re-work and would not provide flexibility potential.

From the architecture examples, the matrices also highlight the complications that arise with coupled attributes. The examples suggest that when attributes are coupled, increasing the linkages can increase the flexibility potential, by giving additional levers with which to affect attributes. However, this also increases the risk of an unintended result.

Although numerical analysis of flexibility potential is not in the scope of this thesis, the analysis and examples able suggests that a numerical rating could be developed based on the number of linkages captured in Matrix 3 and Matrix 4. The rating would need to detract for coupled attributes. For Matrix 3, the rating would need to differentiate between linkages across rows, which would provide more flexibility potential than a linkage down a column, due to simpler engineering. Also, a normalization scheme, probably based on the number of matrix cells, would be needed to allow comparisons between architectures.

4.7 Comments on Design Drivers, Flexibility Genes, and Modularity

Design drivers, as described in Chapter 1, offer flexibility potential, if planned from the start. They also offer flexibility potential if significant re-work and extra time is acceptable. However, a design driver with few leverage points will become a constraint and inhibit flexibility potential if it is not planned to be amenable to change from the beginning. This means that early, fundamental decisions about architecture must should include flexibility potential if derivative products are anticipated.

Regarding the flexibility genes introduced previously, the first gene, Improved-range, is not explicit in either matrix. This gene is a product of the other two genes. It emerges from the other two genes, which are products of the architecture and represent leverage points on the architecture. This is not intuitive and requires discussion, which will come later in examples. Overall, the relation between the flexibility potential, which depends on the three flexibility genes, and the interactions and linkages captured in Matrix 3 and Matrix 4 suggests that the linkages improve the flexibility potential.

However, flexibility potential cannot be considered only in the context of the genes. The effect on the difficulty of the physics and engineering must be considered. The examples in the previous section indicate that a trade-off is required between ease of engineering and flexibility potential implied by the flexibility genes. More linkages means more difficult engineering and less predictable physics, while also indicating the existence of flexibility genes and improved flexibility potential. It seems reasonable that, taken to an extreme, a multiplicity of linkages would mean a product that must be completely engineered in a trial and error fashion, due to the unpredictability of the physics. Also, the linkages between parameters and attributes would become overly redundant, in terms of achieving specific attribute ranges. This implies that there is some optimum value for the linkages that yields acceptable engineering and flexibility. Intuition suggest that the number will be small compared to the number of unique attributes and the number of objective metrics.

Another observation involves modularity and its relation to the heuristics described above. Specifically, does modularity improve flexibility or hinder it? As shown in the examples in the previous section, modular architecture would have few linkages (or zero linkages) crossing boundaries, which would result in simpler engineering and simpler physics, which would make changes more predictable. The key question, in terms of flexibility potential, is whether changing the component in question causes significant changes to at least one important consumer-perceived attribute. If it does, then, as noted in the previous section, this would provide flexibility potential. However, this flexibility potential can be improved upon, as was shown in the example matrices in Section 4.6. The ideas behind the flexibility gene do not necessarily conflict with the ideas of uncoupled architecture, modular, flexible designs. If the architecture is not modular, or if the attributes involved cannot be decoupled, the linkages could become useful.

To provide a brief example of flexibility potential and modularity, consider the Sony walkman, which is considered to be an excellent example of modularity [Sanderson and Uzumeri, 1996]. Its primary successes have come from mixing of modular elements. But, of utmost importance, has been changes to the casing: colors, materials, buttons, water-proofing. These changes allowed it move into new uses and markets, such as fashion accessories, recreational sports, and children's toys. The casing, as a component, is tied to several key customer-perceived attributes. In this respect, the walkman casing has the multi-attribute (or efficiency) gene which allowed the Improved-range gene to emerge.

4.8 Chapter Summary

Chapter 4 introduced some tools that could potentially have been used in this analysis and then introduced the chosen methodology. A step-by-step process to create four matrices was described which culminated in the development of two key products, a Joint Matrix (Matrix 3) and a DSM (Matrix4). Then a step-by-step process for qualitatively evaluating the matrices was presented, along with heuristics for analyzing the matrices. Along the way, examples of how the evaluation could be executed was presented and the basis for the heuristics was described. The chapter completed with a discussion of observations and issues involving design drivers, flexibility genes, and modularity..

In Chapter 5, the process is followed for simplified, high-level vehicle architecture. The heuristics are then applied, to demonstrate how insight and a set of conclusions could be drawn. These insights are compared with empirical knowledge about the vehicle architecture.

Chapter

5 Worked Example: Applying The Method.

Chapter four described the method and a set of heuristics developed for assessing design drivers and the flexibility potential for a vehicle architecture using customer attribute, objective metric, and component design information. This Chapter applies the process and the heuristics to a simplified, high-level vehicle architecture. The insights from this analysis will be compared with empirical observations for confirmation and exception.

In this chapter, the terms "objective metrics" and "objective requirements" are used interchangeably, with objective metrics being used in the discussion and objective requirements being used in the figures. As noted earlier, objective metrics are the basis for the objective requirements that a design must meet. For this chapter, the distinction between the two is unimportant.

5.1 Creating The Matrices

The example chosen encompasses the major elements of a vehicle: a body structure, the powertrain, the suspension, steering, and brakes. The construction of the example is intended to be a qualitatively correct though incomplete representation of a vehicle's architecture. The process will be followed step-by-step, as it was presented in Chapter 4.

Step 1 is creating Matrix 1 from information about the relationships between consumer-perceived attributes and objective metrics. For the example, the attributes are:

- sporty appearance (size, shape)
- excellent visibility
- always starts and runs
- outstanding acceleration
- roomy interior
- comfortable for long drives
- smooth braking

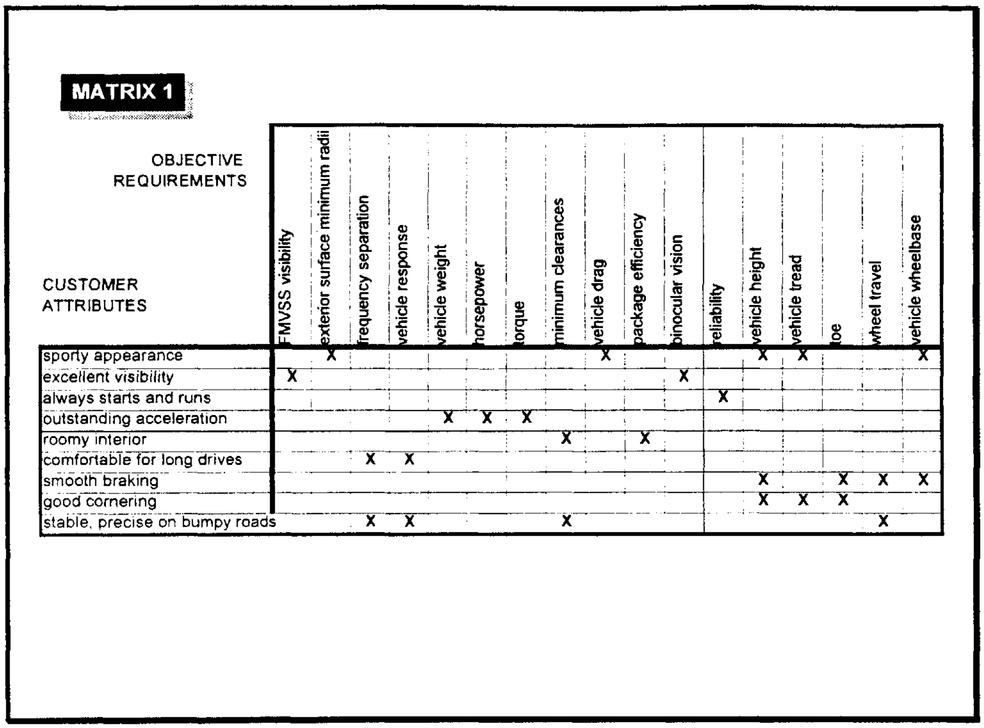
- good cornering
- stable, precise on bumpy roads

The related objective metrics (or objective requirements, as they are labeled in the figures) for the consumer-perceived attributes are:

- FMVSS visibility
- exterior surface minimum radii
- frequency separation
- vehicle response
- vehicle weight
- horsepower
- torque
- minimum clearances
- vehicle drag
- package efficiency
- binocular vision
- reliability
- vehicle height
- vehicle tread
- toe
- wheel travel
- vehicle wheelbase

Chapter 4 describes potential sources for uncovering the needed relations. Figure 5.1 shows the resulting matrix, with the relationships between the attributes and the objective metrics identified by a mark ("X") in the cell. For this example, only strong relationships were identified, so there is no need to characterize the strength of the relationship in the cell.

Figure 5.1 Matrix 1



MATRIX 1

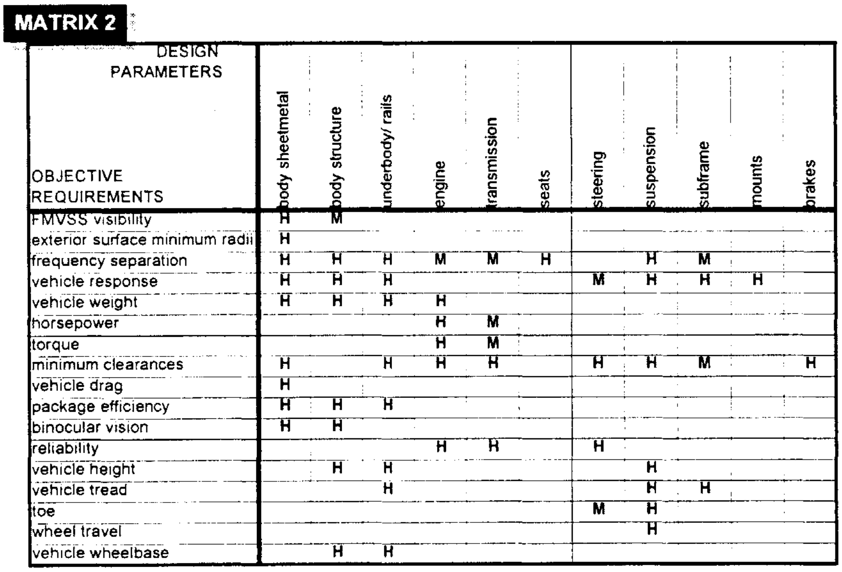
OBJECTIVE REQUIREMENTS / CUSTOMER ATTRIBUTES	FMVSS visibility	exterior surface minimum radii	frequency separation	vehicle response	vehicle weight	horsepower	torque	minimum clearances	vehicle drag	package efficiency	binocular vision	reliability	vehicle height	vehicle tread	toe	wheel travel	vehicle wheelbase
sporty appearance		X							X				X	X			X
excellent visibility	X										X						
always starts and runs												X					
outstanding acceleration					X	X	X										
roomy interior								X		X							
comfortable for long drives			X	X													
smooth braking													X		X	X	X
good cornering													X	X	X		
stable, precise on bumpy roads			X	X				X								X	

Step 2 is creating Matrix 2 from information about relations between the objective metrics and component design parameters. The relevant components (which represent component design parameters) are:

- body sheetmetal
- body structure
- underbody/ rails
- engine
- transmission
- seats
- steering
- suspension
- subframe
- mounts
- brakes

Again, Chapter 4 describes potential sources for uncovering the needed relations. Figure 5.2 shows the resulting matrix, with the relationships between the the objective metrics and the components identified by a mark in the cell. For this example, strong and medium relationships were identified by an "H" (for high or strong relationship) or "M" (for medium strength). Low strength relationships were ignored.

Figure 5.2 Matrix 2



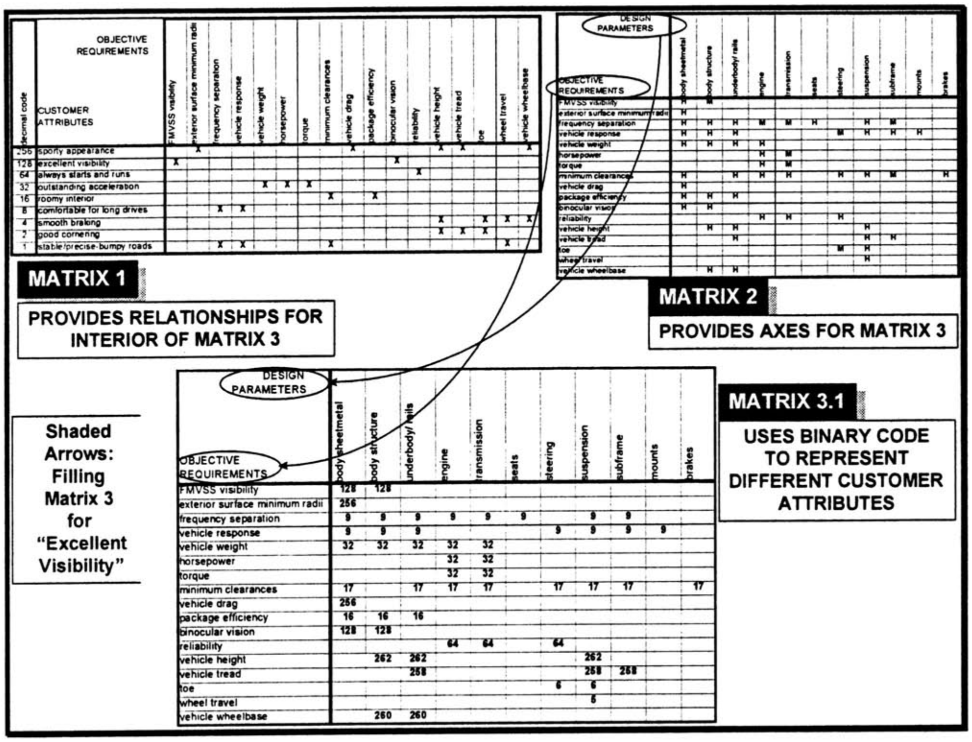
MATRIX 2

DESIGN PARAMETERS OBJECTIVE REQUIREMENTS	body sheetmetal	body structure	underbody/ rails	engine	transmission	seats	steering	suspension	subframe	mounts	brakes
FMVSS visibility	H	M									
exterior surface minimum radii	H										
frequency separation	H	H	H	M	M	H		H	M		
vehicle response	H	H	H				M	H	H	H	
vehicle weight	H	H	H	H							
horsepower				H	M						
torque				H	M						
minimum clearances	H		H	H	H		H	H	M		H
vehicle drag	H										
package efficiency	H	H	H								
binocular vision	H	H									
reliability				H	H		H				
vehicle height		H	H					H			
vehicle tread			H					H	H		
toe							M	H			
wheel travel								H			
vehicle wheelbase		H	H								

Step 3 is creating Matrix 3, the Joint Matrix. As shown in Figure 5.3, this is done using information from Matrix 1 and Matrix 2. Matrix 3 has the same horizontal and vertical labels as Matrix 2. The information from Matrix 1 is used to fill in the cells. First, a code (numbers and/ or letters) must be developed to represent the customer attributes and must be capable of distinguishing between groups made up of different combinations customer attributes. A code based on decimal representation of binary numbers was used for this example, which was possible because there were less than ten attributes. Binary numbers were assigned to each attribute based on its position in the matrix. Thus, the attribute "excellent visibility" was given the binary code "010000000" which translates into the decimal number "128", while "outstanding acceleration" was given the binary code "000100000" which translates into "32". Because there were less than ten attributes, combinations of attributes also had unique binary and decimal codes. The combination of "comfortable for long drives" and "stable, precise on bumpy roads" was given the binary code "000001001" which is equivalent to "9".

For each objective metric in Matrix 1, there are a set of customer attributes that are influenced by the objective metric and which can be represented by the code. This code is inserted in Matrix 2, at each cell where the same objective metric has a mark. In this way, the cells of Matrix 3 are filled. For instance, as shown by the shaded arrows in Figure 5.3, "excellent visibility" is determined or influenced by the objective requirements "FMVSS visibility" and "binocular vision. Since it happens that this is the only attribute that is determined by "FMVSS visibility", the code for "excellent visibility" is inserted in all the cells along the "FMVSS visibility" row that have marks in them. Thus, because "FMVSS visibility" affects the design of the body sheetmetal and the body structure, the code "128" is inserted at the cells that represent the relationship between those components and the objective metric. Figure 5.4 is the resulting matrix, labeled Matrix 3.1, because it utilizes the decimal code.

Figure 5.3 Creating Matrix 3

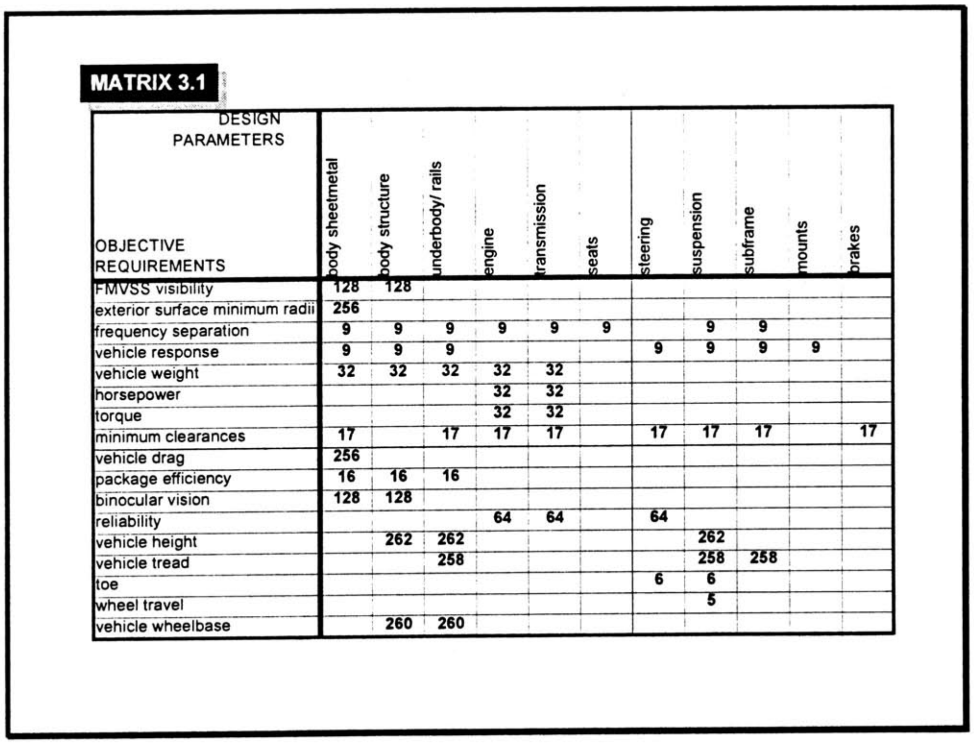


decimal code	OBJECTIVE REQUIREMENTS / CUSTOMER ATTRIBUTES	FMVSS visibility	exterior surface minimum radii	frequency separation	vehicle response	vehicle weight	horsepower	torque	minimum clearances	vehicle drag	package efficiency	binocular vision	reliability	vehicle height	vehicle tread	toe	wheel travel	vehicle wheelbase
256	sporty appearance		X							X				X	X			X
128	excellent visibility	X										X						
64	always starts and runs												X					
32	outstanding acceleration					X	X	X										
16	roomy interior								X		X							
8	comfortable for long drives			X	X													
4	smooth braking													X		X	X	X
2	good cornering													X	X	X		
1	stable/precise-bumpy roads			X	X				X								X	

DESIGN PARAMETERS / OBJECTIVE REQUIREMENTS	body sheetmetal	body structure	underbody/ rails	engine	transmission	seats	steering	suspension	subframe	mounts	brakes
FMVSS visibility	H	H									
exterior surface minimum radii	H										
frequency separation	H	H	H	M	M	H		H	M		
vehicle response	H	H	H				M	H	H	H	
vehicle weight	H	H	H	H							
horsepower				H	M						
torque				H	M						
minimum clearances	H		H	H	H		H	H	M		H
vehicle drag	H										
package efficiency	H	H	H								
binocular vision	H	H									
reliability				H	H		H				
vehicle height		H	H					H			
vehicle tread			H					H	H		
toe							M	H			
wheel travel								H			
vehicle wheelbase		H	H								

DESIGN PARAMETERS / OBJECTIVE REQUIREMENTS	body sheetmetal	body structure	underbody/ rails	engine	transmission	seats	steering	suspension	subframe	mounts	brakes
FMVSS visibility	128	128									
exterior surface minimum radii	256										
frequency separation	9	9	9	9	9	9		9	9		
vehicle response	9	9	9				9	9	9	9	
vehicle weight	32	32	32	32	32						
horsepower				32	32						
torque				32	32						
minimum clearances	17		17	17	17		17	17	17		17
vehicle drag	256										
package efficiency	16	16	16								
binocular vision	128	128									
reliability				64	64		64				
vehicle height		262	262					262			
vehicle tread			258					258	258		
toe							6	6			
wheel travel								5			
vehicle wheelbase		260	260								

Figure 5.4 Matrix 3 Using Decimal Code


MATRIX 3.1

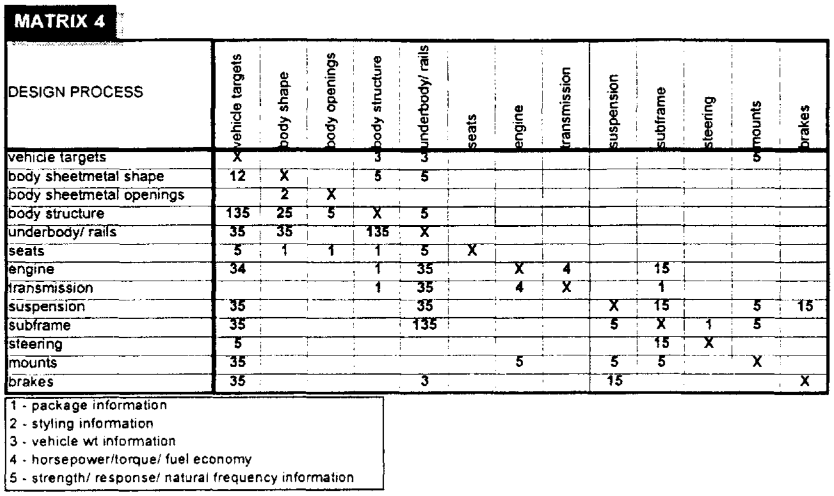
DESIGN PARAMETERS / OBJECTIVE REQUIREMENTS	body sheetmetal	body structure	underbody/ rails	engine	transmission	seats	steering	suspension	subframe	mounts	brakes
FMVSS visibility	128	128									
exterior surface minimum radii	256										
frequency separation	9	9	9	9	9	9		9	9		
vehicle response	9	9	9				9	9	9	9	
vehicle weight	32	32	32	32	32						
horsepower				32	32						
torque				32	32						
minimum clearances	17		17	17	17		17	17	17		17
vehicle drag	256										
package efficiency	16	16	16								
binocular vision	128	128									
reliability				64	64		64				
vehicle height		262	262					262			
vehicle tread			258					258	258		
toe							6	6			
wheel travel								5			
vehicle wheelbase		260	260								

Step 4 is creating Matrix 4, the DSM, which require that the tasks needed to design the components (or component design parameters) be collected. For the example, the relevant design tasks, in order of execution, are:

- vehicle targets setting
- body sheetmetal shape development
- body sheetmetal openings design
- body structure development
- underbody/ rails design
- seats design
- engine development
- transmission development
- suspension design
- subframe design
- steering system development
- mounts design
- brakes development

Initially, the design tasks should be entered in the order in which they occur and numbered sequentially on that basis. Then the tasks should be grouped by organizational responsibility. Figure 5.5 shows the completed Matrix 4.

Figure 5.5 Matrix 4, The DSM


MATRIX 4

DESIGN PROCESS	vehicle targets	body shape	body openings	body structure	underbody/ rails	seats	engine	transmission	suspension	subframe	steering	mounts	brakes
vehicle targets	X			3	3							5	
body sheetmetal shape	12	X		5	5								
body sheetmetal openings		2	X										
body structure	135	25	5	X	5								
underbody/ rails	35	35		135	X								
seats	5	1	1	1	5	X							
engine	34			1	35		X	4		15			
transmission				1	35		4	X		1			
suspension	35				35				X	15		5	15
subframe	35				135				5	X	1	5	
steering	5									15	X		
mounts	35						5		5	5		X	
brakes	35				3				15				X

1 - package information
2 - styling information
3 - vehicle wt information
4 - horsepower/torque/ fuel economy
5 - strength/ response/ natural frequency information

The design information that is transferred between tasks should also be identified and grouped according to some common characteristics that are related to the attributes or objective metrics from Matrix 1. This enables a relationship to customer attributes to be recognized. Again, a code should be developed that allows the cells of the matrix to capture the unique combinations of information types that might be transferred. For this example, the following types of information were identified and given the following codes to be used as representation in the matrix:

1. package information
2. styling/ exterior size information
3. vehicle weight information
4. horsepower/ torque/ fuel economy information
5. strength/ response/ natural frequency information

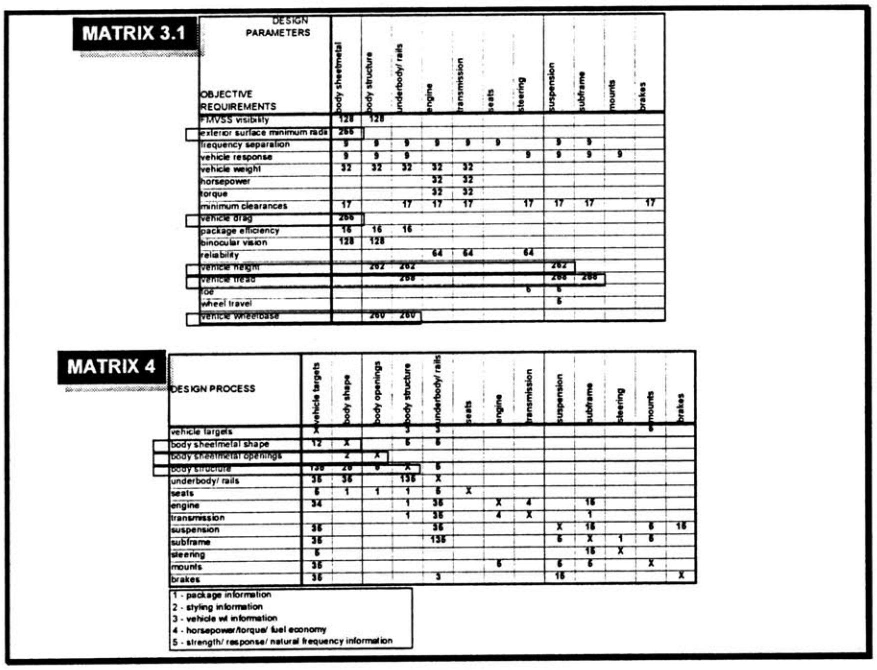
Rather than using the more complicated binary-decimal representation used in Matrix 3.1, a straight-forward number assignment method was chosen, because of there were only a few types. To uniquely represent different combinations of information types, a simple combination of the digit codes was used. For example, the vehicle target setting step provides package (type 1) and exterior size information (type 2) to the body sheetmetal shape development task. To represent this combination, numbers "1" and "2" ("12") are placed in the cell that represent the interaction between the two tasks. For the information transferred from the underbody rail design step to the subframe design step, the code "135" indicates that information type "1", "3", and "5" are being provided.

5.2 Evaluating the Matrices Using the Heuristics

As noted in Chapter 4, Matrix 3 (Matrix 3.1, in this example) and Matrix 4 are the critical products of the process described thus far. Chapter 4 also presented three perspectives and a set of heuristics that could be used to analyze the matrices in terms of design drivers and flexibility potential. To demonstrate the use of these heuristics, the attributes "appearance" and "acceleration" will be examined.

Appearance will be evaluated first. Those objective metrics and component sets that are affected by "appearance" can be identified in Matrix 3.1 because they will have codes greater than 256 in their cell.In Matrix 4, "appearance" is tied to the "styling" information type. Figure 5.6 highlights the objective metrics, components, and design tasks that determine and influence "appearance".

Figure 5.6 Analyzing "Appearance" Attribute



MATRIX 3.1

DESIGN PARAMETERS / OBJECTIVE REQUIREMENTS	body sheetmetal	body structure	underbody/ rails	engine	transmission	seats	steering	suspension	subframe	mounts	brakes
FMVSS visibility	128	128									
exterior surface minimum radii	266										
frequency separation	9	9	9	9	9	9		9	9		
vehicle response	9	9	9				9	9	9	9	
vehicle weight	32	32	32	32	32						
horsepower				32	32						
torque				32	32						
minimum clearances	17		17	17	17		17	17	17		17
vehicle drag	266										
package efficiency	16	16	16								
binocular vision	128	128									
reliability				64	64		64				
vehicle height		262	262					262			
vehicle tread			266					266	266		
toe							6	6			
wheel travel								6			
vehicle wheelbase		260	260								

MATRIX 4

DESIGN PROCESS	vehicle targets	body shape	body openings	body structure	underbody/ rails	seats	engine	transmission	suspension	subframe	steering	mounts	brakes
vehicle targets	X			3	3							6	
body sheetmetal shape	12	X		6	6								
body sheetmetal openings		2	X										
body structure	136	26	6	X	6								
underbody/ rails	36	36		136	X								
seats	6	1	1	1	6	X							
engine	34			1	36		X	4		16			
transmission				1	36		4	X		1			
suspension	36				36				X	16		6	16
subframe	36				136				6	X	1	6	
steering	6									16	X		
mounts	36						6		6	6		X	
brakes	36				3				16				X

1 - package information
2 - styling information
3 - vehicle wt information
4 - horsepower/torque/ fuel economy
5 - strength/ response/ natural frequency information

The matrices do not capture the fact that "appearance" is a key consumer-perceived attribute that is co-owned by two powerful organizations, Design Styling and Body Engineering. Using Figure 5.6, the heuristics provide the following insights:

- Organizational perspective
  - ⇒ The appearance attribute has few linkages that cross organizational boundaries, as shown in Matrix 3 and Matrix 4, indicating that management and communication should be simpler. Regarding flexibility potential, it should be easier to manage and execute for this attribute.
  - ⇒ The appearance attribute is co-owed by two powerful organizations, suggesting that it will be a design driver.
- PD perspective
  - ⇒ According to Matrix 4, styling information is among the earliest information developed., which suggests it might be a design driver. The steps receiving the appearance information develop packaging and weight information, which are provided to many tasks. Thus, it is difficult to say that appearance itself is a design driver, but it could be.
  - ⇒ The styling information is not subject to iteration, indicating that it is not planned to have flexibility potential.
- Architecture Perspective
  - ⇒ Appearance is a key consumer-perceived attribute, which suggests that it and the objective metrics that determine it are design drivers.
  - ⇒ Regarding linkages in Matrix 3.1, appearance is contained within the body system, although it affects vehicle height and vehicle tread, which are affected by suspension and subframe. This suggests the physics and engineering for a derivative should be easier than if there were more couplings, but that there are additional relations to incorporate.
  - ⇒ Matrix 4 suggests that the information that is captured in the linkages involves packaging, which clarifies and indicates that the engineering physics should be simple.
  - ⇒ In Matrix 4, there are no linkages that cross boundaries and iterate, and none that explicitly involve styling that even cross boundaries. Matrix 3.1 also shows few boundary crossings. This suggests that the flexibility genes discussed in Chapter 4 are weak or non-existent in this attribute.

In summary, the managing and engineering of a derivative in terms of the "appearance" attribute should be relatively easy. However, it is a design driver and it's the flexibility potential is low. There are few parameters that can be tuned to affect a major change in appearance once the product is past the earliest stages, and tuning the strongest parameters (such as size) will cause significant changes throughout the product, because it is a design driver.

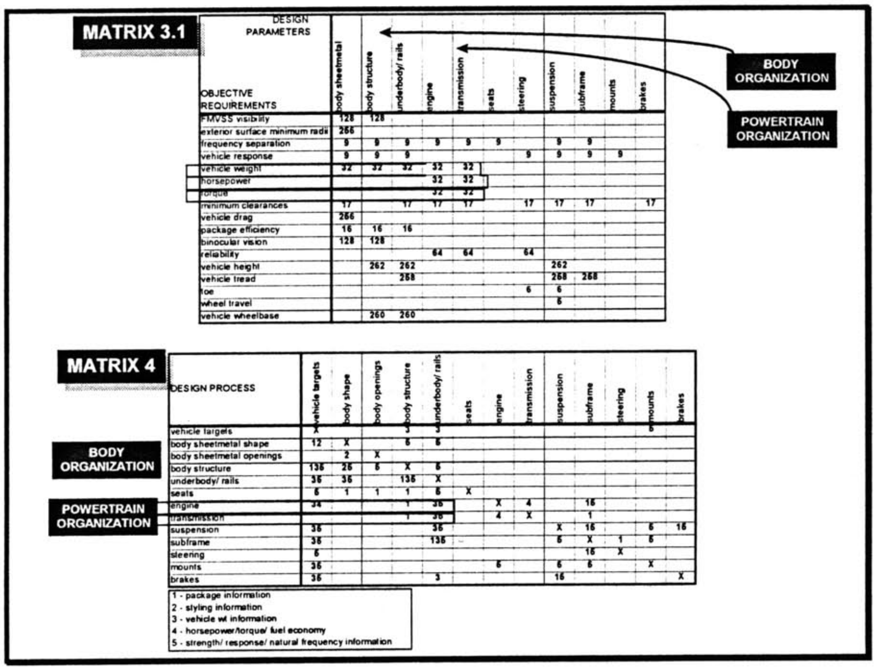
Now "acceleration" will be considered. Regarding Matrix 3.1, those objective metrics and component that have codes between 31 and 64 affect and are affected by "acceleration. The remaining filled cells would need to be inspected to see if they include "acceleration" in combination with a higher-coded attribute. In practice, it is easier to review Matrix 1 to verify that all instances of the attribute in question have been identified. In Matrix 4, the design tasks that affect and are affected by "acceleration" will be providing and receiving "vehicle weight" (type 3) and "horsepower/ torque/ fuel economy" (type 4) information. Figure 5.7 highlights the objective metrics, components, and design tasks that determine and influence "acceleration". Again, there is relevant information that is not captured in the matrices. Acceleration and fuel economy are linked attributes whose relative importance varies by market segment However, in most segments, one of them is considered important. The engine and transmission design is performed by the Powertrain organization, one of the most powerful (if not the most powerful) product organizations.

Using Figure 5.7, the heuristics suggest the following conclusions

- Organizational perspective
    - ⇒ In Matrix 3.1, the acceleration attribute crosses the organizational boundaries of Body Engineering and Powertrain. This means that management and communication will be more difficult.
    - ⇒ In Matrix 4, the weight information, which is tied to acceleration, does cross organizational boundaries and is subject to iteration. This suggests that it will be more difficult to manage.
    - ⇒ In Matrix 4, the development of horsepower/ torque/ fuel economy information does not cross organizational boundaries, being largely contained within the powertrain organization. This suggests that changes in this objective metric set will be easier to manage.
    - ⇒ Aspects of acceleration are owned by two powerful organizations, which suggests that acceleration will be a design driver. In addition, acceleration is impacted by federal fuel consumption targets and emission regulations. Both of these could have been captured on the map as objective metrics and would have strengthened the argument.

- PD perspective
    - ⇒ In Matrix 4, The development of horsepower/ torque/ fuel economy information does not cross organizational boundaries, being largely contained within the powertrain organization, and does not feed multiple tasks. This suggests that it is not a design driver.
    - ⇒ There is some iteration on horsepower/ torque/ fuel economy, suggesting some flexibility available to powertrain.
    - ⇒ Vehicle weight, which affects acceleration, is developed early and provided to several downstream tasks. However, it is subject to iteration. This suggests it is not a strong design driver but that it does provide some flexibility potential.

Figure 5.7 Analyzing Acceleration Attribute



OBJECTIVE REQUIREMENTS / DESIGN PARAMETERS	body sheetmetal	body structure	underbody/ rails	engine	transmission	seats	steering	suspension	subframe	mounts	brakes
FMVSS visibility	128	128									
exterior surface minimum radii	266										
frequency separation	9	9	9	9	9	9		9	9		
vehicle response	9	9	9				9	9	9	9	
vehicle weight	32	32	32	32	32						
horsepower				32	32						
torque				32	32						
minimum clearances	17		17	17	17		17	17	17		17
vehicle drag	266										
package efficiency	16	16	16								
binocular vision	128	128									
reliability				64	64		64				
vehicle height		262	262					262			
vehicle tread			268					268	268		
toe							6	6			
wheel travel								6			
vehicle wheelbase		260	260								

DESIGN PROCESS	vehicle targets	body shape	body openings	body structure	underbody/ rails	seats	engine	transmission	suspension	subframe	steering	mounts	brakes
vehicle targets	X			3	3							5	
body sheetmetal shape	12	X		5	5								
body sheetmetal openings		2	X										
body structure	135	25	5	X	5								
underbody/ rails	35	35		135	X								
seats	5	1	1	1	5	X							
engine	34			1	35		X	4		15			
transmission				1	35		4	X		1			
suspension	35				35				X	15		5	15
subframe	35				135				5	X	1	5	
steering	5									15	X		
mounts	35						5		5	5		X	
brakes	35				3				15				X

1 - package information
2 - styling information
3 - vehicle wt information
4 - horsepower/torque/ fuel economy
5 - strength/ response/ natural frequency information

- Architecture Perspective
    - ⇒ Acceleration (either high or low) is an important consumer-perceived attribute, which suggests that it and the objective metrics that determine it are design drivers.
    - ⇒ In Matrix 3.1, acceleration is affected by the total weight of the vehicle along with the horsepower and torque supplied by the powertrain. Weight, as an objective metric, is

affected by all components, although the body and powertrain chunks are by far the largest contributors. Thus, the physics and engineering for a derivative should be relatively easy, due to the simple nature of the relation and the few primary relations to consider.

⇒ Matrix 3.1 shows that there are several objective metrics and component design parameters that can be used to affect acceleration. This indicates the existence of the multi-path flexibility gene, discussed in Chapter 4, and suggests an improved potential for flexibility.

⇒ Matrix 4 shows that vehicle weight is provided to many tasks, crosses boundaries and is determined iteratively. This also suggests improved potential for flexibility.

In summary, the managing and engineering of a derivative in terms of the "acceleration" attribute will have some difficulties. It is a design driver but it does have good flexibility potential due to the existence of multiple leverage points. Weight, horsepower, and torque can be tuned to create different levels of acceleration.

5.3 Summary And Insights On The Example And The Method

The previous section walked through an example to demonstrate how the methodology can be applied. This section will tie those results to real-world knowledge, to demonstrate their correlation and identify weaknesses. Additional observations about the matrices will be also be provided.

To confirm the findings about design drivers and flexibility potential developed in Section 5.2 using the matrices and heuristics, the results can be compared to anecdotal evidence regarding the development of those attributes in industry. For instance, in the automobile development industry, appearance, as an attribute, is generally difficult to change late in a program. Size metrics (wheelbase, height, tread) are difficult to vary. Sheetmetal shape is really the primary leverage point. It can be varied somewhat, as long as attachments are not changed. Hence, the flexibility potential, particularly the range of appearances, are greatly constrained if size cannot be changed. Appearance, particularly size, are defined early in the program, and are resistant to change. Reviewing the analysis developed in the previous section captured, it can be seen that these ideas and issues were captured and substantiated.

In deciding on the acceleration performance for a new product, programs balance market needs, government regulations, vehicle weight, engine package space, and available engines. When a product is aimed at a specific market, most of those parameters are determined, except for weight and available engines. Engine availability is largely handled internally by the Powertrain Engineering organization, which can provide specific levels (discrete increments rather than continuous spectrum) of performance. However, weight still remains as a parameter that can leveraged to increase the range of values or to achieve to specific values. In this way, having additional parameters that affect an attribute can increase the flexibility potential. Again, these points were brought out utilizing the matrices and heuristics.

One observation regarding the matrices and the heuristics is that they probably cannot be used without experience with and knowledge of the product being studied. They require flexibility in thought, an ability to shift perspective. Like pictorial methods, the tools could become overwhelmed by a highly coupled system or product.

Another observation involves Matrix 3. Twelve unique codes were required to characterize the attribute combinations that were attached to the objective metrics and components. If codes are relatively close to each other are grouped, then there are seven distinct sets, which are made up of:

- 256, 258, 260, 262 - appearance, braking, cornering
- 128 - visibility
- 64 - always starts and runs
- 32 - accelerations
- 16, 17 - roomy interior, stable/precise
- 9 - comfortable, stable/ precise
- 5, 6 - braking, cornering, stable/ precise

This tendency to group suggests that are distinct couplings between the attributes. Some of this coupling is due to the way the example was set up (this is true for the relation between roomy interior and stable/precise.) The others are due to coupled affects of objective metrics on multiple attributes. This phenomena is not limited to this example but is a reflection of the limited coupling of the objective metrics and the components design parameters. As noted in Chapter 4, a completely uncoupled architecture would have only the "pure" attributes, while a completely coupled architecture would have a different combination of attributes for every objective metrics. In this case, there are 17 objective metrics and 7 distinct groups of attributes, which suggests this is moderately coupled.

It seems likely that this would be typical of a complex product. There would be uncoupling for some attributes and sets of attributes that would be coupled. There would not be situation where every possible combination (or half the possible combinations) exist in Matrix 3.1, because it would extremely difficult to untangle the engineering physics and allow tolerable performance predictions.

5.3 Section Summary

This Chapter applied the methodology of Chapter 4 to a simple but useful example. This illuminated how the methodology can provide insights and conclusions regarding design drivers and flexibility potential. Anecdotal confirmation of the conclusions suggested by the method was provided based on engineering experience. Observations regarding the use and the products of the method were also provided

Chapter 6 will document the application of the method to the chassis system. This will provide a more complicated example of how the matrices and heuristics can be used. Chapter 7 will use the example of Chapter 6 to develop focus on organizational issues.

CHAPTER

6 Automobile Chassis Case Study

I have been told, and have had it demonstrated, that people can simultaneously handle or track between five and nine different things, at most. I have seen this principal and experienced it. It is in my organization at work, in the number of tasks I handle at work and at home. It is in the number of team members that I can manage, and in the number of teams I can lead.

According to Warfield [1998], George Friedman (former CTO at Northrup-Grumman Corp.) evaluated over a thousand basic physics formulas and found that 75% of the equations had dimesionality between two and six. Friedman's conclusion was that it is the cognitive limitations of the humans who developed the equations that determined the complexity of the equations, not the fundamental physics. Anyone who has taken an advanced fluids class and watched as the full Navier-Stokes equations are reduced to something comprehensible understands the point. Complexity is difficult, difficult to represent and understand. Something that is complex is difficult to see in its totality and all its richness. It is difficult to explain. It is difficult to capture, to visually display, to map. However, there are tools, such as matrices, that can capture and compactly map complexity, as discussed in Chapter 4. These tools form part of a method that uses the ability of these tools to capture complexity as a way of gaining insight into flexibility potential.

This chapter will use the methodology and heuristics described in Chapter 4 and demonstrated in Chapter 5 to evaluate the flexibility potential of an automobile chassis. First, the method and heuristics will be briefly reviewed, along a description of how information was collected from engineers. The parameters that make up the mapped dimensions will be outlined, starting with the attributes, previously described in Chapter 3. The objective metrics will then be introduced, followed by a description of the specific design that will be used in the case study. Then the matrices described in the method will be developed and analyzed. Then the analysis will be reviewed against examples of chassis derivatives for correlation or refutation.

6.1 Review: Methodology and Heuristics

Chapter 4 described the development of four static maps (matrices) intended to capture the complex relationship between consumer-perceived attributes and design flexibility potential. The four maps were:

- Matrix 1 (attributes-objective metrics), showing consumer-perceived attributes aligned against vehicle dynamics objective metrics.
- Matrix 2 (objective metrics - components) shows influence of chassis key suspension and steering components on the objective metrics. Development of the matrix requires that a specific chassis architecture be selected.
- Matrix 3 (objective metrics - components - attributes), also labeled the Joint Matrix, combines information from Matrix 1 into Matrix 2 to link the influence of the components on the objective metrics to the influence of the objective metrics on the attributes.
- Matrix 4 (system design structure matrix), a DSM, captures information dependency between chassis design activities down to component design, starting from vehicle level design decisions.

As Chapter 4 also showed, these structures are not new ideas or approaches. However, for this analysis, they are used not to just capture the existence of a relationship. The four structures, and particularly the Joint Matrix and the DSM, are also trying to provide insight into the relationships between the attributes and the potential for flexibility, by evaluating the number of boundaries crossed, the number of different elements influenced, and the types of information transferred.

To develop the matrices, customer attributes and sub-attributes were identified from Ford Vehicle and Chassis experts and from corporate and public literature. Vehicle chunks and corresponding systems and sub-systems were also identified from the same sources, along with standard system functional requirements (represented as objective metrics). Churning up this information required interviews with vehicle and chassis engineers and managers, along with searches along the internal Ford website. The information collected from engineers focused on

- what is it they produce/ what is it they do
- what design decisions do they make
- what design parameters do they determine
- what vehicle performance attributes do they determine or influence
- what information do they need to do their job
    - ⇒ specifications
    - ⇒ drawings

  - ⇒ design parameters
  - ⇒ vehicle performance attributes
- To whom do they provide their products, and what is done with those products

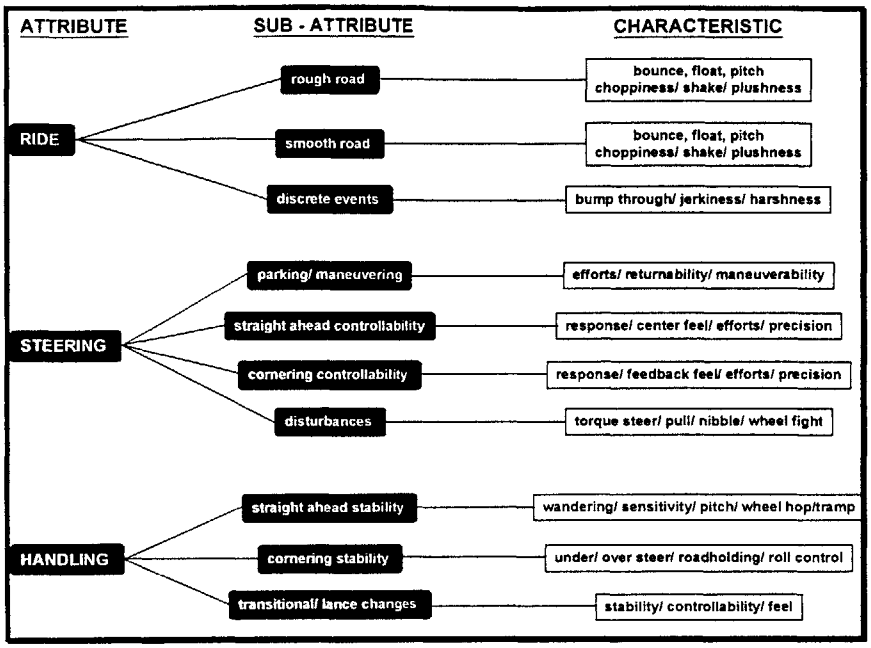
Many of the comments from engineers and managers focused on the role of the organization and management in the product development process. These will be reviewed in Chapter 7, which will focus on the organizational implications of the information captured in the matrices. Matrix 1 was largely available inside Ford [Ford, 1997], although it could be constructed based on the information available in the public literature [Milliken ,1997] [Gillespie, 1992].

As noted in Chapter 4, Matrix 3 and Matrix 4 are the primary matrices to be evaluated. The heuristics used to evaluate these matrices were also outlined in Chapter 4 and demonstrated in Chapter 5. There are three key perspectives to consider: Organizational, PD process, and Architecture. The heuristics used linkages or coupling between organizations, between tasks, and between components, attributes, and objective metrics, as the basis for judgments about flexibility potential based on the perceived management difficulty, process coupling, and architectural complexity.

6.2 Review: Consumer-perceived Attributes

Chapter 3 described the consumer-perceived attributes that are influenced by chassis functions and design. Figure 6.1 (repeated from Chapter 3) captures the key attributes of interest and decomposes them into sub-attributes. Figure 6.1 also provides lower-level characteristics to further describe the consumer perceptions of and differentiation between these attributes. Chapter 3 noted that the discerning and capturing consumer differentiation is imprecise, because consumers have difficulties verbalizing what they are sensing and from where it is coming. This leads to coupling between the attributes.

Figure 6.1 Key Chassis Attributes



6.3 Vehicle and System Objective Metrics

As noted in Chapter 3, vehicle and system objective metrics for chassis performance are generally considered to be part of vehicle dynamics. The objective metrics for vehicle dynamics are mostly standard within the automotive industry and documented in the vehicle dynamics literature [Milliken , 1995] [Gillespie, 1992]. Essentially, these metrics fall into three major categories:

- kinematic objective metrics describe the relative motion of chassis components along with the forces, moments, and axes that enable the motion
- compliance objective metrics describe the compliance, stiffness, spring rates, damping and natural frequencies of chassis systems and components.
- static design objective metrics describe the geometry, shape, material, and functional qualities.

More detailed objective metrics can be identified inside each of these categories. Static design metrics has system-specific metrics. The objective metrics that will be used in this thesis are listed below:

- kinematic objective metrics

  - roll centers, roll center migration
  - kinematic steer front axle
  - kinematic steer rear axle
  - camber change
  - asymmetric suspension set up
  - front axle anti-dive/ anti-lift
  - rear axle anti-dive/ anti-lift
  - kinematic steer asymmetry - front
  - kinematic steer asymmetry - rear

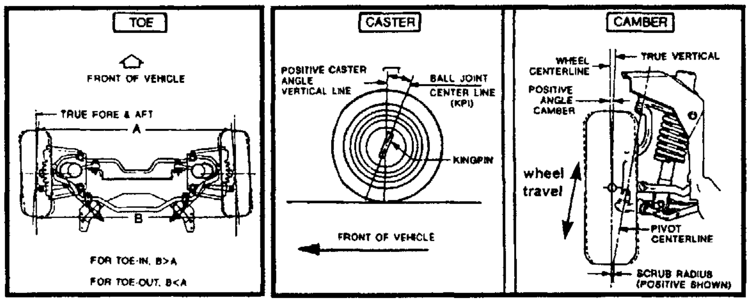
- compliance objective metrics
  - lateral steer front axle
  - lateral steer rear axle
  - lateral stiffness - front axle
  - lateral stiffness - rear axle
  - longitudinal steer front axle
  - longitudinal steer rear axle
  - longitudinal front axle
  - longitudinal rear axle
  - rubber damping
  - camber compliance front/ rear
  - castor stiffness
  - tyre stiffness
  - spring stiffness
  - shock damping
  - roll bar stiffness
  - roll bar mounting stiffness
  - roll stiffness distribution
  - suspension hysteresis
  - steering stiffness/ friction
  - steering mounting stiffness
  - steering isolator

- static design objective metrics

⇒ toe front and rear
⇒ trail
⇒ camber front and rear
⇒ camber asymmetry front and rear
⇒ ackermann angle
⇒ castor
⇒ ground offset/ scrub radius
⇒ wheel travel/ suspension travel
⇒ vehicle wheelbase
⇒ vehicle track width
⇒ center of gravity location
⇒ weight distribution
⇒ front axle weight
⇒ unsprung mass
⇒ total mass of vehicle
⇒ tyre design/ width
⇒ tyre imperfections
⇒ wheel balance
⇒ steering boost
⇒ steering joint phasing
⇒ steering lock angles
⇒ steering ratio

Most of these terms may be unfamiliar, and it is not the purpose of this paper to provide a fundamental background in vehicle dynamics. However, Figure 6.2 [Ford - A, 1996] provides a definition of some of the key objective metrics that are tied to the static design. These are affected by the static design set up but also change with wheel travel, which generates the kinematic effects measured by the kinematic objective metrics. Toe, caster, camber, and wheel travel are generally some of the key

Figure 6.2 Key Objective Metrics



The objective metrics are parameters that can be measured, predicted, and to which engineers can design. The objectives metrics, when assigned specific values or target envelopes, become functional requirements that the system, sub-system, or component must achieve to be acceptable to the consumer. Objectives metrics support the following actions:

- setting of engineering targets and specifications
- benchmarking of competitive product
- product testing and verification proceeds.

They are initiated by selection of vehicle-level performance images, which are based on the target consumer, as described by the PD process outlined in Chapter 2. The target images define the values for the attributes described in section 6.2 and Chapter 3.

6.4 Vehicle and Chassis Architecture and Components

Chapter 3 provided a relatively concept-free description of the expected functions of the chunks that make up a vehicle and the systems that make up the chassis chunk. Being a little more concept-specific, these functions can be summarized as:

- facilitate interactions between the powertrain and the ground
- constrain the wheels to move in a prescribed path relative to the body
- control the transmission of forces to the body.
- facilitate the directional guidance and stability of the vehicle
- isolate the passenger cabin from harsh road inputs
- provide appropriate steering feel and feedback

As with any set of functions, there are several concepts that can accomplish those required of the chassis system. In general, modern designs consist of a mixture recent innovations and proven technology and mechanics. The specific concept selected depends on the functional image, the drivetrain layout (front wheel drive, rear wheel drive, all-wheel drive), manufacturing capability, and corporate engineering experience. For some companies, corporate tradition and experience alone dictate the concept design.

As noted earlier, a specific architecture is required to utilize the method described in Chapter 4. For the case study, a very common architecture was chosen:

- front wheel drive layout with half-shafts and front sub-frame
- front MacPherson suspension
- power rack and pinion steering
- independent rear suspension

The selected chassis architecture and the functions of the key elements are described in more detail below [Ford-B,1996]:

Front Suspension

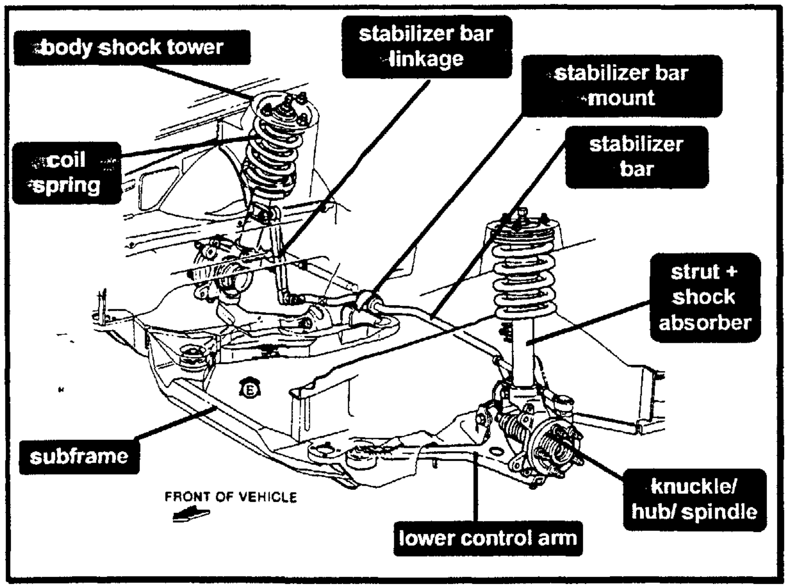
- hub and spindle
- knuckles

Houses the hub , bearing, and spindle, and facilitates tyre/wheel pivoting about the lower ball joint, which attaches to the lower control arm.

- lower control arms (including ball joints and bushings)

Stamped, A-shaped component that provides lateral and fore/aft wheel control, and facilitates vertical wheel travel. Along with strut/shock assembly, defines steer (kingpin) axis.

Figure 6.3 Front Suspension Overview



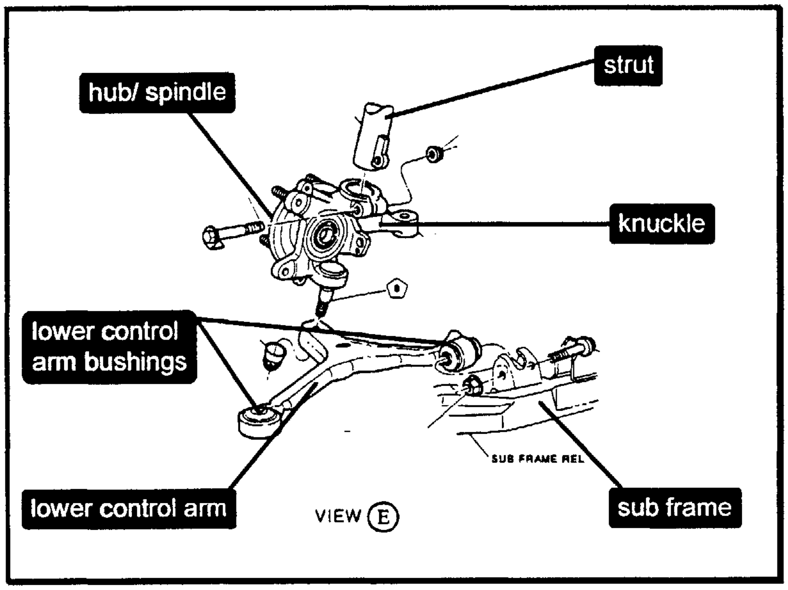
- struts/ shock absorber/ dampers

Along with control arm, defines steering axis and vertical wheel travel limits. Also provide lift, dive, and pitch control.. Shocks also dampen coil spring oscillations.

- coil springs
- stabilizer/ torsion bars and linkages (including ball joints and isolators)
- Provides vehicle roll control. Attaches via linkages to the shock/struts on either side of the vehicle.

Figure 6. 3 is a drawing of the front suspension with the key components identified. Figure 6.4 isolates the knuckle/ hub/ spindle assembly.

Figure 6.4 Knuckle/ Control Arm Detail



Rear Suspension

- hub and spindle

Provides support and attachment for control arms and shock absorbers. Also houses the rear wheel bearing.

- upper control arms (including ball joints)

Forged metal, U-shaped arm that provides transverse wheel control and serves as an upper pivot point for vertical wheel travel. Isolation is provided by rubber bushings.

- lower control arms (including ball joints)

Stamped A-shaped component that also provides transverse wheel control and serves as a lower pivot point for vertical wheel travel. Also has isolation provided by rubber bushings at pivot attachments

- shock absorber/ damper

Provides damping control (for coil spring oscillations) and limits vertical wheel travel

- coil springs
- tension struts (including bushings)

Provides fore/aft control by connecting lower control arm and body rail. Isolation provided by rubber bushings at each attachment.

- stabilizer/ torsion bars and linkages (including ball joints and isolators)

Provides vehicle roll control. Attaches via linkages to the lower control arms on either side of the vehicle.

Figure 6. 5 is a drawing of the rear suspension with the key components identified. Figure 6.6 isolates the knuckle/ hub assembly, and shows the rear stabilizer bar.

Figure 6.5 Rear Suspension Overview

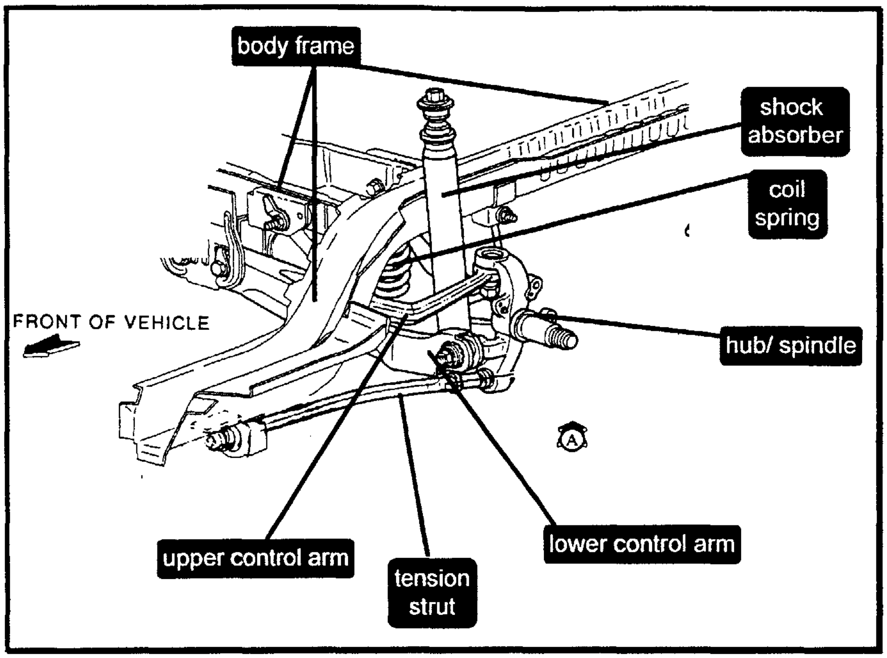
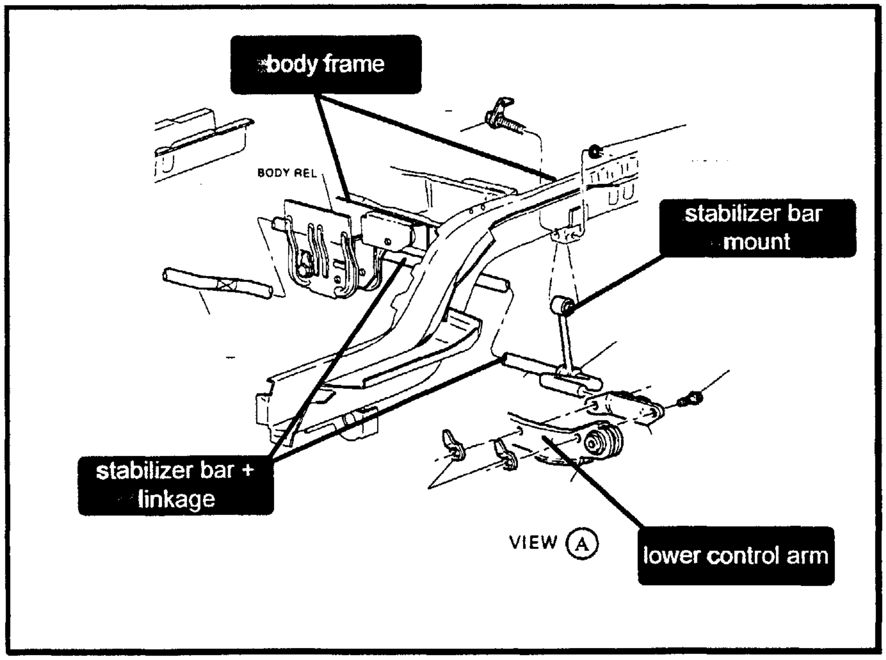


Figure 6.6 Rear Suspension Detail



Power Steering

- tie rods and linkages (including ball joints)

Mechanical linkages that connect the steering gear/ rack to the knuckle.

- steering gear and rack

Primary device for converting steering wheel rotary motion into linear transverse motion.

- steering column
- pump and hydraulic lines

Figure 6. 7 is a drawing of the steering system with the key components identified and showing how it attaches to a member of the subframe. Figure 6.8 isolates the steering gear and the tie rods.

Figure 6.7 Steering System Overview

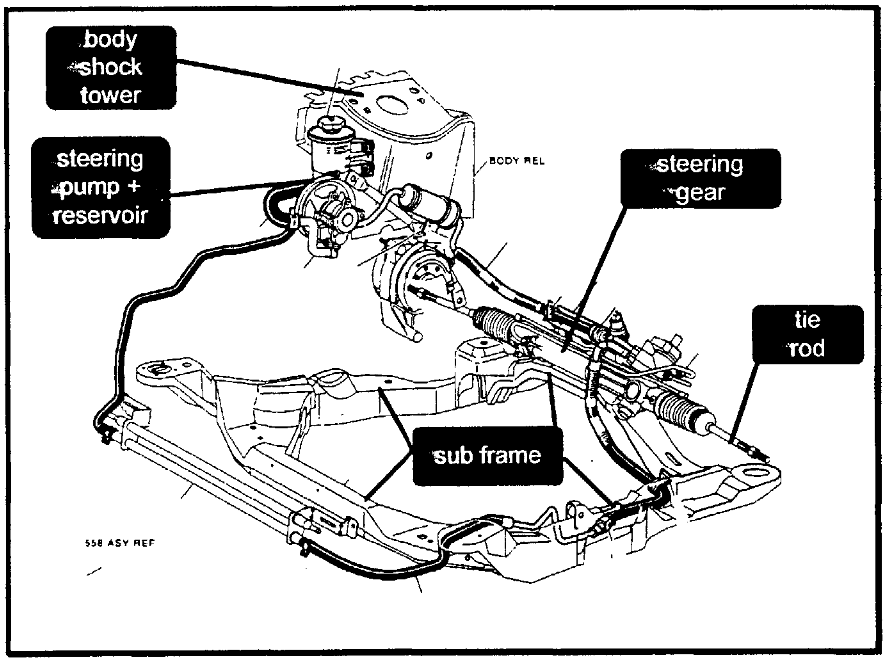
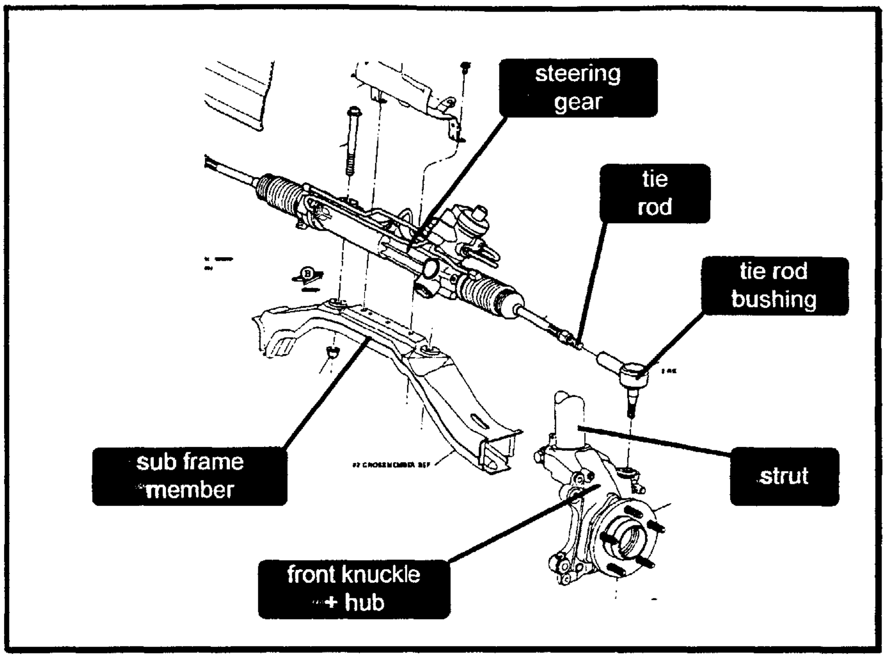


Figure 6.8 Steering Gear and Tie Rods

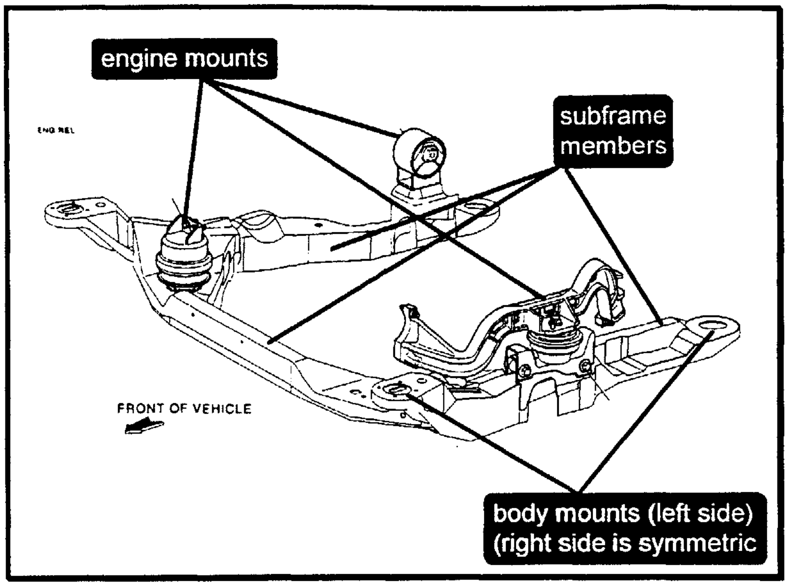


Front Subframe

- Stamped frame
- body mounts
- engine mounts

Figure 6. 9 is a drawing of the subframe with the key components identified. The cross member that supports the steering gear is not shown.

Figure 6.9 Subframe and Body and Engine Mounts



These systems and components, working together, must provide the total functionality required of the chassis system and meet the functional requirements specified by the objective targets.

6.4 Developing Matrix 1 and Matrix 2

As noted earlier, Matrix 1 shows the dependency relations between the customer-perceived attributes and the engineering objectives. Matrix 1 has:

- customer-perceived attributes along the left side
- vehicle dynamics objective metrics (which become functional requirements) along the top

Although it is not considered one of the key tools of the process for analyzing for flexibility potential, reviewing Matrix 1 does yield insight on the complexity of the attributes. For instance, because the cell markings in Matrix 1 indicate dependency or influence of an objective metrics on an attribute, large areas of non-influence, as indicated by no marking, indicate independence of an attribute relative to the particular objective metric. Independence of an objective metric with respect to a customer attribute means that changing that the requirement associated with that objective will not affect the customer's perception of the attribute.

Matrix 1 For Chassis

SUBJECTIVE EVALUATION			CHASSIS OBJECTIVE METRICS	Suspension Kinematics									Suspension Compliance											Static Geometry										Suspension Set Up												Wheel Assembly								Vehicle (general)								Steering System									Body and Powertrain												
ATTRIBUTE	Sub-Attribute	Characteristic	Property	Roll Centres and Roll Centre Migration	Kinematic Steer Front Axle	Kinematic Steer Rear Axle	Camber Change	Front Axle Anti Dive / Anti Lift	Rear Axle Anti Squat / Anti Lift	Kinematic Steer Asymmetry Front	Kinematic Steer Asymmetry Rear	Asymmetric Suspension Set Up	Lateral Compliance Steer Front Axle	Lateral Compliance Steer Rear Axle	Lateral Stiffness Front Axle	Lateral Stiffness Rear Axle	Longitudinal Compliance Steer Front Axle	Longitudinal Compliance Steer Rear Axle	Longitudinal Compliance Front Axle	Longitudinal Compliance Rear Axle	Rubber Damping (Bushes)	Camber Compliance Front/Rear	Castor Stiffness	Static Toe Front	Static Toe Rear	Hub Trail	Static Camber Front	Static Camber Rear	Camber Asymmetry Front	Camber Asymmetry Rear	Ackermann	Castor	Ground Offset / Scrub Radius	Spring Stiffnesses / Ride Frequencies	Bump Stops	Rebound Springs / Rebound Stops	Damping (low - mid - high speed)	Damper Gas Pressure	Twn Tube or Monotube Type	Damper Mountings	Anti Roll Bars Stiffness	Anti Roll Bar Mountings	Roll Stiffness Distribution	Wheel Stroke / Suspension Travel	Suspension System Hysteresis / Friction	Tyre Characteristic and Build	Tyre Pressure	Tyre Imperfections	Tyre Section Width Front / Rear	Rim Widths	Wheel Balance	Wheel bearings	Unsprung mass	Wheelbase	Track Width	Centre of Gravity Height	Weight distribution	Front Axle Weight	Overall mass of vehicle	Aerodynamic Centre of Pressure (side view)	Aerodynamic Centre of Lift (plan view)	Steering System Friction	Steering Ratio	Power Steering (T-Bar and Boost Curve Char.)	Strg. Column Velocity Change Effects (Joint Phasing)	Available Wheel Lock Angles	Rack / Column Mounting Stiffness	Steering Column Isolator	Pinion Cross Over Angle	Steering Wheel Mass	Local Body Stiffnesses	Body Torsional and Bending Stiffnesses (nat. frequ.)	Powertrain Mountings	Frequ. Response of Subframe / Driveline Masses	Driveshaft Angularity (FWD) in End and Plan View	Unequal Driveshaft Lengths	Unequal Driveshaft Stiffness	Throttle Damper	Engine Torque	Limited Slip Differential	Brake balance front to rear	Discs or drums	Shielding
RIDE	CONTINUOUS EVENTS (Smooth Road)		Primary ride/ body motion:	X	X	X	X	X	X				X	X	X	X			X	X							X	X						X	X	X	X	X		X	X	X		X	X	X	X							X		X																										
			Secondary ride/vibrations:	X				X	X										X	X	X													X			X	X	X	X	X	X			X	X	X	X		X	X		X														X	X		X	X	X	X	X									
	OUS EVENTS (Rough Road)		Primary ride/ body motion:	X	X	X	X	X	X				X	X					X	X							X	X						X	X	X	X	X		X	X	X	X	X	X	X	X							X		X																										
			Secondary ride/ vibration	X				X	X										X	X	X													X			X	X	X	X	X	X			X	X	X	X		X	X		X														X	X		X	X	X	X	X									
	DISCRETE EVENTS		Primary ride motion: abrupt	X			X	X	X										X	X							X	X						X	X	X	X	X		X	X	X		X	X	X	X																																						
			Impacts: harshness - tactile	X				X	X										X	X	X							X	X						X	X	X	X	X	X	X	X	X		X	X	X				X			X																		X	X	X	X									
STEERING	PARKING / MANEUVERING		Efforts: standstill, rolling, ur																					X		X	X				X	X	X													X	X			X								X				X	X	X	X																	X			
			Returnability: smoothness /																					X		X	X				X	X	X								X	X				X	X			X												X	X	X	X				X											X			
			Maneuverability																												X																						X									X			X																			
	STRAIGHT AHEAD CONTROLLABILITY		Response	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X			X	X	X	X		X					X	X						X	X	X	X		X	X			X									X			
			Center feel: torque deadban	X	X	X							X	X	X	X	X	X	X		X		X	X	X							X	X	X			X			X	X	X			X	X	X			X			X									X	X	X	X		X	X			X									X			
			Center feel: friction feel																																		X																									X																			X			
			Center feel: compliance fee																																		X									X	X			X													X				X	X			X												
			effort level																													X	X													X	X			X								X				X	X	X	X																	X			
		modulation / precision			X	X							X	X	X	X	X	X	X		X	X	X	X	X		X				X	X	X				X			X	X	X				X	X			X					X	X						X	X	X	X		X	X			X									X			
	CORNERING CONTROLLABILITY		Response	X	X	X	X	X					X	X	X	X	X	X	X	X	X	X	X	X	X		X	X			X	X	X	X	X		X	X		X	X	X			X	X	X		X	X			X		X	X	X		X			X	X	X	X		X	X			X									X			
			Torque/ feedback feel: tor	X	X	X	X	X					X	X	X	X	X	X	X		X	X	X	X	X	X	X				X	X	X	X	X		X			X	X	X			X	X	X		X	X			X									X	X	X	X		X	X			X									X			
			effort level																								X					X	X													X	X		X	X			X					X				X	X	X	X				X											X			
			Returnability: smoothness/ unif		X	X							X	X			X		X				X	X		X	X				X	X	X								X	X				X	X			X			X									X		X		X	X		X		X											X			
			Returnability: overswing	X	X	X	X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X		X	X			X	X	X	X	X		X			X	X	X	X	X		X	X		X	X			X	X	X	X						X	X	X			X			X			X		X					X			
		modulation / precision		X	X	X	X	X					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X				X			X	X	X			X	X	X			X												X	X	X	X		X	X			X									X			
	STEERING DISTURBANCES		Torque steer		X												X							X			X																			X		X																				X				X		X		X	X	X			X			
			Pull: hands-off drift									X																	X	X																	X		X																											X		X	X							
			Pull: correction efforts									X																				X															X		X															X	X												X	X				X			
		wheel fight																X		X												X	X				X									X				X			X									X		X			X	X	X															
		nibble																																																X	X												X		X			X	X		X														
HANDLING	HT AHEAD STABILI		Straight running: wandering	X	X	X	X			X	X	X	X	X	X	X	X	X	X			X	X	X	X		X	X	X	X	X	X		X		X	X			X	X	X	X	X		X	X		X	X				X	X	X	X		X	X	X		X				X	X			X												
			Straight running: bump steer		X	X	X			X			X	X	X	X	X	X					X	X	X				X	X		X		X	X		X				X	X				X				X																		X	X																
			Side wind sensitivity: reactio	X	X	X	X			X	X	X	X	X	X	X	X	X				X	X	X	X		X	X	X	X		X		X			X				X	X				X	X			X				X		X	X		X	X	X	X	X		X		X	X			X												
			Acceleration pitch (lift/ squa					X	X																									X	X	X	X							X										X		X	X		X																										
			Accelration capability/ tract	X				X	X															X				X						X	X											X	X		X					X		X	X		X																							X	X			
			Accelration capability/ tract					X	X										X	X																	X									X																									X		X										
	CORNERING STABILITY		Under/ over steer	X	X	X	X			X	X	X	X	X	X	X	X	X				X			X	X	X	X	X	X	X	X		X	X	X	X			X	X	X	X	X	X	X	X		X	X				X	X	X	X			X	X																					X			
			Power on/off	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X		X	X				X	X	X	X			X	X	X	X	X	X		X	X			X							X		X			
			Braking in a turn	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	X	X		X	X	X	X	X	X	X	X	X	X	X				X	X	X	X	X	X	X	X		X	X				X	X	X	X		X	X	X	X	X	X	X		X	X			X							X		X	X		
			Road holding	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X			X	X	X	X		X	X	X	X		X		X	X	X	X			X	X	X	X	X	X	X	X		X	X				X	X	X	X		X	X	X						X																			
			Roll control: initial roll	X	X	X	X	X	X	X	X	X	X	X	X	X						X		X	X		X	X	X	X				X	X		X	X	X	X	X	X			X	X	X			X					X	X			X				X																						
			Roll control: roll damping	X	X	X	X	X	X	X	X	X	X	X	X	X						X		X	X		X	X	X	X			X	X	X	X	X		X	X	X	X			X	X	X			X					X	X			X				X																						
			Roll control: roll angle	X																														X	X	X					X	X		X		X				X					X	X			X																									
	IONAL / LANE CHANGE		Stability	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X	X				X	X	X	X		X	X	X		X	X	X		X	X			X	X			X			X		X			
			Controllability	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X				X	X	X	X	X	X	X	X	X	X	X	X		X	X			X	X								X			
		capacity feel		X	X	X	X						X	X			X	X									X	X	X	X				X	X					X	X					X			X	X					X	X			X	X	X										X									X			

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Surveying Matrix 1, the following observations can be made:

- The dependency marks in the matrix are very dense in many regions. This not only indicates that many of the sub-attributes are dependent on cross-functional requirements, it also suggests that sub-attributes are coupled.
- It takes several requirements to specify the sub-attributes properly, and those same requirements also apply across several sub-attributes. This suggests that the requirements may be coupled.
- Suspension Set-Up And Suspension Kinematics influence many aspects of the ride attributes, indicating a strong dependency. This suggests that these requirements can control the ride performance.
- Compliance has some influence on ride attributes but a stronger influence on steering (particularly Cornering Controllability) and handling (especially Cornering Stability and Lane Change).
- Cornering Controllability is strongly influenced cross-functionally. This is particularly true for Response. This makes it difficult to single out a particular requirement as a good candidate for modification to achieve flexibility
- Steering Disturbance has fewer influencing factors.
- Handling is strongly influenced cross-functionally across all its characteristics
    - ⇒ Cornering stability and translational stability are very strongly influenced by many objectives
    - ⇒ The objective metrics that influence the handling attributes are cross-functional, indicating strong interdependencies.

In general, all sub-attributes are influenced multiple objective metrics, and that the influencing metrics are cross-functional. The information does not indicate if the degree of influence, but it appears that there is significant coupling.

Matrix 2 shows the dependency between objective metrics and key chassis components and the influence of the components on the system objectives. The components are based on the architecture described in Section 6.3. Matrix 2 rates the influence/ dependency as high or medium. Low or null influences are ignored.

Matrix 2 For Chassis

	DESIGN RESPONSIBILITIES	vehicle dynamics										front suspension							SF	chassis steering					rear suspension				
	SUSPENSION/ CHASSIS COMPONENTS	front tyre / wheel	- rear tires	frnt stabilizer/torsion bars	front springs	front control arm bushings	- body mounts	- engine mounts	rear control arm bushings	- rear stabilizer/torsion bars	rear springs	front spindle	front hub & bearing	front knuckles	front control arms assy.	front stabilizer bar linkage	frnt struts/ shock absorbers	front control arm ball joints	- subframe structure	- steering gear/ rack	steer hydraulics (pump, etc.)	- steering column	- tie rods	steering linkage ball joints	rear hub & bearing	rear spindle	- rear struts/ shock absorbers	- rear sta-bar link	- rear control arms assy.
	VEHICLE & SYSTEM OBJECTIVE METRICS																												
suspension kinematics	Roll Centres and Roll Centre Migration			H	M		H		M	H	M	M		M	H		H		M						M	M	H		H
	Kinematic Steer Front Axle											M		M	H		M			M			M	H					
	Kinematic Steer Rear Axle																									M	M		H
	Camber Change														H		H	H											
	Front Axle Anti Dive / Anti Lift				M	H	M	M							H		M	M											
	Rear Axle Anti Squat / Anti Lift						M		M		H							M											H
	Kinematic Steer Asymmetry Front														H														
	Kinematic Steer Asymmetry Rear																												H
	Asymmetric Suspension Set Up														H														
suspension compliance	Lateral Compliance Steer Front Axle	M			H	H									H			H					M	M					
	Lateral Compliance Steer Rear Axle		M						H		H																	M	H
	Lateral Stiffness Front Axle			H	H							H			H	H			M										
	Lateral Stiffness Rear Axle										H															H	H	H	H
	Longitudinal Compliance Steer Front Axle					H												M	M										
	Longitudinal Compliance Steer Rear Axle																												H
	Longitudinal Compliance Front Axle					H												M											
	Longitudinal Compliance Rear Axle																												H
	Rubber Damping (Bushes)					X			X																				
	Camber Compliance Front/Rear								H						H		H	H											
	Castor Stiffness					H			H						H														H
static geometry	Static Toe Front											M		M	H					M			H	M					
	Static Toe Rear																									M			H
	Trail													M	H		H												
	Static Camber Front														H		H	H											
	Static Camber Rear																										H		H
	Camber Asymmetry Front														H		H	H											
	Camber Asymmetry Rear																										H		H
	Ackermann													M	M														
	Castor	M										H	M	H	H										M	H			H
	Ground Offset / Scrub Radius	M										H					H	H											
Suspension Set Up	Spring Stiffnesses / Ride Frequencies				H						H																		
	Bump Stops				H												H												
	Rebound Springs / Rebound Stops				X						X																		
	Damping (low - mid - high speed)																H										H		
	Damper Mountings						H										H												
	Anti Roll Bars Stiffness			X						X	M					H												M	
	Anti Roll Bar Mountings														M	H													
	Roll Stiffness Distribution			H	M	H	H		H	H	M			M	M		M	M											
	Wheel Stroke / Suspension Travel	H			L						L			M	H		H	M					L	M	M				H
	Suspension System Hysteresis / Friction					H	M	M	M								H	H									M		
Wheel Assembly	Tyre Characteristic and Build	H	H																										
	Tyre Pressure	H	H																										
	Tyre Imperfections	H	H																										
	Tyre Section Width Front / Rear	H	H																										
	Wheel Balance	H	H									H	H	H											H	H			H
	Unsprung mass	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Vehicle (general)	Wheelbase																												
	Track Width											M		M	M				M				M		M	M			M
	Centre of Gravity Height																M		M								M		
	Weight distribution																M		M								M		
	Front Axle Weight			H											H		H		H	M		M							
	Overall mass of vehicle																		M										
	Aerodynamic Centre of Pressure (side view)																												
	Aerodynamic Centre of Lift (plan view)																												
Steering System	Steering System Friction																	H		H	M			M					
	Steering Ratio																			H									
	Power Steering (T-Bar and Boost Curve Char.)																				H								
	Strg. Column Velocity Change Effects (Joint Phasing)																					H							
	Available Wheel Lock Angles	H										H		H						H									
	Rack / Column Mounting Stiffness																					H							
	Steering Column Isolator																			H		M							
	Pinion Cross Over Angle																			H		M							
Kinematic and Compliance Objectives	kingpin inclination														H		H	H											
	kingpin offset	H													H		H	H											
	scrub radius	H													H		H	H											
	roll steer													H	H		H			M			H						
	side force steer	M										H	M		H		H												
	roll stiffness			H	H	M	H		M	H	H					M	H										H	M	
	tire stiffness	H																											
	sprung mass																												
	recession compliance				H	H						M					H	M						M					
	spring ratio				X						X																		
	damper ratio			H		M	M	M	M																		H		
	toe change (jounce & roll)														H								H						
	compliance steer	M				H						M						H		H			H	H					
	camber change																H	H											
	camber stiffness					H									M			H		H			M	H					
	drive steer	H						M				H	H		H		H	H											
	castor	M										H	M		H		H												

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In the matrix, the components are grouped by organizational design and release responsibility. Chapter 7 will describe the organization structure but the key points are that vehicle dynamics, front suspension, rear suspension, steering, and subframe (SF) are separate work groups. Vehicle dynamics has responsibility for ensuring attributes are delivered, and have design responsibilities for tires, torsion bars, mounts, and bushings. The other work groups design specific systems and components. With this in mind, the large marked areas in Matrix 2 show strong influence between related components and objectives. Again, although not explicitly part of the methodology described in Chapter 4, a study of Matrix 2 yields some preliminary knowledge of the complexity that is being addressed. Examining Matrix 2 yields the following information and observations:

- front suspension components greatly influence all objective metrics, except steering and wheel metrics.
- rear suspension influence mirrors the front suspension, except for objective metrics specific to the front end.
- Steering objective metrics are primarily influenced by the steering system. Very little cross-functional influence.
    - This makes it seem that the steering can be separated from the suspension.
    - However, no account is taken for packaging concerns, which can cause interactions between many of the front end vehicle components.

In the matrix, the objective metrics are grouped into functional areas such as suspension kinematics, suspension compliance, static geometry, suspension setup, wheel assembly, steering system. These describe the primary functional nature of the objective metric, and will be used in the DSM as the basis for information types.

6.5 The Joint Matrix and the DSM

Chapter 4 described the contents of the Joint Matrix (Matrix 3 and Matrix 3.1) and the DSM (Matrix 4). Matrix 3.1 captures the dependencies between attributes, objective metrics, and components by inserting information from Matrix 1 into Matrix 2. In Matrix 3, the influence of the components on the objective metrics is linked to the influence of the objective metrics on the attributes. The goal is to visually portray the influence of the components on the attributes while identifying the mechanism (the objective metric) that carries that influence.

In developing Matrix 3, attribute information has been treated at a moderately aggregated level. That is, instead of using the properties shown in Matrix 1, the components and objectives are linked using:

- 3 ride sub-attributes (continuous events-smooth road, continuous events-rough road, discrete events)
- 4 steering sub-attributes (parking maneuvering, straight ahead controllability, cornering controllability, steering disturbances)
- 3 handling sub-attributes (straight ahead stability, cornering stability, transitional lane changes)

The aggregation was done to simplify the appearance of the matrix in the hope of exposing high-level patterns that might get lost in the details. In addition, upon inspecting the Matrix 1 prior to doing the aggregation, it was determined that each of the sub-attributes was generally dominated by a set of correlated properties (correlation was judged subjectively by identifying similar dependency patterns exhibited in Matrix 1)

Matrix 3 (or Matrix 3.1) shows that components that greatly influence sub-attributes often transmit that influence through more than one objective path. The more paths (or objective metrics) through which a component influences a sub-attribute, the more complex is the relation between the component and the attribute. More complexity means less predictability, especially for CAE models. More complexity also means less ease of flexibility, because the effect of changes will cascade through the dependencies in complex ways yielding results that are largely unpredictable.

Matrix 4 is a design structure matrix (DSM) that identifies dependencies in the design of the components. It lists key chassis design activities, starting from vehicle level design decisions down to component design, and includes influential body and powertrain decisions. Component names represent the task of determining component design, including geometry, dimensions, material, stiffness, and location and orientation in the vehicle.

Matrix 3 For Chassis: Objective Metrics Grouped by Organization, Linked to Components Via Simple Code

--ABBREVIATED EXAMPLE--

	DESIGN RESPONSIBILITIES	vehicle dynamics										front suspension			
	SUSPENSION/ CHASSIS COMPONENTS	front tyre / wheel	- rear tires	frnt stabilizer/torsion bars	front springs	front control arm bushings	- body mounts	- engine mounts	rear control arm bushings	- rear stabilizer/torsion bars	rear springs	front spindle	front hub & bearing	front knuckles	front control arms assy.
	VEHICLE & SYSTEM OBJECTIVE METRICS														
suspension kinematics	Roll Centres and Roll Centre Migration			R1,2,3 S2,3 H1,2,3	R1,2,3 S2,3 H1,2,3		R1,2,3 S2,3 H1,2,3		R1,2,3 S2,3 H1,2,3	R1,2,3 S2,3 H1,2,3	R1,2,3 S2,3 H1,2,3	R1,2,3 S2,3 H1,2,3		R1,2,3 S2,3 H1,2,3	R1,2,3 S2,3 H1,2,3
	Kinematic Steer Front Axle											R1,2 S2,3,4 H1,2,3		R1,2 S2,3,4 H1,2,3	R1,2 S2,3,4 H1,2,3
	Kinematic Steer Rear Axle														
	Camber Change														R1,2,3 S2,3 H1,2,3
	Front Axle Anti Dive / Anti Lift				R1,2,3 S2,3 H1,2,3	R1,2,3 S2,3 H1,2,3	R1,2,3 S2,3 H1,2,3	R1,2,3 S2,3 H1,2,3							R1,2,3 S2,3 H1,2,3
	Rear Axle Anti Squat / Anti Lift						R1,2,3 S3 H1,2,3				R1,2,3 S3 H1,2,3				
	Kinematic Steer Asymmetry Front														S2 H1,2,3
	Kinematic Steer Asymmetry Rear														
	Asymmetric Suspension Set Up														S2,4 H1,2,3
suspension compliance	Lateral Compliance Steer Front Axle	R1,2 S2,3 H1,2,3			R1,2 S2,3 H1,2,3	R1,2 S2,3 H1,2,3									R1,2 S2,3 H1,2,3
	Lateral Compliance Steer Rear Axle		R1,2, S2,3 H1,2,3						R1,2, S2,3 H1,2,3		R1,2, S2,3 H1,2,3				
	Lateral Stiffness Front Axle			R1 S2,3 H1,2,3	R1 S2,3 H1,2,3							R1 S2,3 H1,2,3			R1 S2,3 H1,2,3
	Lateral Stiffness Rear Axle										R1 S2,3 H1,2,3				
	Longitudinal Compliance Steer Front Axle					S2,3,4 H1,2,3									
	Longitudinal Compliance Steer Rear Axle														
	Longitudinal Compliance Front Axle					R1,2,3 S2,3,4 H1,2,3									
	Longitudinal Compliance Rear Axle														
	Rubber Damping (Bushes)					R1,2,3 S2,3,4			R1,2,3 S2,3,4						
	Camber Compliance Front/Rear								S2,3 H1,2,3						S2,3 H1,2,3
	Castor Stiffness					S2,3 H1,2,3			S2,3 H1,2,3						S2,3 H1,2,3

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Chassis Design Structure Matrix

DESIGN TASK		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	45	46	47	33	34	35	36	37	38	39	40	41	42	43	44
wheelbase/ track	1	0																2	2																													
Engine/ Transmission	2		0	2																																												
vehicle loads	3		2	0		4												3	3		3																											
engine layout	4	2	2		0																2																											
CG location	5	2	2		2	0	2	2						2																																		
Body shell/ fenders	6	2				2	0	5			5							1	1			1			1																							
Body front structure/ rails	7			3	2	2	5	0	5	5	5							1			2																											
Body dash panel	8				2		5	5	0																																							
Body shock towers	9						5	5	5	0																																						
Body rear structure/ rails	10					2	5	5	5	5	0		1						1																													
Transaxle halfshafts	11		2		2							0																																				
Exhaust system	12		2										0																																			
kinematic axis definition	13	2	2	3		3	2							0			6								4	4		3																4	4		6	
suspension geometry defn	14	2	2	3		2	1	1						2	0		6																															
compliance budget defn	15			3				3						6		0	6	3							3	3		3			3	3	3	3			3				3					3	3	3
vehicle response properties	16	2		3		2	3	3			3			6	4	3	0	3		5	3			4	6	6								6	6		7							4	4	6	6	6
front tyre / wheel	17			3		3	1	1						2	2	3	6	0					2																									
rear tires/ wheel	18			3		3	1				1			2	2	3	6		0																													
Brake system	19		1	3		3											6	1		0																												
frnt subframe structure	20	2	2	3			3	5				1	1			3	6				0																											
front hub & bearing	21				2		1					2						2		1		0	2					1																				
front knuckle	22				2		1					2								1			0	4	4		5																					
front control arms assy.	23							1				1		2	2		6	4			2		2	0	4																							
frnt struts/ shock absorbers	24						1	1		5		1		2	2	3	6	4			1		2	4	0			5	2																			
front coil spring	25									5						3	6	4							7	0																						
ball joint - frnt cntrl arm/ knuckle	26															3							4	7			0																					
frnt stabilizer/torsion bars	27											1			2	3	6	3			1			1	5	3		0																				
front stabilizer bar linkage	28											1									1			1	1			5	0																			
front stabilizer bar insulator	29															3	6				2				2			3		0																		
front control arm bushings	30															3	6	3						7		3	5				0																	
body mounts/ isolator	31							5								3	6				5				3	3						0																
engine mounts	32		2		1											3	6								3	3						3	0															
rear tension strut bushing	45															3	3		3															0													7	
rear stabilizer/torsion bars	46										2				2	3	3																		0										7	3		
rear stabilizer bar linkage	47										1																								7	0									2			
steering gear/ rack	33				1								1			3	6				5						3										0			7								
steer hydraulics (pump, etc.)	34				1					2			1																								2	0										
steering column	35								5							3	6																				5		0									
tie rods	36																6				1		6	1			6	1	1								2			0								
steering linkage ball joints	37															3							2														5			7	0							
rear hub & bearing	38				2		1												5	1																						0	2					
rear spindle	39				2		1													1																							0	2	2			
rear upper control arm	40										5			2	2		4		4																									0	4			
rear lower control arm	41										5			2	2		4		4																									4	0			
rear shock absorber	42										5					3	3		3																								2	1	4	0		
tension struts (fore/aft control)	43										5			2		3	6		3							3																					0	
rear coil spring	44										5					3	3		3							3																		3	7	3		0

- boxes in matrix indicate activities handled by single organization/ sub-organization

mark indicates information transfer
types of information transfer:

1 - packaging envelope/ proximity information
2 - static design information (geometry, material strength, mass, orientation, location)
3 - compliance/ stiffness/ damping/ natural frequency information
4 - kinematic information (relative motion, force, moments, angular/linear displacement)
5 - compliance/stiffness and static design information
6 - kinematic and compliance information
7 - kinematic, compliance, and static design information

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The design tasks were described in Chapter 3. The are approximately numbered in the order they can occur, but, as was noted in Chapter 3, the process is highly flexible, with most of the chassis and vehicle dynamics tasks trying to occur simultaneously and iteratively. The tasks generally grouped by the following organizational design and release responsibilities:

- vehicle attributes - wheelbase, track, engine layout, load, engine, transmission, and exhaust packaging
- powertrain - engine, transaxle halfshafts, exhaust system design.
- body - body shell, fender, front structure/rails, dash panel, shock towers, and rear structure/rails
- vehicle dynamics - kinematic axis definition (including steer axis, pitch and roll axis, wheel travel), suspension geometry definition, compliance budget definition, vehicle response properties, front stabilizer torsion bars, bushing, mounts, isolators
- wheels/ tyres
- sub-frame
- brakes
- front suspension - knuckle, lower control arms, struts/shocks assembly, coil spring, ball joints.
- rear suspension - spindle, upper and lower control arms, shocks, coil springs, tension strut.
- steering - column, shaft, gear/rack, tie rod and ball joints, pump and fluid lines.

The cells of the DSM contain numbers zero through seven. Zero sits on the diagonal as a land marker for reading the map. The other numbers (one through seven) represent the types of design information transferred or exchanged from one task to the next. The numbers are ranked in order of increasing complexity and represent the following:

1 - packaging envelope/ proximity information/ requirements

2 - static design information/ requirements (geometry, material strength, mass, orientation, location)

3 - compliance/ stiffness/ natural frequency information/ requirements

4 - kinematic information/ requirements (relative motion, force, moments, angular/linear displacement)

5 - compliance/stiffness and static design information/ requirements

6 - kinematic and compliance information/ requirements

7 - kinematic, compliance, and static design information/ requirements

Some discussion on the DSM and the information types is needed, to support the analysis in the next section. Generally, information that is taken is a requirement or a constraint. This is particularly true for kinematic, compliance, and packaging information. The compliance budget can be thought of as providing both requirements and constraints. The kinematic axis definition and the vehicle response tasks provide requirements that the system must meet. Compliance budgets and vehicle response targets are generally achieved through iteration of component designs.

The static design information (which includes geometry and set-up) crosses fewer boundaries than the kinematic and compliance information, and is more often contained within a single organization. More importantly, there is very little backward dependency (iteration) around this information, and the iteration that does occur happens near the beginning of the chassis design process. One reason for this is the facilities and tooling time and costs involved with static design require that these designs to meet these requirements be fixed early and then be left alone.

6.6 Analysis of the Matrices: Applying the Heuristics

This section will apply the heuristics presented in Chapter 4 (and repeated in Section 6.1) to Matrix 3.1 (Joint Matrix) and Matrix 4 (DSM). The Joint Matrix is not an easy study, which is probably a reflection of the truth of Warfield's observation regarding self-imposed cognitive limits that was stated at the beginning of the chapter. Matrix 3 has 60 objective metrics, 30 components, and 28 different codes occupying the cell. Using the digital-decimal code described that was utilized in Chapter 5, Matrix 3.1 was developed. Although the coding algorithm made the matrix compact, interpreting the integers in the matrix is still difficult, due to the number of codes, objective metrics, and components that must be evaluated. For the case study, the Joint Matrix is much more complicated than the one developed in the example of Chapter 5. To help with the analysis, Figure 6.10 below was developed. The "code" column in the figure lists all the codes in Matrix 3.1 (in descending order), while the "no" column shows the number of objective metrics in the matrix that each code is able to affect. The marks in the attribute columns show the attribute combinations that each code represents.

Matrix 3.1: Objective Metrics Grouped by Organizational Ownership, linked to Components, and Attributes Using Binary-Digital Code

	DESIGN RESPONSIBILITIES	vehicle dynamics										front suspension							SF	chassis steering					rear suspension						
	SUSPENSION/ CHASSIS COMPONENTS VEHICLE & SYSTEM OBJECTIVES	front tyre / wheel	- rear tires	frnt stabilizer/torsion bars	front springs	front control arm bushings	- body mounts	- engine mounts	rear control arm bushings	- rear stabilizer/torsion bars	rear springs	front spindle	front hub & bearing	front knuckles	front control arms assy	front stabilizer bar linkage	frnt struts/ shock absorbers	front control arm ball joints	- subframe structure	- steering gear/ rack	steer hydraulics (pump, etc.)	- steering column	- tie rods	steering linkage ball joints	rear hub & bearing	rear spindle	- rear struts/ shock absorbers	- rear sta-bar link	- rear control arms assy.	BODY	POWERTRAIN
		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
suspension kinematics	Roll Centres and Roll Centre Migration	0	0	475	475	0	475	0	475	475	475	475	0	475	475	0	475	0	475	0	0	0	0	0	475	475	475	0	475	475	0
	Kinematic Steer Front Axle	0	0	0	0	0	0	0	0	0	0	415	0	415	415	0	415	0	0	415	0	0	415	415	0	0	0	0	0	0	415
	Kinematic Steer Rear Axle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	411	411	0	411	0	0
	Camber Change	0	0	0	0	0	0	0	0	0	0	0	0	0	475	0	475	475	0	0	0	0	0	0	0	0	0	0	0	0	0
	Front Axle Anti Dive / Anti Lift	0	0	0	475	475	475	475	0	0	0	0	0	0	475	0	475	475	0	0	0	0	0	0	0	0	0	0	0	475	0
	Rear Axle Anti Squat / Anti Lift	0	0	0	0	0	459	0	0	0	459	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	459	0	459	459	0
	Kinematic Steer Asymmetry Front	0	0	0	0	0	0	0	0	0	0	0	0	0	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Kinematic Steer Asymmetry Rear	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19	0	0
	Asymmetric Suspension Set Up	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
suspension compliance	Lateral Compliance Steer Front Axle	411	0	0	411	411	0	0	0	0	0	0	0	0	411	0	0	411	0	0	0	0	411	411	0	0	0	0	0	0	0
	Lateral Compliance Steer Rear Axle	0	411	0	0	0	0	0	411	0	411	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	411	411	0	0
	Lateral Stiffness Front Axle	0	0	283	283	0	0	0	0	0	0	283	0	0	283	283	0	0	283	0	0	0	0	0	0	0	0	0	0	0	0
	Lateral Stiffness Rear Axle	0	0	0	0	0	0	0	0	0	283	0	0	0	0	0	0	0	0	0	0	0	0	0	0	283	283	283	283	0	0
	Longitudinal Compliance Steer Front Axle	0	0	0	0	31	0	0	0	0	0	0	0	0	0	0	0	31	31	0	0	0	0	0	0	0	0	0	0	31	0
	Longitudinal Compliance Steer Rear Axle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	27	0
	Longitudinal Compliance Front Axle	0	0	0	0	479	0	0	0	0	0	0	0	0	0	0	0	479	0	0	0	0	0	0	0	0	0	0	0	0	0
	Longitudinal Compliance Rear Axle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	475	0	0
	Rubber Damping (Bushes)	0	0	0	0	476	0	0	476	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Camber Compliance Front/Rear	0	0	0	0	0	0	0	27	0	0	0	0	0	27	0	27	27	0	0	0	0	0	0	0	0	0	0	0	0	0
	Castor Stiffness	0	0	0	0	27	0	0	27	0	0	0	0	0	27	0	0	0	0	0	0	0	0	0	0	0	0	0	27	0	0
static geometry	Static Toe Front	0	0	0	0	0	0	0	0	0	0	63	63	63	63	0	0	0	0	63	0	0	63	63	0	0	0	0	0	63	0
	Static Toe Rear	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	0	0	27	27	0
	Trail	0	0	0	0	0	0	0	0	0	0	0	0	56	56	0	56	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Static Camber Front	0	0	0	0	0	0	0	0	0	0	0	0	0	511	0	511	511	0	0	0	0	0	0	0	0	0	0	0	0	0
	Static Camber Rear	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	475	0	475	0	0
	Camber Asymmetry Front	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	23	23	0	0	0	0	0	0	0	0	0	0	0	0	0
	Camber Asymmetry Rear	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	23	0	0
	Ackermann	0	0	0	0	0	0	0	0	0	0	0	0	59	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	59	0
	Castor	63	0	0	0	0	0	0	0	0	0	63	63	63	63	0	0	0	0	0	0	0	0	0	63	63	0	0	63	0	0
	Ground Offset / Scrub Radius	61	0	0	0	0	0	0	0	0	0	61	0	0	0	0	61	61	0	0	0	0	0	0	0	0	0	0	0	61	0
Suspension Set Up	Spring Stiffnesses / Ride Frequencies	0	0	0	475	0	0	0	0	0	475	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	475	0
	Bump Stops	0	0	0	459	0	0	0	0	0	0	0	0	0	0	0	459	0	0	0	0	0	0	0	0	0	0	0	0	459	0
	Rebound Springs / Rebound Stops	0	0	0	451	0	0	0	0	0	451	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	451	0
	Damping (low - mid - high speed)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	479	0	0	0	0	0	0	0	0	0	479	0	0	479	0
	Damper Mountings	0	0	0	0	0	473	0	0	0	0	0	0	0	0	0	473	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Anti Roll Bars Stiffness	0	0	479	0	0	0	0	0	479	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	479	0
	Anti Roll Bar Mountings	0	0	0	0	0	0	0	0	0	0	0	0	0	507	507	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Roll Stiffness Distribution	0	0	139	139	139	139	0	139	139	139	0	0	139	139	0	139	139	0	0	0	0	0	0	0	0	0	0	0	139	0
	Wheel Stroke / Suspension Travel	459	0	0	459	0	0	0	0	0	459	0	0	459	459	0	459	459	0	0	0	0	459	459	459	0	0	0	459	459	0
	Suspension System Hysteresis / Friction	0	0	0	0	473	473	473	473	0	0	0	0	0	0	0	473	0	0	0	0	0	0	0	0	0	473	0	0	0	0
Wheel Assembly	Tyre Characteristic and Build	511	511	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	511	0
	Tyre Pressure	507	507	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	507	0
	Tyre Imperfections	404	404	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tyre Section Width Front / Rear	11	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Wheel Balance	388	0	0	0	0	0	0	0	0	0	388	388	388	0	0	0	0	0	0	0	0	0	0	388	388	0	0	388	0	0
	Unsprung mass	0	0	0	0	0	0	0	0	0	0	0	0	412	412	0	412	0	412	412	0	0	0	0	412	0	412	0	412	0	412
Vehicle (general)	Wheelbase	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	427	0
	Track Width	0	0	0	0	0	0	0	0	0	0	27	0	27	27	0	0	0	27	0	0	0	27	0	27	27	0	0	27	27	0
	Centre of Gravity Height	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	411	0	411	0	0	0	0	0	0	0	411	0	0	411	411
	Weight distribution	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	11	0	0	0	0	0	0	0	11	0	0	11	11
	Front Axle Weight	0	0	56	0	0	0	0	0	0	0	0	0	0	56	0	56	0	56	56	0	56	0	0	0	0	0	0	56	56	56
	Overall mass of vehicle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	11	11
Steering System	Steering System Friction	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	63	0	63	63	0	0	63	0	0	0	0	0	0	0
	Steering Ratio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	63	0	0	0	0	0	0	0	0	0	0	0
	Power Steering (T-Bar and Boost Curve Char.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	61	61	0	0	0	0	0	0	0	0	0	0
	Strg. Column Velocity Change Effects (Joint Phasing)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	57	0	0	0	0	0	0	0	0	0
	Available Wheel Lock Angles	32	0	0	0	0	0	0	0	0	0	32	0	32	0	0	0	0	0	32	0	0	0	0	0	0	0	0	0	32	0
	Rack / Column Mounting Stiffness	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	415	0	0	0	0	0	0	0	0	0
	Steering Column Isolator	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	415	0	415	0	0	0	0	0	0	0	0	0
	Pinion Cross Over Angle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	44	0	44	0	0	0	0	0	0	0	0	0

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Using Figure 6.10, Matrix 3.1, and Matrix 4, the Organizational and PD process analysis perspectives will presented:

Figure 6.10 Joint Matrix Codes and Associated Attribute Combinations

		ATTRIBUTES									
		RIDE			STEERING				HANDLING		
	ATTRIBUTES	smooth road	rough road	abruptness/ harshness	parking	straight control	cornering control	disturbances/ pull/ nibble	straight stability	cornering stability	transitional
CODE	no	256	128	64	32	16	8	4	2	1	1
511	2	X	X	X	X	X	X	X	X	X	X
507	2	X	X	X	X	X	X	X		X	X
479	3	X	X	X		X	X	X	X	X	X
476	1	X	X	X		X	X	X			
475	6	X	X	X		X	X		X	X	X
473	2	X	X	X		X	X			X	X
459	3	X	X	X			X		X	X	X
451	1	X	X	X					X	X	X
427	1	X	X		X		X		X	X	X
415	3	X	X			X	X	X	X	X	X
412	1	X	X			X	X	X			
411	4	X	X			X	X		X	X	X
404	1	X	X			X		X			
388	1	X	X					X			
283	2	X				X	X		X	X	X
139	1		X				X		X	X	X
63	4				X	X	X	X	X	X	X
61	2				X	X	X	X		X	X
59	1				X	X	X		X	X	X
57	1				X	X	X			X	X
56	2				X	X	X				
44	1				X		X	X			
32	1				X						
31	1					X	X	X	X	X	X
27	5					X	X		X	X	X
23	3					X		X	X	X	X
19	2					X			X	X	X
11	3						X		X	X	X

Organizational Perspective:

⇒ Matrix 3.2 is moderately filled by codes representing the key attributes, and all the codes cross some group or organizational boundary, indicating that the management and communication will be somewhat difficult.

⇒ Matrix 3.2 shows that all attribute combinations that contain all ride and handling attributes (codes 451, 459, 475, 479, 507, and 511) cross most organizational boundaries. The linkages between vehicle dynamics and front suspension components (as represented by the information transferred between these the vehicle dynamics work group and the front suspension work group) make up the majority of marks. This indicates that these attributes are largely contained within these two groups, reducing the challenges to managing and communicating during the development of a derivative product.

⇒ The most significant challenge to the management of derivative product development will be the interaction with the Body organization, which is powerful. This alone may inhibit the ability to do a derivative product.

⇒ Matrix 3.2 shows that the attribute combinations that contain primarily steering and handling attributes (codes 23, 27, 31, 57, 59, 63) are largely controlled by the groups owning the front and rear suspension design and the steering system. There are some linkages with the vehicle dynamics and subframe group, as well as body engineering. Again, this suggests that management and communication issues will moderately inhibit the flexibility potential, and the interaction with Body could be a major issue.

⇒ The groups that design the steering and sub-frame systems have very few boundary interactions and few communication and management issues. However, they are also less influential.

⇒ Kinematic and compliance information cross several organizational and system boundaries. This suggests that managing these requirements will be difficult as responsibility for them is spread around and changes with time.

⇒ Packaging information also crosses many boundaries, and is the subject of traditional turf battles between organizations. The packaging and static design information provided by the body engineering and powertrain engineering can be considered fixed, due to the power of these organizations. This indicates they will be design drivers and will inhibit flexibility potential due to their resistance to change.

PD Process Perspective (DSM only)

⇒ As noted above, packaging and static design information for the body and powertrain cross boundaries. These elements are also developed early in the process and feed multiple design tasks, which again indicates that these will be design drivers and will inhibit the flexibility potential of the chassis.

⇒ Compliance and kinematic information is the most transferred information in the DSM. Many tasks are involved with determining this information. Targets are developed early in the process, but the information is developed iteratively across the core of the chassis tasks. This implies that they are probably not design drivers.

⇒ Compliance and kinematic information are iterated around a fairly large loop. Changes are cascaded, but they cascade as part of the planned process and are largely contained within the vehicle/chassis organization. This implies that they provide more flexibility potential than the packaging and static design information, which crosses body, powertrain, and vehicle/ chassis organization boundaries.

Before moving onto the Architectural Perspective, some additional matrices need to be introduced to aid in the Architecture perspective analysis. First, Figure 6.11 was developed based on Figure 6.10. The codes have been re-ordered and clustered by the attributes and sub-attributes that are being influenced. This will make it easier to see which attributes and sub-attributes are coupling and which (if any) are uncoupled.

Figure 6.11 Joint Matrix Codes Clustered By Attributes Influenced

			ATTRIBUTES									
			RIDE			STEERING				HANDLING		
INFLUENCE SUMMARY		ATTRIBUTES	smooth road	rough road	abruptness/ harshness	parking	straight control	cornering control	disturbances/ pull/ nibble	straight stability	cornering stability	transitional
	CODE	no	256	128	64	32	16	8	4	2	1	1
all sub-attributes	511	2	X	X	X	X	X	X	X	X	X	X
	507	2	X	X	X	X	X	X	X		X	X
	479	3	X	X	X		X	X	X	X	X	X
most sub-attributes	473	2	X	X	X		X	X			X	X
	427	1	X	X		X		X		X	X	X
	415	3	X	X			X	X	X	X	X	X
	411	4	X	X			X	X		X	X	X
ride & steering	476	1	X	X	X		X	X	X			
	412	1	X	X			X	X	X			
	404	1	X	X			X		X			
ride & handling	475	6	X	X	X		X	X		X	X	X
	459	3	X	X	X			X		X	X	X
	451	1	X	X	X					X	X	X
steering & handling	283	2	X				X	X		X	X	X
	63	4				X	X	X	X	X	X	X
	61	2				X	X	X	X		X	X
	59	1				X	X	X		X	X	X
	57	1				X	X	X			X	X
	31	1					X	X	X	X	X	X
	27	5					X	X		X	X	X
	23	3					X		X	X	X	X
ride	388	1	X	X					X			
steering	56	2				X	X	X				
	44	1				X		X	X			
	32	1				X						
handling	139	1		X				X		X	X	X
	19	2					X			X	X	X
	11	3						X		X	X	X
		60										

Matrix 3.2: Objective Metrics Grouped by Attribute Combinations, Linked to Components Via Attribute Codes

	DESIGN RESPONSIBILITIES	vehicle dynamics										front suspension							SF	chassis steering					rear suspension						
	SUSPENSION/ CHASSIS COMPONENTS VEHICLE & SYSTEM OBJECTIVES	front tyre / wheel	- rear tires	frnt stabilizer/torsion bars	front springs	front control arm bushings	- body mounts	- engine mounts	rear control arm bushings	- rear stabilizer/torsion bars	rear springs	front spindle	front hub & bearing	front knuckles	front control arms assy.	front stabilizer bar linkage	frnt struts/ shock absorbers	front control arm ball joints	- subframe structure	- steering gear/ rack	steer hydraulics (pump, etc.)	- steering column	- tie rods	steering linkage ball joints	rear hub & bearing	rear spindle	- rear struts/ shock absorbers	- rear sta-bar link	- rear control arms assy.	BODY	POWERTRAIN
most ride steering handling attributes	Static Camber Front	0	0	0	0	0	0	0	0	0	0	0	0	0	511	0	511	511	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tyre Characteristic and Build	511	511	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	511	0
	Anti Roll Bar Mountings	0	0	0	0	0	0	0	0	0	0	0	0	0	507	507	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Tyre Pressure	507	507	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	507	0
	Damping (low - mid - high speed)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	479	0	0	0	0	0	0	0	0	0	479	0	0	479	0
	Anti Roll Bars Stiffness	0	0	479	0	0	0	0	0	479	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	479	0
	Longitudinal Compliance Front Axle	0	0	0	0	479	0	0	0	0	0	0	0	0	0	0	0	479	0	0	0	0	0	0	0	0	0	0	0	0	0
some ride steering handling attributes	Damper Mountings	0	0	0	0	0	473	0	0	0	0	0	0	0	0	0	473	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Suspension System Hysteresis / Friction	0	0	0	0	473	473	473	473	0	0	0	0	0	0	0	473	0	0	0	0	0	0	0	0	0	473	0	0	0	0
	Wheelbase	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	427	0
	Kinematic Steer Front Axle	0	0	0	0	0	0	0	0	0	0	415	0	415	415	0	415	0	0	415	0	0	415	415	0	0	0	0	0	0	415
	Steering Column Isolator	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	415	0	415	0	0	0	0	0	0	0	0	0
	Rack / Column Mounting Stiffness	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	415	0	0	0	0	0	0	0	0	0
	Lateral Compliance Steer Front Axle	411	0	0	411	411	0	0	0	0	0	0	0	0	411	0	0	411	0	0	0	0	411	411	0	0	0	0	0	0	0
	Lateral Compliance Steer Rear Axle	0	411	0	0	0	0	0	411	0	411	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	411	411	0	0
	Kinematic Steer Rear Axle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	411	411	0	411	0	0
	Centre of Gravity Height	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	411	0	411	0	0	0	0	0	0	0	411	0	0	411	411
ride steering	Rubber Damping (Bushes)	0	0	0	0	476	0	0	476	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Unsprung mass	0	0	0	0	0	0	0	0	0	0	0	0	412	412	0	412	0	412	412	0	0	0	0	412	0	412	0	412	0	412
	Tyre Imperfections	404	404	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ride handling attributes	Roll Centres and Roll Centre Migration	0	0	475	475	0	475	0	475	475	475	475	0	475	475	0	475	0	475	0	0	0	0	0	475	475	475	0	475	475	0
	Camber Change	0	0	0	0	0	0	0	0	0	0	0	0	0	475	0	475	475	0	0	0	0	0	0	0	0	0	0	0	0	0
	Longitudinal Compliance Rear Axle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	475	0	0
	Front Axle Anti Dive / Anti Lift	0	0	0	475	475	475	475	0	0	0	0	0	0	475	0	475	475	0	0	0	0	0	0	0	0	0	0	0	475	0
	Spring Stiffnesses / Ride Frequencies	0	0	0	475	0	0	0	0	0	475	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	475	0
	Static Camber Rear	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	475	0	475	0	0
	Wheel Stroke / Suspension Travel	459	0	0	459	0	0	0	0	0	459	0	0	459	459	0	459	459	0	0	0	0	459	459	459	0	0	0	459	459	0
	Rear Axle Anti Squat / Anti Lift	0	0	0	0	0	459	0	0	0	459	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	459	0	459	459	0
	Bump Stops	0	0	0	459	0	0	0	0	0	0	0	0	0	0	0	459	0	0	0	0	0	0	0	0	0	0	0	0	459	0
	Rebound Springs / Rebound Stops	0	0	0	451	0	0	0	0	0	451	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	451	0
steering handling attributes	Lateral Stiffness Front Axle	0	0	283	283	0	0	0	0	0	0	283	0	0	283	283	0	0	283	0	0	0	0	0	0	0	0	0	0	0	0
	Lateral Stiffness Rear Axle	0	0	0	0	0	0	0	0	0	283	0	0	0	0	0	0	0	0	0	0	0	0	0	0	283	283	283	283	0	0
	Static Toe Front	0	0	0	0	0	0	0	0	0	0	63	63	63	63	0	0	0	0	63	0	0	63	63	0	0	0	0	0	63	0
	Castor	63	0	0	0	0	0	0	0	0	0	63	63	63	63	0	0	0	0	0	0	0	0	0	63	63	0	0	63	0	0
	Steering System Friction	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	63	0	63	63	0	0	63	0	0	0	0	0	0	0
	Steering Ratio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	63	0	0	0	0	0	0	0	0	0	0	0
	Ground Offset / Scrub Radius	61	0	0	0	0	0	0	0	0	0	61	0	0	0	0	61	61	0	0	0	0	0	0	0	0	0	0	0	61	0
	Power Steering (T-Bar and Boost Curve Char.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	61	61	0	0	0	0	0	0	0	0	0	0
	Ackermann	0	0	0	0	0	0	0	0	0	0	0	0	59	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	59	0
	Strg. Column Velocity Change Effects (Joint Phasing)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	57	0	0	0	0	0	0	0	0	0
	Longitudinal Compliance Steer Front Axle	0	0	0	0	31	0	0	0	0	0	0	0	0	0	0	0	31	31	0	0	0	0	0	0	0	0	0	0	31	0
	Longitudinal Compliance Steer Rear Axle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	27	0
	Camber Compliance Front/Rear	0	0	0	0	0	0	0	27	0	0	0	0	0	27	0	27	27	0	0	0	0	0	0	0	0	0	0	0	0	0
	Castor Stiffness	0	0	0	0	27	0	0	27	0	0	0	0	0	27	0	0	0	0	0	0	0	0	0	0	0	0	0	27	0	0
	Static Toe Rear	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	0	0	27	27	0
	Track Width	0	0	0	0	0	0	0	0	0	0	27	0	27	27	0	0	0	27	0	0	0	27	0	27	27	0	0	27	27	0
	Camber Asymmetry Front	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	23	23	0	0	0	0	0	0	0	0	0	0	0	0	0
	Camber Asymmetry Rear	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	23	0	0
	Asymmetric Suspension Set Up	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ride	Wheel Balance	388	0	0	0	0	0	0	0	0	0	388	388	388	0	0	0	0	0	0	0	0	0	0	388	388	0	0	388	0	0
steering	Trail	0	0	0	0	0	0	0	0	0	0	0	0	56	56	0	56	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Front Axle Weight	0	0	56	0	0	0	0	0	0	0	0	0	0	56	0	56	0	56	56	0	56	0	0	0	0	0	0	56	56	56
	Pinion Cross Over Angle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	44	0	44	0	0	0	0	0	0	0	0	0
	Available Wheel Lock Angles	32	0	0	0	0	0	0	0	0	0	32	0	32	0	0	0	0	0	32	0	0	0	0	0	0	0	0	0	32	0
handling	Roll Stiffness Distribution	0	0	139	139	139	139	0	139	139	139	0	0	139	139	0	139	139	0	0	0	0	0	0	0	0	0	0	0	139	0
	Kinematic Steer Asymmetry Front	0	0	0	0	0	0	0	0	0	0	0	0	0	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Kinematic Steer Asymmetry Rear	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19	0	0
	Weight distribution	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	11	0	0	0	0	0	0	0	11	0	0	11	11
	Overall mass of vehicle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	11	11
	Tyre Section Width Front / Rear	11	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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To further help this analysis, the rows in Matrix 3.1 were clustered according to the 8 code groupings identified in Figure 6.11, creating Matrix 3.2. The groupings are boxed in Matrix 3.2, and give a clearer picture of the relation between attributes, objective metrics, and components.

The Architectural perspective is the most difficult one to follow for this case, due to the size and complexity of the Joint Matrix. The analysis below will start with a set of observations on Matrix 3.1 and Matrix 3.2. This will be followed by implications and conclusions based on the observations.

Continuing with the heuristics:

Architecture Perspective: Observations on Matrix 3.1 and Matrix 3.2

- ⇒ As shown in Figure 6.11, there are 28 unique attribute combinations needed to represent the information in Matrix 3, out of a possible 60. This indicates that the attributes are highly coupled with the objective metrics and that this is a complex architecture with complicated physical interactions.
- ⇒ There are 8 primary combinations:
    - ⇒ contain all sub-attributes of all three attributes: 479, 507, 511
    - ⇒ contain most sub-attributes of all three attributes : 411, 415, 427, 473
    - ⇒ contain primarily ride and handling sub-attributes: 451, 459, 475
    - ⇒ contain primarily ride and steering sub-attributes: 404, 412, 476
    - ⇒ contain primarily steering and handling sub-attributes: 23, 27, 31, 57, 59, 61, 63, 283
    - ⇒ contain primarily ride attributes: 388
    - ⇒ contain primarily steering attributes: 32, 44, 56
    - ⇒ contain primarily handling attributes: 11, 19, 139
- ⇒ The ride sub-attributes generally appear together, meaning they are influenced by the same components. If a component has an influence on one ride sub-attribute, it usually also influences a second ride sub-attribute. The smooth and rough road continuous event sub-attributes appear most often together.
- ⇒ The three handling attributes generally appear together, indicating that they are coupled or share dependencies.
- ⇒ The steering and handling attributes are strongly coupled, have more combinations, and appear more often in the matrices. Cornering controllability and stability, and straight ahead controllability and stability appear to be coupled because they often appear together.

⇒ Ride and handling are moderately coupled.

⇒ The sub-attributes for ride do not separate cleanly a majority of the time. The "ride" -only combination (code 388) is a single line, which is tied to the objective metric wheel balance. This indicates little flexibility potential in this particular path.

⇒ In Matrix 3.1 (or Matrix 3.2), there is no attribute that is dependent on a single component. Likewise, there is no component that affects just a single attribute.

⇒ Matrix 3.2 shows that all attribute combinations that contain all ride and handling attributes (codes 451, 459, 475, 479, and 511) cross most organizational boundaries. However, the linkages between vehicle dynamics and front suspension components are particularly numerous, indicating significant points of leverage and interaction. Steering and sub-frame are less influential and have very few boundary interactions around these attributes.

⇒ Steering components have little affect on ride. They do not appear often with ride or ride and handling attributes, and do not affect the primary ride objective metrics (kinematics and suspension set-up). Steering can not support flexibility potential on ride.

⇒ The rear suspension's primary effect on ride and handling is through the rear axle stiffness. The components of the rear suspension can strongly affect ride.

⇒ The handling-only attribute combinations are linked primarily with the vehicle dynamic components and front suspension components, mainly through the roll stiffness distribution objective metric, which is a compliance metric.

    ⇒ the front stabilizer bar, front springs, front control arm bushings, body mounts are vehicle dynamic components that can be adjusted

    ⇒ front knuckle, front control arm, front shocks, and front control arm ball joints are front suspension components that can be adjusted.

⇒ The steering-only attribute combinations are influenced by the front suspension and steering components.

⇒ Tie rods and steering linkage ball joints primarily affect handling, by influencing wheel travel and toe

⇒ Front suspension components greatly influence almost all ride, steering, and handling sub-attributes. For some components, the influence is transmitted via several objectives for each sub-attribute.

⇒ For instance, the lower control arms affect ride, steering, and handling attributes by influencing the camber and the kinematics of the front suspension. It affects ride and handling by influencing roll center/ roll center migration, camber change, and wheel travel (which are related). The lower control arm affects steering and handling through its influence on suspension lateral stiffness, toe, castor, ackermann angle, and overall suspension asymmetry. Through its influence on trail, it can affect steering, particularly parking and straight and cornering controllability. Through its influence on roll stiffness distribution, it can affect handling.

⇒ Coil springs primarily affect ride and handling attributes, by influencing roll center, roll stiffness distribution, ride stiffness, pitch, suspension travel. The coil springs do not affect steering greatly, except through its influence on roll and cornering controllability.

⇒ Front shock absorbers influence primarily ride and handling attributes, by affecting and controlling damping, suspension travel, roll center, roll stiffness distribution, camber, pitch (anti-lift/ anti-squat), scrub radius. The shock absorbers do affect steering via the effect on camber.

⇒ Body mounts primarily affect ride and handling attributes, by influencing suspension hysteresis, damping, roll center migration, pitch, and roll stiffness distribution. Again, the primary effect on steering is the influence on the cornering controllability attribute.

⇒ Front stabilizer bar affects primarily ride and handling through the roll center and roll center migration. It affects steering and handling through its influence on the lateral stiffness of the suspension. It affects handling through its influence on the roll stiffness distribution.

⇒ Bushings (particularly front control arm) affect ride, steering, and handling through longitudinal and lateral damping, affects ride and handling through pitch influence, affects steering and handling through longitudinal compliance influence, and affects handling through roll stiffness distribution influence.

Architecture Perspective: Implications and Conclusions

⇒ Ride and steering are less strongly coupled than steering and handling or ride and handling. There are few codes and few occurrences of their combination in the matrix. This suggests that there are few opportunities for affecting these two attributes simultaneously.

⇒ The front suspension and the steering systems have multiple leverage points (in terms of components) on the steering attributes but also can influence the same attributes via the same objective metrics. This implies these provide flexibility potential for steering.

⇒ Shocks, springs, stabilizer bars, body mounts and bushings all affect stiffness/ compliance. The linkages noted in the observations suggest that these provide leverage for flexibility potential on ride and handling in particular, with some affect on steering. That there are multiple components to use as levers suggests that the range can be broad. However, the engineering and the physics of performance prediction will be difficult.

⇒ The static design of the front suspension, particularly the knuckle (and its connection to the tie rods), the lower control arm, and the strut angle set up the kinematics axis of the front end. As noted in the observations, the components influence all the key attributes but primarily ride and handling. This implies these offer multiple levers for flexibility potential on ride and handling but, again, the physics and the engineering will be difficult to sort out.

⇒ The lower control arm and the knuckle, besides offering flexibility potential on ride and handling, can also influence steering, particularly by affecting ackermann angles, trails, and scrub radius. Thus, it offers an extra degree of flexibility potential.

⇒ The coil springs, various bushings, and stabilizer bars, along with the static design, complete the definition of kinematics, including suspension travel, pitch, camber change, and roll center migration. Again, as captured in the observations, each of these components can influence multiple attributes, suggesting flexibility potential but difficult engineering physics.

⇒ The statements above, suggest that kinematics, compliance, and suspension set-up objective metrics are the most active, which is further evidenced by the relative density of marks on their lines. They provide more paths of dependence between the components and the attributes. Also, they generally affect a couple of sub-attributes for each attribute. This suggests that the components in these sets provide flexibility potential.

⇒ In the DSM, compliance information is the most common information that is exchanged between systems and crosses many organizational boundaries. Compliance is also iteratively determined. This suggests that compliance offers flexibility potential.

⇒ In the DSM, kinematics information is also exchanged often, and crosses many organizational boundaries. The kinematics is subject to some iteration, but not nearly as much as compliance. This suggests that kinematics offers some flexibility potential, but only as much as the static design and packaging will allow.

⇒ Packaging and static design information are not highly iterative information, which indicates they do not offer significant flexibility potential to the chassis-influenced attributes.

6.7 Case Study: Summary and Real-world Relevance

The analysis of the Joint Matrix and the DSM using the heuristics from Chapter 4 provided the following conclusions:

- The management of chassis derivatives will be moderately complicated by the organizational linkages.
- Suspension set-up, kinematics and compliance provide the best flexibility potential for chassis-influenced vehicle performance attributes (ride, handling and steering). They provide opportunities for changing key consumer-perceived attributes. Together, they define the total vehicle dynamics character of the automobile. This suggests that suspension set-up, kinematics and compliance provide leverage points on multiple attributes and that they provide flexibility potential for chassis-influenced vehicle performance attributes (ride, handling and steering).
- Kinematics and compliance offer the possibility of extending the range of the derivative due to influence on the same attributes.
- Suspension set-up components provide leverage points on multiple vehicle dynamics sub-attributes, particularly ride and handling. However, suspension set-up (particularly geometry and kinematic axis definition) is not subject to extensive iteration (this may not be evident from DSM, due to the information aggregation). Aspects of these components tend to become constraints once set, due to tooling lead-time requirements. Thus, for derivative products that are known from the beginning, there are opportunities offered by the suspension design and set-up.
- Once this stage is past and the static design and packaging information have been set, the primary recourse for effecting a derivative chassis is through the kinematics and compliance objective metrics. As shown in the DSM, only kinematics and compliance requirements have the latitude (as represented by iteration) to change late in the process.

The DSM captures an observation made in Chapter 3 about the process. At first, the primary task of the chassis design engineer is hitting the cost, weight, and packaging requirements. The design is changing very little in terms of desired functional performance. Design engineers often lament how few opportunities they get to actually design and engineer a product. During the design process, vehicle response targets are generally achieved through iteration of component designs in response to subjective management review drives. This occurs only after full vehicles are available. this is the largest source of iteration, and is due to the variation between the predicted behavior of the vehicle and the actual behavior after integration of the systems and chunks has occurred.

According to Senge [1990] small changes can produce big results. However, the areas of highest leverage are often the least obvious. One of the goals of this method has been to highlight some these leverage points and identify when they can and cannot be activated. The summary above provides guidance for affecting key consumer-perceived attributes, but a couple of examples may help illustrate the messages in this Chapter

First, consider the Ford Mustang, which competes in the small sports car market. Two primary derivatives (some would call them variations) are the GT and the coupe. The body sheetmetal between the two vehicles are not significantly different. The primary differences are the powertrain (V8 engine is standard in the GT, optional in the coupe), the price (the GT can be $5,000 more expensive), and the ride and handling characteristics. The two versions do reach different markets: the GT attracts about 30% female buyers, while the coupe attracts about 65 % female buyers. Engineers on the vehicle think that the difference in ride and handling is the main factor in this market difference. The GT has a traditional sports car ride that emphasizes road feel, precise, responsive handling, and lots of torque feel in the steering. The coupe has a softer, less harsh, ride and has handling and steering that is easier (low effort) and more forgiving. This is accomplished by using different springs, shocks, stabilizer bars, and steering boost curves to affect the ride, handling, and steering characteristics, and then tuning the ride and handling by changing bushings and mounts for the body, powertrain, and suspension linkages. An important point also is that the range of the attributes, particularly ride and handling, although invisible to the eye, is not imperceptible by the consumer. Without the multiple leverage points, the components could not get the ride and handling to change over the range needed to satisfy the males who prefer the GT and the females who prefer the coupe.

Regarding leverage points, an objective metric that affects several attributes and is tied to several components could be an excellent leverage point, if it can changed correctly. Of course, changing one such objective (by changing a component) would probably require other changes. In the absence of good predictive CAE models, this implies experimentation (using a full vehicle) to optimize the total vehicle performance. This is exactly how tuning of vehicle dynamics is done. This analysis reveals the reasons behind this methodology.

Next, consider doing an all-wheel-drive derivative off a current front-wheel-drive vehicle, with a goal of maximum chassis component commonality to minimize tooling investment and assembly plant changes. From Matrix 3.2 and Matrix 4, the difficulties are clear. The vehicle packaging and static design must be completely revised to support a driveshaft to the rear of the vehicle, and the rear suspension must be revised to support the new components. This alone is a major engineering task. However, the new design will also impact vehicle weight and center of gravity, which affects the ride and handling of the vehicle. The suspension geometry will be affected, which will require tooling investment and lead time. Eventually, nearly all the major chassis components will be affected. In this example, there are no good leverage points, because the change affects some of the design drivers that do not flexibility potential.

The functions of the chassis in Section 6.3 and the results of the analysis suggest that, because the chassis functions as an interface and one of its functions is to provide a path for interactions, coupling is fundamental to its architecture. That might account for the need to violate of some of the good design guidelines presented in Chapter 3. Another observation is that the consumer-perceived attributes of vehicle dynamics are coupled in the eyes of the consumer, which makes it difficult for the objective metrics to uncouple cleanly. As noted in Chapter 4, coupling of attributes sets up a need for linkages, to provide more levers and to allow flexibility potential.

The strategy for chassis flexibility potential is not to try to use all components to attack all attributes. Rather, it is like the Taguchi approach to robustness, which is to reduce variability in a design parameter and then to adjust (or tune) the mean appropriately. In the case of chassis, the coarse characteristics of ride, steering, and handling (particularly straight ahead, pitch and rough road performance) are set-up with the suspension geometry and body attachments. Then the finer aspects (particularly cornering performance and harshness) are tuned via compliance and stiffness by changing springs, shocks, bushings, and mounts. This requires iteration and experimentation to learn how to tune a given architecture.

BMW, Honda, and Toyota create this learning by using fairly common architectures (although not necessarily common parts) across several platforms. By doing this across several vehicles and over years of development work, they learn which levers provide pressure and sensitivity on a set of attributes. As a result, their vehicles are consistently rated (by car experts and consumers) as among the best in their classes for vehicle dynamics performance. Interestingly, they are each using a different fundamental architecture strategy to achieve this excellence.

6.8 Chapter Summary and Closing Comments

This chapter presented a case study that utilized the methodology and heuristics described in Chapter 4 to evaluate the complexity and flexibility potential of a front-wheel drive automobile chassis. The methodology allowed the complexity of the architecture to be captured and visualized, using a set of matrices. The methodology also suggested a set of leverage points that could be used to enhance flexibility potential. The matrices highlighted the idea that suspension set-up, kinematics and compliance have the greatest affect on vehicle performance, in terms of ride dynamics, handling and steering, and provide flexibility potential. However, as shown in the DSM, only kinematics and compliance requirements have the latitude to change late in the process.

A recommendation supported by this study is that, rather than using different architectures across its products, Ford should identify a corporate architecture for suspension and refine its expertise and knowledge of the interactions, sensitivity, flexibility potential, and manufacturability. Companies such as BMW, Honda, and Toyota are currently using this approach. It will take time and capital investment in assets (changes in tooling and plant fixtures) but, in the long run, Ford's ability to quickly develop derivative products would be enhanced.

Another recommendation is to plan for derivatives or to not do them. This is particularly important with front-wheel drive vehicles, where packaging constraints in the front end can eliminate the ability to support a derivative product. Planning will be discussed further in Chapter 7.

Some final comment are appropriate on the method and the heuristics. First, one of the areas of interest for this study involved the achievable attribute range that could be supported by flexibility potential in a component. The conclusions above provide qualitative guidance but do not support a definitive answer to how large a range can be achieved. This is a shortcoming in this method, with respect to objectives of this thesis. Second, the method and heuristics were overwhelmed by the number of objective metrics, components, and linkages captured in Matrix 3. The codes made the matrix compact, but did not help clarify relations without deep study. Nothing appeared to be uncoupled, and it was necessary to modify this matrix (creating Matrix 3.2) to move the analysis forward. Also, knowledge of chassis design was needed to help draw out the conclusions. This is also a shortcoming in the method that the case study has exposed.

The next chapter focuses on how the organization elements and the management strategy impact the ability to develop derivative products. It will draw on some of the organizational and process insights developed in this chapter, as well as on industry and academic examples.

Chapter

7 Organizational Strategies For Derivative Product Development

The automotive industry is a tough, competitive, investment-draining industry. Any legal advantage that can be found, be it an improved business strategy or technological innovation, is welcomed, studied and, more often than not, implemented by somebody, somewhere, some how. Derivative products, although not new, [Freyssenet et al., 1998] identify them as part of the Sloanist model, after Alfred P. Sloan, who championed the idea of derivative products at General Motors in the 1930's), offer cost-efficient strategies for reaching new markets and new consumers, as noted in previous chapters. As Freyssenet points out, derivative products offer a resolution to the contradiction between economies of scale and product diversity. But often, an organization's make-up (its DNA, to use a popular analogy) can hinder its attempt at doing derivatives.

This chapter focuses on different strategies for managing derivative products in a company that is developing many products simultaneously. Cusumano and Nobeoka [1998] label such an environment multi-project, and this chapter will use their work and others (including the three lenses of Anacona, Kochan, et al. [1996] as starting points and frameworks for analyzing the current approach to derivatives used at Ford Motor Company. The different frameworks will be introduced first. Then the frameworks will be used to describe and evaluate Ford's approach to derivative product development , the political and cultural environment at Ford, and the Chassis and Vehicle Engineering organization design. These discussions will incorporate organizational and strategy insights from Chapter 6 . Industry examples and academic suggestions will be then be used to illustrate alternate management strategies for derivative product development. Finally, suggestions for improving Ford Motor Company's approach to the management of derivative product development, and potential roadblocks associated with those suggestions, will be presented and discussed.

7.1 Organization and Management Strategy: Analysis Frameworks

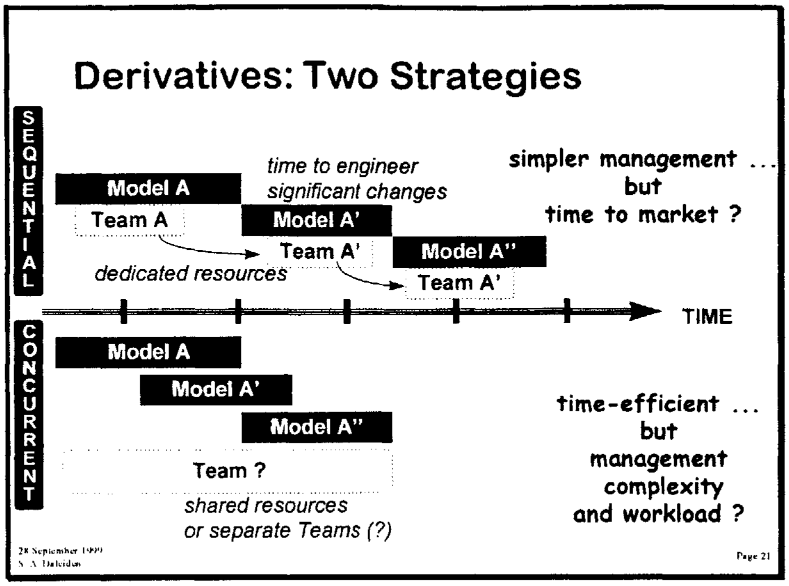
Before proceeding to examine Ford Motor Company's organization and its effect on its management strategy for derivative product development, the frameworks that will be used for analyzing and discussing different aspects of the company's organization will be presented.

All product development teams at Ford work in what Cusumano and Noebeka [1998] have designated as a "multi-project environment". Essentially, at any given time, there are different products at different stages of development throughout the company, and that each of these products is important enough to justify investing resources. Such an environment puts different demands on resources and management attention than an environment that handle single, unique projects. There are also different approaches that can be taken to managing the resources and demands of multiple projects. Cusumano and Noebeka introduced 4 types of multi-project strategies that could be used:

- New design - brand new architecture/ platform.
- Concurrent technology transfer - new project uses architecture/ platform still under development.
- Sequential technology transfer - new project uses architecture/ platform that is recently developed.
- Design modification - new project uses very mature architecture/ platform.

Although Cusumano and Noebeka describe projects in terms of technology, they treat platforms and new products as technology. **Error! Reference source not found.** provides examples of concurrent technology transfer and sequential technology transfer, two strategies that will be discussed later in this chapter. In the sequential case, a product team develops Model A, then Model A', and then Model A" serially, completing each effort before starting the next, and using elements from the preceding model to develop the following model. This is simpler to manage, due to less simultaneous activity, which reduces the need for coordination, and there is more time to do the engineering. However, the derivative products risk being late to market, when the competition will be stiffer and the profits lower.

Figure 7.1 Two Strategies for Derivative Product Development



Derivatives: Two Strategies

SEQUENTIAL

Model A

Team A

time to engineer
significant changes

Model A'

Team A'

Model A"

Team A'

dedicated resources

simpler management ...
but
time to market ?

TIME

CONCURRENT

Model A

Model A'

Model A"

Team ?

shared resources
or separate Teams (?)

time-efficient ...
but
management
complexity
and workload ?

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In the concurrent example, the Model A and its derivatives A' and A" are developed concurrently (or nearly so). The products may be handled by the same teams or by separate teams. The product timing is vastly improved however the management challenge and the need for communication are greater. The work load on the company is also greater, making the cross-company allocation of resources an issue.

The model and diagram above provide a framework for looking at a derivative product strategy inside a company. But the company itself is also a factor in successful derivative product strategies. To analyze organizations, Anacona, Kochan et al. [1996] describe the use of three perspectives, or "lenses", that can be used as frameworks for developing insights. The three lenses are:

- Strategic design, which looks at the physical structure of the organization, formal hierarchies, roles and responsibilities, and information and task flow.
- Political, which looks at the distribution and application of power and influence.
- Cultural, which looks at the traditions and assumptions that govern employee behaviors and create informal hierarchies.

Viewing an organization through the three lenses establishes a more holistic understanding of the organization, because it takes into account the formal and the informal, the prescribed and the intuitive.

Ancona, Kochan, et al. [1996] also provide a set of identifiers for a classical formal organization. In particular, they have identified five key features that are present in the classical organization:

1. Clearly delineated specialized individual positions and jobs
2. Formal hierarchy of positions, with clearly defined lines of authority and power
3. Formal rules and standard operating procedures that govern activities
4. Set boundaries for each department and sub-unit
5. Standardized training and training requirements, career paths, reward systems

As a counter-point, they have identified a set of key features for a new organization model:

- Networked - internally emphasizing cross-functional teams and building relationships with suppliers
- Flat - fewer layers of management
- Flexible
- Diverse
- Global

Together, the features for the classical organization and the features of the new organization provide a framework for evaluating an organization and understanding any changes or attempted changes. As these authors point out , embracing the new organization requires giving up some of the predictability and control associated with the classical organizations.

Power is a key element in the political lens, and understanding power is important to understanding a company. To support an analysis of power, Pfeffer [1992] lists four primary sources of power:

- Control over resources - the person with the gold makes the rules
- Control over or extensive access to information and communication
- Formal authority (position, expertise; personal charisma
- Subunit unity and expertise at solving problems

Pfeffer's list can act a framework for analyzing power in an organization, and can support the framework of the three perspectives described above.

These concepts above provide frameworks and guidance for evaluating an organization and how it operates. The next chapters will apply these analysis tools to Ford Motor Company and its strategy on derivative products development.

7.2 Ford Motor Company: Current Derivative Product Strategies

Ford uses the two approaches to derivative products shown previously in Figure 7.1. The first approach uses an existing product (either mature or recently launched) to provide the basics (powertrain, chassis components, under-body structure) for a new product. There is no established protocol about maintaining the product team from the original product to work on the new product. The difficulties with this sequential approach revolve around the inability of the base product to accommodate sufficient changes to support the derivative. Also, this result sometimes results in the product being viewed as late to market or as a knock-off. Other times, it has created a market.

The other approach has been to develop derivatives products together. The same team develops both products concurrently, which invariably leads to a sharing of nearly every component except for a few body panels, interior trim colors, and maybe special options. For instance, the 1996-1998 Ford Taurus SHO had a unique engine, wheel, tires, fascias, and decklid wing. The 2000 Mercury Sable, which is considered upscale from the Ford Taurus, is available with power adjustable pedals and has unique hood, fenders, decklid, and headlamps.

The fragility of the concurrent approach, as executed by Ford, lies in the consumer's perception of what is different. Although the company, engineering team, and the marketing managers intend the products to be derivatives and to attract different consumers, the final products are not viewed, by the consumer, as being different. Derivatives of this type are often called "sisters" or "twins", because they have achieved little differentiation in terms of architecture or consumers. For example, the basic architectures of derivative vehicle lines (such as the Ford Taurus and the Mercury Sable, the Ford Crown Victoria and the Mercury Grand Marquis, the Ford Expedition and Mercury Navigator) are not extensively differentiated, and they are generally recognized as sister products. Table 7.1 below presents some simple, traditional demographics for some derivatives that are generally recognized as "twins".

Table 7.1 Comparison Of Consumer Demographics For Selected Derivative "Twins

VEHICLE (STRATEGY)	AVERAGE AGE (years)	AVERAGE INCOME (thousands of dollars)	FEMALE (%)	COLLEGE GRAD (%)
Ford Expedition (S-b)	41	93	47	60
Lincoln Navigator (S)	47	139	35	61
Ford Explorer (S-b)	45	72	46	53
Mercury Mountaineer (S)	50	84	41	56
Ford Taurus (C -b)	53	52	48	43
Mercury Sable (C)	58	60	46	44
Ford Crown Victoria (C)	66	53	35	32
Mercury Grand Marquis (C)	68	55	25	30
Lincoln Town Car (C-b)	67	80	28	36

(C)	Concurrent Development Strategy - derivative
(C-b)	Concurrent Development Strategy - base vehicle
(S)	Sequential Development Strategy - derivative
(S-b)	Sequential Development Strategy - base vehicle

SOURCE: Internal Ford Survey

In the table, derivative vehicles developed using a concurrent strategy are marked with (C) after the product name, while the sequential strategy vehicles are marked by (S). The base vehicle for each set of twins is also labeled with a (-b).

In Table 7.1, only the Lincoln products, particularly the Navigator, attract significantly different customers (wealthier, more males). This is probably due more to brand image than design differences. For the other vehicles, this data suggests that, rather than attracting consumers from different market segments, the twins are competing against each other for the same consumers in the same market. Of course, there may be more relevant demographics by which to segment markets. For instance, "needs-based" segmentation might provide different results, although that seems unlikely, given the similar functional abilities and options available on the sister car lines. Some consumers respond to the brand image but the products are not providing anything unique for their consumers.

Contrast Table 7.1 with Table 7.2, which looks at derivatives that are not considered twins, and that the buying public may not realize are related (except for the Escorts and the Mustangs). The Escort and Cougar derivatives achieve a much lower age group than their base products. They are also visually different from the base products, designed to look sporty, and also designed to feel sporty, compared to the base products. As noted in Chapter 6, the Mustang coupe is much more popular with females than the GT version, even though there is little visual differentiation (the GT has a rear decklid spoiler and slightly different fascias).

TABLE 7.2 Comparison Of Consumer Demographics For Selected Derivative Vehicles

VEHICLE (STRATEGY)	AVERAGE AGE (years)	AVERAGE INCOME (thousands of dollars)	FEMALE (%)	COLLEGE GRAD (%)
Ford Contour (S-b)	47	46	53	34
Mercury Cougar (S)	38	56	62	46
Ford Escort (S-b)	48	40	62	31
Ford Escort ZX2 (S)	37	42	57	30
Ford Mustang Coupe (C-b)	42	75	65	33
Ford Mustang GT (C)	46	85	35	28
Toyota Camry (S-b)	51	63	54	24
Toyota Avalon (S)	50	86	43	31
Toyota Solara (S)	56	68	48	36
VW Passat (C-?)	39	85	44	31
Audi A6 (C-?)	51	140	30	29

(C)	Concurrent Development Strategy - derivative
(C-b)	Concurrent Development Strategy - base vehicle
(C-?)	Concurrent Development Strategy - base vehicle unknown
(S)	Sequential Development Strategy - derivative

(S-b) Sequential Development Strategy - base vehicle
SOURCE: Internal Ford Survey

Finally, consider a couple of competitive products. The Toyotas do not appear to achieve much differentiation in the demographics presented. However, it could be argued that, because three vehicles are different sizes and compete in different markets, the demographics are not capturing all the needs being satisfied. The Solara, being a two-door coupe, will satisfy different needs than the Camry. The Avalon, being a longer, roomier car than the Camry, also satisfies different needs. The VW Passat and the Audi A6 achieve significant differentiation in terms of the average age, the average income, and the percentage of females. Although it is not known which of the cars is the base, it is known that there are separate teams (an Audi team and a VW team) for each vehicle.

The data in Table 7.1 and Table 7.2 tables indicates that Ford Motor Company has some success differentiating products (even twins) using the sequential approach but that its execution of concurrent product development is not often successful. The reasons behind this are not engineering issues. Rather, these are product strategy and management issues. The product and business strategy issues relate to the following goals for a program:

- minimize product development and production costs
- maximize usage of manufacturing facilities
- provide both Ford and Mercury dealers with product in key consumer segments.

The management issues relate to how a project and its resources are planned and structured to support a derivative. As noted in Chapter 1, at some point mid-way through the development of a new product, most product development teams at Ford are asked to investigate some product derivatives that go beyond the scope of a derivative twin. This is almost always in response to fresh and emerging consumer markets, wants or purchasing trends. The intent of the request is to spur the team to find a way to stretch or flex their in-development product to meet the specifics of this new trend, and to achieve this concurrently with the base product. If teams were successful at stretching or flexing, they would be getting greater utility out of their product than a derivative twin would provide.

An example of such a situation would be a request from a brand manager to develop an inexpensive, two-door sports coupe from a new four-door family sedan that is still being developed, to meet an emerging youth trend towards sporty cars. An alternate example would be direction from a vice-president to provide sport-utility vehicle function using an in-development mini-van design.

The team reaction to such a request is very dependent on the pressure and interest shown by their immediate management. Typically, the proposal is dutifully (sometimes enthusiastically, sometimes not) investigated and then rejected for one or more of the following reasons:

- The team cannot contain the proper development of the derivative product and associated manufacturing processes, and resolve engineering issues between the requirements of the derivative and the main product within the time allocated for the main project.
- The variable and investment costs needed to incorporate necessary architecture or manufacturing changes are beyond the scope of the targeted budget.
- The engineering and support resources needed to properly develop both the derivative product and the main product are not available or are beyond the scope of the levels allocated to the base project.
- The level of complexity caused by the derivative is unacceptable to manufacturing. This is usually less of an issue for less differentiated twin derivatives, due to lower numbers of differentiated components for the plant to handle.

The development process does not allow teams and products to easily or quickly change during the process without affecting the quality of the base product. There are real technical reaons for this. Because of the lead time required to analyze, engineer, design, tool, manufacture, and test new components and systems, product changes identified less than 2 years before launch will not be fully validated prior to launch. Also, as the number of tasks and the complexity of the product increases, proper management of limited resources, particularly people, will become extremely critical. The team will be stretched, putting the integrity and the focus of the main program at risk.

But there are other, less tangible reasons that concurrent derivative products are difficult. During interviews with engineers, it was discovered that many felt that the biggest obstacles to doing derivative products was management's unwillingness to accept the cost and the time required to do additional engineering. Essentially, the sentiment was that engineers could deliver whatever management wanted, as long management was willing to spend the money and provide the extra time.

Another intangible was the perception by engineers that indecisiveness and a lack of commitment on the part of management led to re-work and iteration. In particular, late changes in program objectives and content, driven by upper management, were perceived as being responsible for program delays. Engineers saw the late requests for product derivatives as another example of poor planning, indecisiveness, and direction changes from management. They often sensed a lack of commitment or confidence on the part of management

The observations above suggest that Ford's approaches to product derivative development, and the relative success of those approaches, are shaped by the factors other than engineering difficulty or team size. Concurrent product development seems to be particularly difficult, and much of the anecdotal evidence suggests that culture and politics have a powerful influence. The next section will examine the role of culture and politics on strategies for developing product derivatives, using the cultural and poltical perspectives described by Anacona, Kochan et al. [1996].

7.3 Culture and Politics at Ford

As introduced in Section 7.1, cultural and political perspectives are key elements of a framework for analyzing the behaviors and traditions of a company [Anacona, Kochan et al., 1996]. This section will use this perspective to look Ford Motor Company and how it responds to the challenge of concurrent product development.

Ford Motor Company, as a corporate entity, is seemingly not afraid of change, at least at the very highest level. Freyssenet et al. [1998] discuss changes made in the 1940s, late 1960s, and early 1980s, all in response to internal crises. Since 1994, Ford Motor Company has made extensive and visible efforts to change how it operates. It re-organized to more closely align people with products, and, as mentioned earlier, is currently changing again to more closely align with brands and improve its connection to consumers. It has re-made and tuned its product development process, formalized and sought to improve its production processes, and is working with dealers to make the sales and delivery process more efficient.

Freyssenet et al. also describe the Ford model as exhibiting a powerful hierarchy, rigid, compartmentalized functions, centralized decision-making and control of financial and production elements. mass production and high volumes to get economies of scale, and resulting inflexible production and low product diversity. Since their description is based on an overview of the Ford's corporate history and performance, and because it is still largely accurate, despite the evolution of the company, the description can be thought to captures the essential culture of the company. It is the company's DNA.

Contrast this with Honda or Chrysler, which are recognized as being very good at developing derivative products concurrently with core products. Cusumano and Noebeka [1998] and Freyssenet et. al. [1998] describe these companies as relying on technology and product innovation to be competitive and attract consumers. These companies are described as being very quick to transfer and share technology and innovations between products, especially those with common platforms [Cusumano and Noebeka , 1998]. Honda's management career path for top executives goes through Honda R&D. Chrysler's most recent leaders were both former engineers. Volkswagon/Audi, who has been doing very well recently with product derivatives that were developed concurrently, also has a history of having technical people at the highest reaches of the corporation. Very striking is Honda's organizational theme, which is overcoming the rigidities that beset organizations in large industrial corporations [Freyssenet et. al. ,1998].

Ford's rigid hierarchy and compartmentalization of responsibilities, which is driven not just by reporting structure but also by the performance review and reward structure, encourages people to satisfy those who have the power to reward them. This is revealed in the comments from engineers noted earlier, that they will do whatever their management asks them to do. If management wants something done, they will give it a high enough priority, provide resources, and back-off on other assignments.

Power is an important part of the Ford culture. It is expected that people pay attention to power, that they respond to it, and that those with power will use power to get what they want done. At Ford, all of the sources power described by Pfeffer [1992] are used, and it is up to the product engineers to decide to which ones they must respond and which ones they can safely ignore. Most often, their decision is based who controls their resources or who has formal authority over them. An engineer's impression of the wants of their immediate management (either spoken or unspoken - despite their image, most engineers are astute interpreters of the unspoken message), not a notion of what may be best for the customer or the product in the long run, usually provides direction.

Consider recent attempts at performance-based merit (pay) increases tied to competitive rankings, which was championed at General Electric by Jack Welch and is planned for implementation at Ford Motor

Company. The strategy of ranking employees against each other is intended to make people more competitive. However, the strategy has them competing against each other, not their real competitors (who work at the other automotive companies). Competitive ranking, in this case, reduces people's willingness to work on teams or to support others' ideas, particularly if the other is in the same ranking group. Ford culture, like that of U.S companies, is more comfortable rewarding the individual, because the efforts of the individual, and the ensuing results, are supposedly easier to see, measure, track and assess.

So what is the effect of Ford's cultural and political DNA on the development of derivative products and multi-project management? Management is skeptical and resistant to initiatives and product ideas that originate outside their organization, because the idea will add to their people's workload and dimish their efforts on behalf of the manager's favored projects. Also, if successful, the idea could help a competing manager or organization during the competitive ranking process. Management's skepticism and resistance will certainly be sensed by the engineers asked to evaluate the idea and they will tune their efforts accordingly.

The resistance may be well-intentioned. As Senge [1990] points out, management teams spend a great deal at turf-fighting and face-saving (or face-protecting). Failure, especially financial failures, generally comes with a price. There are documented examples of Ford managers whose careers ended after leading teams that delivered products that were market successes but did not achieve financial targets. The message is clearly understood, that failure can be fatal to one's career. This type of culture makes people risk-averse.

One comment about the costs of risk in the automotive industry. The primary argument against risk-taking is the amount of investment required to make the simplest design change. As noted earlier, automobiles are investment-intensive products. Tooling for new suspension elements starts at one million dollars, while simple body or subframe tooling can cost 10 to 50 million dollars. Minor changes to tooling on something as invisible (and yet so critical to safety) as door latch can cost fifty thousand dollars. The financial risks are not negligible, but the payoff could be substantial.

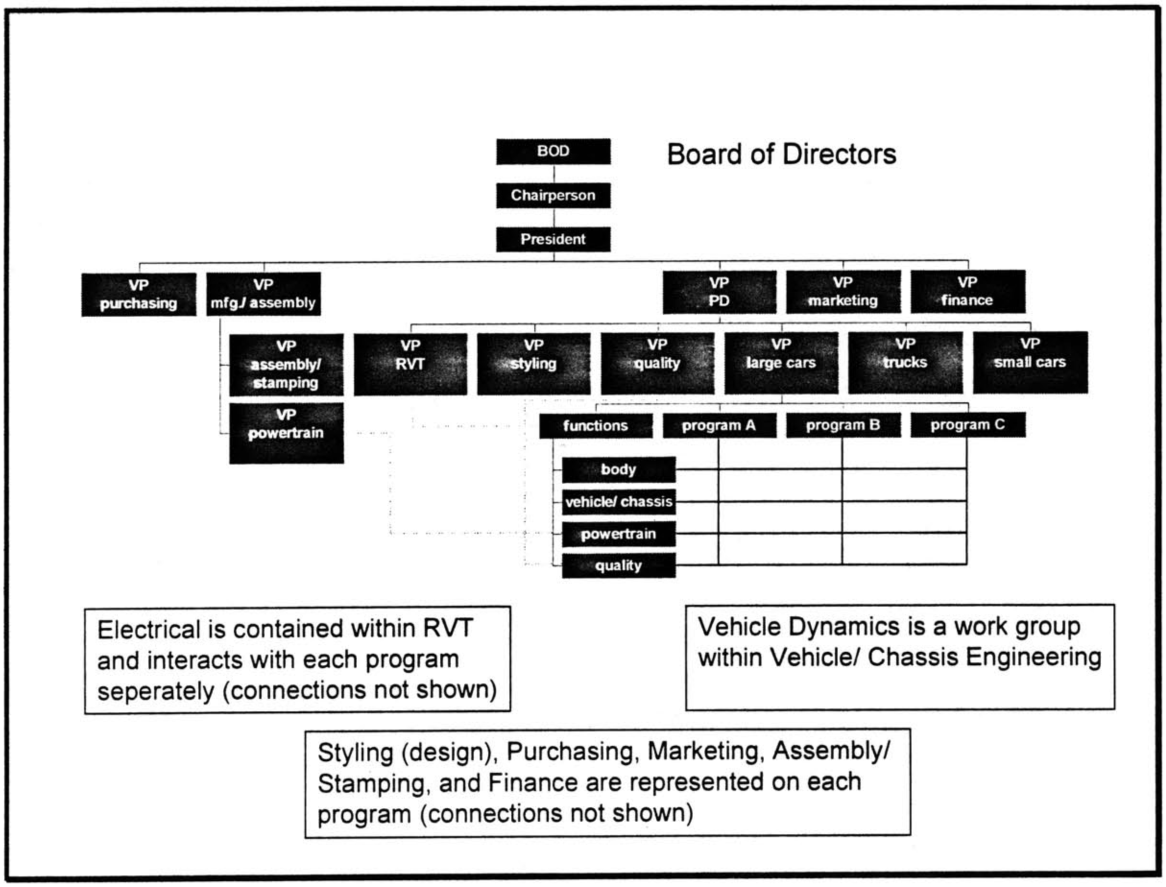
As noted earlier, most ideas for product derivatives first surface either in marketing (which has the data to identify new patterns in purchasing) or product planning (who continually watch the competition as well as the market). Neither of these groups wield significant power over product definition once the product development team is kicked-off, so they have two option on getting a product derivative idea off the ground. One option is they can find a pre-program product to use a basis and use their organization's influence to have the derivative built-into the program before the team is kicked off. The other option is to go up the management hierarchy with the idea and try to get upper management to re-direct an in-process product development team. Being late to market is a risk with the first option. Being stone-walled or ignored is a risk with the second option.

Regardless of the source, strategies for developing derivative products concurrently challenge the cultural and political traditions of Ford. The ideas are faced with significant inertial drag that is difficult to overcome, because the sources are ingrained into people's behaviors, making them very powerful. There are ways to change those behaviors, as will be discussed in Section 7.6. However, as will be discussed in the next section, an organization's strategic design can also inhibit success at concurrent product development.

7.4 Current Chassis Engineering Organization Structure

Section 7.1 outlined three perspectives for analyzing a company [Anacona, Kochan et al., 1996]. The previous section examined two of those perspectives, the cultural and political perspectives. This section will use the structural design perspective to examine Ford Motor Company, and specifically the Chassis and Vehicle Engineering Organizations, to understand how its physical design affects the success of concurrent product development.

Figure 7.2 Ford Motor Company: Simplified Organization Chart



Electrical is contained within RVT and interacts with each program seperately (connections not shown)

Vehicle Dynamics is a work group within Vehicle/ Chassis Engineering

Styling (design), Purchasing, Marketing, Assembly/ Stamping, and Finance are represented on each program (connections not shown)

Figure 7.2 is a simplified organizational chart for Ford Motor Company. It is simplified in that non-automotive business have been excluded and many lines of responsibility are not shown. Using the organization type identifiers described by Anacona, Kochan, et. al [1996] and introduced in Section 7.1, Ford Motor Company's current product development (PD) organization would be classified as a classical formal organization. As shown in Figure 7.2, it is a matrix structure encompassing product- focused vehicle centers, function/ hardware-focused organizations, and support organizations. As this is being written, the organization chart for Ford is being re-drawn to more strongly align resources with brands. Even so, regardless of changes in the number, names, and products contained within the vehicle centers, the essential function/hardware-focused organizations will remain, as will the fundamental structural design.

Figure 7.2 shows the primary groups that develop new products. The function/hardware organizations are body engineering (which includes body structure, body sheetmetal, door systems, and interior systems), vehicle and chassis engineering, electrical/electronics engineering, and powertrain engineering. Of these functional organizations, only powertrain has a vice-president-level executive at its head. The other organizations are headed by chief engineers. The product development engineers work at the intersection of the product and the hardware/function, reporting to a functional manager who reports to both the product chief engineer and the functional chief engineer.

Clearly, this makes for some very complex team interactions, but complexity is not necessarily bad, especially when it leads to optimality. However, consider the Vehicle and Chassis Engineering department. On some mature programs, there is both a Vehicle Engineering manager and a Chassis Engineering manager, although the current trend is to have a vehicle engineering and chassis engineering under a single manager. The people responsible for vehicle engineering manage vehicle-level development tasks such as attribute development, target setting, packaging and system integration. Chassis engineers handle the design and release of components and manage component suppliers, and are divided sections working on wheels, front suspension, rear suspension, subframe, and steering system. Vehicle engineers coordinate and manage certain aspects of chassis development, particularly those that influence key vehicle attributes such as vehicle dynamics (ride, steering, and handling) and noise, vibration, and harshness. For instance, engine mounts, body mounts, spring rates, and tire selection is often handled by vehicle engineering, with support from the appropriate chassis engineer. The sub-system design engineers must support the proper development of attributes across all derivatives, which is led by the vehicle engineers but generally requires engineers from many functional areas.

The vehicle engineers and the chassis engineers must maintain strong communication within their department to keep the design and any issues on track and properly coordinated. Because the chassis is such an integral part of the vehicle (as discussed in Chapter 3), the vehicle engineers and chassis engineers must also communicate regularly with all engineers from all the major vehicle chunks, and especially with body structure engineers and engine engineers. Typically, special teams are formed to handle cross-functional issues. Responsibilities are negotiated, changed, and handed off. Issues are often tracked by more than one person.

Consequently, the department responsible for developing the chassis is complex, and operates inside a complex organization. As seen in Chapter 6 and shown in the DSM (Matrix 4), as well as Matrix 3.1, the complexity takes the form of information transfer between work groups and organizations, between organizational layers, and over time and task iteration. This makes communication and coordination of information and people difficult. For the most part, this is manageable inside a program team. However, communication on product strategy and corporate initiatives, which usually involves groups from outside the program team, can be diluted, mis-construed, and mis-interpreted. This is the type of communication that is needed for concurrent product development, and this complexity in the development and management of the strategy is a significant inhibitor to success.

Another structural design issue that frustrates product derivatives is accounting procedures. Lead programs often want following programs to help pay for facilities and tooling from which both will benefit, but accounting procedures require that facilities and tooling costs be accounted for when incurred. This generally puts the financial burden on the lead program while giving the derivative program a free ride. For this reason, lead programs will often not support a derivative program that is not captured under the same project budget.

The structural design of Ford Motor Company's product development organization can contribute to the difficulties encountered when it trys to execute a concurrent derivative product strategy. Complex lines of communication, and Ford's hierarchical, procedure-driven, compartmentalized approach sets up patterns , of behavior, and these behaviors, because they remain in spite of re-organizations, yield consistent results, even when it comes to developing and implementing product development strategies. As noted earlier, there are companies that are successful with aspects of concurrent development of derivative products, and there are ideas about how this can be done better. These will be discussed in the next section.

7.5 Alternate Management Strategies for Derivative Product Development

The previous sections have described and analyzed the strategies used by Ford Motor Company to develop derivative products and have highlighted concurrent product development as a derivative strategy that can be improved. The influence of culture, politics, and structural design on Ford's ability to implement concurrent product development strategies were also discussed. Using industry examples and proposals from the literature, this section will introduce other organizational or management strategies that could be used to improve concurrent product development implementation.

Product development efforts have an insatiable appetite for resources, and managing multiple products efficiently and getting world-class results stretches those resources. The fundamental task for management is finding the best way to use limited resources and assets to respond quickly to customer wants and emerging markets. According to Cusumano and Noebeka [1998], Ford should be striving for concurrent technology transfer or concurrent product development. Companies as diverse as General Motors, Honda, Chrysler, and Volkswagon/Audi are successful and profitable at concurrent product development. These companies have little in common, from the standpoint of corporate management structure, career paths, corporate culture, and even their platform technology strategies.

Honda keeps product variety low and emphasizes technological innovation, particularly in chassis and engine design. It applies common design philosophies and architectures across models. This increases corporate learning and understanding of the physics behind that particular architecture. According to Freyssenet et. al. [1998], this also facilitates sharing of assembly tasks and tool sharing and allows the use of mixed-model production at plants to get full production capacity utilization.

It is also reported that that Honda uses project-based teams, led by powerful project leaders, that disperse once the design is delivered [Cusumano and Noebeka , 1998]. Honda also uses respected, high-level, experienced project leaders to champion cross-car and manage the product development project leaders. Chrysler also emphasizes technological innovation, but it is primarily in styling and packaging. Chrysler uses project-based, dedicated teams that roll-over onto the follow-up product. However, they depend on informal "Tech clubs" to promote cross-platform sharing, rather than developing structured mechanism.

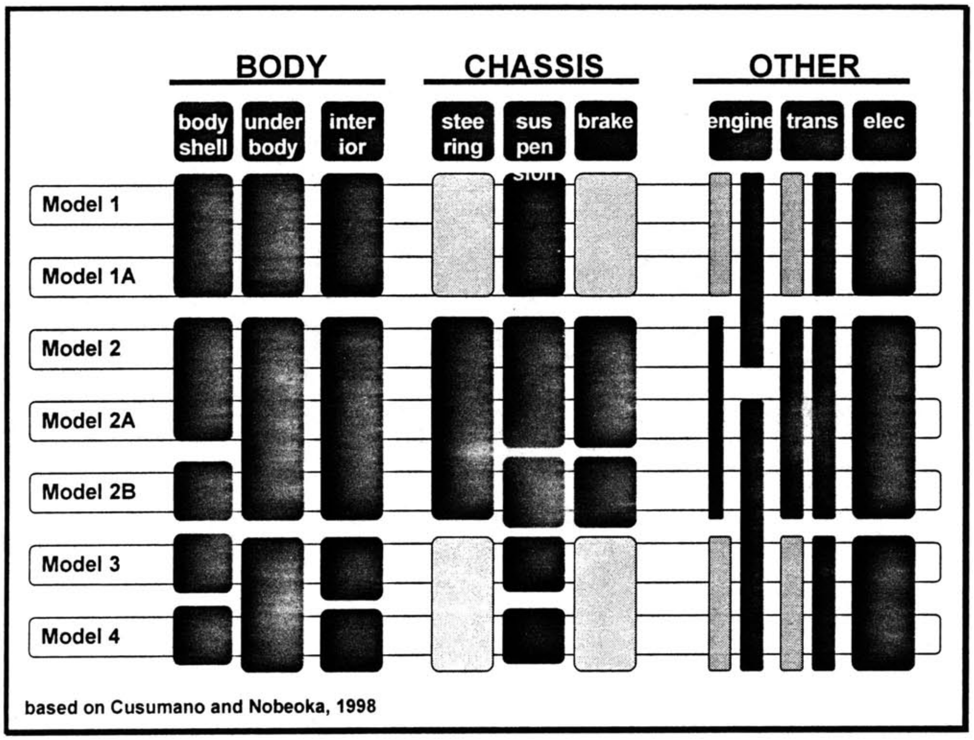
Volkswagen/Audi, Chrysler, and Honda appear to assign one team to handle the base product and another team to handle the derivative. For instance, there were two different high-level Large Project Leaders for Honda Accord Sedan and the Honda Accord Coupe, which lagged just a little behind the sedan's development. Volkswagen/Audi have different engineering groups, with the Volkswagen side handling small cars (Polo and Golf) and the Audi side handling larger cars (A4, A6, but also VW Passat). How they manage derivative products such as the A4/ Passat is not documented.

Toyota appears to practice sequential technology transfer when they do derivative products. This is evidenced by the Camry being followed two years later by the Solara Coupe and the Sienna mini-van. Actually, both Toyota and Honda may be considered to use either a very fast sequential technology transfer strategy or a slightly lagging concurrent technology transfer strategy. The information on when teams are kicked-off is not available, but the timing of the products indicates significant overlap during the product development process and suggests that this is a concurrent strategy. Toyota's project center organization facilitates coordination of technically related projects, which strengthens the authority of project managers over functional managers and improves integration across functions. [Cusumano and Noebeka , 1998]

Research performed by Cusumano and Noebeka led them to conclude that concurrent technology transfer (or concurrent product development) had distinct and measurable advantages (over the other three strategies) in terms of cost, lead time, and engineering hours. In reaching this conclusion, they assume that the number of body types and new design will affect the engineering hours required to develop the design but will not affect lead time. This is true as long as there are enough tooling sources to support the scope of the program. However, it is common for tooling shops in the automotive industry to be short of capacity. Their research also suggests that concurrent product development will yield a superior family of products, as measured by market share and sales growth, which should translate into improved shareholder value. They also note that project-centered organizations seem to be doing better, although some functional/hardware group is needed if deep technical expertise or innovation is to be part of the company's core competence.

Cusumano and Noebeka conclude that companies that do well in the market use concurrent technology transfer with a multi-project strategy that combines strong cross-project interaction with strong cross-functional interaction. For multi-project management of concurrent product development, Cusumano favors the use of a "Differentiated Matrix" organization structure. This structure, which is quite common, uses different engineering teams working on one or more projects simultaneously possibly with some shared sub-teams where systems are shared. Figure 5.2 is an example based on Cusumano and Noebeka.

Figure 7.3 Differentiated Matrix Example



based on Cusumano and Nobeoka, 1998

The model numbers down the side are base and derivative products. Models with common pre-fixes are are similar in size and features and aimed similar markets. The bars under the organizations represent how each functional manager is assigning his resources. Thus, Model 1 and Model 1A have common engineering resources for all sub-systems. They also share steering and brake resources with Model 3 and Model 4. Model 2 and Model 2A have common engineering resources across all functions except one engine, and must share some resources with Model 2B (in underbody, interior, steering, and electrical).

To support this structure appropriately, it is recommended that subsystems that require a high levels of coordination and that are to be shared across projects be identified early. In general, the preference is for "invisible" sub-systems such as brakes, subframes, suspension, and transmission [Cusumano and Noebeka, 1998]. These must be tuned for the application but the general design can be the same. One team should be established to develop the common sub-systems, while separate teams are established for non-common sub-systems. Engineers on the common sub-systems will have dual responsibility --

system/ sub-system/ component design on one project and managing and coordinating design information sharing across projects.

These steps improve communication, through comparison of the required coordination among functional departments against required coordination among projects, and should encourage leveraging of total corporate knowledge, resources & capability. As stated, it is expected by Cusumano and Noebeka, that the systems such as subframes, suspensions be shared, because they are invisible to the consumer. However, if the consumer is differentiating products on the basis of steering, ride, and handling attributes, and if the derivative product strategy (which is driven by an identified consumer want) calls for such differentiation, then this approach would demand a separate team for the suspension and possibly the steering and the subframe.

As noted, to effectively handle coordination of engineering across different functional areas, the Differentiated Matrix of Cusumano and Noebeka requires a dual responsibility (project system design and cross-project system design coordination) for some engineers to provide a measure of complexity management in communication. Part of the strategy is to assign specific cross-project responsibilities to project teams, based on the project's distinguishing functional features. For instance, Mustang might be responsible for all high performance powertrains, Town Car would develop and set standards for luxury suspensions, and Taurus would set standards for steering systems on large cars. What remains unassessed is the ability of the engineer to manage the workload, although, since many companies operate this way, the workload must be somehow manageable. This could be taken to a higher level, by looking for projects or engineers to provide cross-project integration for designs with common architecture. This would encourage learning and retained knowledge about the advantages and weaknesses of specific architectures and architectural strategies.

Rather than assigning specific engineers to provide cross-project communication for designs with similar architecture, Ford usually makes a specific engineer responsible for the sub-systems design (and its potential variations) across all the affected projects and then expects them to remain in communication with his counterparts on other projects. Together with the relatively high turnover rate of engineers and the trend towards full-service suppliers, this approach has not promoted strong cross-project or function-specific learning. This structure also leads to over-worked engineers and little differentiation between the base product and the derivative.

It might also be that changing the structure of the team could improve the ability to do derivative products. According to Elter [1998], Xerox uses cross-system systems engineers to manage functionally important topics (FITS) such as safety, noise, and power. FITS form a network of inter-linking system constraints and provide a mechanism for managing the integration of functions. It is the job of the systems engineers to manage these across the product platform. Such cross-functional people would coordinate the engineering of FITS (or attributes) and the systems/ components that influence them.

This idea is close to one that was studied briefly during the 1996 product development process re-engineering effort at Ford Motor Company. At that time, the concept of organizing teams around attributes was studied as an alternative to the standard functional decomposition of teams. Functional hardware engineers would be shared across attribute teams as needed, or there would specific functional engineers for each attribute team. The conclusion was that such a re-organization would be a huge transformation requiring years of work, and that such a new way of functioning would leave teams confused and paralyzed. The re-engineering group decided instead to use Program Attribute Teams (PATs). PATs are led by an attribute leader (normally a person from the Vehicle Engineering organization) and include design engineers whose sub-systems/components influenced the attribute. The design engineers are drawn from the program team and are expected to handle the needs of the PAT along with their other tasks. Generally, design engineers are members of more than one PAT. This structure is currently being implemented, but does not seem to be improving the ability of product teams to handle derivative products, event though it has provided champions for the attributes

Another structural change, suggested by Dr. Whitney, is the use of small, upfront "tiger" teams, who would set up the derivative product for integration into the core product. Tiger teams could also be used from the start of the core project, to work with the core team to provide adequate architectural flexibility for the derivative product. Conceptually, the Tiger team would not follow the derivative product all the way to production. Rather, they would hand it off to the core team once its integration path with the core product was defined and the fundamental architecture stable. The Tiger team would then move onto another derivative product. This would address issues of coherent, consistent, upfront planning. However, it would not help the teams handle downstream cross-project interactions or later changes.

To help cross-functional communication within a team, Steward [1999] has suggested that "situational visibility", which could also improve cross-project interactions. Rather than relying on top-level management for direction, teams can be provided with sufficient, relevant, properly-presented information to allow those affected by a situation, or those who can affect it, to see the situation when it occurs and decide (at the lowest level) on a course of action. The application to product derivatives would pertain to those suggesting derivative products and those project teams that might be asked to participate. Making the market situation, the profit situation, and the total product strategy visible to all those potentially affected would increase the understanding of the need for the derivative, and probably build enthusiasm for it. However, the visibility of the situation would not alleviate the political and cultural pressures it would be working against. The source of the idea and the amount of additional work can still work against it. Also, as noted, the reward and punishment system at Ford encourages people to avoid risk and be conservative.

One method for improving situational visibility that is being used and relied upon extensively is Ford intranet system. This internal Web is being used by teams to communicate just about every type of relevant project management and product development information imaginable. Product teams have generally embraced it as an extremely friendly communication, idea-sharing, and information-sharing tool. For instance, most programs are using a web-based quality operating system (QOS) to manage and track the status of deliverables. This system can be accessed by team members or Ford management at anytime, to updated status or get a snapshot of what the team has done, what it is doing, and what it plans to do. However, for the most part, the information on the Ford Web is fairly unstructured and inconsistent, and many of the web sites are difficult to navigate. It is also very dense, with teams trying to capture everything about their program, from meeting minutes (some of which have little value) to breaking program changes.

Another situational visibility tool used at Ford Motor Company is C3P. This computer-based system uses CAD files, CAE tools, and project information management (PIM) to communicate system/ sub-systems/ component design changes to those affected. Unlike the Web-based QOS described earlier, which was passive and waited to be accessed, the PIM automatically alerts affected users to design changes made by other users. This fosters communication within a project. It can also create cross-project communication, by linking (via a mailing list) with other projects.

Most of these ideas are focused on the structural design of product teams. However, the structural design of the total company, and its political, and cultural traditions discussed in Section 7.3, can create resistance and work against any attempts to implement these ideas. One suggestion is to move towards the "new" organization [Anacona, Kochan et al., 1996] described in Section 7.1. This means fewer management levels, stronger networking with suppliers, and surrendering the predictability and control of a classical organization. Ford, however, has recognized that, in today's competitive environment, control is in the hands of the consumer, not the producer, and that the company's actions have to be for the good of the consumer. With this attitude, Ford is working to reduce the layers of management, to improve supplier relationships, and to think globally and locally. Ford is also working to change the face of its culture. It has goals for the demographic makeup of its management team and its work force that reflect the changing demographics of the U.S. work force population. However, it remains to be seen whether this change can affect the political and cultural traditions, which will be the strongest impediments to change.

Ford is also trying to change to allow decision making at the lowest level, through the development of smaller business units and the emphasis on shareholder value. The company's current reorganization has this as one of its goals. However, one effect of these changes that remains unassessed is top-level management's response to a lack of uniformity of execution. In a large company such as Ford, to encourage innovation, the small business units must be allowed to do things differently. Yet, to those at the top, the different approaches make look more like chaos than control. The cultural norm at Ford has generally been to drive for uniformity, which will be a challenge to the potential of the small business units.

Regarding career paths, Womack and Jones [1994] suggest a trajectory that alternates between concentration on a specific product or product platform and focused knowledge-building in a specific functional or technological areas. Under this model, Human Resources, an organization which lacks traditional sources of power at Ford, functions as a key player, identifying assignments and creating career paths. This lack of power would make this concept a untenable proposal for most organizations at Ford. However, there is movement to modify the traditional career paths at Ford, emphasizing greater, deeper technical knowledge. To support this, internal standards and tests have been established to certify engineers in key methods and tools that are necessary for product development, with certification being a requirement for promotion. These are encountering some resistance, but management is leading the way and leading by example, taking the tests and striving to meet the standards.

Reviewing the strategies used by other companies and those suggested by researchers, there are many different options that Ford could implement to improve its ability at developing derivative products concurrently, and, as pointed out, some aspects of them are currently being implemented. However, there are roadblocks and resistance to some ideas and there are other ideas that have not been considered. The next section will discuss some recommended actions that Ford should take to improve their success at concurrent product development.

7.6 Recommendations for Mult-project Managment at Ford Motor Company

The previous section described different approaches to developing derivative products and managing multiple projects. It also described how Ford is already implementing some of these concepts, and what is known about the success of those implementations. This section will use the ideas implmented and those not implemented to build suggestions for improving Ford's implementation of concurrent derivative product development.

Developing derivative products in a multi-project environment requires a resource efficient way to manage the complexity of consistently developing the products without affecting the products ability to satisfy the customer. As noted in the previous section, literature and corporate practices have many guidelines on the subject but no guarantees. Evidence is anecdotal, and conclusions are based on a few case studies. With that qualification, the following are guidelines for derivative products in a multi-project environment:

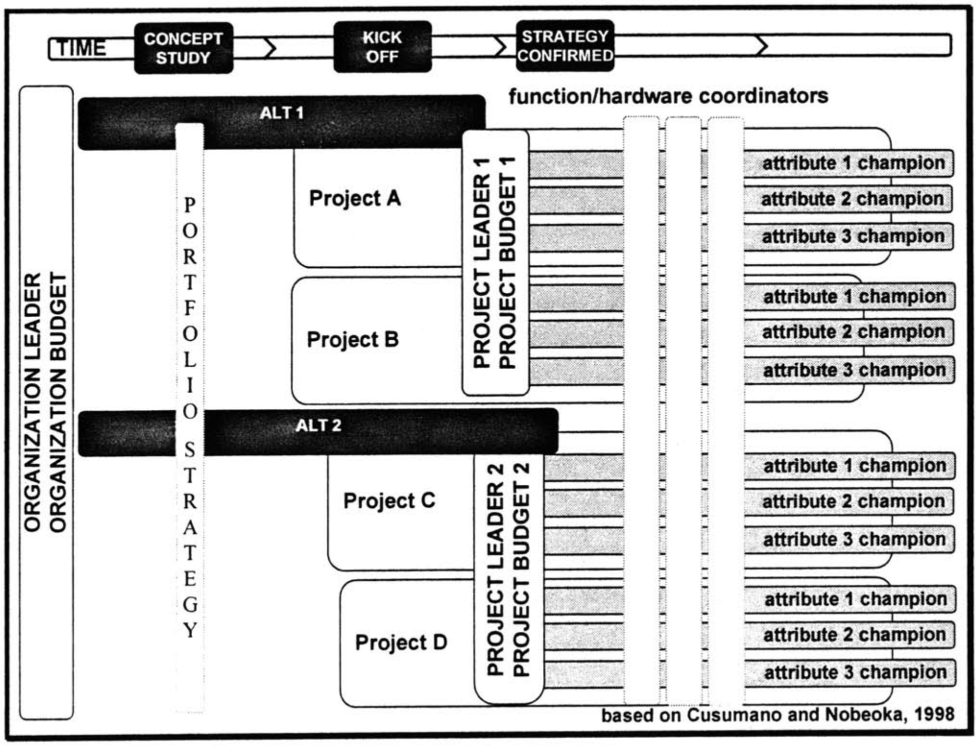
- Prepare for the future, by being poised to expand product lines and introduce new technologies into existing products. This requires a corporate portfolio strategy that describes cycle plans and markets for new products and the phasing-out of the old. The portfolio strategy is dependent on corporate financial, organizational, and human resources capabilities.
- Plan for a variant that is substantially different in performance, from the beginning. It is not important that the specifications be exactly right, but it is important that a degree of flexibility is incorporated from the start.
- Quickly leverage investments in new platforms across markets, by spinning off derivative products while the platform is new, rather than slowly across time [Cusumano and Noebeka, 1998].
- Establish a group whose task is to develop and initialize derivative products.
- Integration of design information must occur simultaneously across different engineering functions as well as across different projects.

- Base projects and concurrent or sequential derivative projects should be separated. Single projects should not be expanded to accommodate multiple distinct products, because teams that get too large lose focus on product uniqueness and quality.
- Use Web-based tools to provide project information to team members as well as to other projects, to promote information sharing. Incorporate automated messaging of project changes.
- Hold regular design reviews with functional/hardware peers.

Figure 7.4 is a multi-project organizational structure that incorporates the above suggestions or provides implementation mechanisms for them. It uses pre-program Architecture Leadership Teams (ALT1 and ALT2) that work together to develop a portfolio strategy, then initiate the development of the architecture that will support that strategy. Members of ALTs are envisioned to be highly experienced engineers who are knowledgeable in systems engineering and architecture principals, in addition to having critical functional hardware design and manufacturing knowledge. There is a certain art to spotting promising architectural paths, so ALT membership should be fairly stable to provde time to accrue experience and develop intuition.

The ALTs work on different aspects of the portfolio, but maintain communication, to ensure the strategy is maintained and that inconsistencies are resolved. The ALTs develop the architecture strategy, including concepts, attribute targets, and initial layouts. The ALTs are responsible for understanding and communicating the attributes that drive design parameters, evaluating the flexibility envelope and ensuring compatibility with the portfolio strategy and market differentiators. At project kick-off, the ALTs continue to work with the project leader and the project teams to implement the strategy. In this way, they learn about how they can serve project teams better. Some ALT members might even join a project team, or become the project leader.

Figure 7.4 Recommended Multi-project Organization



The project leader is responsible for a product and its derivatives. Because the derivatives are expected to be substantially different, the project leader has different teams for each derivative. Inside each project, engineers could be expected to fill one of two dual responsibility roles. One role is cross-functional attribute champion within a project. The other role is cross-project functional hardware design coordinator. Although Figure 7.4 shows all the coordinators communicating across all the projects, that may not necessarily be the case. There may be projects that remain independent in some functional hardware areas.

The structure provides mechanisms for the application of systems engineering to handle attribute coupling and organizational decision linkages, both before and after kick-off. It also makes sure that projects are grouped logically. A more far-reaching implication of the structure is the four career paths it establishes. First, it establishes positions for multi-project leaders who would be responsible technical engineering content and architectural design philosophy, not just the financial analysis. It also provides paths for developing functional hardware knowledge and for developing cross-functional attribute knowledge. Finally, there is the product architect teams, the ALTs, and their leadership, which should be highly desirable positions.

Though the model does provide a framework for systems engineering to occur, it also does not adequately address most of the learning disabilities identified by Senge, particularly the limitations on learning due to the time and spatial distance between cause and effect and the tendency of organizations to fixate on events. It does address, to a certain extent, ownership issues, which should reduce turf battles. In terms of Senge's Five Disciplines, it does encourage, though not enforce, shared visions or systems thinking.

One of the dangers of project organizations is that, by themselves, they do not promote deep technical excellence or specialization or naturally encourage radical innovations. The structure also does not prevent pervasive personnel changes and dispersal of project personnel at termination. Guidelines would be required to reduce such churning, in order to facilitate the development of deep technical expertise. Ford is already moving down this road by implementing a certification process and standards for engineering and product development knowledge.

Generally, functional organization are not good at multi-project management that goes beyond their technical specialty [Cusumano and Noebeka, 1998]. The suggested structure above does not explicitly handle this issue, so it would need to be considered during development of the product portfolio strategy. Specifically, the core technical competencies of the organizations inside Ford Motor Company would need to be specified to ensure that all critical functions are covered. The structure also says nothing about the role of full-service suppliers, who are handling an increasing amount of design and engineering on key systems. Ideally, capable suppliers should work with the ALTs, to bring expertise in areas that are not considered to be core.

There is room to improve the reward system, to encourage and support calculated risk-taking and team behavior. Part of this would require a shift to strong team-based rewards. The difficulty is that the immediacy and effective duration of the consequences determine how much behavior can be affected. There must be a correlation between action, result, and reward, and the reward cannot precede the result, which means teams must wait years to see results and rewards. However, the effect on next year's salary, raise, bonus, or profit-sharing is not close enough in time to tie effect to cause and becomes too abstract a pressure for most employees to respond. Increasing the time will not make the linkage any more visible or powerful. Also, moving decisions points downward in the organization, and creating smaller business units, will help make these ideas more implementable.

Learning is a weak point that is slowly being attacked. Yet traditional mistakes are still being made, historical mistakes are repeated, both in how the product is engineered and how needs of consumers are interpreted. The cycle between cause and effect is too long, the movement of people work too rapid, to allow deep learning in a technical area or extensive knowledge of a product. Knowledge is not retained in the long-term, although there is extensive use of the web, as noted in Section 7.5, to make information visible and accessible. However, it is extremely disorganized, with much out-dated information. For the Web to be useful, the validity of the information must be verified and its usefulness assessed periodically. Section 7.5 also disclosed that Ford is looking into creating career paths that drive greater technical knowledge and that knowledge certification standards were being established and tied to promotions. These actions should bring benefits in the long-term.

These recommendations should improve Ford's ability to develop derivative products concurrently across multiple projects. Some of the ideas, particularly those involving team rewards and learning, will help all projects, regardless of scope. The key, however, remains in establishing a firm, recognized strategy for product portfolios, and basing that strategy on knowledge of the consumer and their needs.

Chapter

8 Conclusions and Future Research

This paper has examined on the technical and management challenge of developing derivative products at Ford Motor Company, a company that has multiple projects under development simultaneously. Of primary interest was the role that an automobile chassis can play in enabling and hindering derivative products. The early chapters provided background on the problem and its importance, defined key product architecture concepts, outlined Ford's technical and management approach. Subsequent chapters described an analytical approach for qualitatively assessing the flexibility potential, a quality of an architecture which was identified as being needed to support the development of derivative products. The process used a set of matrices and heuristics to evaluate a product's architecture and gain insight regarding the flexibility potential of the architecture. Examples of how the method could be applied were provided, including extensive exploration and assessment of specific chassis architecture. Finally, discussions regarding the impact of management strategies and organization structure were presented.

This chapter, the final one, will summarize the conclusions and insights provided in the previous chapters and will point to other research that could be performed. The primary conclusions for the paper can be broken down into three categories: management, chassis flexibility, and methodology. The following sections examine each of these categories. This will be followed by ideas for follow-up research.

8.1 Conclusions: Management of Derivative Product Development

Chapter 7 discussed management issues and ideas about handling or avoiding the issues, either by changing the organization structure, the derivative product strategy, or the cultural norms. The primary conclusions and suggestions are summarized below:

- The primary management challenges behind developing derivative products is effectively and efficiently distributing limited resources (particularly people and investment dollars) and ensuring timely completion and transfer of information

- Timely decisions are crucial. Delays and direction changes create tension and orphaned issues. To this end, Ford Motor Company needs a cohesive product portfolio strategy that drives opportunities for derivative products without narrowing options.
- Architectures need to plan for variants that are substantially different from the beginning. This could be accomplished with Architecture Leadership Teams who would develop and manage product portfolios and architecture. Responsibility for development of a product would be handed off to a product team once a viable concept was prepared and the business case confirmed.
- Cross-project communication is as important as internal project communication, if the organization is to learn and to transfer ideas and technology quickly across products and platforms. A structure that could enable this would make experienced product engineers also responsible for championing cross-project communication and learning.
- Rewarding people for individual achievement does not make team work and team goals primary. Modifying rewards structures to provide team-based metrics and rewards might shift the cultural norm to support teams and encourage communication.
- Rewards also need to do more to encourage calculated risk-taking. One method for doing this would be to provide funds for special product research teams that could be formed by first-line supervisors and working-level engineers. These teams would be self-motivated and entrepreneurial, if the proper rewards are provided. However, the people involved would also require some relief from their current work assignments.

8.2 Conclusions: Chassis Flexibility and Derivative Product Development

Chapter 6 explored chassis flexibility using the methodology. The primary conclusions and suggestions are summarized below:

- Changing attributes influenced by the chassis rarely brings significant differentiation in the market place between a base product and a derivative product. However, changes to the chassis-influenced attributes can provide necessary secondary effects that will bring in different consumers.
- One of the primary functions of the chassis is to act an interface. As such, it cannot help having linkages to other systems.

- The coupling of chassis-influenced attributes made this system difficult to assess using the matrices and the heuristics. It diluted the conclusions and insights by making the assessment of the Matrices (particular the Joint Matrix) ambiguous.
- An architecture that has planned for flexibility potential will support adjustments to kinematics by allowing packaging space and attachments. It will also support extensive compliance adjustments. An architecture that has not planned for flexibility potential will support some compliance adjustments.
- The analysis justified the rationale behind the industry technique of tuning the ride and handling of a vehicle using prototype vehicles. The compliance is part of the architecture that supports flexibility potential, as are certain aspects of the kinematics.
- Learning about chassis architecture is a key issue. Ford Motor Company would be better served to identify a few (no more than three: truck, front wheel drive car, rear wheel drive car) base chassis architectures and to evolve these forms. This would also allow the knowledge and understanding of the different attribute-component relationships to be refined.
- Although the process did not yield definitive conclusions about flexibility, as far as the chassis is concerned, it did identify adjustments to kinematics and compliance as potential areas. This is consistent with industry practice.

8.3 Conclusions: Methodology

There were some insights that this work provided that pertain to the methodology that was used. These insights can be categorized as benefits and weaknesses of the process. The weaknesses outnumber the benefits, so the benefits will be described first. The primary benefits were:

- The methodology highlighted the different perspectives of organization, PD process, and architecture and how they each affect flexibility potential differently.
- The methodology encourages a thoughtful review of the relations between attributes, objective metrics, and components. It also highlights what attributes are coupling and how dense the couplings might be.
- The DSM highlighted the key information types that are developed early in the process and could drive the process. It also identified those types that were involved in iteration and that could lengthen the process.

However, the case study also highlighted some issues with the method and the heuristics that were not apparent from the simple examples. The major concerns were:

- The methodology can be overwhelmed by complex architecture. That is, many interacting components, many interacting organizations, many interacting objective metrics, and many interacting attributes can make a matrix large and unwieldy to create, read, and use. One of the advantages of a matrix is its ability to precisely, compactly represent information. As was demonstrated in Chapter 6, the matrices lost much of their clarity.
- The method requires experience with the system and commodities being evaluated to execute. This means the analysis and results may be susceptible to bias.
- The method is qualitative, not numerical, which does not allow a quantification of flexibility potential. That is not a major issue, as long as the qualitative assessment is decisive or can provide direction. As shown in the chassis case study, the qualitative results were not compellingly decisive.
- Matrix 3 has questionable usefulness as it gets larger or when it has to capture attributes that are coupled in many different permutations. Even though the code allowed the separation of different attributes, it made it laborious to sort out what was going on and identify what components could drive what attributes.
- Attribute coupling can make drawing conclusions using this method difficult. This is especially true when the attributes are coupled in several different permutations. This leads to a serious break-down in the method, making it difficult to utilize.

8.4 Suggested Future Research

Numerical Methods

The methodology as developed results in a qualitative assessment of flexibility potential. However, qualitative analysis is often not regarded as being rigorous or detailed enough to support firm conclusions. Future research could focus on creating a numerical rating system that could align with the heuristics. As noted in the discussion in Chapter 4, it is conceivable to assign numerical values to architecture based on the complexities highlighted by the organizational perspective and the architectural perspective. The organizational rating could be quite straightforward, relying primarily on an accounting of the linkages identified between organizations and assuming that more linkages means more difficult management due to confusion over responsibility and poor communication. This in turn would impact the overall flexibility potential. To make results between architectures comparable, it would be necessary to normalize the ratings for the number of components, objective metrics, and attributes. Otherwise, an architecture with few components and objective metrics that that requires much organizational interactions might appear to be easier to manage (and easier to manage the development of derivative products) than an architecture which has more components and objective metrics and whose organizations are less coupled. Also, it would be necessary to develop some type of weighting system to account for the relative power of an organization and their ability to drive other organizations.

Developing a numerical method for the architectural perspective is more difficult. The biggest issues, as discussed in Chapter 6, are coupling between attributes and having many different coupling permutations. Without coupling between attributes, coupling between components can be favorable for flexibility potential, as shown in Chapter 4 and Chapter 5. Coupling between objective metrics via components can also be favorable, although the physical relations involved can make the situation less desirable than the component coupling case. When attributes are coupled, as shown in Chapter 6, the assessment insights are less clear. The accounting for this perspective would need to increase ratings for linkages between components and pure attributes (attributes that are not coupled to other attributes) and detract for linkages to impure attributes (attributes that are coupled to other attributes). The numerical rating would need to normalize for the total number of possible attribute combinations and for the number of objective metrics and components. Also, weightings for design drivers could be incorporated, to highlight their ability to hinder flexibility potential. Weightings might also be wanted to capture the relative strength of the relationships between components and attributes. Some of these weightings could be based on equations relating components and objective metrics, for the situations where the equations are available and reliable.

Improving The Joint Matrix and DSM

The Joint Matrix (Matrix 3, Matrix 3.1, and Matrix 3.2) was a key tool in the methodology. In the simple examples of Chapter 4 and Chapter 5, it appeared to work acceptably well. That is, it compactly represented a system and allowed insights and conclusions about flexibility potential to be drawn. However, as noted above, when the elements of the chassis system were used to fill the cells, the results became less definitive and conclusions became more difficult to reach. This could be due to the aggregated parameters (sub-attributes, objective metrics, components) that were used in the Joint Matrix.

Consequently, one improvement to the method that might allow stronger conclusions could be to drive down deeper into the elements. That is, replace the components in the Joint Matrix with their associated design parameters, such as mass, natural frequency, length, strength, spring constant, and relative position, and replace the sub-attributes with lower-level characteristics. This might create more differentiation between the elements that sit on the top axis, as well as the elements that fill the cells, and make the individual relations clearer. It might also be necessary to develop lower-level objective metrics

The DSM for the chassis development process is not very large compared to other DSMs. This is due to the level of process decomposition that was chosen. Future research could dive deeper into the chassis design process, by focusing on the development of component design parameters and delving down deeper into the information types. It may be that identifying the specific information (rather than using information types) that is exchanged would break-down the linkages. Another suggestion regarding information types is to replace them with attributes. This was tried, but it was found that nearly attribute type was involved with nearly every component. However, going deeper, down to the component design parameter level, might break up these linkages.

Re-framing the Attributes

As noted earlier, the attributes for the chassis are highly coupled, which was one of the reasons that the Joint Matrix was difficult to interpret. The chassis-influenced attributes are traditional - ride, handling, and steering have been discussed and studied in industry and technical papers and books for decades as the key customer concerns that chassis design must address. Objective metrics have been developed that link to what the customer senses but the linkages are intermixed. This suggests that there might be another set of attributes or another reference frame in which the couplings and linkages are reduced, which would result in a Joint Matrix with fewer linkages. Conceptually, the major change would need to come in the relations between the objective metrics and the attributes, and would involve a redefinition of these relations in such a way that the attributes no longer couple. Of course, no amount of redefinition is going to change the way people sense the attributes influenced by the chassis. The challenge is change the perspective from which the attributes are viewed. For instance, the current attributes are tied to different scenarios (rough road, smooth road, cornering) and focus on the vehicle response.

Another approach would be to try clustering the objective metrics and components in the Joint Matrix according to some objective logic. For instance, re-ordering the objective metrics and clustering them by the attribute codes created Matrix 3.2. This could be done for the components as well, although it would be more difficult, because they influence several different codes. One way around this would be to re-order the components by clustering by the fewest number of attributes that each component affects. This would be clustering by the lowest level of coupling, which could yield a matrix that appears less random.

A different perspective would be to consider the sensations felt by the different parts of the consumer's body. This perspective has been used to a certain extent. For instance, thigh shake and "head toss" (unintended movement of the drivers head caused by vehicle motion) is sometimes used to evaluate ride characteristics. Extending this idea to focus attributes on the response of the entire human body, and developing objective metrics that align to these attributes without coupling, could yield a Joint Matrix that was less filled and more understandable. At the same time, the engineering components to support such attributes might also be easier. However, this would be a major undertaking. One idea would be to take acceleration measurements (assuming acceleration is a legitimate metric) on the body parts a cross-section of real, live consumers driving cars from specific vehicle segments. Their specific perceptions and opinions about what they are feeling would need to be captured to provide correlation to what they perceive as good and what they perceive as bad. Although laborious and probably expensive, this would allow the development of a mapping of the response of various human body parts to the vehicle segment. Hopefully, this mapping would suggest natural objective metrics that would align neatly with these new attributes. However, it is possible that the attributes will still be coupled with their relations with the components are explored.

Beyond Analysis by Matrices

One of the shortcomings of the method is that it does not capture the relative sensitivities between components and attributes. In this method, all components have an equal influence on the attributes that they effect. However, that is not reality. Chapter 4 identified some tools that promise the ability to go beyond the static mapping of the matrices and capture the relative sensitivities. System Dynamics has the potential to capture both management influence and engineering physics. Such a model would include organizational interactions, attribute coupling, and linkages with objective metrics and component design parameters, and would allow weightings to be given to organizational power and component influence. Building a Systems Dynamics model would require capturing and formulating how organizations communicate and how task difficulty influences the timeliness of communication. Also, the model would need to formulate complicated physical relationships between components and attributes, and between components and components.

This suggest another approach, to use dynamic CAE tools such as ADAMS™. Ford has this capability, although there is no single model or CAE tool for simulating the complex physics of ride, steering, and handling. Rather, characteristics of the attributes are aggregated, some are ignored, and then the different aggregations are modeled differently, depending on what issue, attribute, or scenario is of interest. These models could provide guidance on the relative sensitivities between different components and different attributes. However, it is not clear how the management influence could be built into a CAE model. What might be more reasonable would be to use the aggregations and relations from the CAE tool in a Systems Dynamics model.

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