Managing the Proliferation of Digital Technology in the Automotive Industry
A Systems Engineering Approach to Embedded Software

by

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

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ABSTRACT

The automotive industry is in the midst of a quiet revolution involving the expanding use of digital technology in automotive systems. Over the last ten years, the average retail price of most vehicles has remained relatively flat and industry profits have lagged behind many firms in the technology sector. Increasingly, automotive firms have turned to new technologies to create profit in the industry through performance enhancements and increased brand differentiation. Active control systems and X-by-wire systems are two categories of digital technology making their way into vehicles at an increasing rate.

The current economics of the automotive industry have profoundly influenced the nature of competition in the industry. Automotive OEMs are struggling to increase profits and streamline operations. The entire industry is embracing a more horizontal supply structure with suppliers taking on more of the engineering, test and development capabilities. As a result, many suppliers have had to take on a role that has long been reserved exclusively for the OEM – the role of systems integrator. This thesis argues that suppliers cannot effectively fulfill the role of systems integrator in the automotive industry. Some of the most important desired functions of complex digital systems are emergent properties, such as overall system safety and reliability. A meaningful analysis of the emergent properties of the system requires an analysis of the interactions between components in the system as well as an analysis of the system's interaction with its environment. Automotive OEMs must perform these types of analyses because suppliers lack access to components beyond their own parts and they lack the overall system knowledge to understand how these parts interact in the broader system. Systems integration in the automotive industry is a function that must be performed by the automotive OEMs.

Retaining the role of systems integrator has significant implications for the core competencies that OEMs must preserve and develop. Many key skills that have generically been outsourced in the past, such as system CAE modeling, control algorithm design and system verification capabilities, must be brought in-house. If OEMs do not develop these core competencies, they

run the risk of becoming dependent on their suppliers for key system knowledge and surrendering much of the profit and power in the industry to their suppliers. Due to the difficulty of determining the design of digital components through examination and the tendency of suppliers to tightly hold intellectual assets, it is imperative that OEMs retain the ability to be innovators in the field of digital technology.

In addition to having a profound effect on the nature of competition in the automotive industry, digital technology has also introduced new technical challenges to the engineering community. The vast majority of failures in complex systems are the result of systemic flaws based on the unexpected or hidden interactions between components. Digital system complexity and the lack of a physical manifestation of the interactions make finding these systemic flaws extremely difficult. The ease with which changes can be made to the digital system can lead to a lack of adequate forethought and analysis during the design phase and communication gaps within the design and development organizations. Digital technology also introduces new requirements for system design and verification. New hazards are introduced that traditional design techniques such as redundancy and system back-ups do not adequately address. The nature of reliability has considerably changed from a basic assessment of component "durability" to a measure of the correctness and completeness of the system logic under all operating conditions. In addition, digital technology has created an unprecedented need for industry-wide standards to minimize reengineering across programs and reduce overall development cost and time.

Systems engineering provides a way for automotive OEMs to deal with the increasing complexity of digital systems and address these new technical challenges. Systems theory shifts engineering thought and practice away from an emphasis on optimization of the individual parts to an optimization of the whole. Increased attention is given to upfront requirements, documentation, design interfaces, functional coupling, system hazard analysis, testability and usability. If systems engineering is to proliferate further in the automotive industry, OEMs must prioritize it as a core competency. The role of the systems integrator must be redefined to more closely match the definition of a true systems engineer and the most technically qualified individuals in the organization must be recruited to assume these positions. Finally, management must re-emphasize the importance of requirements and documentation throughout the entire vehicle development process.

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CHAPTER 1: INTRODUCTION

1.1 Introduction

Imagine for a moment that your house had its own embedded network … a series of networks, in fact. Imagine one network that provided you with a real time security system, complete with motion detectors, silent and audible alarms and personal property retrieval assistance. Imagine another network that automatically sensed where every member of your household was located: a system intelligent enough to tell the difference between your two-year-old daughter and your eight-year-old son. Imagine a third network that provided your family with personalized information and entertainment in a completely hands-free, voice-activated environment.

Does this sound like a futuristic scenario from a science fiction novel? Perhaps it is for the average homeowner, but it's not that far off for the average car buyer of the twenty-first century. Technology in automobiles is increasing at an astonishing rate and one of the major areas of growth is embedded systems. Networks like the ones mentioned above manage everything from anti-theft security to active safety systems to multi-media infotainment. The more networks that are designed into vehicles, the more complex the vehicle design process becomes.

1.2 Motivation

"A shortcut is the longest distance between two points." – Charles Issawi[1]

The automotive industry is in the midst of a quiet revolution involving the expanding use of digital technology. Automotive electronics accounted for roughly 19 percent of a mid-sized vehicle's cost in the 2001 model year. It is estimated that in the year 2005, electronics may

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[1] From Re-Creating the Corporation. Russell Ackoff. Oxford University Press. 1999. Pg. 251.

account for 25 percent of a mid-sized car's cost and perhaps 50 percent of a luxury vehicle's.[2] Although this estimate may seem high, it is clear that more electronic features are making their way into vehicles every year. As auto manufacturers struggle to keep pace with the rapid expansion of automotive electronics and increased function, they also find themselves under immense pressure to decrease costs and accelerate cycle times. This pressure filters down to the product development organizations in the form of competing technical and business objectives.

Many firms in the automotive industry do not yet fully understand the far-reaching impact these new technologies have on their product development processes and organizations. New technologies are currently developed using existing product development frameworks and the results are often compromises between cost, function and time. To avoid these compromises, a transformation must occur in product development frameworks in the automotive industry. The successful proliferation of digital technology requires a transformation from component engineering to systems engineering principles. In many cases, this transformation will require a cultural and systemic change to the product development processes and organization.

1.3 Objectives

The objective of this research is to define the unique nature of digital technology and understand its impact on existing automotive product development frameworks. An attempt is made to understand how systems engineering principles can help overcome issues related to the successful proliferation of these new technologies. Recommendations for change in the automotive industry are developed through subject matter research and cross industry interviews. Areas for future study and development are outlined in the concluding thoughts.

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[2] "Can You Trust Your Car?". Ivan Berger. IEEE Spectrum. April 2002. Pg. 41.

1.4 Approach and Methodology

This thesis approaches digital technology as a disruptive force in the automotive industry. It is assumed that generically all automotive firms face similar struggles in implementing these new technologies and that product development frameworks are shaped in part by the technologies they produce. For the most part, differences in the competitive positions of different firms within the industry to react to the new technologies are not addressed.

The beginning chapters of this thesis define digital technology in an automotive context and attempt to characterize its disruptive nature in the industry. The middle chapters address the unique nature of digital technology and several of its departure points from existing product development frameworks. The final chapters discuss recommendations for overcoming the inherent conflicts between the new technologies and the current way of doing business. Concluding thoughts regarding areas for future study and development are provided in the final chapter.

CHAPTER 2: LITERATURE REVIEW

"Explanations lie outside the system."
– Russell L. Ackoff[3]

2.1 Introduction

The following sections outline several key frameworks that facilitate further discussion in later chapters. The intent is not to provide an exhaustive review of the subject material but rather a brief overview of significant concepts, models and terminology. The primary objective of this section is threefold: (1) to introduce the concepts of disruptive technology and market diffusion, (2) to define the theory of value creation and the implications of using new technologies to create value and (3) to review some of the main ideas of systems thinking and systems engineering.

2.2 Technology Discontinuity

In every industry, new technologies and processes are created to improve products and ways of doing business. Competition continually drives firms to generate innovations that will allow them to excel in their given industry or to compete in new ones. Ironically, change is one of the few constants that managers can consistently expect. The framework of technology strategy was created to help managers and executives deal with the changing nature of technology and the implications it can have on their firms. The main components of technology strategy, as defined by Professor Rebecca Henderson, consist of value creation, value capture and value delivery.[4] The two key elements of value creation are the concepts of disruptive technology and the evolution of markets.

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[3] "A Day with Dr. Russell L. Ackoff – Making a Difference: Systems Thinking/Systems Change". Girls Link Live Webcast. Chicago-Kent College of Law. November 29, 2000. http://www.judgelink.org/Presentations/GirlsLink/

[4] Rebecca Henderson Summary Slides. http://web.mit.edu/15.932/www/home.html. Referenced October 20, 2002.

2.2.1 Disruptive Technology

Every industry is assumed to have a life cycle that is characterized by the state of the technology upon which it is based. Firms in the industry generally behave very differently depending on where they are in the industry life cycle. Strategic decisions are made at different points that influence the state of the organization and its goals for the future. The technology life cycle is divided into four distinct categories: the era of ferment/disruption, the emergence of a dominant design, the period of incremental innovation and the state of maturity (see Figure 1).

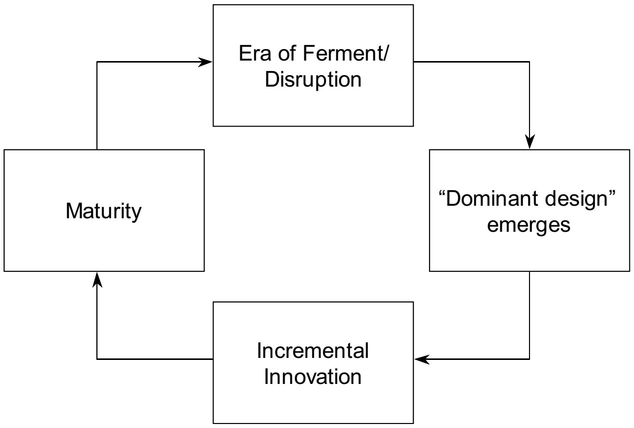

Figure 1: Professor Henderson's Industry Life Cycle Model[5]

When new technologies are created, they often undergo much iteration by different industry players before a dominant design emerges. During this ferment phase, many companies compete on the unique merits of their individual designs and try to gain broader market acceptance. Once an industry standard or "dominant design" emerges, firms in the industry begin to compete on a cost and value perspective rather than on the uniqueness of their designs. During this phase, incremental innovations are developed that allow the inventing firms to gain a market advantage and potentially become leaders in the industry. Eventually, the rate of incremental innovation

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[5] 15.984 – Technology Strategy. Professor Rebecca Henderson. Lecture 1 Class Slides. Pg. 12. February 12, 2001.

slows and an increasing amount of effort is required to achieve ever-smaller increases in performance. At this point, the industry is said to be in a state of maturity. Ultimately, a natural limit will be asymptotically approached where gains in performance take enormous amounts of effort and resources to achieve.

When the four phases of the technology life cycle are plotted on a two-dimensional graph of performance versus effort, the cycle takes on an S-curve shape (see Figure 2). The first S-curve on the bottom left represents the life cycle of an older technology through its four phases of development: ferment, takeoff, incremental innovation and maturity. The second S-curve on the top right represents the life cycle of a newer technology in the same market.

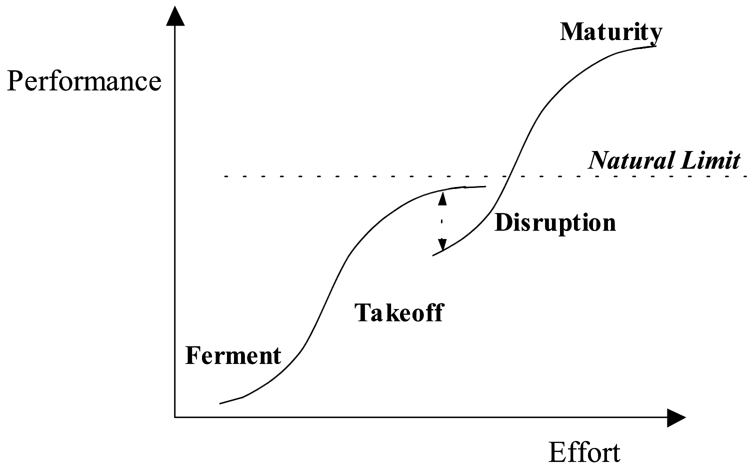

Figure 2: Professor Henderson's Industry Life Cycle as an S-Curve[6]

In classical technology strategy theory, the initial performance of the new technology is characterized as lagging behind the existing technology in one or more performance categories. However, the existing technology is more mature and closer to reaching its natural performance limit where additional performance gains are increasingly difficult to achieve. It is at this crucial

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[6] Adapted from 15.984 – Technology Strategy. Professor Rebecca Henderson. Lecture 1 Class Slides. Pg. 14. February 12, 2001.

stage that firms must decide whether to stay with the existing technology or switch to the new one. It is this reason that the new technology is termed "disruptive" for its potential ability to disrupt the entire industry focus. Since many new technologies never progress past the ferment stage, this decision can be very risky for many firms. The switching costs to new technologies are generally very high and picking the wrong technology can sometimes lead to failure of the entire company. However, switching to the disruptive technology is not without its rewards if the new technology truly is disruptive and becomes the new standard in the industry.

2.2.2 Evolution of Markets

The two main concepts in the evolution of markets are the ideas of market segmentation and the chasm that exists between the early adopters and the early majority. Professor Rebecca Henderson drew upon the works of Everett Rodgers and Geoffrey Moore to create the market diffusion model depicted in Figure 3.[7] In loose terms, the market diffusion model can be thought of as the integral of a graph of market share versus time. The diffusion model defines five broad classifications of people in relation to their willingness to accept new technology. These five categories are: innovators, early adopters, early majority, late majority and laggards.

Innovators are the first people to acquire new technology when it comes on the market. They generally have heard about the technology through trade magazines, websites or other technology-oriented publications. They are willing to pay additional amounts for cutting edge performance and features and have a higher risk tolerance for early obsolescence. The early adopters follow the innovators and are still very concerned about increased function and

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[7] Everett M. Rodgers. Diffusion of Innovations. 3rd edition. The Free Press. 1983. and Goeffrey Moore. Crossing the Chasm. HarperBusiness. Revised edition. 2002.

performance; however, they are more cautious than the innovators. They wait to see how the initial release of the product is received before investing. The model is then marked by a chasm that separates the early adopters from the early majority.[8] It is at this point that many new technologies fail to "catch on" with a wider audience and are either replaced by newer technologies or relegated to a unique, niche market. If a technology makes it beyond the chasm, it is assumed that it will progress through the early majority, late majority and into the laggards market segments.

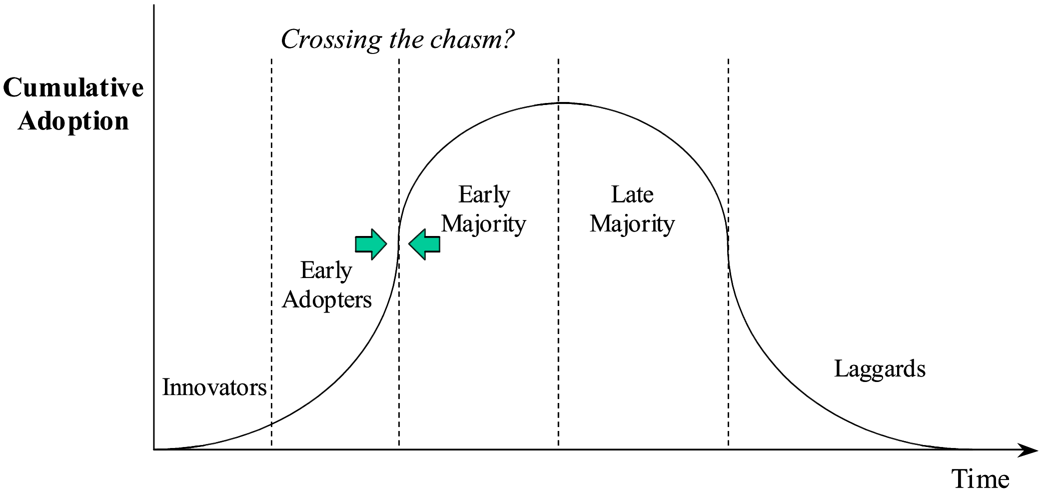

Figure 3: Professor Henderson's Understanding Market Dynamics[9]

One of the key challenges facing companies that introduce new technologies is how to gain wider marketplace acceptance to "cross the chasm" into the mainstream. Often, the innovators and early adopters "pull" the technology from firms in their search for increased performance even at additional cost. The main marketing goal of firms at this point is to get the word out that a new technology is coming and then deliver the technology on time with representative

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[8] Goeffrey Moore. Crossing the Chasm. HarperBusiness. Revised edition. 2002.
[9] Adapted from 15.984 – Technology Strategy. Professor Rebecca Henderson. Lecture 3 Class Slides. Pg. 5. February 26, 2001.

performance. Sale of the technology to customers across the chasm usually requires a different approach. Marketing must make a concerted effort to "push" the technology by way of advertising in mainstream media such as television, national magazines or newspapers. The selling points of the new technology are also different. Value is a much bigger concern for customers in the early majority. These particular customers are willing to pay a little extra for the new technology but only if there is a clear benefit defined and the benefit outweighs the additional cost.

2.3 Value Creation

The idea of value creation through new technology appears in several different forms in the literature, but the underlying message is similar in all works. If a new technology is to succeed, it must provide additional value to the customer. A new device by itself can be the most fascinating invention in the world, but if no additional value is created then there will be no customer for the device. History is replete with many attention-grabbing technical exercises and novel ideas that never quite caught on in the marketplace.

Since all of the automotive firms in the domestic industry are commercial ventures owned in large part by public stockholders, it is assumed that these firms intend to profit from most new technologies they develop. If this is the case, then automotive manufacturers should be concerned with making sure their new technologies provide additional value to at least some of their customer base. In other words, implementation of new technology should follow a strategic business plan that takes customer needs and wants into consideration. The following sections describe in more detail the concepts of value creation and strategic implementation.

2.3.1 Definition of Value

Value, as defined by Womack and Jones, is "a capability provided to a customer at the right time at an appropriate price, as defined in each case by the customer".[10] Rebentisch takes this idea further by defining value as "… a function of the product's usefulness to the customer, its relative importance to the customer's need, its availability relative to when it is needed, and how much the customer has to pay for it."[11] The main concepts behind each of these definitions are the ideas that new technologies and products must first create value for the customer and that second, it is the customer that decides what the value of the new technology or product is.

In most definitions of value, there are at least two components to the product-oriented value equation: performance and cost.

$$Value = \frac{Performance}{Cost}$$

Breaking the value equation into a nine-panel chart, several different strategies emerge for creating value (see Figure 4). Obviously, the most profitable strategy involves increasing performance while simultaneously decreasing cost. This is labeled on the figure as the ideal. In a mature industry, it is almost impossible to achieve these types of gains, even with new technologies. Therefore, more realistic strategies involve optimization along one of two primary axes – cost or performance. In a mature industry where firms compete heavily on price, the prime incentive is to reduce cost while maintaining or slightly degrading non-essential performance characteristics. In non-essential areas of automotive design, this approach has been

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[10] James P. Womack and Daniel T. Jones. Lean Thinking: Banish Waste and Create Wealth in Your Corporation. Simon and Schuster. 1996. Pg. 311.

[11] Rebentisch, MIT, 2000. From Integrating the Lean Enterprise Lectures Notes: "Lean Enterprise Principles and Practices". September 19, 2001. Professor Deborah Nightingale. Slide 7.

used successfully to maintain customer feature content from model year to model year while decreasing the overall cost to the consumer.

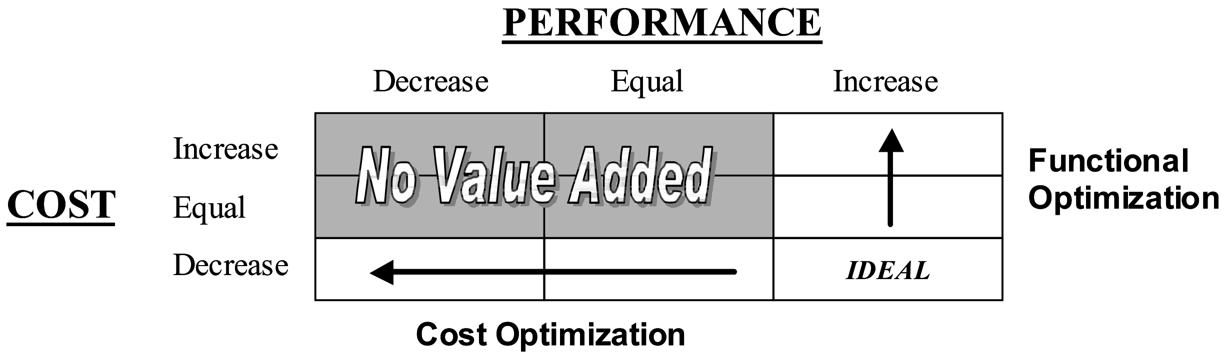

Figure 4: The Nine-Panel Value Creation Chart

In other areas in the automotive industry, new digital technology has been used to achieve the inverse – an increase in features and performance at a minimal level of increased cost to the customer. There are two apparent challenges in this type of activity. First, the overall value equation must be managed in a way that the customer clearly perceives an increase in value from the new technology. Second, the incremental cost to the organization cannot exceed the price the customer is willing to pay for the new technology. Failure to achieve either of these goals would significantly affect the viability of the proposed technology.

A final note on value creation is a reminder that customers represent more than a homogeneous group of consumers. As Everett Rodgers' market diffusion model clearly illustrates, the consumer base can be divided into five major categories and undoubtedly several sub-categories beneath those.[12] A complete understanding of the consumer base in a complex industry such as automotive is a formidable task and clearly beyond the scope of this research. However, it is

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[12] Everett M. Rodgers. Diffusion of Innovations. 3rd edition. The Free Press. 1983

worth noting that new technologies must satisfy a variety of different consumer group's needs if they are to succeed. A secondary point to remember is that customers are not always the end users of the product. Shareholders, employees, environmental regulators, magazine writers, dealers and other stakeholders also represent customers in their own right with their own definitions of value.

2.3.2 Strategic Implementation

As stated earlier, one of the central ideas in technology strategy is the concept of how firms capture value from new technology. Professor Rebecca Henderson cites appropriability as one of the three main ways to capture value. She defines appropriability as the ability to control the knowledge that surrounds or enables an innovation. Firms in an industry generally appropriate key knowledge either through intellectual property protection, secrecy or speed of innovation.[13]

As firms in the automotive industry attempt to generate additional value through digital technology, issues regarding who captures the value from these innovations become more important. Relationships between the Original Equipment Manufacturers (OEMs) and their suppliers often dictate the terms of the technology acquisition and transfer. If OEMs are to capture value from digital technology, generation and appropriation of key knowledge in the industry are of major strategic importance.

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[13] 15.984 – Technology Strategy. Professor Rebecca Henderson. Lecture 6: "Profiting from Innovation". Slides 6-8.

2.4 Systems Thinking and Systems Engineering

An attempt is made in this thesis to explain how systems thinking and systems engineering can help overcome some of the challenges surrounding the successful proliferation of digital technology in the automotive industry. As such, it is important that common definitions for systems thinking and systems engineering are established. The following sections describe in more detail the origin of systems thinking, the main principles upon which it is based and the attempt to apply these principles to made-made, engineered systems.

2.4.1 Systems Thinking

Systems thinking emerged in the 1930s as an analysis tool to help scientists deal with the complexity of the world around them. Until that time, the primary analytical tool available to most researchers was the scientific method, which relied on the principles of analytic reduction, repeatability and refutation. In the theory of analytic reduction, it was assumed that the division of the whole into parts and the subsequent analysis of the parts taken separately yielded similar results as an analysis of the whole.[14] This theory held true in many cases. However, in some instances, the mere division of the whole into parts distorted the behavior of the individual parts or the disassembly of the whole into parts was a complex and flawed process. Researchers began to discover that certain biological and social phenomena could be more easily understood when placed in the context of a broader system. The concepts of a general systems theory emerged as a new way for scientists to observe and explain these phenomena.

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[14] Nancy Leveson. Safeware: System Safety and Computers. Addison-Wesley Publishing Company. 1995. Pgs. 135-136.

Throughout systems theory literature, several key concepts appear that define the inherent nature of systems. Defining the nature of systems is the first step in understanding how to manage them. In his book *Re-Creating the Corporation*, Russell Ackoff lists five essential properties of systems that touch upon many of these concepts. His list is recreated in its entirety below.

1. *The whole has one or more defining properties or functions.*
2. *Each part in the set can affect the behavior or properties of the whole.*
3. *There is a subset of parts that is sufficient in one or more environments for carrying out the defining function of the whole; each of these parts is necessary but insufficient for carrying out this defining function.*
4. *The way that each essential part of a system affects its behavior or properties depends on (the behavior or properties of) at least one other essential part of the system.*
5. *The effect of any subset of essential parts on the system as a whole depends on the behavior of at least one other such subset.*[15]

There are several key take-aways from this list that can be applied to the management of digital technology in the automotive industry. First, it is necessary to understand what the defining function or functions of the overall system are and how the individual parts of the system act together to achieve this defining function. Second, it is important to understand which parts of the system are essential for the overall functioning of the system and which are not. Third, it is the interaction of the parts of the system that define its overall function, not the performance of the individual parts taken alone. Fourth, improvement of individual parts of the system alone may actually degrade the performance of the entire system.

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[15] Russell Ackoff . Re-Creating the Corporation. Oxford University Press. 1999. Pgs. 5-8.

2.4.2 Systems Engineering

"Systems theory provides a theoretical foundation and approach for systems engineering, which is concerned with optimizing the design and development of an overall system as opposed to optimizing the components."
- Nancy Leveson[16]

As the complexity of man-made systems increased throughout the twentieth century, engineers eventually applied systems theory to the design and development of complex machines. What emerged was a discipline known as systems engineering. Many of the fundamental processes in systems engineering were not new; they already existed in the realm of component engineering. However, the application of these processes shifted from an emphasis on optimization of the parts to an optimization of the whole.[17]

According to the work of Professor Charles Boppe, systems engineering can simultaneously be described as a formal discipline, an engineering process, an integration method and a collection of best practices.[18] Although many different definitions can be presented for systems engineering, two key themes resonate throughout the literature. First, systems engineering is a process by which complex systems are conceived, designed, verified and implemented. Second, it is a mindset by which these complex systems are integrated and managed.

One of the key elements of the systems engineering process is the Vee model diagram depicted very generically in Figure 5. In this development model, the requirements of the system are decomposed and defined in a serial process on the left hand side of the Vee, the design/synthesis is performed along the bottom and the physical systems are integrated and verified against these

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[16] Nancy Leveson. Safeware: System Safety and Computers. Addison-Wesley Publishing Company. 1995. Pg. 140.
[17] Nancy Leveson. Safeware: System Safety and Computers. Addison-Wesley Publishing Company. 1995.
[18] Charles W. Boppe. ESD.33J Systems Engineering Summary. August 16, 2001. Slides 3-6.

requirements on the right hand side. Throughout the design process, trade studies are performed to ensure optimization of the system as a whole. The entire process is designed to be iterative so that additional information found at various points in the development process can be fed back into the design cycle of the overall system. However, due to cost and timing constraints on most projects, the iterations are often limited in scope and size.

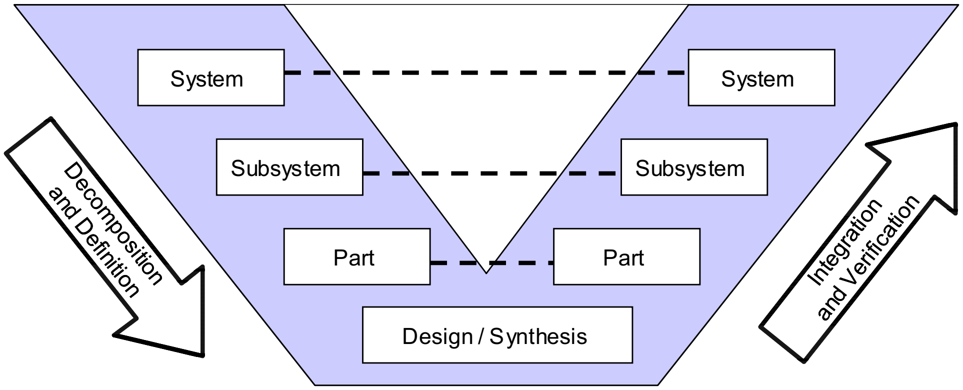

Figure 5: The Systems Engineering Vee Model Diagram

Perhaps the most critical component of the systems engineering process is the initial requirements definition phase. The initial requirement writing, cascading and binning affects all downstream activities including architectural decisions, trade studies, feasibility studies and design verification. Another important aspect of systems engineering, missing from the Vee diagram above, involves management of the interfaces across system boundaries. To paraphrase Professor Russell Ackoff, it is the interaction of the parts that describes the ultimate behavior of the whole, not the action of the individual parts taken alone.[19] In this way, systems engineering is unique in relation to many other engineering disciplines. Systems engineering, unlike other disciplines, is concerned with the overall management of the engineering process and

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[19] "A Day with Dr. Russell L. Ackoff – Making a Difference: Systems Thinking/Systems Change". Girls Link Live Webcast. Chicago-Kent College of Law. November 29, 2000. http://www.judgelink.org/Presentations/GirlsLink/

management of the interfaces across boundaries. It is understood that both of these play an important role in the ability of the overall system to meet its objectives.

2.5 Relevance

In subsequent chapters, an attempt is made to characterize digital technology as a disruptive force in the automotive industry. As such, automotive manufacturers must be aware of the potential of the technology to diffuse through the marketplace and the challenges involved with marketing to a wide variety of customers in the market diffusion model. In order to "cross the chasm" and gain wider market acceptance with these new technologies, a small majority of the customers must perceive additional value created by digital technology. This value equation is a delicate balance that manufacturers must manage between additional performance and price.

Since customers ultimately purchase vehicles and not individual technologies, automotive manufacturers have an opportunity to increase overall value to the customer at an acceptable cost by maximizing the value of the overall vehicle. This requires OEMs to recognize the vehicle as an overall system, of which digital technology is only a part. To date, many OEMs have tried to create value from digital technology on a sub-system application basis. As a result, the performance of individual sub-systems has been optimized, at times to the degradation of the overall vehicle value equation. If OEMs are to capture value from the proliferation of digital technology in the automotive industry, they must prioritize value creation from an overall system (vehicle) perspective. Changes to the overall automotive enterprise may be required to enable this change in perspective.

CHAPTER 3: DEFINING DIGITAL TECHNOLOGY IN AN AUTOMOTIVE CONTEXT

"It's never what we don't know that stops us. It's what we do know that just ain't so."
– Dean Kamen[20]

3.1 Definition of Key Terminology

One of the first steps in understanding the impact of new digital technology on the automotive industry is to define and understand some of the new terminology. The following sections outline a series of key terms and concepts unique to the digital world and provide examples of digital technology in an automotive context.

3.1.1 Digital Technology

According to Merriam-Webster's Collegiate dictionary, digital is defined as "of, relating to, or using calculation by numerical methods or by discrete units".[21] Digital technology is unique in that information is transferred in the form of discrete (digital) signals rather than continuous, analog signals. Embedded microprocessors are able to manipulate and store the digital signals in a variety of ways and use the information in software calculations. Digital technology is a broad category that encompasses all electronic devices that rely on digital as opposed to analog signals. Several of the major benefits of digital technology are functionality, speed, reliability and size. Examples of digital technology include satellite navigation systems, anti-lock braking systems and electronic power-assisted steering systems.

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[20] Dean Kamen. President of Deka Research. Fall 2001 SDM Business Trip Guest Lecture. October 22, 2001.
[21] http://www.m-w.com/cgi-bin.dictionary. Referenced September 21, 2002.

3.1.2 Embedded Systems

To embed one device in another is to make one or both of the units integral to the function of the other. The embedded device loses its ability to function if it is separated from its intended environment. In addition, the system into which the device was embedded also loses some or all of its function if the embedded device is removed. An engine control unit (ECU) is an example of an embedded system in the automobile. If the ECU were removed from a vehicle, it would lack the necessary input and output connections to perform its intended function. Also, the vehicle as a whole would cease to provide its primary function of automotive transportation.

3.1.3 Telematics

Much has been written about the emergence of telematics in the automotive industry and the blurring line between transportation and infotainment. Currently telematics refers to an embedded automotive system that provides a wireless communications link between the vehicle and a customer call center. The interface is usually achieved through a voice-activated, hands-free cellular service coupled with an embedded global positioning system (GPS) and possibly a satellite communications system (see Figure 6). In most cases, the customer activates the service by pushing a button in the vehicle that automatically connects to a live operator. One of the leading telematics systems today is the General Motors OnStar® Service. According to their website, OnStar® provides "Driving directions, emergency assistance, up-to-the-minute stock quotes, email and more, all in your vehicle."[22] Additional features provided by OnStar® include:

- Air Bag Deployment Notification
- Stolen Vehicle Tracking
- Remote Door Unlock
- Remote Diagnostics

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[22] http://www.onstar.com/visitors/html/ao_features.htm. Referenced September 22, 2002.

- Personal Concierge Services
- Personal Calling
- Roadside and Accident Assistance
- Information/Convenience Services
- Alternate Ride Assistance[23]

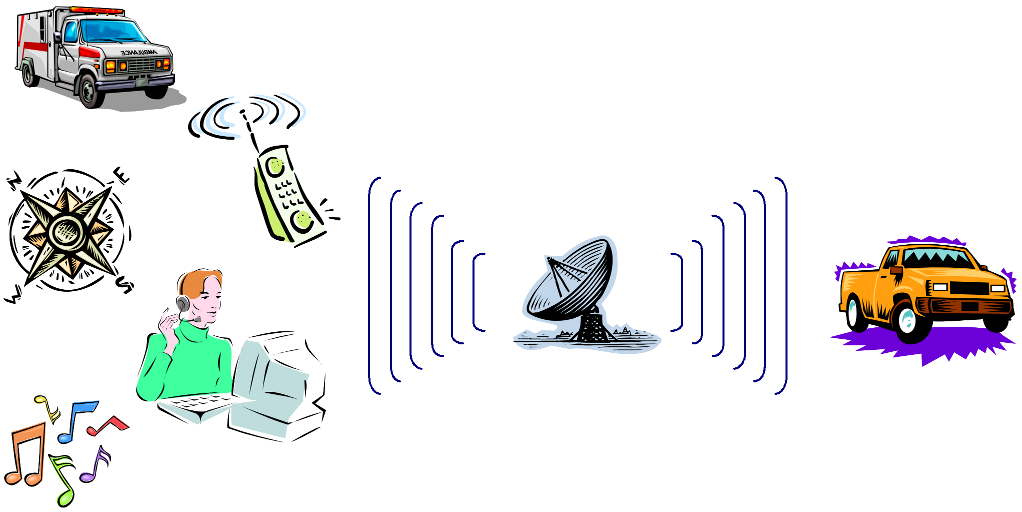

Figure 6: Graphical Representation of a Generic Telematics System[24]

3.1.4 Vehicle Control Systems

Vehicle control systems provide real-time, continuous monitoring of vehicle conditions and provide open-loop system control to achieve an optimal response. The main components in a vehicle control system include sensors, actuators and a central processing unit. The primary goal of a vehicle control system is to maintain a given state of system equilibrium that matches the desired vehicle response. In general, these systems provide electronic intervention to mainly mechanical systems.

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[23] http://www.onstar.com/visitors/html/ao_features.htm. Referenced September 22, 2002.

[24] Adapted from Sean Newell's thesis "Distortion of 'Fast Clockspeed' Product Development: Using Web-based Conjoint Analysis, Clockspeed Analysis and Technology Strategy for an Automotive Telematics System". MIT-SDM. February 2001.

One example of a vehicle control system is the anti-lock braking system (ABS). In a four channel ABS system, sensors continually monitor the actual speed of all four wheels and compare them to a desired, optimal wheel speed for the given vehicle conditions. When the processor determines that one or more of the wheels has "locked up" during deceleration, it immediately restricts the flow of hydraulic brake fluid through the control valve to the affected wheel. This action reduces brake pressure on that wheel in order to increase traction. Once traction is achieved, the processor opens the control valve and increases pump flow to increase brake pressure on that wheel to slow the vehicle. This cycle is iterated many times before the vehicle is brought back to its desired state.[25] With the speed of the digital system, these iterations occur much faster than a human could achieve with purely mechanical controls.

One of the key elements of the anti-lock braking system is the control algorithm. Different systems define a "locked" wheel in different ways. One system may define a certain semi-locked state as an "unacceptable" deceleration rate and "gradually" engage the actuators, whereas another system may wait longer and then provide a more abrupt engagement of the actuators. These engagement points and corrective actions are defining features of control algorithms and are generally kept as tightly held proprietary information by their creators.

3.1.5 X-by-wire

In some ways, vehicle control systems are seen as precursors to X-by-wire systems where the mechanical linkages are removed from the system and electronics connect the driver's input to the vehicle's output. Like vehicle control systems, X-by-wire systems provide real-time,

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[25] http://www.howstuffworks.com/anti-lock-brake2.htm. Referenced September 22, 2002.

continuous monitoring of vehicle conditions and system control of a desired response. However, unlike vehicle control systems, X-by-wire systems are embedded into a vehicle's architecture. Their primary goal is to replace mechanical systems and provide increased levels of response and performance unattainable without electronics. In the automotive industry today, these systems are generally applied in braking, steering, throttle and suspension control applications.

An example of an X-by-wire system is the Electro Mechanical Brake (EMB) system offered by the automotive supplier Continental-Teves. This system is designed to replace the brake master cylinder and hydraulic brake lines with individual wheel brake modules (see Figure 7). An electronic control unit (ECU) receives driver demand information through an electronic pedal module and provides the necessary signals to the electric motors at each wheel to slow the vehicle.[26] Wheel speed sensors are an integral part of the system design; therefore, EMB comes equipped with ABS and traction control (TCS) functionality.

One of the additional functions of the electronic pedal module is to simulate the "pedal feel" of a conventional hydraulic system for the driver. Since there are no hydraulic components in the EMB system, there is no inherent resistive pressure on the brake pedal. In order to make the transition to EMB as seamless as possible for customers, an artificial resistive force on the brake pedal must be simulated in a way that mimics a conventional system. This feature is characteristic of many electronic systems in that the driver interface must be transparent to the customer even though the supporting technology is all new.

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[26] http://www.conti-online.com/generator/www/de/en/continentalteves/continentalteves/themes/products/electronic_brake_systems/brake_by_wire/emb_0602_en.html. Referenced September 21, 2002.

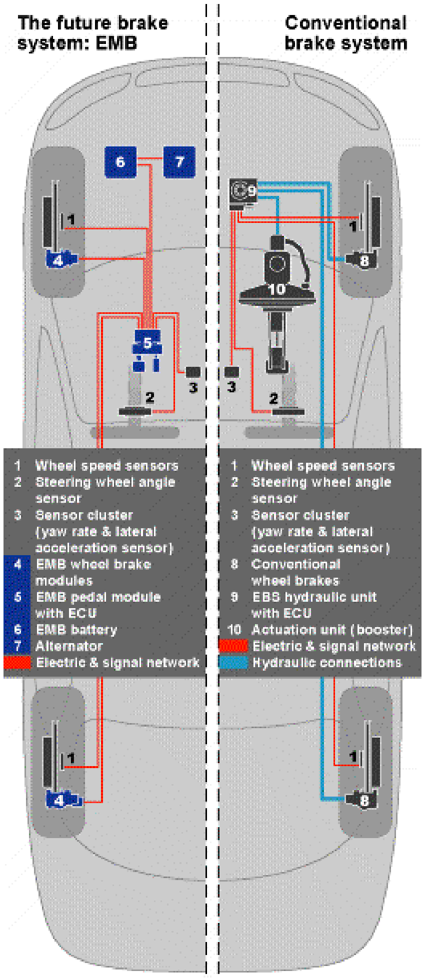

Figure 7: Continental-Teves EMB System vs. Conventional Brake System[27]

There are many inherent benefits of X-by-wire technology. Due to their innate speed, X-by-wire systems can often provide levels of actuating performance that are unattainable by human drivers with mechanical systems. Linked X-by-wire systems also provide a level of communication between systems that does not require an additional driver interface. X-by-wire systems also provide benefits to the OEM in the form of increased design flexibility and reduced development time. Depending on the application, electronic control units may have more package flexibility than conventional hardware mechanisms that rely on physical proximity for their function. Also,

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[27] http://www.conti-online.com/generator/www/de/en/continentalteves/continentalteves/themes/products/electronic_brake_systems/brake_by_wire/emb_0602_en.html

the time required for development tuning of such systems can be greatly reduced since many system parameters can be changed quickly in the software, eliminating the need to order more hardware.

Some of the major technical challenges of X-by-wire systems include system reliability, heat management, Electro-Magnetic Interference (EMI) and the lack of current industry standards.[28] X-by-wire systems also pose a unique marketing challenge. In general, X-by-wire systems are not well understood by the majority of today's automotive consumers. OEM marketing departments tend to avoid complex, technical ads that may confuse or alienate potential customers. Also, in order to put customers at ease with the new technology, these systems are designed to seamlessly maintain conventional driver interfaces. Often, these interfaces perform so well that customers may never see or even know they have the new technology. Since the variable cost is still high in many of these systems, it is often difficult to price for the additional functionality that the customer may not value, understand or even know they have.

3.2 A Bit about Network Standards

As digital technology in the automotive industry proliferates, network standards can help reduce costs and increase interchangeability between systems and suppliers. Like the personal computer industry, standard network interfaces and communication protocols can speed the acceptance of digital technologies by making them easier to "plug and play" into existing vehicle architectures. However, unlike the personal computer industry, the automotive industry generally has greater

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[28] http://42volt.dupont.com/en/Systems/bywire_main.html. Referenced September 21, 2002.

needs for system reliability, vehicle network partitioning and firewall security.[29] Different network protocols may co-exist in the same vehicle depending on the needs of the system. Systems can be grouped together by purpose and share a common network protocol for efficiency. Groups of systems that do not communicate with one another may have different network protocols and may be further separated by a firewall. A graphic representation of a generic vehicle network is included in Figure 8.

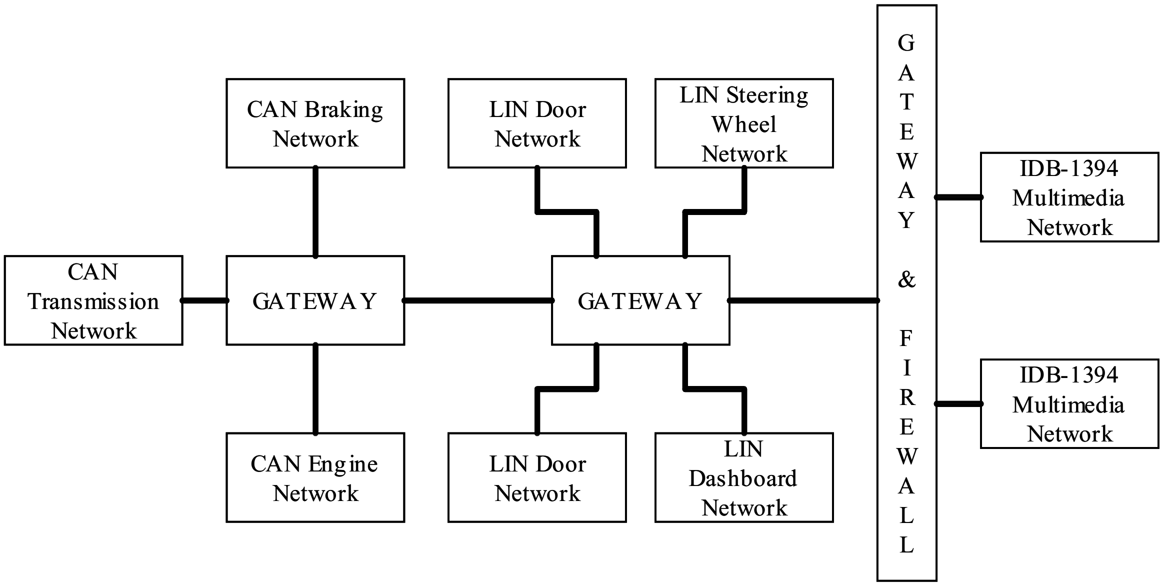

Figure 8: Block diagram of a partitioned vehicle network[30]

Three of the most common network types in use today are CAN, LIN and IEEE-1394. CAN is generally used for high-speed control system applications such as ABS. LIN is generally used for lower-speed control modules such as power door locks or memory seats. IEEE-1394 (a.k.a. "Firewire") is generally used in high speed multimedia applications. X-by-wire network protocols are still under development, but two emergent types are TTP/C and Flexray.

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[29] "Software and Hardware In-Vehicle Network Growth: CAN networks and OSEK/VDX-compatible operating systems will drive tomorrow's vehicles". Wong, William. Electronic Design. January 8, 2001. Pg 62-70.

[30] Adapted from "Software and Hardware In-Vehicle Network Growth: CAN networks and OSEK/VDX-compatible operating systems will drive tomorrow's vehicles". Wong, William. Electronic Design. January 8, 2001. Pg. 64.

3.2.1 Controller Area Networks (CAN)

CAN is a serial (or linear) bus system capable of network speeds up to 1 Mbps. The linear network structure (see Figure 9) makes CAN more reliable than many other network configurations. The failure of one ECU on the network does not necessarily affect the communication of other ECU's on the same network.

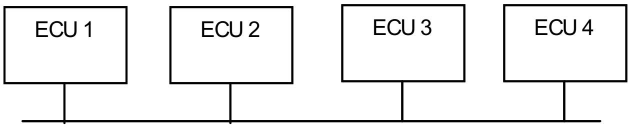

Figure 9: CAN linear bus structure[31]

The speed and reliability of CAN are two reasons why it is often used in vehicle control systems. Vehicle control systems, such as ABS, generally require high network speeds to monitor systems in real time and provide adequate system response time. CAN's collision-resolution arbitration method also ensures priority data transmission. As described by Warren Webb in EDN magazine, "When multiple nodes simultaneously transmit data, lower priority nodes retransmit, and the highest priority message continues to its destination."[32]

3.2.2 Local Interconnect Network (LIN)

LIN was created to be a low cost, sub-bus network for "decentralized, small ECU's (e.g. switches – actuators – sensors)".[33] It is an open standard with speeds up to 20 kbps. LIN operates on a master-slave protocol and is usually implemented in conjunction with a CAN network structure. By utilizing only one wire on the network instead of two, LIN reduces wiring costs in

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[31] Bosch Automotive Electrics and Electronics – 3rd Updated Edition. Pg 7.

[32] "Embedded technology transforms the automobile". Webb, Warren. EDN v.44 no.17. August 19, 1999. Pg. 91-98.

[33] http://www.infomicom.mesc.co.jp/CAN/lin/whatlinf/whatline.htm. Referenced September 21, 2002.

applications that may be more cost sensitive. An example of a LIN application on a CAN network structure is included in Figure 10.

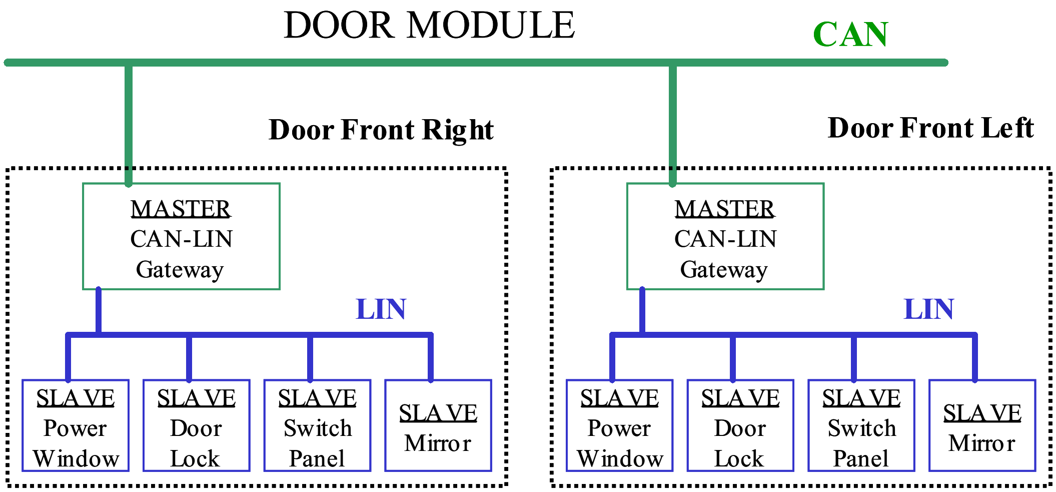

Figure 10: Potential LIN application on a CAN network bus[34]

3.2.3 IEEE 1394 (a.k.a. "Firewire")

IEEE 1394 is a fiber-optic, high-speed network used primarily in multimedia applications. It was originally created outside the automotive industry and has since been adapted to work in the harsher automotive environment. IEEE 1394 networks are capable of speeds up to 300 Mbps.[35] The structure of the network be can either a daisy chain or tree configuration. One of the primary goals of the network configuration is to allow multiple access ports and interoperability between components.

3.3 Examples of Embedded Software

The focus of this research is mainly on the embedded systems aspect of digital technology. Rather than concentrate on the customer interface of telematics and infotainment, this analysis

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[34] Adapted from Mitsubishi Electric Europe Semiconductor presentation. EDEC AAE-JJA 19-July-01. Downloaded from http://www.infomicom.mesc.co.jp/CAN/lin/whatlinf/whatline.htm. Referenced September 21, 2002.

[35] "Software and Hardware In-Vehicle Network Growth: CAN networks and OSEK/VDX-compatible operating systems will drive tomorrow's vehicles". Wong, William. Electronic Design. January 8, 2001. Pg 62-70.

concentrates mainly on the parts of the systems unseen by the average customer … the embedded software. This facet of digital technology presents a unique challenge to the automotive industry and many of the largest issues have yet to be fully defined. A brief overview of several embedded systems technologies is contained in the following sections.

3.3.1 Electronic Stability Program - ESP

Most of the major automotive manufacturers today employ some form of electronic stability program (ESP). Depending on the manufacturer, this type of system may go by a different name such as interactive vehicle dynamics (IVD) or dynamic stability control (DSC). Whichever name is used, the main objective of the system is to control vehicle yaw motion and prevent unstable under or oversteer conditions. The primary components in an ESP system include the wheel speed sensors, steering angle sensor, yaw rate sensor, lateral acceleration sensor, engine control unit and brake modulators with control units (see Figure 11).

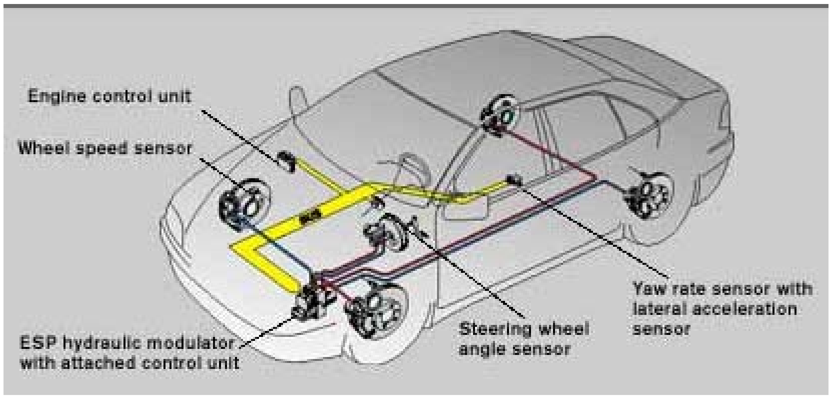

Figure 11: Bosch ESP System Schematic[36]

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[36] http://www.boschusa.com/AutoOrigEquip/Braking/ElectronicStability/. Referenced October 4, 2002.

ESP is perhaps one of the least understood vehicle control systems from a customer perspective. Unlike a cruise control system, the driver does not engage or disengage the system for operation. The system sensors continuously monitor the vehicle's performance and the control unit automatically engages the actuators as necessary. Like an ABS system, the control mechanisms intervene only in accident avoidance situations to help maintain a vehicle's directional stability.

ESP is comprised of several other stand-alone control systems such as ABS, traction control (TCS), electronic brake power distribution (EBD) and engine drag torque control (EDC). As such, ESP has the ability to sense longitudinal instability due to wheel slippage or wheel lock-up and provide the appropriate braking countermeasures to correct the instability. ESP also goes beyond the sub-component functions and provides an additional level of lateral stability to the vehicle. Through what Continental Teves describes as a "permanent comparison of driver requirement and reality", the ESP system continuously monitors the vehicle's actual yaw moment and compares it with the "intended" yaw moment computed from the wheel speed and steering angle sensors.[37] When the system senses a discrepancy between intended and actual, the system uses a combination of automatic braking and engine torque reduction to provide additional assistance to the driver. In the case of vehicle understeer, ESP slows the inside wheels to induce additional yaw moment to achieve the intended turning radius. In the case of vehicle oversteer, ESP slows the outside wheels to counteract the perceived excessive yaw moment.

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[37] Continental Teves Press Release. Auburn Hills, MI. August 24, 1999. http://www.contitevesna.com/0824993.htm. Referenced October 4, 2002.

3.3.2 Roll Stability Control - RSC

Ford Motor Company recently developed an "active stability-enhancing system" known as Roll Stability Control (RSC) that goes a step beyond ESP in maintaining vehicle directional stability in accident avoidance maneuvers.[38] All of the main components in ESP are also used in RSC with the addition of roll sensors and supplementary control algorithms. Vehicle roll sensors continuously monitor the vehicle's roll angle and roll rate. The RSC control unit uses this information and data from the other system sensors to calculate vehicle roll stability at a rate of over 100 times per second.[39] When a potential excessive roll event is detected, RSC activates a combination of engine torque reduction and/or brake application to reduce the vehicle roll moment and maintain vehicle stability.

3.3.3 Steer-by-Wire – EPS

Conventional hydraulic power assisted steering systems rely on continuous power from the engine to run a power steering pump. Since the steering pump is directly connected to the engine through a FEAD belt, a certain amount of power is constantly drawn from the engine. This power is used to keep hydraulic fluid flowing through the system even during low demand conditions such as vehicle idle at a stoplight. Also, since the amount of power supplied to the steering system is directly proportional to engine speed, excess power may be supplied to the steering system during conditions such as straight ahead driving on the highway. Both of these conditions have a measurable effect on fuel economy and acceleration performance.

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[38] http://www.fordbetterideas.com/tc/main/featuredtech/vehicleroll.htm. Referenced October 4, 2002.

[39] http://www.fordbetterideas.com/tc/main/featuredtech/vehicleroll.htm. Referenced October 4, 2002.

In an effort to reduce the parasitic effect of the steering system on the engine, electric motors have been suggested as an alternative source of power. In an electric power assisted steering system (EPAS), the hydraulic pump is replaced with an electric motor. In this system, the electric motor provides the power assist rather than the hydraulic pump and fluid lines. The mechanical link between the steering column and road wheels is still intact. An electronic control module decides how much power assist to provide and when. One of the major benefits of this type of system is that overall fuel economy can be improved by as much as 3%.[40] This technology is an example of a vehicle control system.

Steer-by-Wire or Electronic Power Steering (EPS) systems go a step further. In these systems, the mechanical linkage between the steering column and road wheels is severed and an electronic control system is inserted. When the driver inputs a torque on the steering wheel, a sensor in the steering column ascertains the rate and amount of steering input. A control module determines the correct amount of steering force to be applied at the road wheels to meet the driver demand. Actuators in the steering column are also activated to give the driver a sense of tactile "road feel". (Steering torque build-up with increasing steering angle is one such example.) This feedback is required to give the driver a sense of the vehicle response. One of the major benefits of steer-by-wire systems is the virtual elimination of certain vehicle error states such as steering wheel nibble and steering vibration that are an inherent part of mechanical systems.

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[40] http://e-www.motorola.com/webapp/sps/site/application.jsp?nodeId=04M0ym4Psy0. Referenced October 4, 2002.

CHAPTER 4: STRATEGIC ASPECTS OF DIGITAL TECHNOLOGY

"There is no such thing as a Chief Car Guy at Microsoft ..."
– John Couretas[41]

4.1 Major Trends in the Automotive Industry

The automotive industry is continually one of the largest grossing industries worldwide. Four of the top ten companies in Fortune's Global 500 are automotive manufacturers (General Motors, Ford Motor Company, Daimler-Chrysler and Toyota Motor). The combined total revenues of these four automotive manufacturers were almost 600 billion dollars in 2001. By comparison, Microsoft Corporation's total revenues for the same period were just over 25 billion dollars.[42]

Despite strong sales and high revenues, most automotive manufacturers have been struggling to turn a profit. Calculating profit as a percent of total revenue, the average return for the four automotive companies named above was only 0.16% in 2001. By comparison, Microsoft Corporation's return was a significant 29% for this same period.[43] The reasons behind the considerable performance differences between these companies are certainly too varied and too complicated for this analysis. The major goal of this comparison is to point out that the automotive industry is a significant player in world economics, but it is also a mature industry where profits are difficult to achieve and the cost of failure is high.

Charting the average retail price of both a mid-size family sedan and a high-end luxury vehicle over the last ten years illustrates that average retail prices of vehicles have actually declined slightly over this period after adjusting for inflation (see Figure 12). This has put significant

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[41] Couretas, John. "Clueless in Seattle: Microsoft wants to put talking PCs in everybody's new car, but automakers question the technology's cost and reliability." Source: Automotive News no.5788. October 12, 1998. Pg. 35-36.
[42] http://www.fortune.com/lists/G500/index.html. Referenced November 5, 2002.
[43] http://www.fortune.com/lists/G500/index.html. Referenced November 5, 2002.

pressure on automotive manufacturers to both decrease internal costs and also market higher-priced, upscale vehicles to consumers to generate additional revenue.

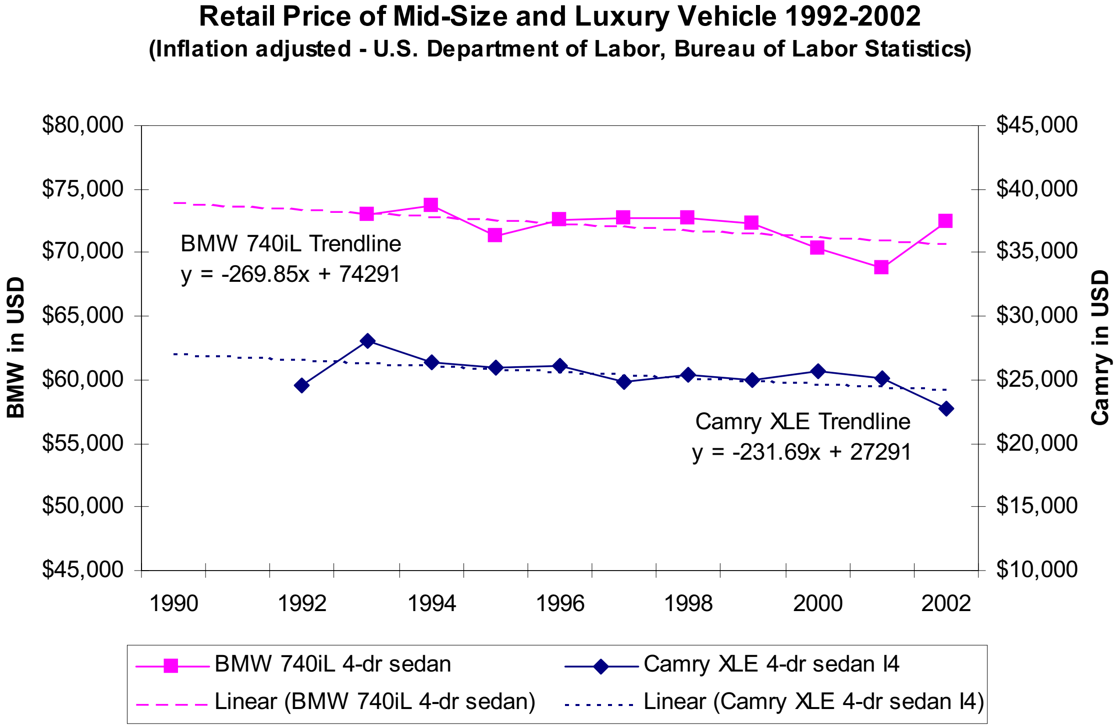

Figure 12: Inflation Adjusted Retail Vehicle Price 1992-2002[44]

Market share has also become increasingly important as OEMs vie for limited sales in an industry that already has too much production capacity. As automotive manufacturers use size to their advantage by selling many different products to fill unique customer needs, brand differentiation plays an important role. New technology is one way that manufacturers try to differentiate their products in the marketplace and also generate additional revenue through higher-priced option content. Many in the industry believe that embedded software enables brand differentiation among products for little or no cost as software can be reused and modified from application to application. Subsequent analysis in this thesis debunks this theory as myth.

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[44] Ward's Automotive Yearbook. 1992-2002. Published by Ward's Communications. Southfield, MI.

4.2 Changing Nature of Competition in the Automotive Industry

As mentioned earlier in this thesis, the cost of automotive electronics in vehicles is increasing at a significant rate. It is estimated that in the year 2005, electronics may account for 25 percent of a mid-sized car's cost and perhaps 50 percent of a luxury vehicle's.[45] The available features list of one of the current industry-leading luxury vehicles, the new 2002 BMW 745iL, reveals a staggering amount of electronic content (see Appendix A). Although this amount of electronic content in an automotive vehicle is far from the norm, it provides a glimpse into the potential future of the mainstream automotive market. As the amount of embedded software in vehicles increases, the complexity of the overall product grows exponentially.

Amid the wave of change in vehicle content, an equally sweeping level of change in the supply chain structure is taking place in the automotive industry. As OEMs struggle to streamline operations and reduce capital-intensive assets, the industry is embracing a more horizontal structure with suppliers taking on more of the engineering, test and development capability. The term *full-service supplier* is often used to describe a supplier that goes beyond traditional fabrication and delivery of the part to include the design, development and validation against the given requirements. In exchange for taking on additional design and development roles, the full-service supplier is generally paid additional money in the form of increased piece price or a lump sum payment. This arrangement reduces the manpower, facilities and investment required at the OEM and increases it at the supplier.

The changing nature of the supply chain has enabled many suppliers to increasingly take on a role that has long been reserved exclusively for the OEM – the role of system integrator. In

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[45] "Can You Trust Your Car?". Ivan Berger. IEEE Spectrum. April 2002. Pg. 41.

addition to outsourcing engineering responsibilities on a single part, entire sub-systems or systems are outsourced to one full-service supplier in the hope of gaining increased efficiency and improved integration. Brakes systems, for example, are often sourced as a single entity and include the calipers, rotors, hydraulic lines, master cylinder and ABS components. The brake supplier may have responsibility for developing the mechanical brake system as well as the entire ABS control system that integrates with it. In the case of ABS, the OEM may receive a "black box" system from the supplier where the software code and control algorithms are the intellectual property of the full-service supplier. In these types of cases, the supplier is developing the core competency of ABS control system design rather than the OEM.

4.3 Chassis Control Systems as a Disruptive Technology

As mentioned earlier, this thesis approaches digital technology as a disruptive force in the automotive industry. As such, there are unique challenges required to implement these new technologies that automotive companies must address in their business and technology strategy plans. In the following paragraphs, automotive chassis designs are used as an example to highlight the disruptive nature of active control systems and some of the competitive reasons for using them.

Automotive chassis suspensions, on the highest level, perform the primary function of controlling the motion of the vehicle in relation to the road. The majority of chassis systems in use today are passive control systems that utilize purely mechanical components to provide the interface between the vehicle and the road. Much of the enabling technology behind these passive control systems was developed in the 1930s and 40s. For example, the Hotchkiss multileaf suspension was a concept borrowed from early horse-drawn wagons and employed on some of the first automobiles. Over the years, advances were made such as the use of steel leaves instead of iron, and then composite materials instead of steel. New concepts were also developed such as replacing the leaves with springs and control arms, and the addition of dampers to provide a more controlled movement of the body in relation to the road.

Large advances in system and component performance occurred in the 1980s and 90s, with the aid of computers. Computer Aided Engineering (CAE) allowed for more iteration during the design phase, which ultimately reduced development time and optimized system and component designs along many axes. New production techniques also gave rise to large advances in tire and damper technology as well as the reduction of component and system variability.

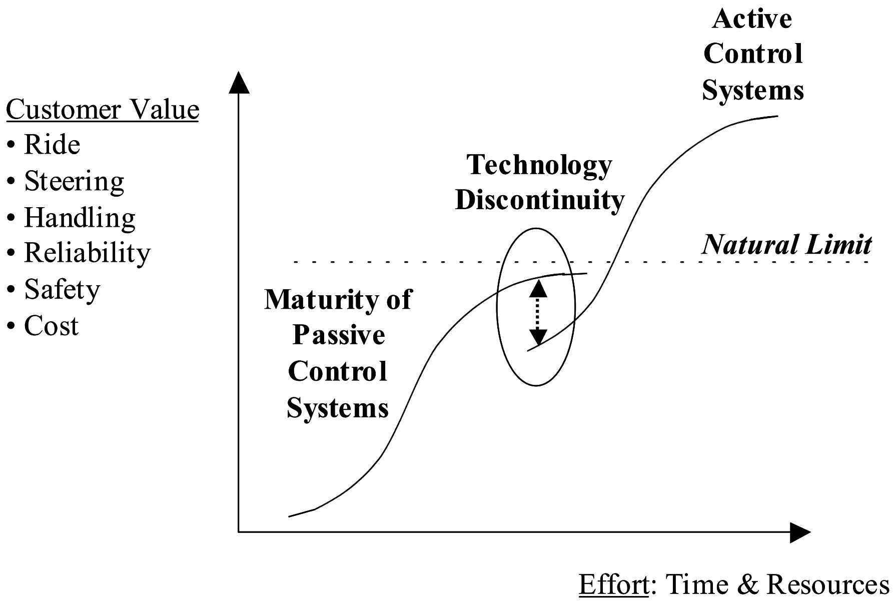

Figure 13: Chassis Active Control Systems as a Disruptive Technology

Figure 13 provides an illustrated comparison of passive versus active control systems using Professor Henderson's disruptive technology framework. As passive chassis system designs have evolved, significant advances in customer value have occurred. System performance has improved more than the relative cost of the chassis system design. However, increased gains in performance and value have become increasingly difficult to attain with conventional concepts. Many more hours of development, test and CAE time are required to achieve ever-smaller improvements in performance and cost.

The technology discontinuity expressed in Figure 13 results from the emergence of new active control systems in suspension design. Technologies such as the electronic stability program (ESP), roll stability control (RSC) and active damper systems employ electronic sensors combined with computer control algorithms and sophisticated actuators to go beyond passive control performance. However, the cost of these systems is significant and the designs are still in their infancy. Customer value in many cases still lags behind passive systems because the current gains in performance do not exceed the increased cost to the consumer. Eventually, chassis suspension designs that do not utilize active controls may encounter a natural limit in the amount of additional value they provide to the customer. The laws of physics and the threshold of perceived customer value would ultimately define this limit.

4.4 Capturing Value from Digital Technology

Digital technology is poised to be the next step in the technological evolution of automotive design. As the technology changes, the strategies required to capture value in the industry also change. Before industry leaders tackle the technical challenges of proliferating digital technology in the industry, they must first address several significant business challenges. Appropriability of the technology and supply base relationships are two central ideas that OEMs must revisit in light of the changing nature of the technology.

4.4.1 The Use of Appropriability and Complementary Assets

In the automotive industry, appropriability has traditionally come in the form of intellectual property rights. Whether on the system level or component level, automotive firms have used industrial patents as a main line of defense against imitation by competitors. However, as the industry moves to develop more active control systems and X-by-wire technologies, secrecy is increasingly being used to supplement and in some cases, even replace, intellectual property rights. The major reason for the increasing importance of secrecy is that the technology behind active control systems is much less transparent through examination. The intricate coordination of the sensors, algorithms and actuators cannot be determined without extensive analysis and testing by a trained engineer. The controlling algorithms often can only be surmised, as the code is highly encrypted, making it unavailable to benchmarking and teardown efforts. Even if the system designs were fully understood, the implementation of the code is highly application specific. System designs are tailored to specific vehicle characteristics including weight, center of gravity, wheelbase, track width, powertrain and unique brand characteristics.

Strategic barriers to the proliferation of digital technology also exist in the form of complementary assets. System hardware design, software design and the process knowledge required to integrate and test these systems are the most significant. Much of the technology behind the sensors and actuators is freely available in the marketplace. However, the controlling algorithms, the integration/development knowledge and the testing capabilities are all tightly held assets. In addition, the capital investment, supply base and process skills necessary to achieve economies of scale in the industry are also tightly held. Firms in the industry must utilize large-scale production in order to recover the significant research and development costs of digital technology while still making the products affordable to the end customer.

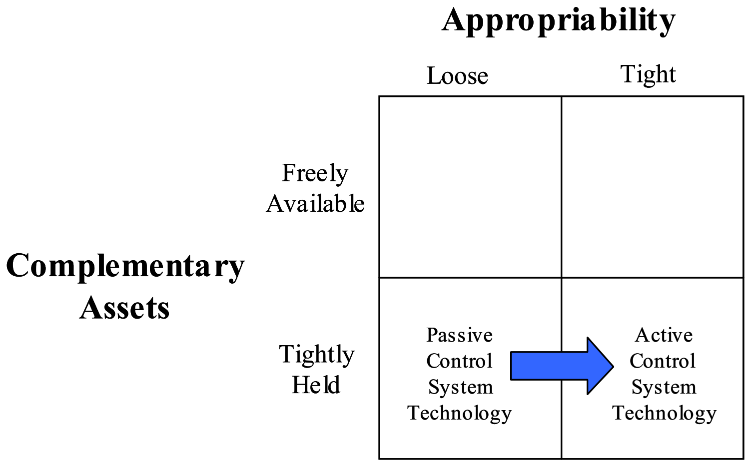

Figure 14: Appropriability and Complementary Assets of Control System Technology

Figure 14 is a 2x2 matrix of control system appropriability and complementary assets in the automotive industry. Based on the position of active controls technology in the matrix, the innovators of the technology should keep tight controls over its use in order to retain the maximum share of profit. As automotive manufacturers increasingly rely on suppliers for system design and development, they are increasingly relinquishing the source of innovation in the industry to the supply base. If suppliers continue to be the primary innovators of active controls technologies, OEMs run the risk of also surrendering much of the profit in the industry to their suppliers.

4.4.2 Rethinking Supply Base Relationships

As technology in the automotive industry changes, the business equation in the industry also changes. If OEMs are to capture value from digital technology, they must reevaluate some of their key sourcing strategies in light of the evolving market dynamics. Modularity of the technology and dependency on suppliers for knowledge and capacity are two key elements in the sourcing decision.

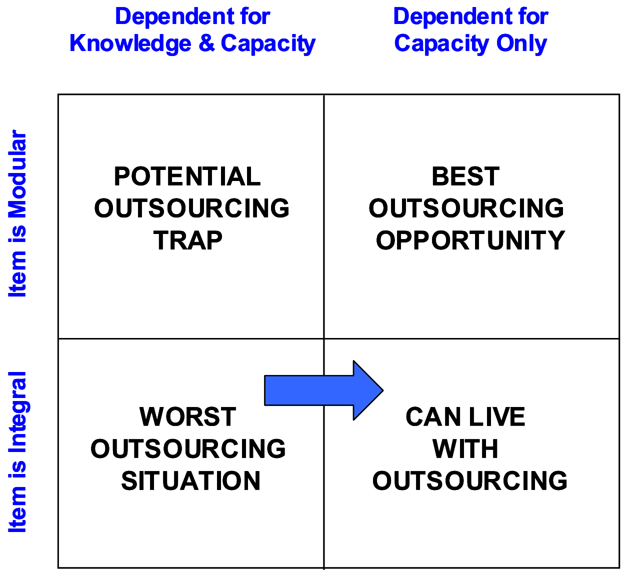

Figure 15: The Make/Buy Decision Matrix Adapted from Fine/Whitney[46]

Based on the work of Professors Charles Fine and Daniel Whitney, Figure 15 illustrates that the worst outsourcing situation is one in which the technology is integral to the overall design and the manufacturer is dependent on the supplier for both knowledge and capacity. Embedded control systems are currently very integral elements of vehicle design due to their proprietary nature and their close coupling with individual vehicle properties such as weight, size, power and brand character. As discussed in previous sections, the design and manufacture of complex

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[46] Adapted from Charles Fine lecture “Strategic Supply Chain Design”. 15.761-Operations Management. July 2001.

control systems also requires a significant set of complementary assets in the form of design knowledge, integration skills, testing skills and mass production capabilities. Applying the decision matrix from Professors Fine and Whitney to the digital technology scenario, automotive OEMs should move to a situation where they are no longer dependent on suppliers for key system knowledge. That would mean bringing in-house key skills such as system CAE modeling, control algorithm design and system verification capabilities that have generally been outsourced in the past.

CHAPTER 5: TECHNICAL CHALLENGES OF DIGITAL TECHNOLOGY

"Computers do not produce new sorts of errors. They merely provide new and easier opportunities for making the old errors."
– Trevor Kletz, Wise After the Event[47]

5.1 Introduction

To a certain extent, the quote above by Trevor Kletz highlights a truth about digital technology. Many of the errors found in computer code today are the result of logic flaws based on the inability of humans to fully account for the complexity of software. The speed with which software changes can be made often limits the amount of thought and analysis that precedes the changes. Designers and managers are tempted to quickly "try it and see what happens" rather than take the time to engineer changes based on analytical evidence. The speed of software change also magnifies existing communication gaps within design and development organizations. Communication is always a critical component in the design and development of complex mechanisms; however, it is even more crucial when a lone programmer can achieve multiple iterations of design components in the time it takes to order a pizza.

In addition to the usual challenges facing most product development organizations, software-intensive systems also pose some unique challenges to the automotive industry. Differences exist in the way software is designed, tested and verified – differences that may be difficult for a traditionally hardware-oriented industry, such as automotive, to immediately comprehend. Although it is impossible to cover all of the unique aspects of software design and development in this thesis, several of the major departure points from existing automotive product development frameworks are presented in the following sections. Particular emphasis is placed

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[47] From Safeware: System Safety and Computers. Nancy G. Leveson. Addison-Wesley Publishing Company. 1995. Pg. 359.

on several unique aspects of software reliability, safety and testing as well as the role of standards in the industry and the necessity for high-level coordination and arbitration functions.

5.2 Major Goals in the Industry

Based on a subject-matter literature review, the main goals for the automotive industry in regards to digital technology are safety, cost and reliability.[48] Embedded software systems present a significant opportunity for the industry to create value for the customer and simultaneously to increase profits in the industry. However, these three goals must be met if these new technologies are to deliver the envisioned benefits.

5.2.1 System Safety

Of the three main goals in the industry, safety is clearly the paramount goal that must be directly addressed in the product development frameworks of automotive manufacturers and suppliers as they embark on the design of digital systems. New technology has the potential to eliminate known hazards but it also has the potential to create new hazards that thus far have been unknown in the given context. For example, systems such as adaptive cruise control and onboard navigation create new functionality for drivers. However, these systems also raise new concerns regarding the potential for driver distraction and the loss of situational awareness. Not only are these issues highly complex, they also require significant study in fields outside the engineering disciplines. New methods and expertise for analyzing overall system safety are necessary to address the changing nature of the technology and the increased system complexity.

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[48] "Embedded technology transforms the automobile". Webb, Warren. EDN v.44 no.17. August 19, 1999. Pg. 92.

In her book, *Safeware: System Safety and Computers*, Professor Nancy Leveson provides a unique way of looking at system safety that may be of benefit to the designers of these new systems. She proposes an absolute definition of safety as "…freedom from accidents or losses."[49] Figure 16 represents a graphical view of this absolute definition with a continuum representing the infinite range of possibilities of the actual design.

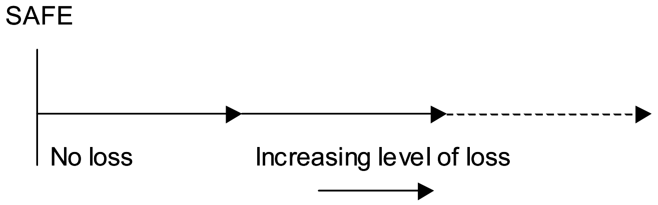

Figure 16: Professor Leveson's Graphic of Safety as a Continuum[50]

By using an absolute definition in lieu of a relative one, Professor Leveson characterizes overall system safety as an ideal goal that can only be approached asymptotically, rather than a set target level that can be over or under achieved. Two of the main benefits of this approach are: (1) it has the potential to focus upfront design efforts on eliminating specific hazards where possible to improve overall safety and (2) it serves to encourage additional review of design alternatives that go beyond relative definitions of safety that may otherwise not be considered.[51]

In her work, Professor Leveson also emphasizes the importance of viewing safety as an emergent property that must be determined on a system level. In relatively simple systems, the root cause of a system failure is often the failure of an individual component. The interactions between the components are correct, but one of the individual parts ceases to function as designed.

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[49] Nancy Leveson. Safeware: System Safety and Computers. Addison-Wesley Publishing Company. 1995. Pg. 181.
[50] Adapted from Nancy Leveson. Safeware: System Safety and Computers. Addison-Wesley Publishing Company. 1995. Pg. 182.
[51] Nancy Leveson. Safeware: System Safety and Computers. Addison-Wesley Publishing Company. 1995. Pg. 182.

Redundancy and system back-ups are generally used to reduce the chances of overall failure in these types of systems. By contrast, the root cause of a system failure in a more complex system is generally systemic in nature. Each of the individual components may continue to function as designed, but the interaction between the components is not correct. In these cases redundancy and system back-ups only exacerbate the original problem.[52]

Overall system safety can be thought of as an emergent property of the entire system, not the result of individual component behavior. As such, design analysis of the individual components alone only provides a limited perspective on the safety of the complete system. A safety analysis of the complete vehicle requires an analysis of the interaction between the components in the system and an analysis of the system's interaction with its environment. The automotive OEM is the most logical choice to perform this type of analysis because suppliers generally have limited access to components beyond their own parts or modules. Digitally controlled systems, however, potentially present an issue for automotive OEMs in that key knowledge required to perform the analyses may be sensitive or proprietary information controlled by the suppliers. The increasing use of "black box" modules from certain suppliers only makes the issue of knowledge transparency that much more difficult for the analysis team. To prevent downstream concerns regarding knowledge transparency and intellectual property rights, OEMs and suppliers need to create knowledge-sharing agreements that become an integral part of the sourcing process.

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[52] Nancy Leveson. "A New Foundation for System Safety". Abstract from a forthcoming book.

5.2.2 Cost of Digital Technology and Software Reuse

As mentioned earlier in this thesis, the cost of digital technology is clearly a major concern of automotive manufacturers. Overall material, design and development costs must be managed if digital technology is to proliferate and OEMs and suppliers are to profit from its proliferation. Many people in the automotive industry see software reuse as one way to recoup initial design costs and create brand differentiation among products for little or no cost. Significant findings from the software industry, however, suggest that software reuse is not the "silver bullet" some may think it is. Reused software presents potential problems involving complexity of legacy code, adequacy of testing routines and sub-optimization of programs for individual applications.

Quality reusable code generally takes longer to write than purely usable code. If a portion of code or an entire program is to be reused from one application to the next, more and better documentation is normally required since programmers rarely transfer with the code they create. Increased attention must be given in upfront requirements to software design interfaces since these interfaces determine how much "bridging code", if any, will need to be created in the new application to make the software work. Also, functional coupling should be kept to a minimum, as designers of the new application may only want certain parts of the software function and not others. In the competitive automotive world, many program managers simply are not given the luxury of spending the additional time and money it takes to create quality reusable code. Due to these schedule and cost constraints, software code is often optimized on an individual project basis, making reuse of the code in other applications difficult and time consuming.

Another commonly held misconception in the industry is that code that operates well in one application will necessarily operate well in another. Lessons learned from significant industrial accidents, such as Ariane 5 and Therac-25, prove that reused software does not necessarily guarantee safe and predictable operation in new applications.[53] Design interfaces and communication signals are generally different from application to application. Errors may exist in the code in both applications, but software developers and testers may never encounter them in one scenario due to the limited operating conditions under which the software is tested and used. Under different operating conditions in a new application, the errors may become apparent and cause the entire system to behave in unintended ways. As a result, software reuse should be considered carefully and appropriate steps should be taken to adequately analyze and test the given code in the new application. Due to cost and timing constraints on many programs, it may actually be easier and less costly to write new code rather than reuse existing code.

In general, software reuse is possible in the automotive industry and may provide some benefits; however, it must be undertaken from an organizational perspective if those benefits are to be realized. Software code must be optimized from the beginning with reuse in mind. Appropriate attention should be given to upfront requirements, documentation, design interfaces, functional coupling, usability and testability. Knowledge transfer and retention should also be important priorities in organizations where reuse is proposed.

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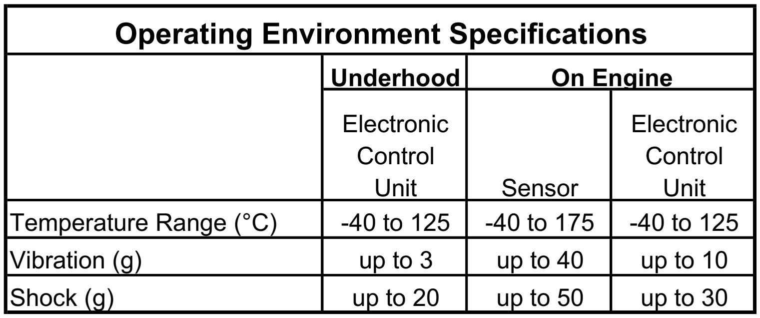
[53] Reference the Report by the Inquiry Board. Ariane 5 – Flight 501 Failure Accident Report. and Nancy Leveson. Safeware: System Safety and Computers. Addison-Wesley Publishing Company. 1995. Pgs. 515-553.

5.2.3 System Reliability

Reliability, as defined by Professor Leveson, is "…the probability that a piece of equipment or component will perform its required function satisfactorily for a prescribed time and under stipulated environmental conditions."[54] Digital system reliability in the automotive industry is certainly a major challenge given the average lifecycle of an automobile and the harsh conditions in which it must consistently operate. Most personal computers are never subjected to the grueling conditions present in the automotive underhood and chassis environments. Major environmental challenges to digital hardware include electromagnetic interference (EMI), temperature extremes, impact shocks, vibrations, corrosion and contaminants.

Heat management is an increasingly significant issue in automotive design that requires ownership by many different design organizations. Over the course of a vehicle's lifetime, ambient temperatures in which the vehicle must operate can vary by as much as 65 degrees Celsius. More significantly, local operating temperatures in certain locations on the vehicle can vary by as much as 200 degrees Celsius. Figure 17 is an example of operating temperatures and acceleration levels that an underhood sensor or electronic control unit may need to endure.



Operating Environment Specifications

	Underhood	On Engine	
	Electronic Control Unit	Sensor	Electronic Control Unit
Temperature Range (°C)	-40 to 125	-40 to 175	-40 to 125
Vibration (g)	up to 3	up to 40	up to 10
Shock (g)	up to 20	up to 50	up to 30

Figure 17: Automotive Operating Environment Specifications[55]

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[54] Nancy Leveson. Safeware: System Safety and Computers. Addison-Wesley Publishing Company. 1995. Pg. 172.

[55] Adapted from Ivan Berger's article "Can You Trust Your Car?". IEEE Spectrum. April 2002. Pg. 42.

As underhood temperatures exceed 175 degrees Celsius, exotic materials and alternative methods for cooling electronic devices may become necessary. Obviously, both of these scenarios would significantly increase the cost of digital systems and could make them even more difficult to package in the tightly constrained underhood environment.

Electromagnetic interference (EMI) from external sources as well as adjacent electronic systems also pose a unique challenge for digital systems. EMI is defined as "the disruption of operation of an electronic device when it is in the vicinity of an electromagnetic field (EM field) in the radio frequency (RF) spectrum that is caused by another electronic device."[56] With electronic devices, incorrect placement and proximity of one component to another can lead to significant functional degradation. Potential EMI effects must be considered in the early stages of the design phase and appropriate countermeasures, such as EMI shielding and line filters, must be available to the designer if the need arises. Adequate testing for the presence of EMI should also be carried out early in the development phase as part of the design and verification plan.

Another new concept for the automotive industry is the idea that reliability is not necessarily synonymous with durability. Software does not "fail" in traditional reliability engineering terms through excessive wear or fatigue. Software-related failures are by nature systemic, where the program's function does not satisfy the intended system goals.[57] Vehicle lifecycle tests and basic durability events are not sufficient to find many of the operating conditions that may cause system faults or failures. Extensive testing and analysis of the code is required to make educated determinations about the reliability of the software in a given application. As a matter of course,

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[56] http://searchnetworking.techtarget.com/sDefinition/0,,sid7_gci213940,00.html. Referenced November 29, 2002.
[57] Nancy Leveson. Safeware: System Safety and Computers. Addison-Wesley Publishing Company. 1995. Pg. 172.

developers should perform load testing, feature testing, performance testing, stability testing and stress testing on the integrated system as well as a detailed static analysis of the overall program.

5.3 Software System Testing

> *"Complexity does not scale linearly with size."*
> *– Jack Ganssle*[58]

Most modern, commercial software programs contain almost an infinite number of unique testable conditions based on programming paths, variable states and communication signals. Due to the countless number of possible states, exhaustive testing of software code is virtually impossible. To make matters worse, software engineers generally do not have the ability to linearly interpolate between test conditions to save time and computing power. It cannot be assumed that "best case" and "worst case" test conditions exist or that all values between certain limits are acceptable under all conditions. In the mechanical engineering world, a chassis engineer can test a component at one load and then at a higher load and assume that if it survives at both of those loads, it will survive at all loads in-between. Software engineers cannot necessarily make the same assumption when testing software code.[59]

Software testing also presents a significant challenge in that realistic test conditions are difficult to simulate based on the complexity of the design interfaces and possible usage conditions. The building of test simulators for sub-system and component code can be very complex and time consuming. As a result, there is a temptation to delay certain testing until representative interfaces are available. When these interfaces do become available, it may be very difficult to

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[58] Jack Ganssle. "Keep It Small". http://www.ganssle.com/articles/keepsmall.htm. Referenced November 29, 2002.
[59] "Why Software is So Bad (And how to fix it)". Charles C. Mann. Technology Review. MIT's Magazine of Innovation. August 2002.

make significant changes to the code if issues are found. Sub-system and component testing also requires certain assumptions to be made about the operating conditions and usage patterns of the device. These assumptions may not be accurate or specific conditions may be omitted, such as emergent properties the designer never intended.

Even though software testing presents significant challenges, it is and should be a significant part of any product development process. Software product managers can maximize the benefit of their testing organizations by designing their test plans around the requirements set and placing specific emphasis on aspects of the design that are difficult to verify through other forms of analysis. Importance should be placed on testing for system stress limits, timing requirements and overall stability. Also, clearly separating the testing activity from the design activity and establishing clear testing milestones and responsibilities could benefit overall test plan integrity.

5.4 The Role of Standards

The role of industry standards in software design and development is unparalleled in established automotive hardware design. Although certain communication protocols such as CAN and LIN have become popular in the automotive industry, individual suppliers still maintain their own designs that are generally not modular from application to application. The non-modularity among supplier designs limits the ability of automotive manufacturers to use common software modules across platforms without using the same supplier. If one or two suppliers become dominant in one particular technology, the balance of power in the industry potentially swings in their favor. This changing power relationship has already occurred in several instances in the automotive industry and the consequences have been less than favorable for the OEMs.

Dominant suppliers have, on occasion, refused to take on new business in small markets or on specialty products where the sales volumes are low. They have also exercised their newfound control over OEMs by dictating piece price or refusing to provide increased feature content that was not already part of their existing product line.

Design incompatibilities can also arise when product developers attempt to integrate new digital technologies into their existing vehicle development cycles. Due to its emergent position on the technology S-curve, digital technology generally develops at a faster rate of change than most other automotive systems. Problems arise when design definition and freeze dates are not compatible between digital systems and the hardware systems in which they are embedded. The rate of digital system change also makes integration of multiple controls applications in one vehicle a challenge due to the significant task of managing version compatibility at the design interfaces.

Professor Charles Fine created the term *Clockspeed* to define the rate of evolution of a product or technology.[60] Several MIT-SDM students have done considerable work to characterize the Clockspeed incompatibilities between emergent electronic technologies and existing automotive development cycles.[61] One of the main hypotheses proposed in this work is that industry standards at the design interface points allow faster Clockspeed technologies to be more easily integrated into slower Clockspeed systems.[62] Although this hypothesis was based on the

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[60] Charles H. Fine. Clockspeed – Winning Industry Control in the Age of Temporary Advantage. Perseus Books. 1998. Pg. 6.

[61] Sean Newell. MIT-SDM Thesis. February 2001. Kurt Ewing and Erika Low. MIT-SDM Thesis. June 2002. And Nathan Everett. MIT-SDM Thesis. February 2003.

[62] Nathan Everett. "Automotive Telematics: Colliding Clockspeeds and Product Architecture Strategy". MIT-SDM Thesis Executive Summary. February 2003.

integration of telematics technologies into automotive design, it does have some applicability for embedded electronic control systems. Several manufacturers have already attempted to create their own proprietary vehicle architectures that would standardize interfaces across their product lines. The proponents of standardized vehicle interfaces believe that proprietary vehicle architectures potentially result in shortened development cycle times for new technologies and improved integration of these technologies into existing vehicle infrastructures.

5.5 Vehicle System Architecture

Historically, functional partitions in the vehicle architecture were synonymous with physical partitions. Suppliers were selected to provide certain components based on the most logical physical decomposition of the vehicle into sub-systems or *chunks*. Communication between owners of different vehicle sub-systems generally occurred only at the interface points, which were also defined by direct physical connections. It was relatively easy upon inspection to determine where the interfaces existed and what the dependency relationships were between sub-systems. By contrast in digital systems, the lines between functional and physical partitions have become significantly blurred. Design interfaces are not always readily apparent and dependency relationships are not always clear. Suppliers of certain modules may not realize the extent of the role they play in the function of other modules. Emergent or *hidden* interactions between modules can be very difficult to trace because there is no physical manifestation of the software connections to inspect. When one supplier makes a change to one subroutine or algorithm, many other suppliers may be affected by the change. Keeping track of the simultaneous coding changes and their interaction effects can be a difficult and complex task.

In the early uses of software controls technologies, individual modules were relatively self-contained with sensors, actuators and controllers unique to a particular application. ABS is one such example that was limited to control of the hydraulic brake system. The increasing numbers of control systems in use today and emphasis on improved vehicle performance have significantly increased the amount of coordination required between applications. Several applications may now use information from the same sensors or desire actuation of the same hardware components to fulfill their purpose. ABS, TCS (Traction Control System) and ESP (Electronic Stability Program) are three systems that overlap in their use of wheel speed sensors and hydraulic brake controllers. Typically, coordination and arbitration of these systems was the responsibility of the individual sub-system teams. However, due to the increasing complexity and scope of the interactions, many people in the industry are now investigating overall vehicle system controllers (VSC) to perform these functions at a meta-level in the vehicle.[63]

Figure 18 is a graphical illustration of a vehicle system control structure proposed by Dr. Anthony Phillips. The Vehicle System Controller is designed to coordinate control of the different modules in the vehicle and mediate conflicting requests as necessary. As Figure 19 illustrates, commands flow in a hierarchical structure down from the VSC to the individual modules. The information flow, however, is not restricted. The different modules are free to share information with one another directly or to broadcast to the entire network.

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[63] Anthony M. Phillips. "Functional Decomposition in a Vehicle Control System". Technical Paper from the Proceedings of the 2002 American Control Conference. Anchorage, Alaska. May 8-10, 2002.

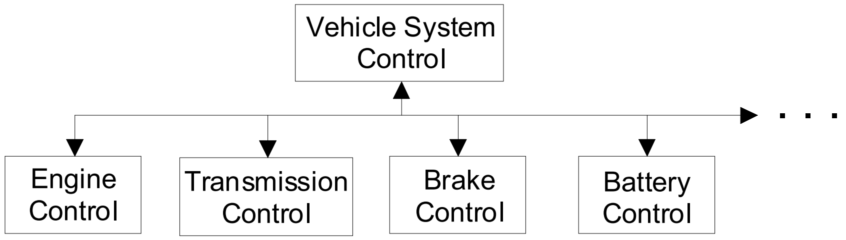

Figure 18: Vehicle System Controller (VSC) Hierarchy[64]

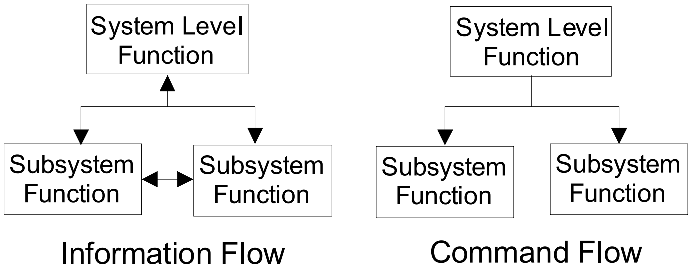

Figure 19: VSC Information and Command Structures[65]

The function of the VSC is not necessarily limited to a single, unique module. In a distributed control structure, segments of the code can reside in different sub-systems, such as the brake control module or the engine control module. Overall VSC function would be clearly defined in the vehicle architecture definition and requirements specification. The benefits of such a structure are generally quicker response times and reduced risk of sub-system EMI interactions. The major drawbacks, however, include a greater reliance on individual module suppliers for various levels of system control function and a potential increase in functional coupling.

As the number of electronic control sub-systems increases and the role of the VSC expands, there is a natural tendency for sub-system interactions to become more tightly coupled. Tightly

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[64] Adapted from Anthony M. Phillips. "Functional Decomposition in a Vehicle Control System". Presentation from the Proceedings of the 2002 American Control Conference. Anchorage, Alaska. May 8-10, 2002. Slide 3.

[65] Adapted from Anthony M. Phillips. "Functional Decomposition in a Vehicle Control System". Presentation from the Proceedings of the 2002 American Control Conference. Anchorage, Alaska. May 8-10, 2002. Slide 3.

coupled systems introduce an inherent complexity into the design in that the number of possible interactions within the system grows exponentially. This exponential complexity makes it more difficult for system designers to understand and consider all possible operating states. New hazards can arise from emergent or unintended interactions not considered during the design phase. Due to the tight coupling in the design, these interactions can have a rippling effect throughout the entire system. Coupling and the inherent complexity it produces can be minimized with a VSC architecture, but steps must be taken early in the design phase to do so. System designers must be aware of the inherent complexity that coupling creates and carefully consider all functional coupling decisions. Steps should also be taken to minimize sub-system dependencies and interactions where possible to reduce complexity and coupling.

5.6 Summary

"Underlying every technology is at least one basic science, although the technology may be well developed long before the science emerges."
– Ralph F. Miles Jr.[66]

In summary, digital systems present a number of unique strategic and technical challenges for the automotive industry. Many of the existing heuristics in automotive design are challenged in this new environment. The ideas of safety, reuse and reliability must be rethought in digital applications. New concepts, such as vehicle system arbitration and the role of industry standards, create implications for the entire product development organization. This fundamental shift in the underlying technology in the industry requires an equally fundamental shift in the approach used to develop products based on the new technology.

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[66] From Safeware: System Safety and Computers. Nancy Leveson. Addison-Wesley Publishing Company. 1995. Pg. 129.

Systems theory emerged in the 1930s as a way to help scientists understand and characterize the complex systems around them. These theories were eventually applied to the design and development of complex machines and the discipline of systems engineering was born. Systems engineering is both a process by which complex systems are conceived and designed and a methodology by which they are integrated and managed. Many of the challenges arising from the proliferation of digital technology the automotive industry are directly addressed in the principles of systems engineering. By optimizing the vehicle as a system rather than a collection of specific technologies, the automotive industry may gain a new perspective on digital technology and perhaps achieve a new global optimum for the overall vehicle.

CHAPTER 6: MULTI-INDUSTRY CASE STUDY IN SYSTEMS ENGINEERING

> *"Good design is easy…comparatively. Transformations to good design are hard."*
> *– Richard Peebles*[67]

6.1 Introduction

Systems engineering is both a change in mindset for the industry and a new set of tools and processes for the design, integration and verification of increasingly complex systems. The previous chapters attempted to characterize the need for this change based on the unique strategic and technical challenges created by digital technology. There remains however, a significant question regarding how to make this type of transformation in a large and complex industry such as automotive. The subsequent sections in this chapter attempt to provide some insights on this question based on a case study of other industries that are further along in the adoption cycle of electronic controls technologies.

6.2 Structure of the Study

Personal interviews were conducted with a selection of engineers from a cross section of the aerospace and aviation industries. These industries were chosen for their knowledge and experience integrating electronic controls technologies into large, complex mechanical systems. Many parallels exist between these industries and automotive. In general, digital technology is used to provide an enhanced level of control and performance over primary physical systems. The aerospace and aviation industries, however, began implementing electronic controls technologies much earlier than the automotive industry. As such, they encountered many of the strategic and technical challenges associated with this technology prior to the automotive

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[67] Richard W. Peebles. Vice President, Office Systems Components Group. Xerox Office Systems Group. "Architecture: Design or Transformation". System Architecture Class Lecture. November 2, 2001. Slide 2.

industry. Much of the early study and implementation of systems engineering began with firms in the aerospace and aviation industries.

In each interview, a standard set of questions was used to begin the discussion and provide a framework for the dialogue. Individual elaboration beyond answers to the standard questions was encouraged to obtain additional information. Figure 20 provides a list of the standard questions used in each interview.

Multi-industry Case Study Questions

1. On a scale of 1-10, how would you rate your organization today in regards to its practice of Systems Engineering principles?
2. How would you rate your organization on the same criteria 10-15 years ago (or when you started with the company)?
3. Have you made progress in implementing Systems Engineering principles? Why or why not? In what ways have you made progress?
4. How did Systems Engineering proliferate in your organization? Was it a grassroots effort from the bottom up or a mandated process from the top down?
5. What were some of the main drivers for the transformation to Systems Engineering?
6. Does your organization have a separate Systems Engineering group? If so, how was it created and why? How was it initially staffed (inexperienced engineers or experienced systems engineers)?
7. If you were the head of your organization, what would you do to improve Systems Engineering practices and behaviors?

Figure 20: Multi-Industry Case Study Standard Questions

The primary goal of the interviews was to understand the main drivers behind the proliferation of systems engineering in each organization and the associated manifestation of the changes. A secondary goal of the interviews was to provide a critical analysis of the effectiveness of the changes and an insight into possible future actions the organizations might take. The rationale behind this type of approach was twofold. First, identifying and understanding the change agents and implemented actions in each organization directly addresses the need to provide direction to the automotive industry on how to accelerate the transformation to systems engineering. Second, assessing the effectiveness of the changes and examining recommendations for future actions provides an insight into the barriers to organizational change and possible ways to address them.

6.3 Key Concepts Derived from the Interviews

The individual responses from the interviews were analyzed and key themes were developed for each of the main areas of study. The responses were divided into four major categories based on the primary and secondary goals of the interviews. These categories are: (1) the main drivers behind the proliferation of systems engineering, (2) the manifestation of the changes at each organization, (3) the effectiveness of the changes and (4) recommendations for future action.

6.3.1 Drivers Behind the Proliferation of Systems Engineering

In most organizations, the creation of a unique systems engineering group or function evolved from a local best practice into a management-mandated directive. As the complexity of systems increased, one or more project teams in an organization realized there was a necessity for a separate group to track design interfaces and manage design integration. A separate sub-group within the project team was created on a local level to address this specific project need. As the projects progressed, senior management began to recognize the contributions of these sub-groups. Eventually, the entire organizational structure of the project team was modified to include this separate function. Subsequent projects from that point on were required to have a separate systems engineering group to manage systems integration and systems interfaces. One interesting point to note is that depending on the position of the employee in the organization, the perception of the same implementation may be very different. An employee in the area that first implemented a unique systems engineering group was likely to realize that the change originated on a local level before gaining wider acceptance. However, an employee in another part of the same organization was more likely to view it only as a management-mandated directive.

In one case study, systems engineering became more of an organizational priority when it was realized there were not enough systems engineers to go around. The first systems engineers in these organizations were highly technical individuals who could inherently grasp the complexity of the emerging technologies and anticipate potential concerns before they occurred. These individuals quickly became the project gurus who were responsible for everything from requirement writing to interface management to target reconciliation. As the demands on these engineers grew, management eventually realized that individual engineers alone, even technical gurus, could not contain the breadth and depth of the assignment. As a result, the role of the true systems engineer was slowly revised and the concepts of systems engineering were disseminated throughout the rest of the organization. Systems engineers became responsible for leading the integration tasks rather than performing all of them. Component and sub-system engineers became responsible for cascading their requirements, tracking their design interfaces and managing their own contribution to the overall system goals.

In another case study, the main driver for the proliferation of systems engineering was a response to a change in the external environment of the organization. In early 1998, the National Aeronautics and Space Administration (NASA) and the U.S. Department of Defense (DoD) created the National Rocket Propulsion Test Alliance (NRPTA). The main goal of the NRPTA was to "shape the government's rocket propulsion test capability to efficiently meet national test needs through intra- and inter-agency cooperation".[68] An attempt was made by the NRPTA to better manage available resources and avoid duplication of effort across several different technical centers. The existence of this oversight board intensified competition between many different governmental organizations and provided a mandate to improve efficiency and quality. At least one organization realized that a significant change in operating policies was necessary to meet this mandate. Systems engineering was seen as a way to optimize the output of the entire organization by reducing redundancy and rework. As a result, this organization took steps to implement systems engineering on a wider basis to improve overall operations.

6.3.2 The Manifestation of Systems Engineering Changes

In each case in this study, a separate systems engineering functional entity was created to lead the organization in systems engineering principles, tools and methodologies. The actual implementation of these groups differed substantially between organizations, as did the effectiveness of the groups. However, in each case an attempt was made to recognize the important of systems engineering and the need for a separate functional entity to lead its implementation throughout the organization.

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[68] https://rockettest.ssc.nasa.gov/nrpta/default.htm. Referenced December 12, 2002.

In one "things gone wrong" example, the effectiveness of the systems engineering group was severely hindered as a result of incorrect staffing, poor communication of the group's mission and a lack of management support. In this case, a need was identified for a separate systems engineering group to help manage the growing complexity of the design and development process. However, it was decided that the best systems engineers in the organization were too valuable in their current positions to risk moving them to a new and as-yet untested functional group. Instead, the group was staffed with relatively inexperienced engineers who were expected to become experts in their new field. The consequence of this staffing decision was a very process-oriented group that specialized in issue tracking and stage gate management. Some of the key functions of such a group, such as upfront program planning, overall system architecting and leadership of systems engineering behaviors, did not occur. As a result, the value the group in the wider organization in regards to the implementation of systems engineering has been somewhat limited.

In a more "things gone right" example, the organization management realized early on that there was a need for diversity and synthesis in the systems engineering group. The original staffing plan predominantly relied on engineers with ten to twenty years of industry experience and an innate aptitude for systems engineering thought. Some inexperienced engineers were also accepted into the group, provided they demonstrated a commensurate aptitude for systems engineering ideas. A training program was created to develop the skills of the inexperienced systems engineers as well as the engineering user base they supported. A synthesis of objectives was also created to provide a balance between systems engineering process and system oriented thinking. Fundamentals of the systems engineering "Vee" model, such as requirements writing, requirements tracking and proper documentation of system tests were stressed on all levels. At the same time, an attempt was made to provide upfront direction on overall system architecting, project planning and interface management. As a result, this group has provided significant value to the wider organization and there is a deeper understanding of systems engineering principles and practices throughout the organization. A separate career path has developed that recognizes the valued contribution of systems engineers as technical leaders.

Several other significant changes were mentioned repeatedly throughout the case studies in regards to the implementation of systems engineering. A renewed and increased emphasis on requirements writing, tracking and verification occurred in all of the organizations. It was widely recognized that some form of requirements management tool was necessary to implement and track program requirements and that responsibility for meeting the requirements extended to all levels in the organization. More and better documentation was also a key component of the transformation to systems engineering. As the complexity of systems increased, more documentation was required to track and record design changes and their potential interaction effects. Documentation of the process also increased so that everyone in the organization was aware of the expectations at each phase in the program. Systems engineering training was another key element in the transformation of the organization. Several case studies mentioned official training programs to develop systems engineers as well as general training programs to educate the overall engineering community in systems engineering fundamentals.

6.3.3 The Effectiveness of the Implemented Changes

The changes mentioned in the previous sections resulted in a more global understanding of systems engineering principles in most of the organizations that implemented systems engineering on a broad scale. The responsibility for delivering an optimized system proliferated to every level throughout the organization and many employees felt more ownership of the integration process. Several key benefits were achieved that could directly be linked to the implementation of systems engineering. In most cases, better systems integration "out of the box" and significantly less rework were mentioned as major areas of improvement. Another sign of the effectiveness of the changes was the increased demand for systems engineers in many organizations. In one organization, systems engineers were historically termed "generalists" and had a difficult time getting promoted. In the same organization today, systems engineers are in high demand and have a distinct career path.

6.3.4. Recommendations for Future Actions

One of the key questions asked in each interview was – *If you were the head of your organization, what would you do to improve Systems Engineering practices and behaviors*? The responses to this question were varied, but they generally fell into two main categories. The first category addressed the need to change the mindset and the behaviors in the organization. The second category addressed specific areas for improvement in process implementation.

Several case studies emphasized the importance of changing the overall mindset of the organization rather than simply implementing a specific process or tool. One engineer directly cautioned against mandating systems engineering as a new "initiative", citing the potential loss of meaning behind the initiative and a potential lack of ownership of the process. Instead, this same engineer emphasized the importance of making the entire process valuable to the people who are responsible for accomplishing the work. He further elaborated that the key to a successful proliferation of systems engineering throughout the organization requires empowering and encouraging employees to use the new methodology in their daily jobs. Systems engineers should be deployed into the programs to assist the teams in applying the frameworks to existing projects. In effect, individual employees should be enabled to become change agents in their respective organizations.

Another key theme from the interviews was the idea that management must support the transformation to systems engineering and they must see it as a strategic necessity. The National Rocket Propulsion Test Alliance created an external impetus for change in one organization. This impetus created an opportunity to educate management on the need for change in view of the changing external environment. Management support was a key driver for the successful transformation to a more systems engineering oriented organization. This same approach could be applied to other organizations. Management should be educated on the necessity for systems engineering given the strategic changes in the industry brought about by a fundamental change in the underlying technology.

Several recommendations from the case studies also addressed areas for improvement in the systems engineering process implementation. Significant emphasis was placed on the practices surrounding the creation and implementation of system requirements. The importance of good requirements was stressed repeatedly throughout the different interviews. Correspondingly, most interview subjects acknowledged the general shortcomings of their respective organizations in regards to actually creating and implementing good requirements. On a high level, the challenge in many organizations was overcoming the idea that "we don't have time" to create, manage and implement good requirements. Three actions were suggested in the interviews to help redress this mindset. First, organizations should provide more emphasis on the importance of good requirements and the consequences of poor requirements. Second, they should provide more training on how to write clear and concise requirements and how to cascade these requirements to other design teams. Lastly, organizations should allot more time early in the program for requirement writing, cascading, reviewing and overall target reconciliation.

6.4 Specific Recommendations for Change in the Automotive Industry

Based on firsthand experience in the automotive industry and lessons learned from the multi-industry case study, the follow three recommendations represent the author's opinion regarding key enablers for the proliferation of systems engineering in the automotive industry. First, systems engineering must be prioritized as a core competency in the industry. Second, the role of the systems integrator, in general, must be redefined to more closely align with the definition of a true systems engineer. Finally, industry management must re-emphasize two key systems engineering fundamentals that enable a quality implementation of systems engineering: requirements and documentation.

If systems engineering is to firmly take root in the automotive industry, it must be prioritized as a core competency. Currently, there is a general understanding in the industry that systems engineering is the right thing to do. However, there must be a greater understanding that systems engineering is a strategic necessity based on the changing nature of the fundamental technology in the industry. The increasing complexity of automotive systems requires a new approach to design, integration, development and verification. Moreover, this work cannot be subcontracted to suppliers because it requires knowledge of the overall system and the detailed interactions within the system. A thorough strategic analysis of digital technology in the automotive industry may help convince industry leaders of the value of this approach.

As automotive systems have become more complex, the role of the systems engineer has become increasingly important. The position of automotive vehicle integrator was created to fill the role of the systems engineer in the automotive industry. In many cases however, the implementation of the vehicle integrator role in practice has been very different from the intended one. The actual function of the vehicle integrator has often been more political than technical. The emphasis has frequently been placed on cascading management directives to engineers and coordinating team reports to management, rather than aiding teams in the implementation of systems engineering behaviors and processes. Engineers selected to become vehicle integrators are often the youngest and least experienced members of the team. They generally do not have the experience or the technical background to be true system engineers nor are adequate training or mentoring opportunities available to them. The automotive industry could learn several lessons from the application of systems engineers in the aerospace and aviation industries.

Another lesson learned from the aerospace and aviation case studies, is the importance of quality requirements and documentation. The successful integration of digitally controlled systems requires a thorough understanding of the inputs, outputs, interfaces and individual requirements of every sub-system. The communication of these sub-system behaviors to every other sub-system owner and system integrator requires an adherence to documentation creation, communication and retention procedures. High quality requirements and documentation procedures generally decrease overall design and development costs rather than increase them. Shorter development cycles can be achieved with significantly less rework and costly downstream design changes can often be avoided through increased emphasis on upfront requirement writing and quality documentation.

CHAPTER 7: CONCLUSIONS AND AREAS FOR FURTHER STUDY

"Without changing our patterns of thought, we will not be able to solve the problems we created with our current patterns of thought."
- *Albert Einstein*[69]

7.1 Main Conclusions

The automotive industry is in the midst of a quiet revolution involving the expanding use of digital technology in automotive systems. Over the last ten years, the average retail price of most vehicles has remained relatively flat and industry profits have lagged behind many firms in the technology sector. Increasingly, automotive firms have turned to new technologies to create profit in the industry through performance enhancements and increased brand differentiation. Active control systems and X-by-wire systems are two categories of digital technology making their way into vehicles at an increasing rate.

The current economics of the automotive industry have profoundly influenced the nature of competition in the industry. Automotive OEMs are struggling to increase profits and streamline operations. The entire industry is embracing a more horizontal supply structure with suppliers taking on more of the engineering, test and development capabilities. As a result, many suppliers have had to take on a role that has long been reserved exclusively for the OEM – the role of systems integrator. Entire sub-systems or systems are outsourced to one full-service supplier in the hope of gaining increased efficiency and improved integration. In many cases, the OEM receives a virtual "black box" system from the supplier where the software code and control algorithms are the intellectual property of the full-service supplier. In these situations, it is the supplier that is gaining the core competency of control system design rather than the OEM.

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[69] From Re-Creating the Corporation. Russell Ackoff . Oxford University Press. 1999. Pg. 3.

This thesis argues that suppliers cannot effectively fulfill the role of systems integrator in the automotive industry. Some of the most important desired functions of complex digital systems are emergent properties, such as overall system safety and reliability. A meaningful analysis of the emergent properties of the system requires an analysis of the interactions between components in the system as well as an analysis of the system's interaction with its environment. Automotive OEMs must perform these types of analyses because suppliers lack access to components beyond their own parts and they lack the overall system knowledge to understand how these parts interact in the broader system. Systems integration in the automotive industry is a function that must be performed by the automotive OEMs.

Retaining the role of systems integrator has significant implications for the core competencies that OEMs must preserve and develop. Many key skills that have generically been outsourced in the past, such as system CAE modeling, control algorithm design and system verification capabilities, must be brought in-house. If OEMs do not develop these core competencies, they run the risk of becoming dependent on their suppliers for key system knowledge and innovation in digital technology applications. As suppliers gain proficiency with the new technologies, OEMs may eventually find themselves surrendering much of the profit and power in the industry to their suppliers. Due to the difficulty of determining the design of digital components through examination and the tendency of suppliers to tightly hold intellectual assets, it is imperative that OEMs retain the ability to be innovators in the field of digital technology.

In addition to having a profound effect on the nature of competition in the automotive industry, digital technology has also introduced new technical challenges to the engineering community.

The vast majority of failures in complex systems are the result of systemic flaws based on the unexpected or hidden interactions between components. Digital system complexity and the lack of a physical manifestation of the interactions make finding these systemic flaws extremely difficult. New methods and expertise for analyzing overall system safety are necessary to address the changing nature of the technology and the increased system complexity. Also, the ease with which changes can be made to the digital system can lead to a lack of adequate forethought and analysis during the design phase and communication gaps within the design and development organizations. Design reviews, change control processes and communication protocols must be consistently implemented on digital software projects.

Digital technology also introduces new requirements for system design and verification. New hazards are introduced that traditional design techniques such as redundancy and system back-ups do not adequately address. Systems such as adaptive cruise control and onboard navigation create new functionality for drivers but they also raise new concerns regarding the potential for driver distraction and the loss of situational awareness. These issues are highly complex and require significant study in fields outside traditional engineering disciplines. The nature of reliability has also considerably changed from a basic assessment of component "durability" to a measure of the correctness and completeness of the system logic under all operating conditions. Analyses and testing must be performed to determine that the system will provide its required function over time under the given environmental conditions. In addition, digital technology has created an unprecedented need for industry-wide standards to allow OEMs to use common software modules across platforms and minimize timing incompatibilities between emergent electronic technologies and existing automotive development cycles. Standardized vehicle interfaces have the potential to create shortened development cycles for new technologies and improve the integration of these technologies into existing vehicle infrastructures.

Systems engineering provides a way for automotive OEMs to deal with the increasing complexity of digital systems and address these new technical challenges. Systems theory shifts engineering thought and practice away from an emphasis on optimization of the individual parts to an optimization of the whole. Increased attention is given to upfront requirements, documentation, design interfaces, functional coupling, system hazard analysis, testability and usability. Systems engineering, unlike other disciplines, is concerned with the overall management of the engineering process and management of the interfaces across boundaries which both play an important role in the ability of the overall system to meet its objectives.

If systems engineering is to proliferate further in the automotive industry, OEMs must prioritize it as a core competency. Based on a study of systems engineering practices in other industries, the role of the systems integrator in the automotive industry must be redefined to more closely match the definition of a true systems engineer. The most technically qualified individuals in the organization should be recruited to assume these high-level positions. Management must also re-emphasize the importance of complete and consistent requirements and proper documentation throughout the entire vehicle development process.

7.2 Areas for Further Study

While researching and writing this thesis, several concepts arose as key areas for further study into the proliferation of digital technology in the automotive industry. A better understanding of these factors may shed new light on how digital technology has already progressed in the industry and how it may continue to progress in the future. The three main areas for further study include a determination of the value of digital technology from the customer perspective, a analysis of the continuing role of standards on technology proliferation and an in-depth review of the progression of systems engineering in the automotive industry in response to the increasing complexity of automotive design.

7.2.1 Defining the Value of Digital Technology in the Automotive Industry

This thesis argues for a need to create value from digital technology in the automotive industry on an overall vehicle level rather than a specific technology basis. Preceding this argument is a fundamental question of what additional functionality customers perceive as creating value in their vehicles. Which functions actually create value for the customer and which merely provide an extra feature at an additional cost? A deeper understanding of the value equation from the customer's perspective as well as the enterprise perspective is required to better understand the strategic decisions surrounding the further proliferation of digital technology.

7.2.2 The Role of Standards on Digital Technology Proliferation

This thesis provides a cursory introduction to several of the dominant standards in the industry and a brief discussion of the effects of standardization on the proliferation of the technology. A detailed review of the current and proposed standards in the industry may shed additional light on the direction of digital technology and some of the potential challenges the industry may face by adopting the given standards. Particular emphasis should be placed on the design interfaces created by the different standards. Design interfaces can be created along functional boundaries, physical boundaries, organizational boundaries or even Clockspeed boundaries. Each configuration has its own unique benefits and challenges that may influence the success of the proliferation of the technology and ability of the different industry players to capture value from the new arrangement.

7.2.3 Analysis of Systems Engineering in the Automotive Industry

Systems engineering emerged as a methodology and a tool to help engineers and managers deal with the increasing complexity of the systems they produced. Digital technology has exponentially increased this complexity and in some cases made the transition to systems engineering an even more urgent task. This thesis attempts to identify some of the change agents in other industries and provide high-level recommendations for the automotive industry on how to accelerate this transformation process. A more detailed analysis of the current state of systems engineering behaviors and practices in the automotive industry is warranted to provide more focused recommendations and insights.

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APPENDIX A: AVAILABLE FEATURE CONTENT IN THE 2002 BMW 745iL

BMW 745iL 2002 Source: http://www.bmwusa.com
Sedan (luxury high-end) Referenced August 8, 2002

Starting at MSRP: $71,850

Performance & efficiency

4.4-liter DOHC (4-cam) 32-valve V-8 engine with Valvetronic
Steplessly variable intake manifold
Double-VANOS steplessly variable valve timing
Aluminum block and cylinder heads
Electronically controlled engine cooling
Digital Motor Electronics engine-management system with adaptive knock control
6-speed automatic transmission with Adaptive Transmission Control (ATC)
Electronic gear selector
Steering-wheel downshift controls ("L/D" range)
Liquid-cooled alternator

Handling, ride, & braking

Aluminum double-pivot strut-type front suspension
Aluminum 4-link integral rear suspension
Aluminum front and rear subframes
Active Roll Stabilization (ARS)
Twin-tube gas-pressure shock absorbers
Self-leveling rear suspension with air springs
Electronic Damping Control, stepless
Vehicle-speed-sensitive variable-assist, variable-ratio rack-and-pinion power steering
4-wheel ventilated disc brakes with electronic brake proportioning
Electromechanical parking brake
Automatic parking brake
Dynamic Stability Control (DSC)
Anti-Lock Braking System (ABS)
Dynamic Traction Control
Dynamic Brake Control

Exterior & aerodynamics

18 x 8.0 Double Spoke alloy wheels
19 x 9.0 front/19 x 10.0 rear Star Spoke alloy wheels
245/50R-18 V-rated all-season tires
245/45R-19 front / 275/40R-19 rear performance tires
Body-color bumpers with hydraulic energy absorbers and (front only) compressible elements
Aluminum hood and front fenders
Bi-xenon low and high beams in outer headlights with dynamic auto-leveling
Halogen ellipsoid front foglights
Wiping sweep regulated for optimum coverage
Variable parking position to reduce wiper blade wear
Articulated passenger-side wiper arm
Single-wipe control
Washer jets in wiper arms, heated fluid supply
Heated wiper parking area
High-pressure headlight cleaning system
Choice of standard or metallic paints
Smooth underbody

Audio

AM/FM stereo radio/CD audio system with 10 speakers, Radio Data System, (RDS), in-dash single-disc CD player, and FM diversity antenna system; includes 2 subwoofers
Logic 7 audio system with 13 speakers, Digital Sound Processing, and 6-disc in-dash CD changer; includes 2 subwoofers and all features of standard system
Cassette player in place of single-disc CD player

Instrumentation & controls

Electronic analog speedometer and tachometer
LCD main and trip odometers
Condition-based Service Display
Expanded Check Control vehicle monitor system
iDrive concept
Start/stop button
Electronic transmission downshift selector and buttons
Electronic control stalks
LCD displays and warning indicators in dial faces
Programmable cruise control
On-board computer
Navigation system
BMW Cellular Phone System, portable with digital-analog operation,
Telecommander keypad, Voice Activation System, BMW Assist, and "Mayday" feature
Tire Pressure Monitor
Brake Wear Display

Interior seating & trim

Nasca Leather upholstery
Matte-finish Black Cherry genuine wood trim
High-Gloss Ash genuine wood trim, light or dark
Memory system for driver's seat, steering wheel, safety-belt height, and outside mirrors
16-way power front Comfort seats with 4-way lumbar support; includes articulated upper backrests, adjustable backrest width, adjustable thigh support, passenger's-seat memory, active head restraints with adjustable side support
10-way power rear Comfort seats with 4-way lumbar support; includes articulated upper backrest, automatic head-restraint height adjustment, and automatic pretensioners
Active Comfort ventilated front seats with gentle massage action
Ventilated front seats
Heated front seats with fast heating and balance control
Heated rear seats
Climate-controlled front console compartment with coinholder, trunk-release lockout, illumination, and phone handset
Leather power/ tilt/telescopic multi-function steering wheel with audio and phone controls, one programmable control; auto tilt-away for entry and exit
Comfort & convenience
Vehicle & Key Memory
Keyless entry with multi-function remote control
Selective unlocking
Remote trunk release
Soft-close automatic doors
Power windows with key-off operation, "one-touch" open/close
Automatic climate control with full separate left/right controls, solar sensor, automatic recirculation, heat-at-rest feature, left/right temperature-controlled rear outlets, auto ventilation
Active-charcoal micro-filter ventilation
Power 2-way moonroof with key-off and "one-touch" operation, conceal panel, and wind deflector
Window and moonroof opening possible from remote control

Dual power/heated auto-dimming outside mirrors
Automatic tilt-down of right outside mirror for visibility of curb when backing up
BMW Universal Transceiver (garage-door opener) integrated into rear-view mirror housing
Enhanced interior lighting system including front and rear left/right reading lights
Footwell lighting front and rear
Exit/entry lighting on interior door panels
BMW Ambiance Lighting front, rear, and door panels
Illuminated visor vanity mirrors front and rear
LED "atmosphere" lights in C-pillars
Illuminated front console compartment
Locking glove compartment with rechargeable take-out flashlight
Illuminated exterior door handles and ground illumination
Rain-sensing windshield wipers with electronically controlled, reversible wiper motor
Park Distance Control with graphic display
Heated steering wheel
Power outlet in passenger's-side footwell area
Dual cupholders front and rear (total of 4-cup capacity)
Rear center armrest with storage compartment
Power rear-window and rear-side-window sunshades with driver and rear-passenger controls
Ski bag
Fully finished trunk with inside trunk release
Automatic trunk opening and closing

Safety & security

Intelligent Safety and Information System (ISIS) for deployment of safety systems
Dual front-impact airbag Supplementary Restraint System (SRS) with dual-threshold deployment, 2-stage Smart Airbags
Front safety belts with automatic pretensioners and force limiters
Automatic-locking retractors (ALR) on all passenger safety belts (for installation of child restraint seats)
Front-seat Head Protection System (HPS)
Front-seat side-impact airbags
Active Knee Protection
Rear-seat side-impact airbags with rear-seat Head Protection System
Active front head restraints
Adaptive brake lights
Battery Safety Terminal
Automatic fuel-pump shutoff upon severe accident impact
Central locking system with double-lock anti-theft feature, selective unlocking
Coded Driveaway Protection
Pathway Lighting feature
Alarm system with operation from remote, interior motion detector
BMW Break-resistant Security Glass