Complex Dynamic System Architecture Evaluation through a Hierarchical Synthesis of Tools and Methods

by

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

Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology

May 2003

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ABSTRACT

The automobile embodies complex dynamic system architecture with thousands of components and as many interconnections. The modern day vehicle architecture attempts to balance significant tradeoffs and constraints to achieve the system goals. There are innumerable combinations, which may or may not achieve success.

This work proposes a new method for evaluation of complex dynamic system architecture through a hierarchical synthesis of specific qualitative and quantitative tools and methods within a system architecture framework. The proposed methodology is applied to key subsystems of a specific high performance car to assess primarily the merits of the process. Current methods for system architecture definition at the automobile manufacturer utilized for analysis rely primarily on experience-based intuition within an architecting framework. Current system architecture frameworks and the manufacturer's process utilized appear insufficient, as significant issues (often dynamics related) arise in the verification and validation phase of their product development process, requiring change to vehicle architecture. Changes in architecture at this phase of the manufacturer's product development process have significant cost, timing and perhaps functional performance implications. Many system architecture and engineering tools exist to aid architecture definition, but a hierarchy in usage and the interrelationships of the tools are not clearly defined.

The proposed solution for rigorous complex dynamic system architecture evaluation includes a four phase hierarchical synthesis of known qualitative and quantitative tools and methods within a holistic system architecture framework. For purposes of this thesis, the proposed evaluation methodology is labeled "CD-SAAM" for Complex Dynamic System Architecture Assessment Methodology. The proposed methodology is a rigorous complement, superimposed on the concept development phase, to the standard product development design process. CD-SAAM mainly combines known system architecting and system engineering framework, principles and tools.

Application of CD-SAAM to a high performance car's powertrain and chassis system architecture's second level form and function decomposition, serve to demonstrate many high level conclusions. The hierarchy and synthesis of framework, principles and tools in CD-SAAM provided a valuable and rigorous method to evaluate complex dynamic system architecture. While certain aspects of the proposed methodology appear time-consuming, each step and the overall process serve to greatly improve consistent success with respect to achievement of a system's goals within its constraints. Application of CD-SAAM also underscores the importance and need for explicit design parameter identification and analysis in complex dynamic system architecture assessment. The performance car application also provides insight into the value of DOE RSE methods in architecture assessment, as opposed to its typical region of use in detailed design analysis. Finally, a positive by-product of the analysis includes CD-SAAM's ability to evaluate the consistency and attainability of goals within the given constraints.

Acknowledgements

This thesis is dedicated to the memory of my mother, Dottie Anderson. Her passion for life, kindness to all, guidance through actions, not just words, and incredible courage remains ingrained in me forever.

In addition, I have many to thank for their considerable support and guidance throughout my education in the MIT SDM program, and in particular, this thesis. The number of people whose interaction over the past few decades has affected this thesis indirectly is innumerable. I have learned and gained from far too many to mention here, but they are not forgotten.

First, no amount of words can thank my wife, Angela, enough for her never ending support, patience and sacrifice of my time over the past two years while I pursued my degree at MIT. A thank you also for the hours of proof reading this very long document!

Thank you to my father, Dennis Ahlman, whose passion for cars and all things mechanical is embedded in me and motivates me everyday.

Thank you to my advisor, Professor Ed Crawley, for his teachings and guidance in System Architecture, which has had a considerable impact on many aspects of the methodology proposed in this thesis. In addition, his patience with my workload and flexibility in his overloaded schedule to provide continual and insightful feedback was greatly appreciated.

This incredible opportunity was made possible by two of my mentors, Tom Reichenbach and John Valentine. A great thank you to them for their belief in my abilities, guidance and support. A thank you also to Neil Ressler for allowing me the opportunity of a lifetime on the vehicle example heavily utilized in this thesis in addition to his support and review of this thesis. Also, thank you to mentors Bobby Rahal and Ron Campbell for their letters of recommendation to the SDM program.

Thank you much to Jeff Chrstos, not only my mentor for vehicle dynamics, but also a great friend. His countless hours of vehicle dynamics advice and analysis aid over the past seven years are invaluable. A thank you also for the numerous hours spent reviewing and providing insightful feedback on this thesis.

Thank you also to colleague and friend Lynn Bishop for his advice and aid in the ADAMS analysis completed in this thesis.

Last but not least, a great thank you to all of my classmates in the MIT SDM program. The level and diversity of talent in their fields, as well as their ability to share their knowledge with others is unmatched. A special thank you to Sridhar Sadasivan and Dan Douglas, my teammates in system architecture coursework, whose efforts and knowledge contributed greatly to my knowledge base in system architecture.

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1 Complex Dynamic System Architecture Evaluation Introduction

1.1 Motivation and Objective

Nine years of chassis design and vehicle dynamics experience at an automotive original equipment manufacturer (OEM) served to underscore the fact that automobiles are very complex, and therefore, complicated dynamic systems with thousands of components and as many interconnections. The modern day vehicle architecture, which embodies its function and form [Cr1], attempts to balance significant tradeoffs and constraints to achieve the system goals/objectives. There are innumerable combinations, which may or may not achieve success. In addition, modern vehicle architecture continues to gain complexity as the customer demands greater function, especially dynamic.

For purposes of this thesis, my employer is referred to as OEM-A. OEM-A utilizes the basic "Vee" Product Development process shown below in Figure 1. The Vee includes system requirements cascade to the system, subsystem function and detailed design of components in the left side of the Vee. In addition, the left side of the Vee contains the design decomposition and definition of the product development process. The right side of the Vee contains component, subsystem and system level integration and verification. Integration and verification takes the form of physical testing on component, subsystem and full system prototypes, to insure the product meets the objectives.

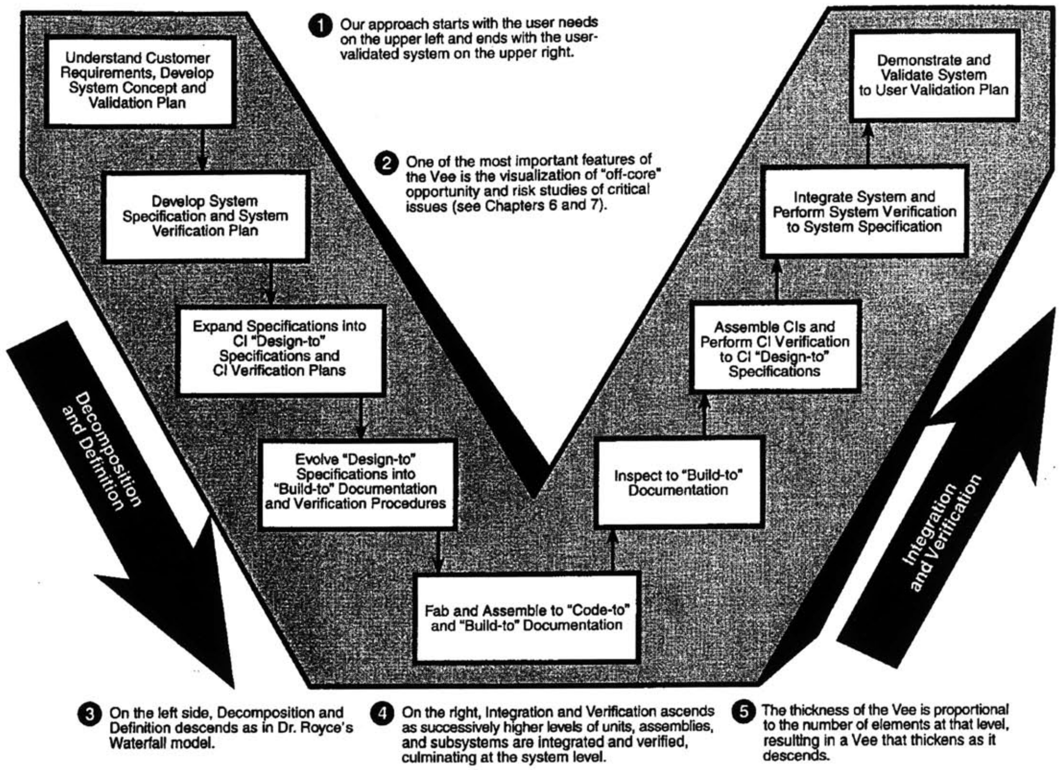


Figure 1: Generic Product Development Process "Vee". [FOR, p. 34]

Unfortunately, significant issues (often dynamic behavior related) are often uncovered in the verification phase of the automotive product development process that requires change to architecture. Changes in architecture at this phase have significant cost, timing and perhaps functional performance implications. The cost and timing implications result from the large number of elements of the design that may be affected if architecture rework is required, and the impact on expensive, long-lead tooling for components, which is often in process or complete by this stage. Overall system functional performance may be compromised due to an inability to rework the entire architecture, so compromises made in interfacing subsystems to achieve synergy may no longer be valid. This described impact of late changes to architecture is in line with the typical product development "influence diagram", shown in Figure 2 below. It demonstrates the decreasing ability to impact a design (without considerable cost and time implications) as time progresses on a project. Note the significant drop in the ability to influence the outcome just after the concept phase in product development. The completion of the concept phase signals the close of the system architecture definition.

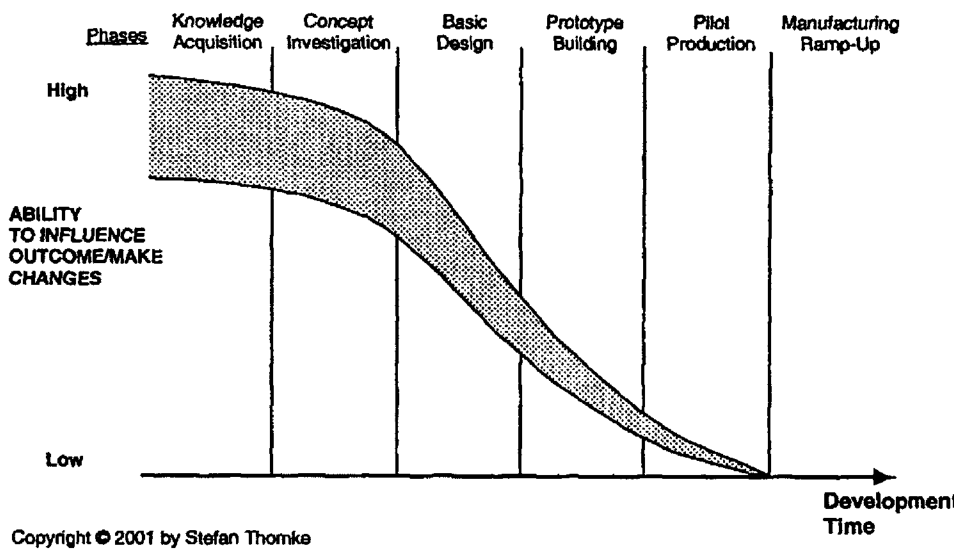


Figure 2: Generic Product Development Influence Diagram. [THO]

The above-described challenges exhibited in the OEM-A product development process motivated considerable thought with regard to root cause and potential solutions. Reflection on root cause determined that often the system architecture chosen and the process utilized to define it was insufficient to consistently achieve the system goals. Consequently, assessment of a proposed methodology to add rigor and improve performance with respect to system architecture evaluation is the high level objective of this thesis.

Involvement in numerous vehicle projects at OEM-A included experience where dynamics issues were uncovered in the verification phase and required costly and time-consuming architecture changes to achieve the system's functional objectives. Often the issues uncovered simply demonstrate the inability to meet the system goals within the given constraints. Other times the uncovered problem involves natural frequency alignment of one of the many components or subsystems requiring architectural change. For example, the rotational frequency of a vehicle's drive shaft at certain speeds can align with the natural frequency, or resonance of the vehicles frame/structure. The resultant issue, as perceived by the customer, results in an annoying vibration and/or noise. Other forms of natural frequency alignment can lead to limitations in ride and handling performance. Dynamics issues arise in the verification phase of the automobile product development plan because many of the behaviors or emergent properties are extremely difficult to predict due to a high degree of interconnectedness throughout the system. The significant interaction between components and subsystems yield very non-linear, counterintuitive behavior. Further, human interaction with the dynamics of the system adds another element of difficulty with regard to dynamic behavior prediction.

An automobile's system architecture heavily affects the difficult to predict dynamic behavior. The architecture of a system creates its foundation and governs the subsequent compromises and ultimate success with respect to the system objectives. However, most system architecture definition methods and the process utilized at OEM-A are purely qualitative. The methods primarily rely on experience-based intuition, perhaps some architecting principles and heuristics within a loose architecting framework. A hierarchy in usage and the interrelationships of the tools are not clearly defined.

1.2 Proposed Solution Introduction

To evaluate complex dynamic system architecture and alleviate the above-described issues, I propose a four phase hierarchical synthesis of qualitative and quantitative tools and methods within a system architecture framework. For purposes of this thesis, the proposed evaluation methodology is labeled "CD-SAAM" for Complex Dynamic System Architecture Assessment Methodology. CD-SAAM primarily combines known system architecting and system engineering framework, principles and tools for qualitative analysis. It also utilizes Design of Experiments (DOE) methodologies at the final, quantitative step, which is chosen for its strengths regarding quantification of dynamic system behavior. This thesis is not intended to invent new, individual processes, but instead synthesize a more rigorous, hierarchical set of steps applied to an actual complex dynamic system in the form of a high performance car.

The proposed methodology explicitly evaluates the importance of design parameters with respect to system constraints and goals, as well as assesses the impact of architecture options on the identified parameters. This methodology is not to be confused with the typical product development concept "funnel" that depicts the narrowing of concepts and resultant design options through the process. Instead the proposed methodology is a rigorous complement, superimposed on the concept development phase of the standard process. See Figure 3 and Figure 4 below for a graphic depiction.

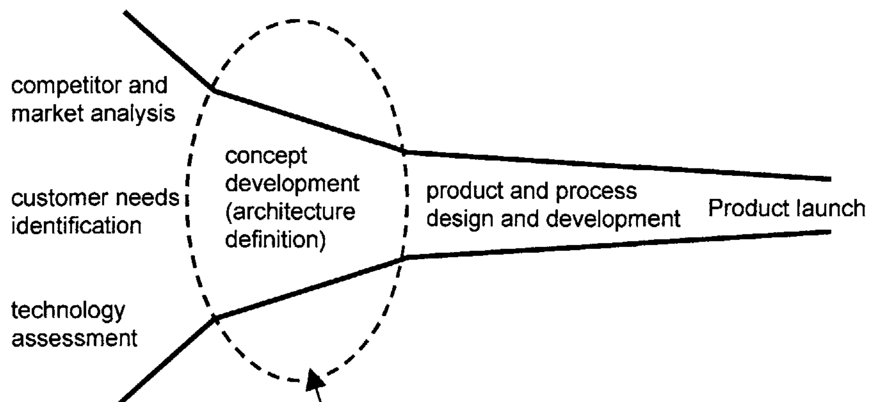


Figure 3: Generic Product Development Design Process "Funnel". [THO]

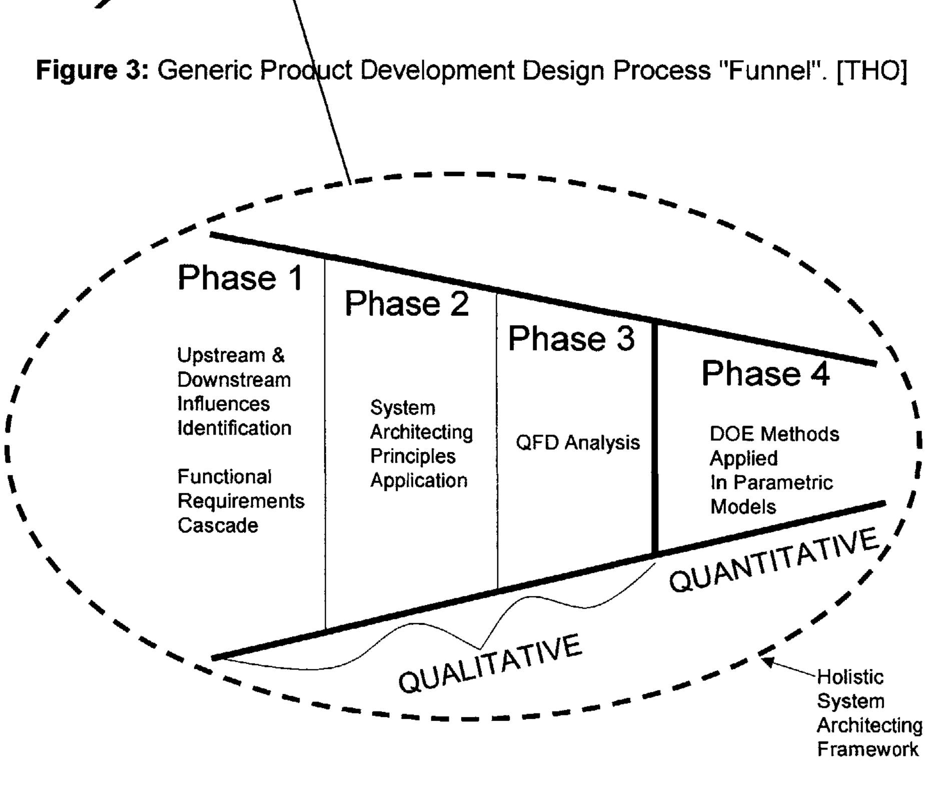


Figure 4: Hierarchical Synthesis of Tools and Methods Framework for Complex Dynamic System Architecture Assessment.

The use of narrowed focus for assessment of product designs, starting with qualitative tools, then moving to quantitative analysis is not new. However, the identification and usage of a specific set of tools and hierarchy as described in the following does appear novel. In addition, CD-SAAM is novel in its approach with regard to a narrowing of focus and increase in fidelity of analysis with respect to specific elements and/or design parameters of an architecture, rather than simply a narrowing of concepts. Completion of each phase of CD-SAAM yields four potential outcomes. The result can involve just one, some or all four of the following conclusions at the end of each phase:

1. *Complete evaluation of certain aspects (function and/or form) of an architecture* deeming them sufficient or deficient with respect to system constraints and goals, with the latter case pointing to alternatives. This means the identified aspects of the architecture do not warrant further, more detailed analysis in the following phases.
2. *Incomplete evaluation of certain aspects (function and/or form) of an architecture* with respect to its constraints and goals. This means the identified aspects of the architecture warrant further, more detailed analysis in the following phases.
3. *Complete evaluation of the importance of specific high level solution neutral system design parameters* (i.e. mass, moment of inertia, stiffness, etc.) and their impact on system constraints and/or goals. This means that these specific design parameters do not warrant further, more detailed analysis in the following phases. It also means form and function attributes of the architecture may be adequately judged with respect to their affect on these design parameters.
4. *Incomplete evaluation of the importance of specific high level solution neutral system design parameters*. The analysis uncovers and highlights specific system design parameters that impact the system constraints and/or goals, but are unable to adequately quantify their importance. The highlighted design parameters require further, more detailed analysis in the following phases until their impact on system constraints and/or goals are adequately quantified.

CD-SAAM Phase Description

As shown in Figure 4, a system architecture framework encompasses the entire process to provide guidance at each step and insure all of the major influences feeding the architecture are accounted for. The chosen system architecting framework for CD-SAAM provides holistic guidance for every step in the process. Competitor and market analysis, customer needs identification, technology assessment, as shown feeding concept development in Figure 3, are a few examples of upstream influences feeding an architecture. However, this is only a partial list, which is highlighted by the chosen framework described in detail in section 2.2. For reference, downstream influences include elements such as manufacturing, assembly and operational sequence, also covered in greater depth in section 2.2.

The first phase of the qualitative analysis in CD-SAAM primarily creates the foundation for system architecture assessment, as opposed to direct evaluation. However, similar to the shape of the funnel shown in Figure 3, concepts and function of the architecture to analyze are heavily reduced as the goals and requirements are defined. Further, the system architecture framework and the two elements of the first phase, upstream/downstream influences identification and functional requirements cascade, serve to insure holistic goals and requirements. Note that the specific method chosen for functional requirements cascade is described fully in section 2.3. While the first three phases of CD-SAAM are labeled as "qualitative", they are not completely devoid of quantitative aspects. The three phases of qualitative assessment are intended to include the application of the basic laws of physics, including review of fundamental equations relevant to the dynamic system at each step.

Direct system architecture evaluation begins in phase two of CD-SAAM shown in Figure 4. This phase of the analysis utilizes five specific system architecting principles. The five chosen principles are enlisted to provide a more focused assessment with regard to attributes of the architecture. Each principle application by itself and resultant evaluation of the system architecture may highlight potential for improvement with respect to the particular principle. However, the resultant assessment is not necessarily the final judge on the merit of the architecture. For example, an architecture may exhibit deficiencies with regard to one or more principles, but in the end result in the best synergy and performance with respect to system goals. The five principles applied in CD-SAAM are described in detail in section 2.4.

The final qualitative step in CD-SAAM involves Quality Functional Deployment (QFD) analysis. QFD, a system engineering tool, is employed to analyze aspects of the architecture that are shown to affect a large degree of the system constraints and goals with conflicting trends in the prior steps. QFD utilizes a weighting and scoring system that transforms a complicated collection of conflicting trends into an organized array with a ranking of each concept. However, it is still primarily qualitative analysis, based on engineering judgment and application of principles; thus the results are not always completely conclusive, especially for complex dynamic systems.

The final step in CD-SAAM involves quantitative DOE methodologies applied to parametric models. The DOE methodologies are focused on critical design parameters of the system architectures based on the prior qualitative analysis. The application of DOE to parametric models yields Response Surface Equations (RSE's) that provide the true sensitivities and interactions of system parameters on chosen responses (system output) and allow for "best balance" (optimization) analysis, if desired. Very few have proposed and utilized quantitative analysis for system architecture assessment and even less apply DOE methodologies. In an automobile, for example, the RSE's can provide the true impact of attributes like system mass, moments of inertia, stiffness, aerodynamic properties, etc. on dynamic functions like straight-line acceleration, cornering and braking. Understanding the true sensitivities and interactions gives one quantitative metrics to finalize evaluation of their architecture. Architecture decisions that cut across subsystem boundaries and multiple managers' areas of discipline increase the need for quantification of design parameter importance. In addition, the constraints, goals and region of design space occupied for a system architecture heavily affect the results. Therefore, a DOE completed for one vehicle system, for instance, does not necessarily apply to another. Ideally, one would apply DOE methodologies to the entire system architecture to insure a robust result, but this is not feasible in complex, dynamic systems like the automobile, based on cost, time and resource constraints.

1.3 Thesis Scope and Specific Objectives

The nature of the proposed process CD-SAAM, where it is primarily a hierarchical synthesis of known tools, forces the need for application of the methodology to a complex dynamic system to assess its merit. While there are a considerable number of complex dynamic system architectures to which this thesis applies, the modern automobile system architecture is chosen for application. Specifically, the application of CD-SAAM focuses on a few key subsystems of the 2^{nd} level decomposition of form for the powertrain and chassis systems for a high performance car, known as "Supercar-A" from this point forward. This high level form of Supercar-A is evaluated against the stated system goals and constraints. The scope of the analysis remains within the typical concept development phase of product development design process shown in Figure 3 and assumes the system goals stated in the application section address the customer needs.

Multiple specific objectives exist for this thesis due to the fact it embodies a combination of new methodology analysis as well as application to specific system architecture. To summarize, the two specific objectives for this thesis are as follows:

1. *Assess the hierarchical synthesis of qualitative system architecting and engineering tools and quantitative analysis for complex dynamic system architecture evaluation (CD-SAAM) through application to Supercar-A.* This is the primary objective of the thesis. Assessment of the proposed methodology for complex dynamic system architecture evaluation includes highlighting strengths and weaknesses of each major step, as well as the overall approach. Metrics include the value of each step and the overall methodology value with respect to time and resources expended versus the results achieved.
2. *Evaluate the selected subsystems of the Supercar-A architecture with respect to its stated constraints and goals.* This is the secondary objective of the thesis. The

evaluation of Supercar-A includes highlighting strengths of the architecture chosen and potential areas of opportunity for improvement. Application to Supercar-A is also meant to underscore the importance of the chosen system architecture and its impact on results.

1.4 Thesis Outline

Chapter Two summarizes the related system architecture and system engineering framework, principles and tools that are applied in CD-SAAM and additional reasoning for their usage. Chapter Two is not intended to teach and/or provide significant background detail for any one of these tools due to the fact that there is a significant body of documentation available on these subjects. However, relevant documentation is cited if the reader requires further information on these subjects.

Chapter Three introduces and provides pertinent background information on the complex dynamic system to which CD-SAAM is applied. This includes the specific high performance car whose architecture is evaluated as well background on its primary competitors. The background information includes vehicle form/function decomposition to the second level as well as numerous examples of concepts for the performance car system architecture. Chapter Three also covers considerable detail on Supercar-A's goals and constraints in addition to highlighting considerable challenges to meeting the system objectives. The chapter closes with final definition of the specific elements of Supercar-A's system architecture chosen for application of CD-SAAM.

The prior work in this thesis leads to the actual application of the proposed methodology, CD-SAAM in Chapter Four. This chapter covers the qualitative analysis application of CD-SAAM to the above stated Supercar-A system architecture. The qualitative analysis includes the first three phases depicted in earlier Figure 5 including: upstream and downstream influences identification, functional requirements cascade through concept mapping, five system architecture principles application and QFD analysis. The upstream and downstream influences are directly mapped to the system goals and constraints introduced in Chapter Three. The functional requirements cascade through concept mapping applies new usage of design parameters at this level of system architecture analysis. The five system architecture principles application represents the first true architecture assessment step in CD-SAAM, which is somewhat lengthy as it represents the highest, most coarse level of analysis. Completion of the principles narrows the focus of system architecture elements for assessment and leads to the QFD analysis, which is the final qualitative phase.

Chapter Five involves the fourth and final phase of CD-SAAM application to the Supercar-A system architecture. As discussed earlier, the fourth phase is quantitative in nature and includes the utilization of DOE RSE methodologies in parametric models to calculate and provide true design parameter to vehicle behavior relationships (sensitivities). The design parameters and vehicle behavior analyzed are those highlighted in the prior phases of evaluation, which require further evaluation. Quantification of the identified design parameters facilitates final assessment of remaining aspects of system architecture, which are inconclusive up to this stage of CD-SAAM. This chapter includes analysis of two DOEs. The first DOE covers Supercar-A's straight-line acceleration performance, while the second covers its handling performance. Chapter Five includes background information on the DOE setup, including high level specifics about the models used. The analysis for each vehicle response includes direct observations on the relative importance of the design parameters and the chapter concludes with final assessment of open aspects of the Supercar-A system architecture.

The sixth and final chapter covers conclusions regarding the merits of the proposed methodology, CD-SAAM, for assessment of complex dynamic system architecture. The conclusions include the value of each phase of the proposed approach as well as the overall value of CD-SAAM. Each section of the conclusions includes relevant recommendations for improvement to aspects of CD-SAAM based on the application analysis completed. Chapter Six concludes with a final high level assessment of the Supercar-A system architecture with respect to its goals and stringent constraints.

2 Relevant System Architecture/Engineering Tools and Principles Summary

2.1 Chapter 2 Scope and Objectives

Chapter Two summarizes the related system architecture and system engineering framework, principles and tools that are applied in CD-SAAM and additional reasoning for their usage. The following tools are reviewed in this chapter:

- Crawley's System Architecture Influences Framework
- Functional Requirements Cascade
- Five System Architecting Principles
- Quality Functional Deployment (QFD)
- Design of Experiments (DOE) Methodology

The CD-SAAM framework is depicted again in Figure 5 to demonstrate the placement of each tool in the process.

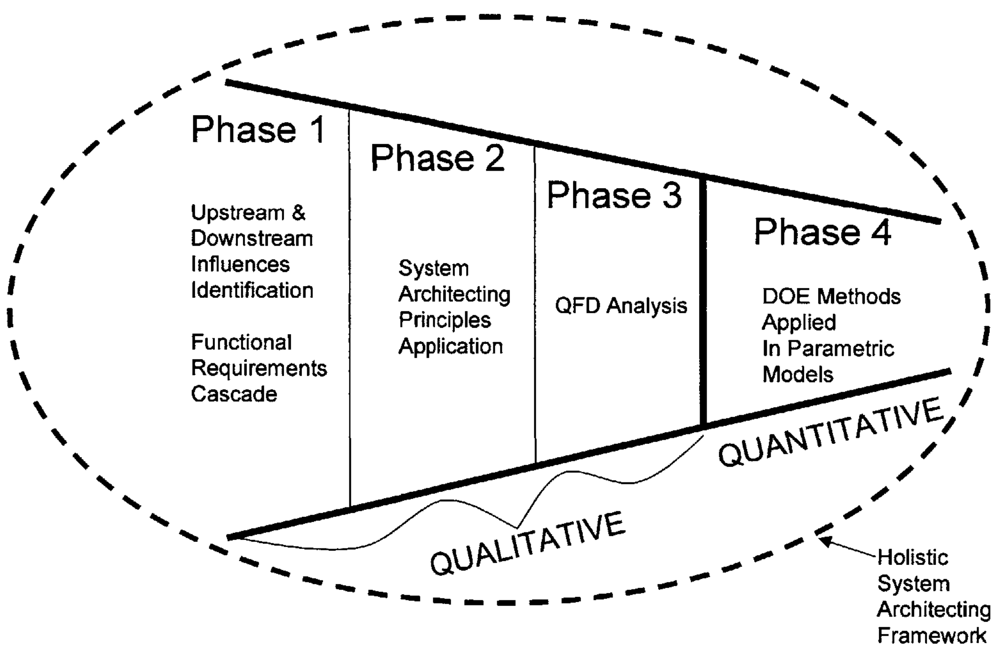


Figure 5: CD-SAAM Framework.

Chapter Two is not intended to teach and/or provide significant background detail for any one of these tools due to the fact that there is a significant body of documentation available on these subjects. However, relevant documentation is cited throughout if the reader requires further information on these subjects. Additional system architecting and engineering tools (including Design Structure Matrices, context diagrams, Object Process Methodology and Axiomatic Design) to those utilized in this thesis were investigated but omitted due to the following reasons:

- Overlap with respect to chosen tools
- Cumbersome usage and perceived insufficient results for a given level of effort
- Inappropriate for application to this thesis

2.2 System Architecture Influences Framework

As stated in section 1.2, the chosen system architecting framework for CD-SAAM provides holistic guidance for every step in the process. As noted earlier, other standard frameworks exhibit some of the necessary influences on the architecture of a system, but none are as complete as Crawley's framework. Figure 6 and Figure 7 below represent the major considerations feeding the form/concept of a system. The influences from this framework are directly applied to the system goals and constraints analysis to insure they are properly represented, as highlighted in section 4.2. This mapping of upstream and downstream influences to the system goals and constraints comprises the work involved in "identification of upstream and downstream influences" in phase one of CD-SAAM.

Many of these influences are self-explanatory but others require some explanation, primarily a few of the downstream influences. The "implementation" influence in Figure 7 represents manufacturing and assembly considerations. "Evolution" represents future adaptation of the architecture with respect to changes in design and usage.

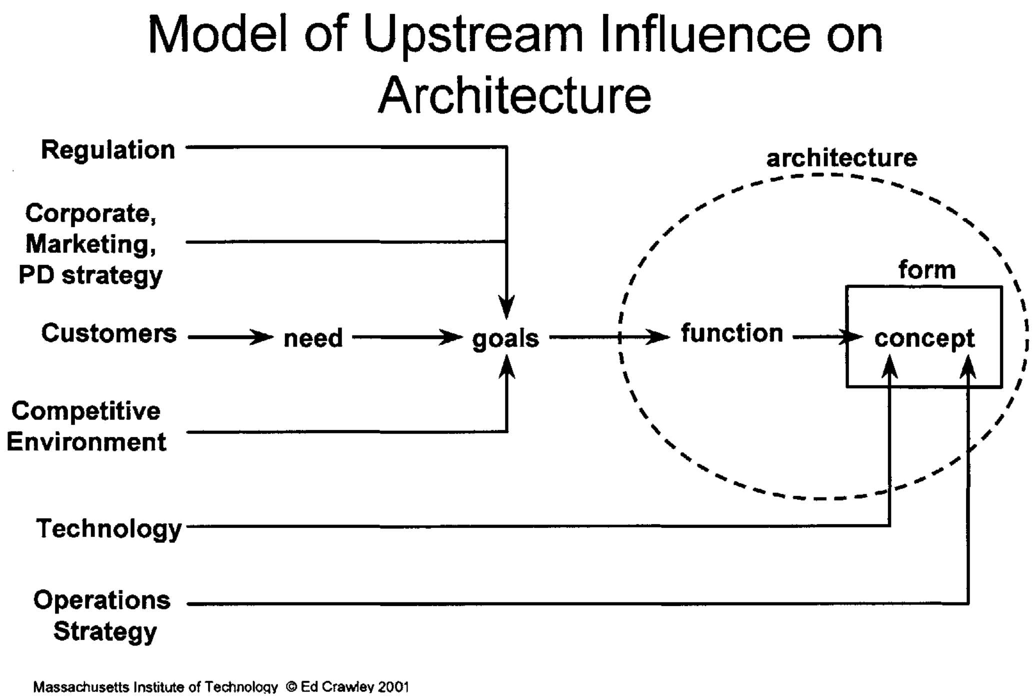


Figure 6: Crawley's System Architecture Upstream Influences Framework. [Cr, Lecture 1, p. 35]

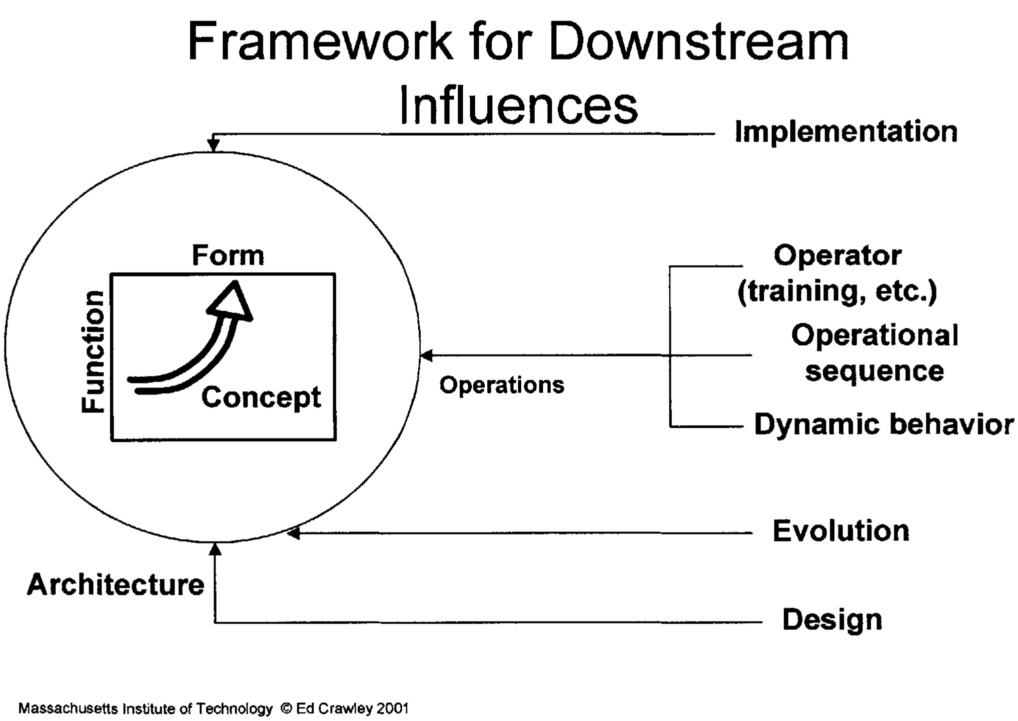


Figure 7: Crawley's System Architecture Downstream Influences Framework. [Cr, Lecture 1, p. 41]

2.3 Functional Requirements-Concept-Form Cascade

Customer needs must be turned into system goals as demonstrated in Crawley's System Architecture framework. For the most part, these "needs" are customer wants or desires and not true needs and could be discussed at length. However, customer needs discussion is beyond the scope of this thesis. Therefore, the next step in the process involves creation of solution neutral functional requirements based on the system goals, starting at the highest (system) level and cascading down, step-by-step, to the subsystems. This cascade is intended as another tool to drive the architect's decision process for concept and form selection. The concept and form needs to appropriately address the functional requirements as well as the other upstream and downstream influences noted in Crawley's framework. The architect for a system should work to the second level of function and form decomposition, as noted by Crawley and shown in his Concept Mapping Diagram in Figure 8. This can be a large task, depending on the size of the system.

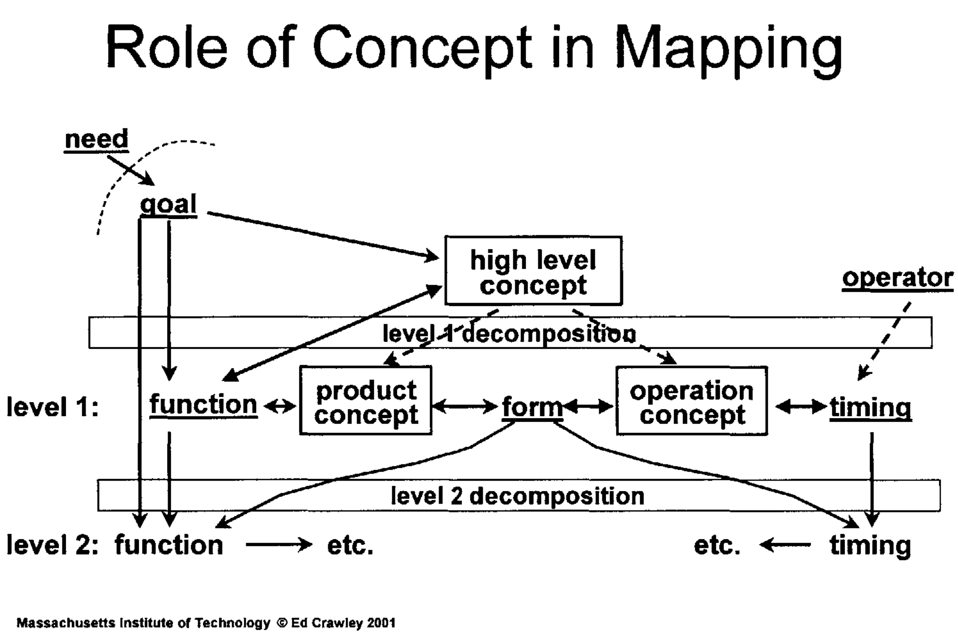


Figure 8: Functional Requirements Cascade through Concept Mapping. [Cr, Lecture 4, p.33]

A solution neutral requirement is intended to mean that it defines "what" is required, not how it is achieved. Of course, as noted by Suh, the design solution chosen at a higher-level impacts the requirements at a lower, subsystem level, so one is never completely solution neutral with requirements. [Suh] For example, lets say a requirement for a system is "Provide human transportation". Choosing an automobile versus a train or plane at the highest level of architecture to meet this requirement certainly yields significantly different lower-level requirements for the subsequent subsystems. At the next level, choosing an internal combustion engine to provide acceleration or "thrust" in a vehicle again yields significantly different lower level subsystem requirements than if a hydrogen fuel cell power-plant was chosen. Note Crawley's example for "Moving People" as the high level function.

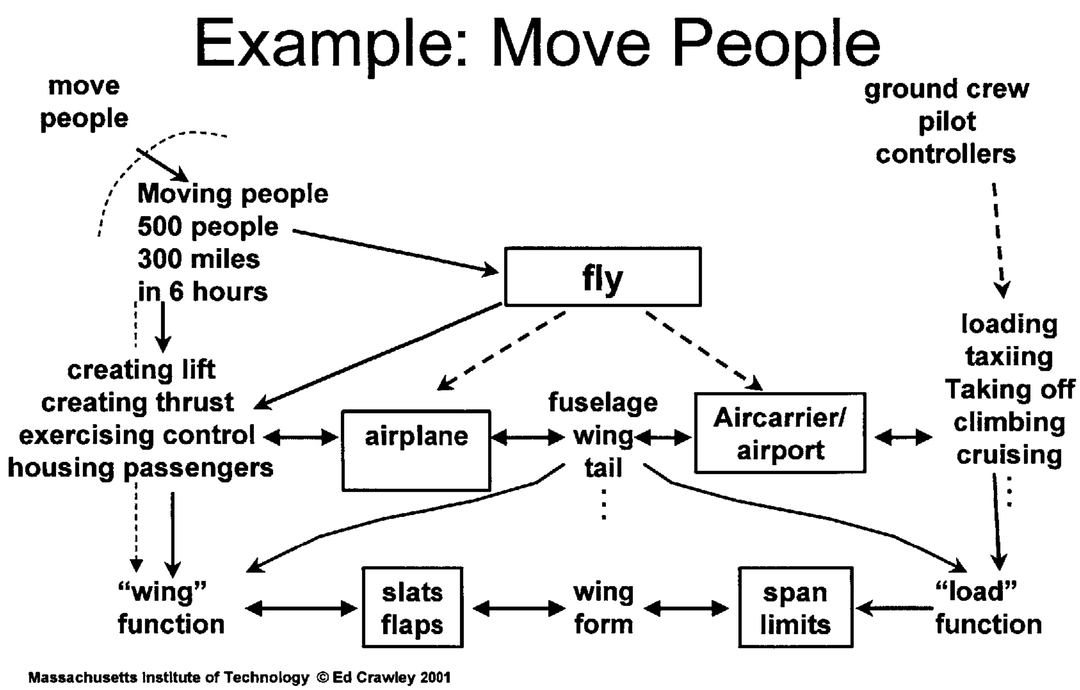


Figure 9: Move People Concept Mapping Example. [Cr, Lecture 4, p.34]

Further research encountered a wide range of methodologies for solution neutral functional flow of requirements down through the subsystems to aid function-concept-form selection. This research demonstrated notable definition differences for function, architecture and design parameters, which certainly explained the range of methods as well as a variety of rigor in the approaches. The best objective analysis of functional requirements cascade methods I encountered was completed in MIT System Design and Management Masters student, Nathan Soderborg's thesis, "Representing

Systems Through Object-Process Methodology and Axiomatic Design". [Sod] Soderborg analyzes the functional requirements cascade methods and corresponding definitions of notable authors including Boppe (Systems Engineering), Crawley (System Architecting), Dori (Object Process Methodology: OPM) and Suh (Axiomatic Design). For the most part, Soderborg favored the OPM approach by Dov Dori for its rigor in definitions and completeness. At a very high level it is a rigorous graphical method for linking intent of requirements, function, behaviors and form. Ultimately, OPM appears very similar to Crawley's Concept Mapping in its primary elements at the architectural level. I have chosen to stick with Crawley's Concept Mapping for Functional Requirements Cascade in this thesis because it is fairly self-explanatory and intuitive in comparison to OPM. This completes the summary of tools utilized in the first phase of CD-SAAM, which primarily serve to create the foundation for evaluation of an architecture in the following phases.

2.4 System Architecture Principles

A principle is defined as an underlying and long enduring fundamental that is always or almost always valid. [Cr1] Principles contain a descriptive component to highlight the philosophy of the principle and a prescriptive or "recipe" component to apply the descriptive portion. [Crt] System architecting principles are qualitative tools to evaluate a given architecture by inspection and comparison to the principles. An assignment during the Fall 2001 System Architecture course ESD.32J, by Professor Crawley at MIT in the System Design and Management Program consisted of compiling a list of System Architecture Principles throughout the semester. The following five principles described in detail represent the most applicable and valuable encountered to date:

1. Minimize Complexity
2. Form, Function and the Laws of Physics/Nature Union
3. Balanced Architecture
4. Synergy
5. Balanced External Forces

Each principle that follows contains a descriptive element, prescriptive aspect for application and further detail for usage context and improved clarity.

1. **Minimize Complexity Principle by Crawley**

Descriptive: Minimize ideal (essential), actual and perceived complexity. (As noted in the glossary, complexity is the level and sophistication of interfaces/interconnectedness in a system.)

Prescriptive: The complexity (especially perceived) of the system must be within human understanding. The interfaces should be well defined for minimal "information" transfer and facilitate system integration. [Lim, principle 18 description paraphrased].

Complexity is a major theme in Crawley's System Architecture course. If complexity is beyond the architect's and/or design team limits of comprehension, then it is impossible to apply a holistic view and achieve a synergistic system. If the system is apparently too complex, then it is obviously complicated. Further, well-defined interfaces with minimal complexity is key to more detailed system design due to the fact that the design engineers tend to spend more time and effort on the "core" and least on the periphery of their subsystems, viewing the latter as external constraints on their internal design." [Rec]

However, complexity remains a difficult aspect of architecture to "quantify". The perception of complexity often depends on one's perspective; therefore, assessment of complexity varies from person to person. For example, a hinged joint with two separate halves and a pin is more complex in part count and the number of interfaces than a "living hinge" or single piece flexure producing the same function. However, the flexure is arguably a more sophisticated joint than the standard hinge and is more difficult to predict and understand its true behavior. Therefore, one may conclude that the living hinge is more complex. Examples of this nature must be kept in mind during application of this principle noting the architecture implementers' (design engineers) perspective and perception of complexity.

2. Form, Function and the Laws of Physics/Nature Union Principle by Frank Lloyd Wright with addition from Ahlman

Descriptive: Form, function and the laws of physics/nature union.

Prescriptive: Marry form and function by architecting them as "one", in unison with the laws of physics/nature. The architect must approach them with a singular vision, concurrently, as opposed to popular credos like "form follows function".

It appears Louis Sullivan coined the phrase "form follows function" which was heavily misinterpreted as a Frank Lloyd Wright statement. Actually, Wright's version of this statement is "form and function are one". I have taken it one more step explicitly and added the laws of physics and nature. Many would argue this is simply part of "function", but to me, there are significant degrees of difference in functional performance between different approaches to an architecture which do not emphasize, or treat as important, the laws of physics/nature. The architect, who applies knowledge and analysis regarding the laws of physics and nature, will achieve a better solution. Often an architecture that embodies this principle is known as "elegant". An elegant architecture demonstrates significant style (aesthetics), simplicity (ease of function, form and understanding) and does not merely meet, but exceeds functional requirements and system goals. In the end, it is typically the "simplest" approach and architecture, which often exceeds users expectations. And elegant designs often cause one to say, "That is so simple, why didn't I think of that?"

True architectural elegance is typically universal, not simply appreciated by a few, rather a large majority. It is also timeless and magical. It creates an emotional response, which is greater than its mere function deserves. Architectural elegance for determining or maintaining a heading is exemplified by the non-complex, aesthetically pleasing and "magical" magnetic compass versus the example of the complicated, complex, "clunky" looking poor performing (very inaccurate) South Pointing Chariot, which only attempts to maintain a heading. The Chinese reportedly invented the South Pointing Chariot around 500 BC. View the complex differential system of the South Pointing Chariot in Figure 10 versus the simple form and function of the magnetic compass in Figure 11, which truly integrates the Laws of Physics. Also, note the resultant reduction complexity.

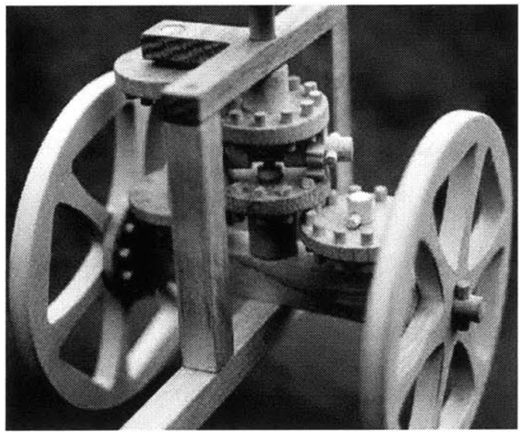


Figure 10: South Pointing Chariot.

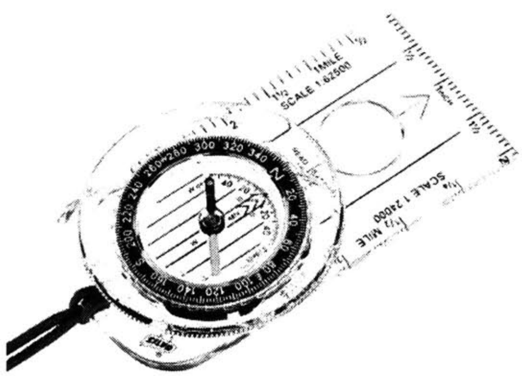


Figure 11: Magnetic Compass.

3. **Balanced Architecture Principle by Ahlman**

Descriptive: A "balanced" architecture is absent of extremes and embodies the necessary compromises.

Prescriptive: Insure the first and second level design parameters of a system architecture are "balanced" or do not exhibit extremes through inspection or "zero-eth" order analysis.

The Balanced Architecture principle is a first order principle, which feeds or is utilized to achieve synergy. It does not entail all of the facets or complete holistic view required to achieve synergy, but it is an important component. Significant experience is required to apply this principle because it requires a feel for the numbers purely by inspection, not more significant numerical analysis. This is "zero-eth" order analysis as taught in systems engineering. Understanding what is extreme is difficult without a healthy dose of application and real-world experience on the product being architected. Ultimately, application of this principle serves to highlight the need for further analysis with respect to the potential compromises that the extreme aspects may affect negatively.

4. Synergy Principle

Descriptive: "Synergy- In essence, the whole is greater than the sum of the parts" (Mid-17th century. Via Latin from Greek sunergia, from sunergein "to work together," from, ultimately, ergos "work.")

Prescriptive: Parts, things, people, organizations "work" together to optimize the whole, the system, rather than the individual parts.

This principle is at the heart of system architecture and engineering as well as life. All too often we optimize the singular parts or even singular attributes of a system, instead of the whole, which results in performance less than the sum of the parts because they do not work together. A quick review of a completely separate but analogous situation highlights this principle. Many top professional sports teams reinforce this fundamental truth when a team is "stacked" with a significant number of elite athletes, yet a collective group of less talented individuals often beats them. One team has created synergy; the other has not.

Creating synergistic systems is especially challenging at OEM-A, which has had a strong heritage of component design and yet such a complex product system (the automobile). Fortunately, a systems approach has been growing at OEM-A. Essentially, it is the interaction between components of a system that produce emergent properties that are desirable and undesirable to create a greater or lesser whole. Holistic thinking and approach, as described in Professor Crawley's System Architecture Course, yields a significant framework toward creating synergy through understanding and infusion of upstream and downstream influences into the function-concept-form of a system.

Brian Lim MIT ME SB Thesis

I also completed further research of related thesis and found one by Brian Lim named "Principles for Architecting Complex Systems" in 1998. [Lim] Lim derived nineteen principles from over 1,000 statements compiled by System Architecture students during Professor Crawley's course at MIT. The nineteen resultant principles provide a combination of principles for the process of architecting as well as a few for architecture determination. A process example as follows: "Mental models and expectations begin forming at the earliest stages of a system development process and quickly gain inertia, so carefully select who participates in the architecting process." [Lim]

This is certainly a factual statement and should be heeded during architectural determination process. However, application of CD-SAAM focuses on the principles specifically directed at architecture evaluation. For example, Lim's eighth listed principle:

> "Risk is inherent and unavoidable, but identified risks can be managed".

and 14th principle:

> "System architecture has no single "right" answer; an optimized system solution can have a number of different forms based on how the architect balanced the goals with the constraints and risks".

I have combined Lim's eighth and fourteenth principles in conjunction with Crawley's teachings and a risk I identified specific to complex dynamic systems to yield the following final principle.

5. Balanced External Forces Principle by Lim, Crawley and Ahlman

Descriptive: Balanced external forces are absent of extremes and embody the necessary compromises.

Prescriptive: Balance the system goals and constraints against inherent risk in the system architecture. Start by identifying the goals, constraints and potential risks. With regard to risk, choose an architecture that enables one to predict its behavior and corresponding emergent properties. This is especially crucial for complex dynamic systems that often exhibit counterintuitive behavior.

This principle could be combined with the "Balanced Architecture" principle above, but decided to leave them separate for clarity. Ultimately, both principles are utilized to achieve a balanced architecture. Examples of goals and constraints for a complex dynamic system are typically numerous but require little explanation. Instead the following focuses on an aspect of risk that is key to architecture decisions, especially for complex dynamic systems.

A major element of risk in complex dynamic system architecture is one's inability to accurately predict the systems true behavior and emergent properties. As highlighted in the introduction and reiterated here, fundamental dynamics issues encountered in the verification phase of the product development process often require change to architecture. Changes in architecture at this phase have significant cost, timing and perhaps functional performance implications. The cost and timing implications result from the large number of elements of the design that may be affected if architecture rework is required, and the impact on tooling for components, which is often in process or complete by this stage. Overall system functional performance may be compromised due to an inability to rework the entire architecture, so compromises made in interfacing subsystems to achieve synergy may no longer be valid.

Therefore, the architect(s) must balance the risk regarding emergent property prediction versus the system constraints and goals. For sure a firm's core competencies and analytical tools must be factored in this decision. For example, OEM-A's gasoline engine architecture of recent history is comprised of inline four or six cylinders and V-6, V-8 or V-10 cylinder configurations. Porsche, on the other hand has a long history of horizontally opposed (flat) four and six cylinder engine architectures. The two companies exhibit different core competencies with regard to engine configurations, which exhibit different dynamics to some degree and resultant strength and weaknesses. For arguments sake, say OEM-A completes some upfront analysis that identifies the flat-six engine architecture may be superior for achieving the system functional performance goals for a particular application. Do they attempt the flat six or stay with an inline or V-6? OEM-A may ultimately choose to stick with an inline or V-6 because the above noted risks to cost, timing and reliability may be too great due to increased potential of unidentified emergent properties prior to the verification phase.

This concludes the five system architecting principles for application in this thesis. This list of architecting principles is not all-inclusive, but it does cover a good range, with some overlap between them. For example, principles one, two, three and five above heavily feed or impact the fourth principle, "synergy". As briefly discussed in section 1.2, the principles are intended as the first and highest level of direct evaluation of an architecture in CD-SAAM. The principles provide a more specific focus for assessment an architecture. However, deficiency with respect to a particular principle does not necessarily mean the architecture is deficient. Ultimately, the architecture that provides the greatest level of synergy with respect to the system's influences and goals is best.

2.5 Quality Functional Deployment (QFD)

QFD methodology is chosen for its ability to transform a complicated collection of conflicting trends highlighted in the prior phases of CD-SAAM into an organized array with a ranking of each concept.

QFD analysis represents the third and final qualitative step in CD-SAAM. QFD is required when prior analysis demonstrates a considerable degree of conflicting trends with respect to the principles, especially synergy, which are difficult or impossible to reconcile by inspection. QFD is a relationship matrix, which aids requirements cascade and minimizes bias. It is a graphical technique that translates customer needs into the parameters or attributes of the product and its manufacturing and quality control processes. [Bop, Section 23, p.5] There are multiple levels of QFD shown below in Figure 12 as one works form customer requirements through manufacturing processes at the final level. The QFD product design matrix is the primary focus for the purposes of this thesis in which requirements (goals and constraints) are weighted on the left and architectural solutions are placed across the top.

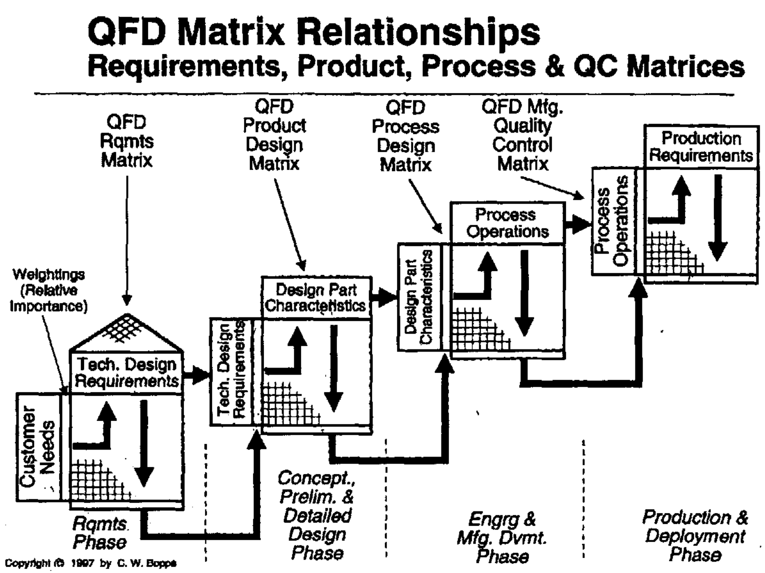


Figure 12: QFD Matrix Types and Relationships. [Bop, section 24, p. 1]

As shown, this is the second level in typical QFD analysis, after the customer needs and influences are utilized to create the constraints and goals used here. Next the engineers score the architectural concept's impact on the weighted goals and constraints of the system. Finally, each concept's score for its impact on each constraint or goal is multiplied by the weighting factor for the corresponding constraint and goal. The combined scores and weighting yields a final rank for each concept. Figure 13 demonstrates the basic layout and components of a QFD relationship matrix.

The importance weightings utilized is typically between one and ten, while the scoring within the relationship matrix are one, three or nine. A score of "1" means the concept provides the smallest positive impact on the constraint or goal while a "9" represents the greatest positive impact. The large separation of the three possible scores emphasizes differences in concepts and forces one to identify considerable gain or deficiency when scoring a concept. This process becomes clearer during its application in section 4.13.

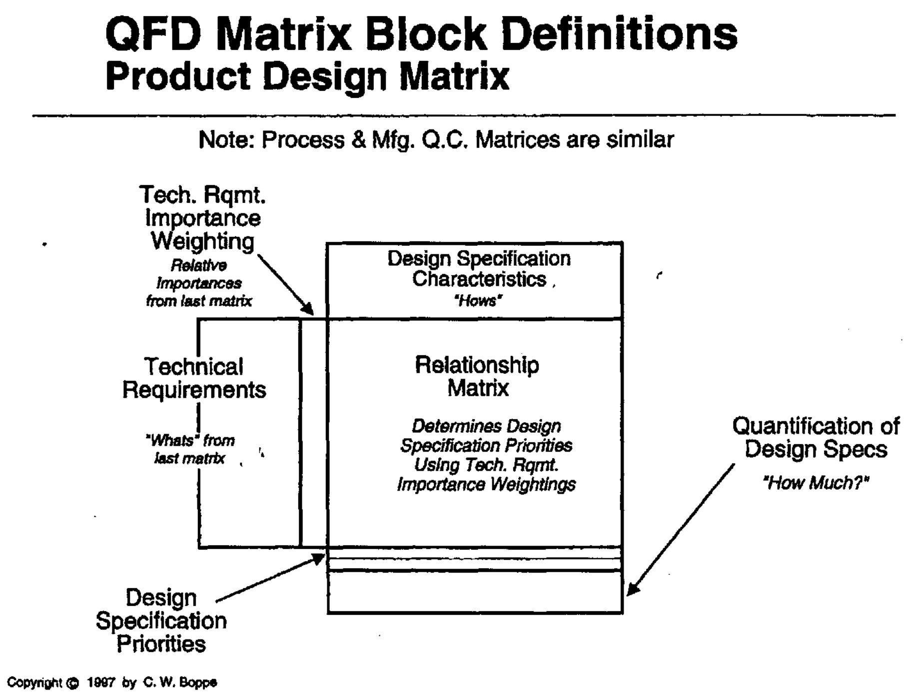


Figure 13: QFD Relationship Matrix Description. [Bop, section 24]

Further, it is the combination of constraints and goals weighting and concept ranking that aids in reducing bias often induced by pure intuition methods. Therefore, the QFD often aids in determining counter-intuitive solutions due to the high degree of interrelationships and needs to be balanced.

2.6 Design of Experiments (DOE)

As described earlier, DOE methodologies are chosen for their strength regarding quantification of dynamic system behavior. The final step in CD-SAAM involves quantitative DOE methodologies applied to parametric models. Parametric models represent behavior and interaction of subsystems, components and interfaces through singular parameters, lookup tables or polynomial curves. For example, engine performance characteristics are represented by a simple torque versus rpm curve as opposed to detailed powertrain models found in more specific component based models. It is this use of parameters to represent more detailed components and systems that make it a "parametric" model. The holistic nature of this analysis in CD-SAAM does not typically warrant the time and effort required to complete a similar DOE in more detailed component based models. Of course, one must understand and assess the fidelity and limitations of a model to insure the information desired is returned with appropriate accuracy. For example, the user of parametric models must take care in parameter setting to insure they do not represent physically infeasible solutions. Also, the use of more detailed models may be required if more simplified models do not provide the necessary confidence in results. In the end, all models may be viewed as "parametric", as they are abstractions of reality and utilize numerical relationships to represent the actual system. Some models just include more numerical relationships than others as well as potentially being more deterministic. The use of the term "parametric" primarily depends on one's perspective and intended use of the model. As an aside, application of DOE methodologies on physical systems through actual testing is feasible for this step in CD-SAAM. However, physical experimentation tends to be less reliable in many respects due to noise factors and far more time-consuming and expensive than analytical analysis on systems as complex as automobiles.

The DOE methodologies in CD-SAAM are focused on critical design parameters of the system architectures based on the prior qualitative analysis. DOE is a statistical based methodology employed to understand system parametric relationships to system responses (behaviors). DOE methods are most often applied in the product design and manufacturing quality control phases. However, DOE is just as powerful and applicable at the requirements and process design phase to determine "what" is important and not just the "how". DOE is applied to physical systems as well as analytical models and is the only mathematically rigorous tool applied in this thesis for complex dynamic system architecture evaluation. DOE methodologies provide true system understanding in the presence of interactions and noise, which the historical and typical "One-factor-at-a-time" methodology cannot. DOE can provide the following information for a system being analyzed:

- Relative importance of the factors (or sensitivities), degree of non-linearity in the responses, degree of interaction between factors through the resultant RSE coefficients
- Quick turn-around analysis and system optimization through the resultant RSE's
- Degree of "noise" in the experiment (if it is physical experimentation as opposed to analytical, which is void of noise)

DOE is included in CD-SAAM due to the significant degree of counterintuitive behavior of complex dynamic systems and enormous solution combinations to balance. DOE and resultant RSE analysis aids the ability to truly understand the system as well as find the global optimum as opposed to the innumerable local optimums of a complex dynamic system.

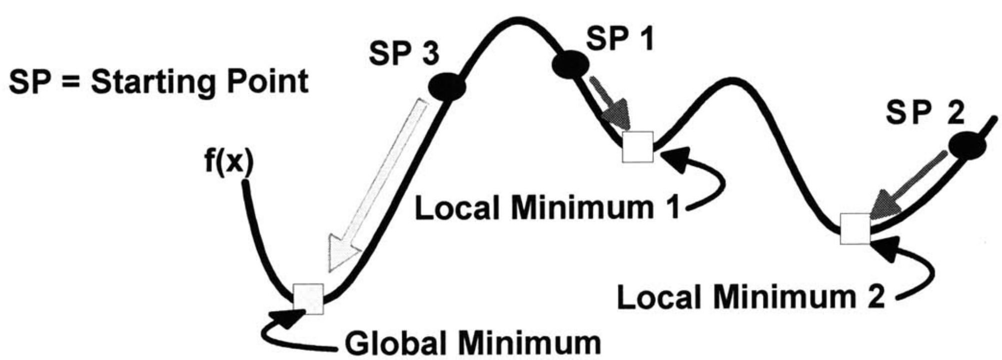


Figure 14: 2D Response Surface Slice Representation.

Figure 14 represents a simple 2D slice of a response surface for a function that requires minimization to achieve the optimum. The figure demonstrates two local optima and the one global. Typical one-factor-at-a-time testing/analysis is heavily dependent on the starting point for system analysis and rarely allows one to achieve the global optimum, unless they are fortunate enough to start at the correct portion of the design space, "SP3" for example. Otherwise, one-factor-at-a-time changes at "SP1" that would start heading in the correct direction to achieve the global optimum cause the system performance to worsen (maximize) prior to improving. This trend typically causes the engineer to quickly change direction and end up at the local minimum because they do not have a representation of the complex response surface provided by proper DOE analysis.

Additional detail and background for DOE is placed below, because it appears to be a lesser known and underutilized tool in educational and even many industrial circles. The two following references are an excellent place to start for those seeking more information about DOE and RSE than covered here. The first reference recommendation is called, " Design and Analysis of Experiments, 5th Edition" by Montgomery provides a good overview of the subject. [Mon] The second book recommendation is a classic DOE reference named "Statistics for Experimenters: An Introduction to Design, Data Analysis and Model Building". [Box]

Some key DOE Definitions follow:

Factors- Parameters changed during the experiment to understand their impact on the system include: components, subsystems and system responses/output.

Levels- Settings utilized for each parameter during the experiment. The settings can vary as follows:

- Minimum of two- low and high (yields linear relationships and interactions between factors)
- Three- low, medium (nominal) and high (yields linear relationships, interactions between factors and second order relationships)
- Mixing within an experiment may be utilized

Responses- System output(s), behavior(s)

Uncontrolled" Factors (noise)- Parameters, which may vary independently during the experiment and affect system response but are not controlled. This applies to physical experimenting only. For example:

- Environmental changes, people, conditions
- Function and time-related
- Part to part variation

Design Matrix- Defines the factor settings for each experiment run in which there are numerous design types. For example:

- Orthogonal arrays- main effects (base information, minimum runs)
- Fractional factorial (maximize information, minimize runs)- many types
- Full factorial (maximum information, maximum runs)

Table 1: Two Factor, Three Level Full Factorial Design Matrix Example.

Run	Factor A	Factor B
1	-1	-1
2	-1	0
3	-1	1
4	0	-1
5	0	0
6	0	1
7	1	-1
8	1	0
9	1	1

Where –1 = low setting, 0 = nominal setting and 1 = high setting for a factor

Response Surface Equations (RSE's)- Once the experiment is completed, the responses are regressed against the factor settings and the corresponding relationships are determined. The resultant response coefficient equation for first order effects (B1, B2), non-linearities (B4, B5) and first order interactions (B3), ignoring higher-level interactions takes on the following form for this example:

$$Y = B0 + B1 * X1 + B2 * X2 + B3 * (X1 * X2) + B4 * X1^2 + B5 * X2^2$$

Where the "B's" represent the regressed coefficients and the "X's" represent the normalized factor settings. This equation forms the basis of further analysis of the system. The magnitude of each of the regressed coefficients, for example, represents the importance of each term and is the foundation of sensitivity analysis.

This concludes the background summary of the framework, principles and tools utilized in CD-SAAM, which are applied to specific elements of Supercar-A for evaluation in Chapter Four and Five.

3 Overview of the System Utilized for CD-SAAM Application

3.1 Chapter 3 Scope and Objectives

Chapter Three introduces and provides pertinent background information on the complex dynamic system to which CD-SAAM is applied. This includes the specific high performance car whose architecture is evaluated as well background on its primary competitors. The background information includes vehicle form/function decomposition to the second level as well as numerous examples of concepts for the performance car system architecture. Chapter Three also covers a summary of Supercar-A's goals and constraints in addition to highlighting considerable challenges to meeting the system objectives. The chapter closes with final definition of the specific elements of Supercar-A's system architecture chosen for application of CD-SAAM.

3.2 Supercars Background

The high performance car chosen competes in a segment of vehicle often referred to in the industry as "supercars". As noted earlier in the introduction, for purposes of this thesis, the specific performance car for application is known as "Supercar-A". Supercar-A car is chosen due its complex dynamic nature, its all-new design and my high degree of familiarity with its system architecture, design and resultant challenges. I am one of the chassis system design engineers for the vehicle from start to finish.

There are three tiers of supercars and the Supercar-A competes in the third tier, which is comprised of vehicles up to $200,000. The second tier of supercar ranges from $200,000 to around $500,000 and includes vehicles like the new 2004 Porsche Carerra GT. The final and top tier of supercars are $500,000 and above with the McLaren F1 as a prime example. Pictured below is another prime example of a third tier supercar, the classic Porsche 911 Turbo.

Figure 15: 2003 Porsche 911 Turbo. Source: www3.porsche.com.

Supercars are known for their bias toward high performance. These cars are typically capable of 180 mph or greater top speeds and can reach 60 mph in less than five seconds with some approaching sub four second times. They also have phenomenal handling capabilities in which they can generate over one G of braking and cornering acceleration. Ultimately, supercars are best known for their overall vehicle dynamic performance. Cut the cornering accelerations by one third, braking deceleration in half, and nearly triple elapsed times for acceleration from 0 – 60 mph and you'll have a comparative capability to an average family sedan. Therefore, the supercar architecture tends to be heavily biased toward performance. Further the supercars tend to be dynamic works of art as displayed by the Porsche 911.

3.3 Automotive Architecture Decomposition

The modern automobile has five major systems at the first level of function/form decomposition. The five systems are shown in Figure 16.

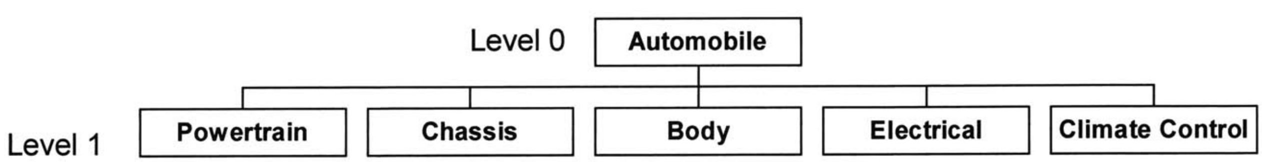


Figure 16: Automobile Function/Form Decomposition- Level 0 and 1.

Further decomposed in Figure 17 and Figure 18 are the two major systems of the vehicle, chassis and powertrain, which dominate the dynamic performance of the vehicle.

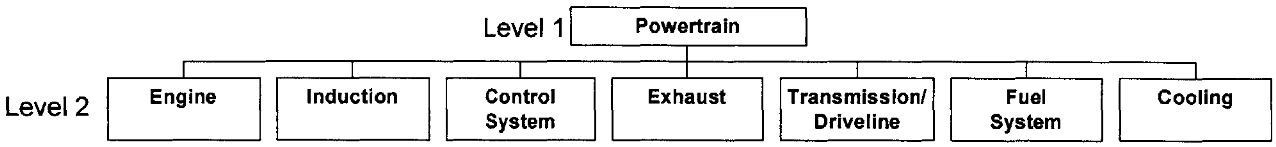


Figure 17: Automotive Powertrain System Function/Form Decomposition- Level 1 and 2.

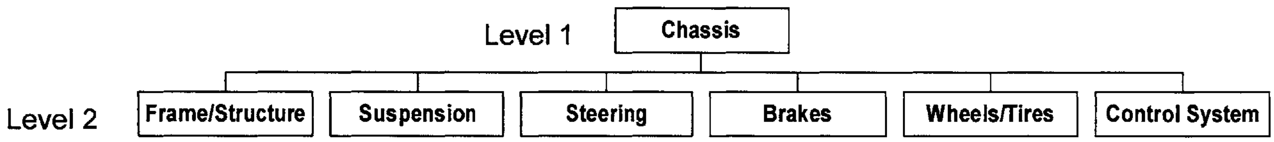


Figure 18: Automotive Chassis System Function/Form Decomposition- Level 1 and 2.

Arguably, some break these systems down differently, with more subsystems or different labels, but these decompositions represent the major systems for the full vehicle, chassis and powertrain, loosely based on the decomposition utilized by OEM-A. A cursory review of the chassis decomposition notes the inclusion of the apparently simple wheel and tire subsystem as a separate element of the decomposition. However, the wheel and tire assembly, especially the tire, exhibits extremely complicated dynamic behavior. In addition, the tire form ends up as one inseparable component, but is comprised of a complicated rubber compound, tread patterns, belt materials, belt orientation and so on. Finally, the wheel and tire assembly is analogous to the wing form on an airplane. The tire is the interface to the road, creating, transmitting and controlling all of the vehicle dynamic forces. Therefore, the wheel and tire system is paramount to the overall vehicle function and warrants separation from the others in the chassis system.

Written and graphical descriptions of representative architectures for the supercar, chassis and powertrain systems are found in the next section to give the reader a better feel for this class of vehicle. It also provides a strong representation of potential relevant system architecture options.

3.4 Supercar-A Competitors

The following covers four competitors within the same supercar tier as the Supercar-A. The competitors for the Supercar-A are fairly obvious based on this class of vehicle and historical competition. Further, the 2003 Ferrari 360 Modena is the Supercar-A program benchmark for ride and handling performance as well as overall vehicle attributes while the 2003 Dodge Viper is the straight-line performance benchmark. The 2003 Ferrari 360 Modena is simply called the 360 Modena from here onward while the 2003 Dodge Viper is labeled as Viper. The 2003 Porsche 911 Twin Turbo and the 2003 Acura NSX are the other two competitors chosen for architecture review as they have been past class leaders and still notable competitors in various aspects and represent alternative architectures for comparison. The 2003 Porsche 911 Twin Turbo is simply called the 911 Turbo from here onward while the 2003 Acura NSX is labeled as NSX. A summary of their high level architecture yields further understanding of the form of this class of vehicle. The tables below cover the major architectural elements for the overall vehicle, powertrain and chassis along with pictures of example architecture for each. Further architecture details are given for the systems analyzed in the application section of this thesis. Engine cooling, exhaust and fuel delivery systems are not included because there are fairly limited architecture options for these elements in the current supercar segment. There are options in material choices for exhaust (stainless versus titanium) and a variety of placement and combination of air to water and oil heat exchangers for engine cooling as examples. However, they are omitted due to more limited impact on system performance compared to the other systems listed. The following also does not list powertrain control systems for comparison due to difficulty in finding accurate information for the competitive systems. In addition, the following tables do not cover all aspects of architecture for each system, but they do highlight a majority of the primary elements for each. The data source for tables 2 through 11 is Supercar-A program data.

Table 2: Supercar Overall System Architecture Examples.

Architectural Element	2003 Ferrari 360 Modena	2003 Dodge Viper	2003 Porsche 911 Twin Turbo	2003 Acura NSX
Overall Vehicle				
Curb Weight (lbf)	3260	3357	3380	3164
Weight Dist. (% Front)	43/57	48/52	39/61	41/59
Wheelbase (in)	102.4	98.8	92.5	99.6
Track front/rear (in/in)	65.7/63.7	57.8/60.9	57.7/58.3	59.5/60.7
Length (in)	176.3	175.5	174.6	174.2
Width (in)	75.7	74.8	72	71.3
Height (in)	47.8	47.6	51	46.1
Ground clearance (in)	5.0	5.0	5.5	5.5
Shadow Area (ft^2)	92.7	91.2	82.4	86.3

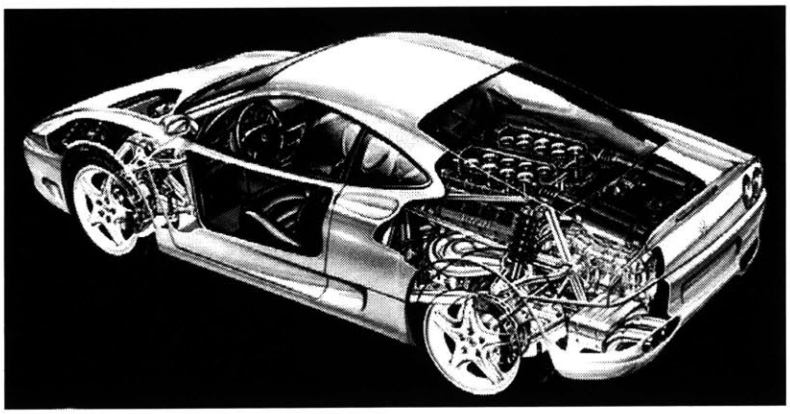


Figure 19: 2003 Ferrari 360 Modena- Overall Vehicle. Source: www.ferrari.com.

Table 3: Supercar Engine System Architecture Examples.

Architectural Element	2003 Ferrari 360 Modena	2003 Dodge Viper	2003 Porsche 911 Twin Turbo	2003 Acura NSX
Powertrain: Engine				
Location	Mid Engine (in front of rear axle)	Front Engine	Rear Engine (behind the rear axle)	Mid Engine (in front of rear axle)
Orientation	Fore-Aft (north-south)	Fore-Aft (north-south)	Fore-Aft (north-south)	Transverse (east-west)
Displacement (cc)	3600	8300	3600	3179
Configuration	90 deg V8	V10	Horizontally Opposed 6-cyl	V6
Valvetrain, type	Variable Valve Timing Quad OHC	OHV	Variable valve timing and lift, Quad OHC	Variable valve timing and lift, Dual OHC
Valvetrain, #	5 valves/cylinder	2 valves/cylinder	4 valves/cylinder	4 valves/cylinder
Block and Head Material	Aluminum	Aluminum	Aluminum	Aluminum
Lubrication	Dry Sump	Dry Sump	Dry Sump	Wet Sump
Max. Power (hp) / rpm	395/8500	500/NA	420/6000	290/7100
Max. Torque (lb-ft) / rpm	275/4750	500/NA	413/4500	224/5500
Redline (rpm)	8,500	6,000 (estimated)	7,200	8,000
Vehicle Weight: Power (lbf/bhp)	8.2	6.7	8.0	10.9
Specific Power (bhp/Liter)	110	60	117	91

Table 4: Supercar Induction System Architecture Examples.

Architectural Element	2003 Ferrari 360 Modena	2003 Dodge Viper	2003 Porsche 911 Twin Turbo	2003 Acura NSX
Powertrain: Induction				
Induction Type	Normally Aspirated	Normally Aspirated	Twin Turbo Charged with intercooler	Normally Aspirated

Table 5: Supercar Transmission/Driveline System Architecture Examples.

Architectural Element	2003 Ferrari 360 Modena	2003 Dodge Viper	2003 Porsche 911 Twin Turbo	2003 Acura NSX
Powertrain: Transmission/Driveline				
Type	Manual Transaxle (integral differential)	Manual Transmission	Manual Transaxle (integral differential)	Manual Transaxle (integral differential)
In Vehicle Gear Set Orientation	Longitudinal (north-south)	Longitudinal (north-south)	Longitudinal (north-south)	Transverse (east-west)
Speeds	6	6	6	6
Case/Structure Material	Aluminum	Aluminum	Aluminum	Aluminum
Drive	RWD	RWD	4WD	RWD
Traction Control System	Traction Control System through ETC	NA	Traction Control System through ETC	Traction Control System through ETC

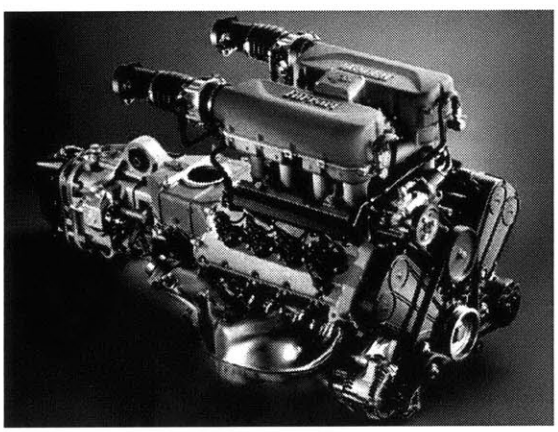


Figure 20: 2003 Ferrari 360 Modena Engine and Transmission (Transaxle). Source: www.ferrari.com.

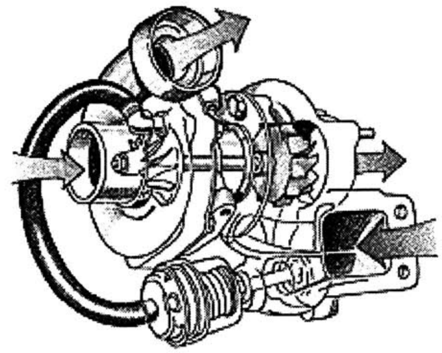


Figure 21: Generic Turbo Cutaway.

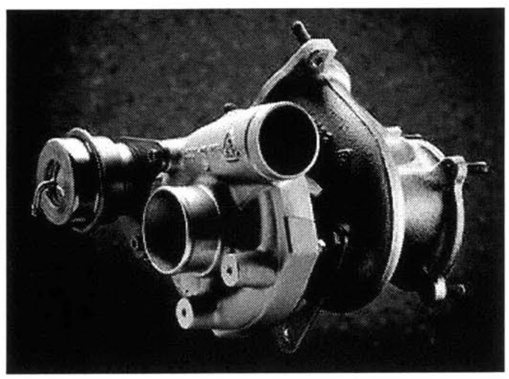


Figure 22: Single 2003 Porsche 911 Turbo Charger. Source: www3.porsche.com.

Table 6: Supercar Frame System Architecture Examples.

Architectural Element	2003 Ferrari 360 Modena	2003 Dodge Viper	2003 Porsche 911 Twin Turbo	2003 Acura NSX
Chassis- Frame				
Primary structure type	Hybrid space frame featuring extruded tubular construction with cast nodes and limited shear panels	Tubular space frame with limited shear panels	Stamped Shear Panels (Body-Frame-Integrated)	Stamped Shear Panels (Body-Frame-Integrated)
Primary structure material	Aluminum	Steel	Steel	Aluminum
Suspension Interface Type	Cast aluminum nodes with machined mounts	Clevis tabs welded to Tubular members	Rubber isolated aluminum subframe	Rubber isolated forged aluminum subframe
Primary load carrying member placement	Rockers/roof cant rails/tunnel	Primarily tunnel and rockers	Rockers/roof cant rails/tunnel	Rockers/roof cant rails/tunnel
Joint Type	MIG Welded extrusion to extrusion and extrusion to cast node	MIG Welded tube to tube	MIG Welded shear panel to shear panel	MIG Welded shear panel to shear panel

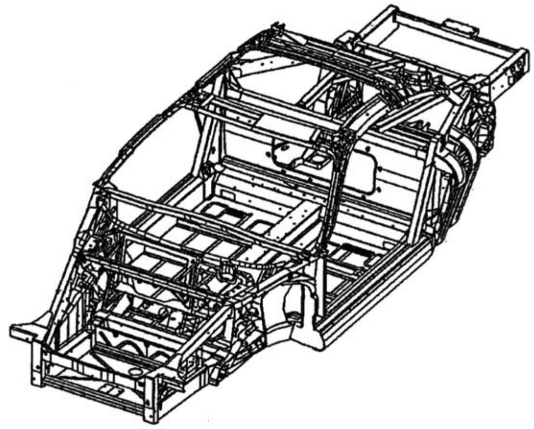


Figure 23: Ferrari 360 Modena Frame. [Nov]

Table 7: Supercar Suspension System Architecture Examples.

Architectural Element	2003 Ferrari 360 Modena	2003 Dodge Viper	2003 Porsche 911 Twin Turbo	2003 Acura NSX
Chassis- Suspension				
Front Suspension Configuration	Independent, Unequal length, Double A-Arm	Independent, Unequal length, Double A-Arm	Independent, McPherson strut	Independent, Unequal length, Double A-Arm
Rear Suspension Configuration	Independent, Unequal length, Double A-Arm	Independent, Unequal length, Double A-Arm	Independent, Multi-Link	Independent, Unequal length, Double A-Arm
Control Arm Material	Cast Aluminum	Cast Aluminum	Cast Aluminum	Forged Aluminum
Frame Interface Type	Bar Pin Style Slippery Bushings bolted to machined mounts	Standard Clevis Style Grippy Bushings bolted to frame clevis	Front-Puck style bushings, Rear-Clevis Style Bushings both bolted to rubber isolated subframe	Multi-piece rotating subframe at the front.
Front Damper/Spring Configuration	Outboard coil-over spring/semi-active damper	Outboard coil-over spring/ damper	McPherson strut	Outboard coil-over spring/damper,
Rear Damper/Spring Configuration	Outboard coil-over spring/semi-active damper	Outboard coil-over spring/ damper	Outboard coil-over spring/ damper	Outboard coil-over spring/damper,
Front/rear anti-rollbar configuration	Standard torsion anti-rollbar	Standard torsion anti-rollbar	Standard torsion anti-rollbar	Standard torsion anti-rollbar attached

Table 8: Supercar Dynamic Control System Architecture Examples.

Architectural Element	2003 Ferrari 360 Modena	2003 Dodge Viper	2003 Porsche 911 Twin Turbo	2003 Acura NSX
Chassis: Dynamic Control System				
Yaw/Stability Control System Type	Stability Control through ABS system and sensors	N/A	Stability Control through ABS system and sensors	N/A

Table 9: Supercar Brake System Architecture Examples.

Architectural Element	2003 Ferrari 360 Modena	2003 Dodge Viper	2003 Porsche 911 Twin Turbo	2003 Acura NSX
Chassis: Brakes				
Caliper Type	Fixed Radial Mount- 4 Piston Aluminum Mono-block	Fixed Radial Mount- 4 Piston Aluminum Mono-block	Fixed Radial Mount- 4 Piston Aluminum Mono-block	Floating axial mount cast iron two piece
Front Rotor Size/Type	13" x 1.1" Internally Vented & Cross-drilled	14" Internally Vented & Cross-drilled	12.5" Internally Vented & Cross-drilled	11.7" Internally Vented & Cross-drilled
Rear Rotor Size/Type	13" x 1.1" Internally Vented & Cross-drilled	14" Internally Vented & Cross-drilled	11.8" Internally Vented & Cross-drilled	11.9" Non-vented
Rotor Material	Cast Iron	Cast Iron	Cast Iron	Cast Iron
Power Assist	Vacuum boost and ABS with EBD	Vacuum boost and ABS with EBD	Vacuum boost and ABS with EBD	Vacuum boost and ABS with EBD

Table 10: Supercar Steering System Architecture Examples.

Architectural Element	2003 Ferrari 360 Modena	2003 Dodge Viper	2003 Porsche 911 Twin Turbo	2003 Acura NSX
Chassis: Steering				
Actuation Type	Rack and Pinion	Rack and Pinion	Rack and Pinion	Rack and Pinion
Rack Position	Front of axle	Front of axle	Front of axle	Rear of axle
Assist Type	Hydraulic	Hydraulic	Hydraulic	Electric

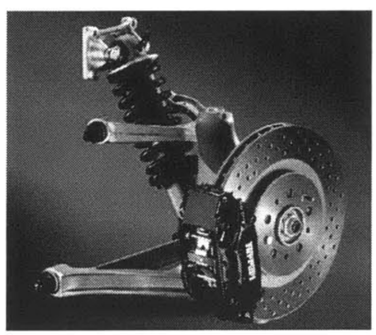


Figure 24: 2003 Ferrari 360 Modena Right Front Suspension and Foundation Brakes. Source: www.ferrari.com.

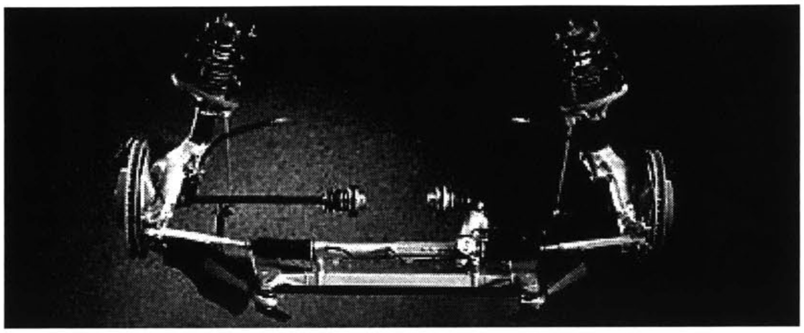


Figure 25: 2003 Porsche 911 Twin Turbo Front Suspension, Subframe, Steering and Foundation Brakes. Source: www3.porsche.com.

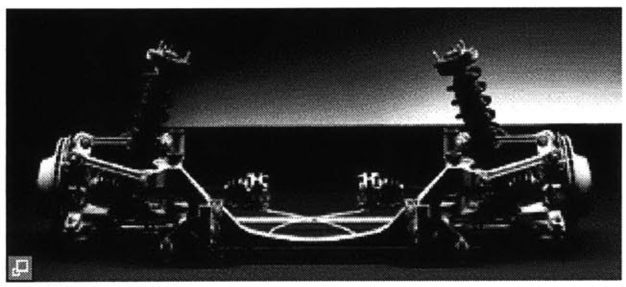


Figure 26: 2003 Porsche 911 Twin Turbo Rear Suspension, Subframe and Foundation Brakes. Source: www3.porsche.com.

Table 11: Supercar Wheels and Tire System Architecture Examples.

Architectural Element	2003 Ferrari 360 Modena	2003 Dodge Viper	2003 Porsche 911 Twin Turbo	2003 Acura NSX
Chassis- Wheels and Tires				
Front Wheel Size	7.5" x 18"	11" x 18"	8" x 18"	7" x 17"
Rear Wheel Size	9.5" x 18"	14" x 19"	11" x 18"	8.5" x 17"
Wheel Material	Cast Aluminum	Forged Aluminum	Cast Aluminum-Hollow Spokes	Forged Aluminum
Front Tire Size	215/45ZR18	305/35ZR18	225/40ZR18	215/40ZR17
Rear Tire Size	275/40ZR18	345/30ZR19	295/30ZR18	255/40ZR17

Figure 27: 2003 Ferrari 360 Modena Front Wheel and Tire. Source: www.ferrari.com.

Figure 28: 2003 Porsche 911 Turbo Wheel and Tire. Source: www3.porsche.com.

One notes a fair degree of similarities between vehicles, but at the same time some significant differences in some of the large subsystems. Note the range of engine configurations, locations, orientation and displacement listed in Table 3; all have a significant effect on vehicle weight distribution, for example.

The two benchmarks and numerous architecture examples above provide a good lead in to the following discussion on the Supercar-A system constraints and goals. The constraints and goals provide the primary metrics to assess the architectural decisions of the system.

3.5 Supercar-A System Goal Statement, Constraints, Live or Die and Other Goals

Prior to covering the Supercar-A constraints and goals it makes sense to list a primary assumption about the goals as applied in this thesis. System architecture assessment application in this thesis assumes that the stated system goals address the customer needs. This thesis does not cover or complete customer needs analysis to insure the goals address customer needs. It is beyond the intended scope.

Ideally system goals are clear, complete, consistent and attainable (humanly solvable within constraints) prior to system architecture creation. The entire Supercar-A program team was well aware of the major elements including the ride and handling and overall vehicle benchmark (360

Modena) as well as the straight-line acceleration benchmark (Viper). The team also knew the program mantra "Looks good, handles great, goes fast". However, some believed the team would benefit from a more explicit System Goal Statement and clear, consistent and attainable Live or Die Goals. Therefore, a few team members worked to generate and communicate an explicit System Goal Statement, Constraints, Live or Die Goals and Other Goals. The Supercar-A System Goal Statement, Constraints, Live or Die Goals and Other Goals were created from the following information:

- Program Mantra- "Looks good, goes fast, handles great!"
- Two stated competitive vehicle benchmarks
- Functional attribute targets
- Supercar-A racing heritage
- Documented program strategy, vision, target customer, program rationale

Crawley's System Architecture Influences Framework was also utilized as a guide to insure the upstream and downstream influences were properly captured. A system goal statement consists of three elements, which are as follows:

Intent + Process + Metric [Cr1]

Using the above three elements, the team developed the following System Goal Statement:

Supercar-A System Goal Statement

"Provide the undisputed performance leader in the two seat tier three supercar segment to customers from 200X – 200Y by creating the best balance of attribute performance, image, quality and refinement in an OEM-A vehicle that provides XXX Shareholder Value Added (SVA) and symbolizes our engineering excellence."

The *intent* of the Supercar-A program is: "Provide the undisputed performance leader in the two seat tier three supercar segment to customers from 200X – 200Y".

The *process* to achieve the intent is: "by creating the best balance of attribute performance, image, quality and refinement in a OEM-A vehicle"

The *metrics* are: "provides XXX SVA and symbolizes our engineering excellence"

One notes that the Supercar-A team combined vehicle attributes and corporate metrics in this statement, which is not ideal, but appeared to convey the message to the team and serve as guidance for the more detailed goals statements.

Next, the Supercar-A program team worked to list the known program constraints. Constraints are objectives, which must be met. There is no gray area. Supercar-A Program constraints are located below in Table 12.

Table 12: Supercar-A Constraints.

Federal Regulations
• Meet all federally regulated standards (US only)
  ○ Safety
  ○ Emissions

Timing • Three production level vehicles complete and functional X months from program inception • Full production begins ~2X months from program inception
Shareholder Value Added (SVA) ≥ XXX
Quality/Reliability • Designed for 10 year life cycle, defined as: The product must consistently perform its "Ideal Function" over the Useful Life Period, in spite of effects from the following Noise Factors; Piece-to-Piece variation, Product Changes (wear, fatigue), Customer Usage and Duty Cycle, External Environment, System Interactions with adjacent components. • Adhere to OEM-A quality and vehicle level design standards except where infeasible for vehicles in this class (Example- ground clearance issues with OEM-A railroad crossing event in structural durability).
Functional Attributes Performance • Achieve acceptable (competitive) subjective levels of all top level functional attributes listed in "Other Goals" or otherwise not noted explicitly
Assembly • X vehicle/day build capability
Technology Strategy • Utilize only known, proven technologies. (Proven in industry, not necessarily at OEM-A)
Maintainability • Vehicle must be serviceable at current OEM-A dealerships • Vehicle must not require service tools outside of the current dealership inventory

Many would only characterize the federal regulations as true constraints. However, the rest of the constraints listed were truly viewed and approached as constraints. For example, vehicle programs' at OEM-A must prove the ability to achieve financial targets at a certain point within the product development process. If the program cannot adequately demonstrate an ability to meet financial targets it is cancelled. Further, quality/reliability and minimum functional attribute performance are non-negotiable as well. Finally, the Supercar-A program was special in its extremely tight timing constraints. This specific vehicle program is analogous to professional motorsports. The race takes place, regardless of whether or not all competitors are ready. The Supercar-A program was identical in this respect with at least one specific delivery date set, without ability to change.

Next, the team created and ranked Live or Die Goals based on the same information utilized for the System Goal Statement. These goals had to be consistent with the System Goal Statement. Live or Die Goals are objectives, which if missed, have the potential to cause the program to fail with respect to the higher-level System Goal. At the same time, the Live or Die Goals are ranked, such that when tradeoff decisions are required, the team biases their decision and resource toward the higher ranked goal. Note that the Live or Die Goals and Other Goals contain primarily performance related functional attributes. Table 13 below lists the Supercar-A Live or Die Goals with their absolute rank, weighting factor for QFD analysis and example metrics for each goal. These are example metrics and are not all-inclusive. The specific metric values have been removed due to proprietary considerations.

Table 13: Supercar-A Live or Die Goals.

Rank	QFD Weighting	Live or Die Goal
1	10	**Overall Vehicle Dynamic Performance**
2	9	**Handling** • Transient o Brake in Turn Yaw Gain <= XX o Frequency Response >= XX o 600 ft slalom >= XX mph • Steady State o 200 ft Skid Pad >= XX G • Overall o Subjectively >= XX point (on a 1-10 scale) better than 360 Modena

Rank	QFD Weighting	Live or Die Goal
3	9	**Straight-line Acceleration Performance** • 0-60 mph <= XX sec • 0-100 mph <= XX sec • ¼ mile time <= XX sec • ¼ mile speed >= XX mph
4	9	**Aesthetic (showroom) Appeal- Supercar-A Concept** • Maintain the integrity of the Supercar-A Concept exterior
5	8	**Braking Performance** • 60 – 0 mph <= XX ft • 100- 0 mph <= XX ft • AMS (fade) <= XX ft
6	8	**Steering Performance** • Phase lag <=XX msec • Steering Wheel Torque vs Yaw Gain Linearity • Subjectively = 360 Modena
7	8	**Craftsmanship** • Subjectively >= 360 Modena
8	7	**Exhaust Tone/Note** • Clean 4^{th} Order w/ minimal SC effect- 4^{th} order "American V8" sound. • Subjectively = 360 Modena Appeal
9	7	**Drivability** • Linear, intuitive relationship between throttle input to acceleration output- good in all gears • Balanced synchro force/clutch load
10	7	**Shift Quality** • Upshifts <XX Ns Synchronization Impulse • Cross gate force <XX N • Cross gate travel <XX mm • Subjectively = NSX
11	6	**Primary Ride (vertical input dominated events <=wheel-hop frequency)** • Subjectively = 360 Modena
12	6	**Seating Package** • Fits 95^{th} percentile male • Straight-ahead steering wheel and pedal package

One quickly notes a significant overlap of goals when reviewing the above list. The Supercar-A Live or Die Goals are primarily vehicle dynamic related, with the top goal stated as overall vehicle dynamic performance. Overall vehicle dynamic performance actually encompasses handling, straight-line acceleration, braking, steering, drivability, shift quality and primary ride performance. Each is a separate element of the overall vehicle dynamic performance. This apparent redundancy was included because the Supercar-A team was aware that there are multiple performance (and architecture) combinations that can achieve the overall vehicle dynamic performance goal. For example, the overall vehicle dynamic performance goal can be achieved with overwhelming straight-line acceleration performance with reduced handling performance. The explicit statements of the various vehicle dynamic elements emphasize the desired balance of attributes to achieve the overall vehicle dynamic performance.

Last, the team compiled and ranked the list of other notable goals, intended to aid tradeoff decisions as they arise. Table 15 contains the list and metrics for the Supercar-A's Other Goals.

Table 14: Supercar-A Other Goals.

Rank	QFD Weighting	Other Goals
13	5	**Powertrain NVH** • Subjectively = XX points (on a 1-10 scale) lower than 360 Modena
14	5	**Wind NVH** • Subjectively = 360 Modena
15	4	**Secondary Ride (impact harshness, event frequencies > wheelhop)** • Subjectively = 360 Modena
16	4	**Road NVH** • Subjectively = 360 Modena
17	2	**Vehicle Range** • Range >=250 highway

The Supercar-A architecture is assessed against the above constraints and goals during application of CD-SAAM.

3.6 Highlighted Constraints and Challenges for the Supercar-A Program

There are a few notable constraints for the Supercar-A program team that deserve additional attention, due to their considerable impact on the vehicle architecture decisions.

Design from the Outside In

Note the fourth "Live or Die Goal" which states the need to maintain integrity of the Supercar-A Concept exterior. The Supercar-A Concept was a show car, designed mainly by the design studio, with some engineering input with respect to possible powertrain and occupant package. Therefore, the concept was primarily an exterior shell with very limited dynamic function. The Supercar-A

Concept was shown at the North America International Auto show and the public loved what they saw. The OEM-A management did as well and wanted it built, without perceptible change to the concept exterior. Basically, maintain the integrity of the concept shown. This included maintaining the wheel and tire diameters, for example. This presented an additional challenge to the Supercar-A design team when they were finally brought together to bring the car from an exterior concept to reality, starting six months later.

Timing Constraints

The Supercar-A was a "Greenfield" project in that it was an all new chassis and powertrain. It was not based on any prior OEM-A platform, because none existed that would remotely meet the goals of this system, especially one that would fit in the Supercar-A concept shell. This meant that the vehicle design was of the highest level of chassis and powertrain complexity at OEM-A.

At the same time, the Supercar-A program team was tasked with designing and producing three production level vehicles for a special event, within in one-third the typical time to complete production vehicle level design and development. This event was the Supercar-A program's "race". The date was inflexible. Further, the timing required the start of full production within about one-half of the normal time allotted for OEM-A vehicle programs of similar complexity. Note the compression of the Supercar-A timeline below in Figure 29 and the fact that the compression is heavily biased toward the front end, where the architectural decisions and detailed designs are completed. The standard timeline was compressed by a factor of six in this crucial first stage! Note the typical pre-program phase at the beginning of the standard timing was completely eliminated for Supercar-A. This pre-program phase typically involves system architecture definition, which was not fully characterized in many respects. This forced many quick decisions regarding architecture definition.

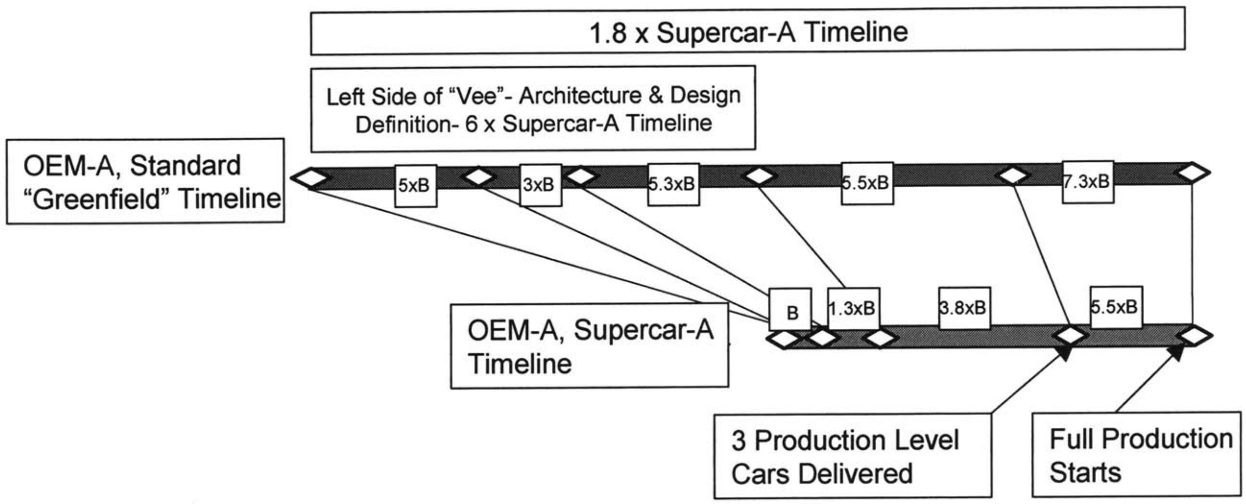


Figure 29: Supercar-A Timeline versus Standard OEM-A "Greenfield" Timeline.

Budget Constraints

The above constraints do not include a specific budget constraint, but the Supercar-A design and development had to stay within an extremely low budget for this ground up vehicle. The budget wasn't necessarily mandated by OEM-A executives, but instead required to meet the SVA goal due to the low volume nature of the Supercar-A. Therefore, many architecture decisions were heavily biased toward minimizing investment costs; often trading it off against increased variable cost options.

Personnel

The Supercar-A program was also tasked with maintaining an extremely low personnel headcount to complete this vehicle. For example, chassis design and release, my function, only had a supervisor and three engineers to lead the design for the entire chassis system. Normally, there would have been 12 or more engineers leading their suppliers for chassis design and release on a program of this complexity. The number of personnel for chassis design and release may be the worst-case example on Supercar-A, but the rest of the team was similarly tasked. At the same time, the limited number of people aided a "singular vision" approach for each system as opposed to design by committee. It also can reduce the amount of communication required.

The combination of the personnel, budget and timing challenges certainly played a large role in all decision-making. It is worth keeping this in mind during the application of CD-SAAM and assessment of the Supercar-A system architecture.

3.7 Supercar-A Architectural Elements for Evaluation

The following cover the specific systems evaluated for Supercar-A. The first and second level system architecture decompositions of the Supercar-A are elements for evaluation with the exception of the systems noted in the following paragraphs. While proper assessment of CD-SAAM requires direct application to a complex dynamic system, it does not warrant or benefit from analysis of the entire system, only key elements. Therefore, electrical and climate control architecture have been omitted from this analysis because of either limited architectural options and/or limited impact on the system goals. The limited impact on system goals is highlighted by the fact that the majority of the goals are heavily biased toward dynamic performance. Also, one of the primary body elements, the exterior for example, was heavily restricted by the goal to maintain the Supercar-A Concept theme without noticeable change. Arguably, plenty of changes to the underside architecture could be made to aid aerodynamic performance, which is quite important on a vehicle of this nature. However, the number of underbody shape option combinations in elements like splitters, air dams, venturis, diffusers, spoilers, etc. is countless. While the system architecture impact on aerodynamic performance, as related to vehicle dynamics, is covered to a small degree in the next two chapters, the body architecture is not explicitly assessed in order to maintain a reasonable scope. This leaves the Supercar-A powertrain and chassis systems for analysis as shown in Figure 30.

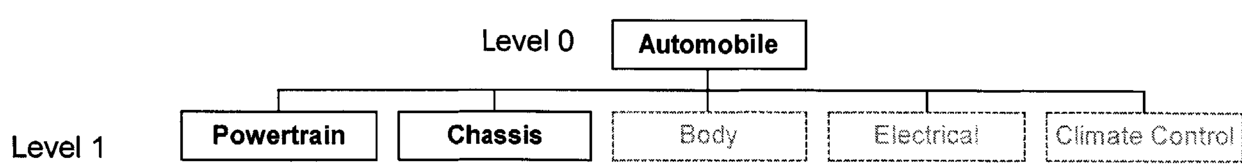


Figure 30: Supercar-A System Architecture for Evaluation: Chassis and Powertrain Systems, excluding Body, Electrical and Climate Control Systems.

The scope is narrowed further within these systems and a few of the powertrain and chassis second level subsystems are eliminated from the analysis. The system elimination reasoning falls into three general categories: limited architectural options, limited impact on Live or Die Goals and/or the need to narrow scope.

The following systems have been removed for the Supercar-A System Architecture Assessment with more detailed reasoning:

- Chassis
  - Steering System removed from analysis due to the following:
    - Electric vs. hydraulic assist as well as rack position are the primary architectural choices for this system. These options potentially affected cost, weight and weight distribution, but to a minor degree in comparison to the systems chosen for analysis.
  - Brake System removed from analysis due to the following:
    - Rotor sizing, venting and material are the primary architectural choices for this system. However, vehicle mass and braking targets narrow the rotor sizing and venting options greatly. More options are present for vehicles exhibiting a greater range of potential vehicle mass and weight distribution. Further, carbon or ceramic rotors are the only alternative to cast iron, but were not chosen for Supercar-A due to the fact that the carbon and ceramic technology is not completely proven in the industry yet. Therefore, carbon or ceramic rotors could not meet the program's technology strategy restrictions.
  - Vehicle Dynamic Control System removed from analysis due to the following:
    - OEM-A's policy with respect to vehicle dynamic control systems mandates acceptable behavior of the vehicle if the system fails. Typically, tuning of the full chassis system to provide performance gains with the control system yields unacceptable behavior during failed system events.

Therefore, the countless vehicle dynamic control system options have limited impact on the Supercar-A's performance related goals. Further, the control system adds complexity, cost and weight without the intended performance gain. This leaves the Supercar-A chassis systems shown in Figure 31 for architectural assessment.

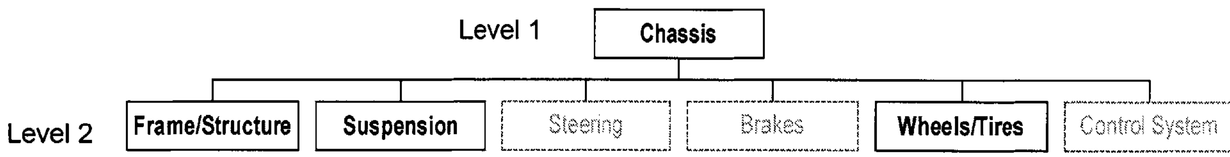


Figure 31: Supercar-A Chassis System Architecture for Evaluation: Frame/Structure, Suspension and Wheels/Tires excluding the Steering, Brakes and Control System.

- Powertrain
  - Cooling System removed from analysis due to the following:
    - The primary options include air over water and oil heat exchangers versus strictly air cooled as utilized in the prior generations of Porsche 911's. However, OEM-A's powertrain options all require water-cooled systems and cooling system size corresponds to the powertrain chosen. A further architectural option is heat exchanger placement, which affects weight distribution and mass, but its impact on the system goals and constraints is limited in comparison to the other major system choices.
  - Exhaust System removed from analysis due to the following:
    - Header type (cast iron versus fabricated steel), exhaust material (stainless steel versus titanium) and muffler type and placement were all architectural decisions that surely impacted weight, weight distribution and cost. Again, their influence on the system goals and constraints is limited in comparison to other major systems.
  - Fuel Delivery System removed from analysis due to the following:
    - Fuel tank placement, for example, certainly plays a role in overall package options on vehicle weight distribution, however, its placement and shape is

somewhat a function of the rest of the vehicle architecture. The number of injectors, placement and type are also architecture decisions, but again has a somewhat limited impact on the system goals and constraints in comparison to the other systems chosen for analysis.

This leaves the Supercar-A powertrain systems shown in Figure 32 for architectural assessment.

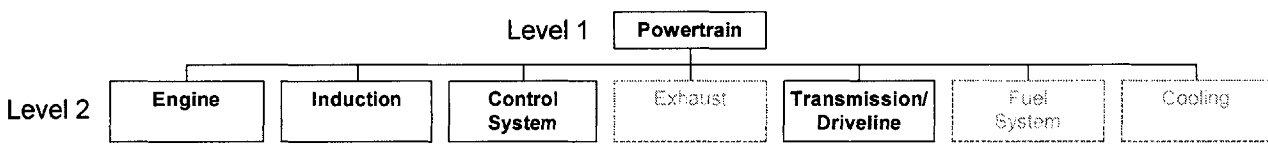


Figure 32: Supercar-A Powertrain System Architecture for Evaluation: Engine, Induction, Transmission and Driveline excluding the Exhaust, Fuel and Cooling Systems.

This completes the background summary of Supercar-A, competitive supercar architectures as well as the specific powertrain and chassis systems to which CD-SAAM is applied as shown in Figure 31 and Figure 32.

4 Qualitative Analysis of the Supercar-A System Architecture

4.1 Chapter 4 Scope and Objectives

The prior work in this thesis leads to the actual application of the proposed methodology, CD-SAAM. This chapter covers the qualitative analysis application of CD-SAAM to the above stated Supercar-A system architecture. The qualitative analysis includes the first three phases depicted in Figure 33 including: upstream and downstream influences identification, functional requirements cascade through concept mapping, five system architecture principles application and QFD analysis.

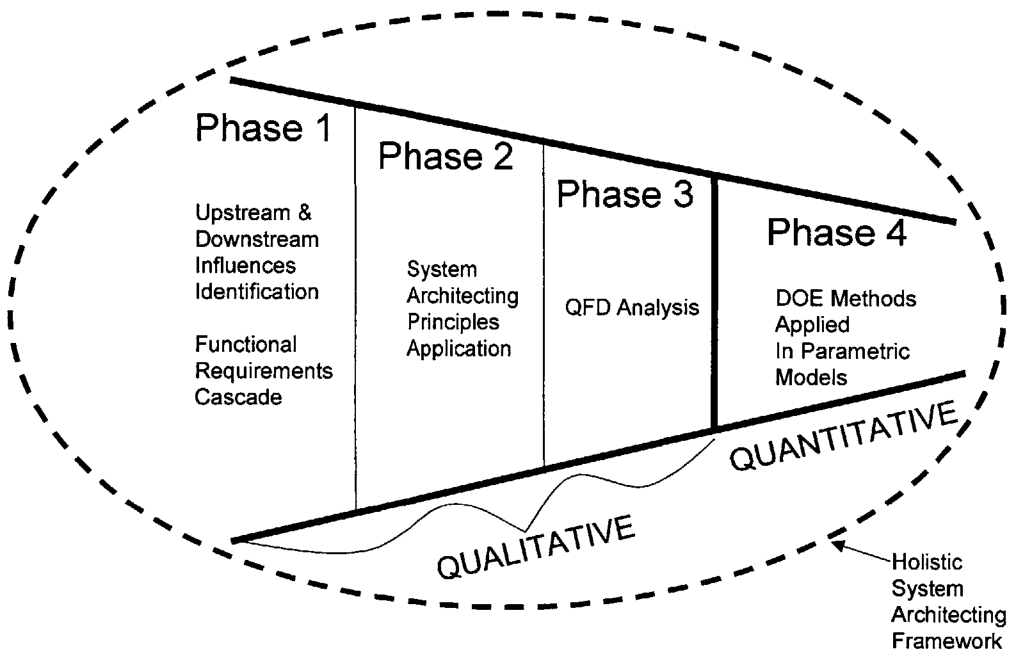


Figure 33: CD-SAAM Framework.

The upstream and downstream influences are directly mapped to the system goals and constraints introduced in Chapter Three. The functional requirements cascade through concept mapping applies new usage of design parameters at this level of system architecture analysis. The five system architecture principles application represents the first true architecture assessment step in CD-SAAM, which is somewhat lengthy as it represents the highest, most coarse level of direct analysis. Completion of the principles narrows the focus of system architecture elements for assessment and leads to the QFD analysis, which is the final qualitative phase.

As covered and summarized in Chapter Three, the overall architecture from a full-vehicle size/dimension standpoint as well as multiple subsystems for the Supercar-A powertrain and chassis system architecture are chosen for the following evaluation.

4.2 Upstream and Downstream Influences Identification

The first two tools in the first phase, upstream and downstream influence identification and functional requirements cascade through concept mapping, in conjunction with the system architecture framework, primarily create the foundation for the architecture assessment. While the first phase is not explicitly utilized to evaluate the architecture in the following, it does facilitate the achievement of holistic and consistent goals as well as serve as an initial concept filter. While not covered here, certain architecture options do not make sense for a high performance vehicle in the Supercar segment, based on the stated goals and requirements. An obvious example includes elimination of a very small displacement four-cylinder engine for the powertrain. The four-cylinder engine would be very light, aiding handling performance, for example, but certainly not achieve straight-line acceleration and overall track performance goals.

The first step in the hierarchal qualitative and quantitative approach to complex dynamic system architecture assessment involves identification of all of the upstream and downstream influences exhibited in Crawley's system architecture framework. The elements of this framework encompass the entire hierarchal process, providing guidance to insure all of the attributes are appropriately accounted for in each step. Actually, the majority of upstream and downstream influences identification is already complete in the form of the Supercar-A constraints and goals shown in section 3.5. Crawley's framework was utilized to insure the constraints and goals captured all relevant influences. The Supercar-A constraints and goals in concise form, without metrics, are placed in Tables 16-18 for quick reference. These tables also include relevant influences next to each constraint or goal.

Table 15: Supercar-A Constraints Mapped to Upstream and Downstream Influences.

Constraints	Upstream and/or Downstream Influence(s)
Meet federal regulations	Regulation
Meet three production level vehicle build and full production timing	Corporate, marketing, PD strategy
Meet Shareholder Value Added target	Corporate strategy
Meet quality/reliability requirements	All upstream influences feeding the goals and functional requirements- reliability based
Meet minimum functional attributes performance for other goals or those unlisted	Customers needs and competitive environment feeding functional requirements- performance based
Meet production cycle time requirements	Operations strategy and implementation (Design for manufacture and assembly)
Utilize only known, industry proven technologies	Technology strategy
Meet maintainability requirements	All upstream influences feeding the goals and functional requirements- maintainability based

Table 16: Supercar-A Live or Die Goals Mapped to Upstream and Downstream Influences.

Live or Die Goals	Upstream and/or Downstream Influence(s)
Meet overall vehicle dynamic performance targets	All upstream influences feeding the goals and functional requirements- performance based
Meet handling performance targets	All upstream influences feeding the goals and functional requirements- performance based
Meet straight-line acceleration performance targets	All upstream influences feeding the goals and functional requirements- performance based
Maintain Supercar-A Concept integrity	Corporate, marketing, PD strategy, competitive environment, customers needs
Meet braking performance targets	All upstream influences feeding the goals and functional requirements- performance based
Meet steering performance targets	All upstream influences feeding the goals and functional requirements- performance based
Meet craftsmanship targets	All upstream influences feeding the goals and functional requirements- performance based
Meet exhaust tone/note performance targets	All upstream influences feeding the goals and functional requirements- performance based
Meet drivability performance targets	All upstream influences feeding the goals and functional requirements- performance based
Meet shift quality performance targets	All upstream influences feeding the goals and functional requirements- performance based
Meet primary ride performance targets	All upstream influences feeding the goals and functional requirements- performance based
Meet seating package targets	Corporate, marketing, PD strategy, competitive environment, customers needs

Table 17: Supercar-A Other Goals Mapped to Upstream and Downstream Influences.

Other Goals	Upstream and/or Downstream Influence(s)
Meet powertrain NVH targets	All upstream influences feeding the goals and functional requirements- performance based
Meet wind NVH targets	All upstream influences feeding the goals and functional requirements- performance based
Meet secondary ride targets	All upstream influences feeding the goals and functional requirements- performance based
Meet road NVH targets	All upstream influences feeding the goals and functional requirements- performance based
Meet vehicle range targets	All upstream influences feeding the goals and functional requirements- performance based

The only two major influences not explicitly captured in Supercar-A constraints and goals is the concept of operational sequence and evolution. The operational sequence aspect is covered in the following Concept Mapping section. Evolution of Supercar-A was not explicitly discussed or addressed for this vehicle.

4.3 High level Vehicle Dynamics Fundamentals Background

The nature of the Supercar and the above goals highlight the importance of vehicle dynamic performance for these vehicles. The following vehicle dynamic fundamentals as related to vehicle systems is the bare minimum to fill a potential knowledge void on this topic that would block one's ability to make reasonable sense of the following architecture analysis. This brief section is not meant to cover the vast topic of vehicle dynamics and the related chassis system details in any great depth. It only attempts to cover the highest level, most important fundamentals, sometimes in layperson's terminology as opposed to specific chassis system terminology. However, a few equations are presented to prove the importance of certain design parameters. Volumes upon volumes of text exist on this complex subject in the form of SAE papers and excellent books like Milliken and Milliken's *Race Car Vehicle Dynamics* for anyone interested in further detail or clarification. [Mil]

Milliken and Milliken's definition of vehicle dynamics is used for the purposes of this paper and is as follows:

> *"Vehicle dynamics, as we use the term, is the branch of engineering which relates tire and aerodynamic forces to overall vehicle accelerations, velocities and motions, using Newton's Laws of Motion. It encompasses the behavior of the vehicle as affected by driveline, tires, aerodynamics and chassis characteristics. The subject is a complex one because of the large number of variables involved."* [Mil]

An example of a typical vehicle global coordinate system is placed in Figure 34 for reference throughout the paper. The following summary focuses primarily on the vehicle's vertical, lateral and yaw degree of freedom. This global coordinate system applies to local coordinate systems for all components.

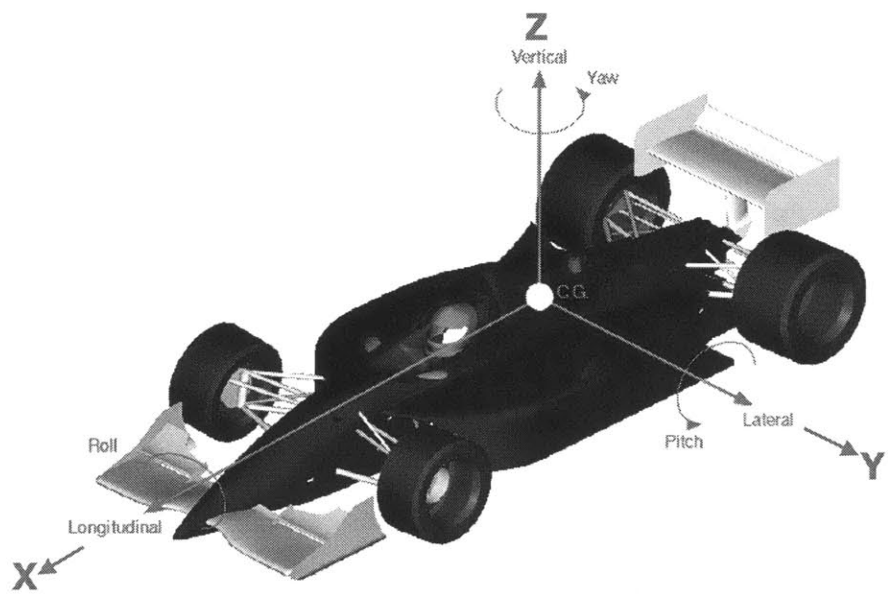


Figure 34: ISO Vehicle Coordinate System.

At a very fundamental level, the vehicle dynamicists and chassis systems engineers work to create and control the described vehicle dynamics through generation and control of the three axis forces and moments at the four tire contact patch (CP) interfaces with the road. Tire dynamics or its three-axis force and moment behavior is a non-linear function of the following four elements:

1. Vertical load on the tire
2. Camber angle (the tire's front view vertical angle with respect to a plane normal to the road surface)
3. Tire lateral slip or slip angle (the angle between the trajectory and heading of the wheel/tire combination in a plane parallel to the road surface at the contact patch)
4. Tire longitudinal slip or slip ratio (the percent difference between the tangential tire contact patch velocity relative to the road velocity)

The following focuses on the vertical loading aspect above and its impact on tire behavior and vehicle dynamics. Tire force and moment testing and resultant data demonstrate that its dynamic behavior becomes more non-linear with increased vertical loading. Further, a tire doesn't achieve instantaneous changes in lateral and longitudinal force capability as loading changes, which increases its non-linear behavior. An increase in a tire's non-linear behavior results in less consistent vehicle dynamic performance. Reduced consistency in vehicle dynamic behavior creates increased effort for the driver to control the system and the resultant vehicle heading and trajectory during dynamic events. The driver requires some degree of sensitivity to their inputs to make corrections during limit handling, but not so much that the "workload" is beyond the driver's capability. Additionally, the tire's non-linear behavior increase with vertical loading tends to reduce the tire's "efficiency" or coefficient of friction, which in turn reduces the vehicle's ultimate cornering capability. Therefore, vehicle dynamicists and chassis systems engineers of high performance automobiles work to minimize the static and dynamic vertical tire loading in order to achieve the best vehicle dynamic performance for the car/driver system.

The following list covers the primary contributors to static and dynamic vertical tire loading during a vehicle-cornering event:

1. Static vertical load at each tire (overall vehicle weight and its center of gravity fore-aft and left-right location).

2. Weight transfer during cornering. For example, a left hand turn transfers weight from the left side of the vehicle to the right side, decreasing the vertical loading on the left side tires with a corresponding increase to the right side vertical loading.
3. Aerodynamic drag and lift properties of the vehicle. Aerodynamic properties can vary as the vehicles attitude and height with respect to ground varies. Changes in the vehicle attitude and ride height may affect the total drag, total lift and the lift center of pressure (CofP). The CofP defines the percentage of aerodynamic lift acting on the front axle versus the rear axle.
4. Bumps in the road surface and resultant dynamic response of the vehicle masses.

"Static" load is straightforward but weight transfer is more specific to vehicle dynamics. The following equations demonstrate the total lateral weight transfer calculations for cornering events and the similar equation for total longitudinal weight transfer during accelerating and braking events:

$$\text{Total Lateral Weight Transfer (lbf)} = (w * Ay * CGz) / t$$

$$\text{Total Longitudinal Weight Transfer (lbf)} = (w * Ax * CGz) / L$$

Where:

w = vehicle weight (lbf)

Ax = longitudinal acceleration (G's)

Ay = lateral acceleration (G's)

CGz = center of gravity (CG) height (in)

L = wheelbase (in)

t = track width (in)

Note, other than lateral and longitudinal acceleration, these are fundamental parameters of an automobile and it is straightforward to understand their impact on weight transfer based on the equations above.

Understanding the automobile attributes and interactions that impact its aerodynamic performance is a far more complicated discussion that is beyond the scope of this thesis. In a similar vain, ride dynamics for a vehicle and resultant equations for this highly coupled system are also beyond this papers scope other than mentioning the fact that a vehicles ride dynamics are a function of the following:

1. The vehicles sprung and unsprung masses
2. Sprung and unsprung mass interconnection stiffnesses
3. Sprung and unsprung mass interconnection damping

Unsprung mass is the vehicle mass that is not supported by a vehicle's suspension system springs. This typically includes tires, wheels, brake rotors, brake calipers, hubs, knuckles and portions of the control arms and spring damper system. Sprung mass is the rest of the vehicle mass, which is supported by the suspension system springs.

While interconnection stiffness and damping are certainly affected by system architecture decisions, they are often more a function of tunable items like springs and dampers. Mass, however, is not typically tunable and is a direct by product of the vehicle system architecture. Generally, reductions in mass, especially unsprung improve ride dynamics, specifically the wheel/tire assembly's ability to follow road surface imperfections. The greater the unsprung mass, the greater its inertia and tendency to continue in the direction accelerated. Increased unsprung mass, for example, yields multiple negative aspects, including increased vertical tire load variation, which is undesirable as described above.

Finally, it is worthwhile completing a very brief discussion on the basic vehicle yaw dynamics in addition to the importance of vertical tire loading dynamics mentioned above. There are three fundamental equations describing a vehicle's inherent yaw natural frequency, yaw damping and linear range understeer gradient. A vehicle's yaw natural frequency dominates its dynamic yaw response to steering input, which combined with the vehicle's yaw damping, affects the level of driver effort required to control its heading and trajectory. This impact on driver effort and resultant cornering performance is coupled with the performance impact of the vertical tire loading discussed above.

For the most part, increased yaw natural frequency and damping reduces the driver's effort for vehicle control and leads to improved performance. This is due to increased vehicle bandwidth yielding reduced lag between the driver input and vehicle response. A vehicle with a very low yaw natural frequency results in too much lag in the system, imprecise and non-linear response to driver input, resulting in high effort to control the vehicle during limit handling. This results in reduced performance. Once again, note the basic vehicle design parameters included in the yaw natural frequency and damping equations. The cornering stiffness terms are primarily a function of the tire architecture and design in high performance vehicles of this nature. Lateral compliance steer in the suspension system plays a far smaller role as its stiffness exceeds the tire stiffness by a large margin for vehicles of this nature.

Yaw Natural Frequency (Hz) =

$$(((Cf * Cr * L^2) / (m^2 * k^2 * v^2)) + ((a * Cf - b * Cr) / (m * k^2)))^{1/2} / 2 * PI$$

Yaw Damping Ratio = $((m * (a^2 * Cf + b^2 * Cr) + m * k^2 * (Cf + Cr)) / (m^2 * k^2 * v)) / (2 * Wn)$

Where:

Cf = front axle cornering stiffness (lbf/rad)

Cr = rear axle cornering stiffness (lbf/rad)

L = wheelbase (ft)

m = vehicle mass (slugs)

k = radius of gyration (ft)

a = longitudinal distance from the front axle to the CG (ft)

b = longitudinal distance from the rear axle to the CG (ft)

v = vehicle speed (ft/s)

Wn = yaw natural frequency (Hz)

Vehicle "balance" also plays a role in driver effort required for vehicle control during limit handling events. The following two terms are used to describe the balance of a vehicle during dynamic events. In simplest terms, *understeer* is used to describe a vehicle that tends to lose cornering potential at the front axle before the rear (i.e. "plow out"). *Oversteer* is used to describe the opposite condition where the rear axle loses cornering potential before the front (i.e. "spin out"). [Chr, chapter 2, p. 14] *Neutral steer* is the "panacea" of vehicle balance for high performance driving yielding a four-wheel drift through a corner, maximizing use of all four tires. However, true neutral steer is a rare condition and often transitions to oversteer quickly with driver interaction. A graphic representation of these three described levels of vehicle balance and resultant path at the limit of capability is shown in Figure 35. Note the resultant front wheel angles.

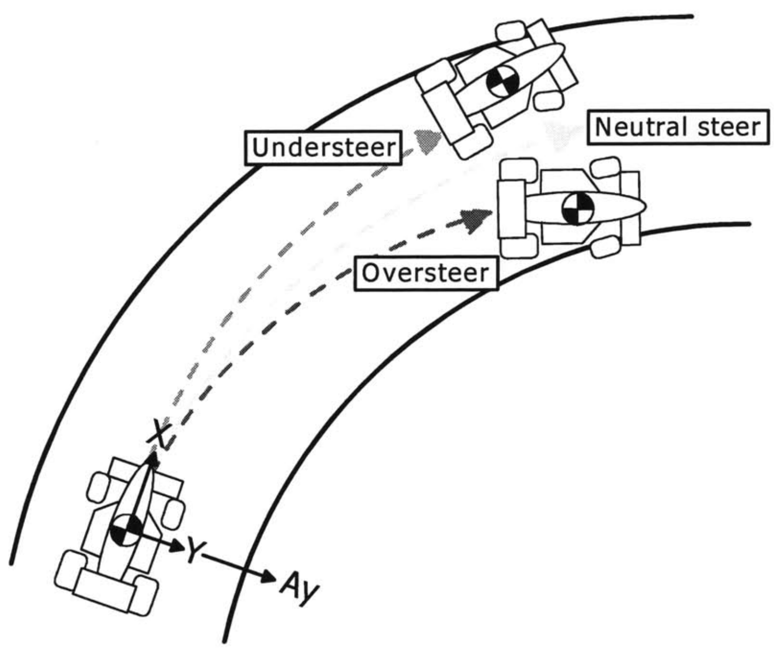


Figure 35: Vehicle "Balance" Depiction: Understeer, Oversteer and Neutral Steer Path on a Constant Radius Turn.

Understeer is preferred for passenger cars and some degree of it for even racecars. An understeering vehicle exhibits a higher yaw natural frequency, less lag, than an oversteering vehicle. The understeering vehicle yields dynamic behavior that typically requires less driver effort to control as the vehicle also provides a stable response to disturbances, whether driver induced or otherwise. At the same time, too much understeer does not allow the driver to maximize the use of all four tires' capability, which leads to reduced cornering performance. The following simplified equation represents sub-limit, linear range understeer. One could use it to calculate an estimate of the understeer level at the limit, but the cornering stiffness terms require more dynamic information than typically available at this level of analysis. However, this equation does serve to demonstrate the importance of front and rear vertical axle loading, whether static or dynamic.

Understeer Gradient or Bundorf's Cornering Compliance (deg/G) = 180/PI * (Wf / Cf – Wr / Cr)

Where:

Wf = front axle vertical load (lbf)

Wr = rear axle vertical load (lbf)

While this short section on vehicle dynamics fundamentals is far from inclusive, even at a high level, it serves to demonstrate many of the important vehicle parameters that impact its dynamic performance. The following sections on concept mapping, principles and QFD application utilize these vehicle parameters and impact on dynamic behavior extensively.

4.4 Supercar Functional Requirements Cascade- Concept Mapping

Prior to architecture assessment, it is advantageous to complete functional requirements cascade through concept mapping. A functional requirements cascade in a solution neutral format gives the architect a good set of "metrics" to evaluate the system architecture against. As shown in section 2.3, Crawley's Concept Mapping framework has been chosen for this process. This framework is again shown in Figure 34 to ease comparison of the mapping completed below for two of Supercar-A's Live or Die Goals.

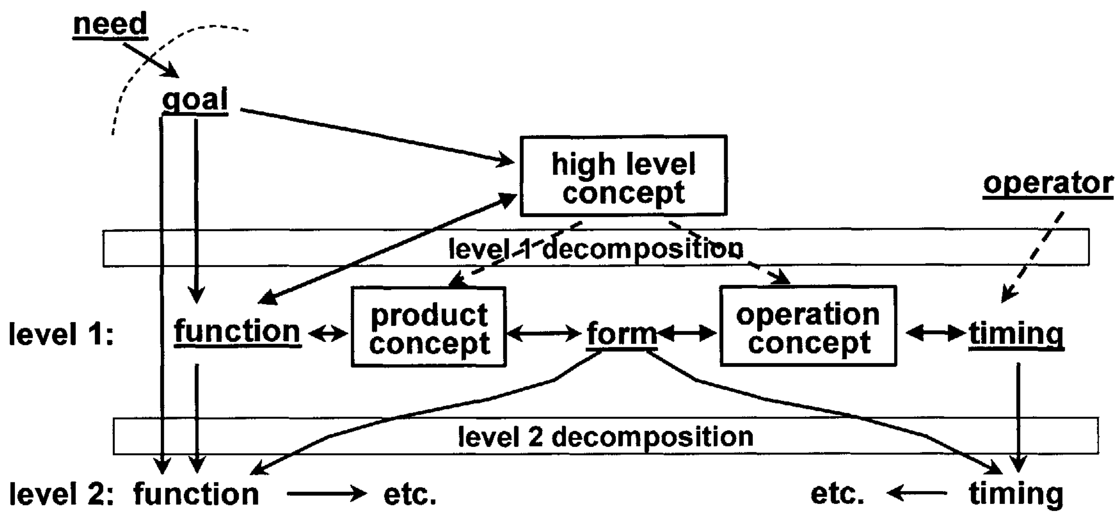


Figure 36: Crawley's Concept Mapping Framework. [Cr1, lecture 4, p. 33]

As noted earlier, overall vehicle dynamic performance (the number one Live or Die Goal) encompasses many of the lower ranked goals; therefore, two of its major components are mapped, which can have conflicting requirements. Handling and steering dynamics goals are mapped together first, as they are very closely linked and then straight-line acceleration concepts second. These two are especially significant in the case of Supercar-A because all of the handling targets are a function of the 360 Modena performance, while the straight-line acceleration targets are based on the Viper. These are two very different vehicles, with different compromises that are highlighted in Tables 2 – 11 in Chapter Three and further depicted in the following analysis.

The highest level design parameters that affected handling performance were listed prior to working on the following concept mapping. This list is based on the above discussed and additional vehicle dynamic fundamentals. A similar list was actually completed for overall vehicle dynamics while working on Supercar-A chassis system design. This list was intended to remind the chassis system design team about the important attributes to keep at the forefront of subsystem and component design decisions.

Handling Dynamics High level Design Parameters and typical units of measure include:

- Vehicle Mass- Sprung and Unsprung (lbm)
- Vehicle Center of Gravity (CG) Three Axis Position- CGx, Cgy, CGz (in)
- Vehicle Three Axis Polar Moments of Inertia (I)- Sprung and Unsprung Mass- Ixx, Iyy, Izz (lbf-ft-s^2)
- Track Width- Front and Rear (in)
- Wheelbase (in)
- Aerodynamics- Lift and Drag (lbf) and Center of Pressure (%) versus vehicle ride height (in)
- Tire Three Axis Force (lbf) and Moment (lbf-in) Properties versus Slip Angle (deg), Slip Ratio (%), Load, Camber (deg)
- Steering Wheel Torque (lbf-in) versus Lateral Acceleration (G's) and Yaw Gain (deg/s)
- Damping- Sprung and Unsprung Mass Three Axis Translation and Rotation (lbf-s/in)
- Suspension Compliance- Unsprung Mass Three Axis Translation Stiffness (lbf/in) and Rotation Stiffness (lbf/deg)
- Suspension Kinematics- Unsprung Mass Three Axis Translation (in/in) and Rotation (deg/in, deg/deg)
- Suspension Friction Between the Sprung and Unsprung Masses (lbf)

These parameters are meant to be at the highest level, solution neutral and often encompass many aspects of a concept. In this case and as applied in this thesis, they are the resultant and important design parameters, which result from the combination of all systems' form/function decomposition at the levels below the level of interest. In this case, handling dynamics are affected by the entire system. For example, suspension compliance noted above is affected by frame torsional and bending stiffness, local frame mount stiffness, control arm bushing stiffness, spring stiffness, etc. By specifying these parameters in a solution neutral way, the design engineer is free to choose a torsion spring versus coil spring as the actual concept-form to achieve the desired vertical suspension stiffness at the full system level, for example.

Completion of the following concept mapping (and prior research to determine the best method for functional requirements cascade) highlighted the fact that there did not seem to be an explicit method to include these parameters at this high level. Nam Suh's Axiomatic Design methodology utilizes explicit functional requirement to design parameter mapping, but it is intended to be a one to one relationship to maintain functional independence. This method is extremely cumbersome and it is difficult to find a complex dynamic system in which true functional independence can be maintained. Review of the fundamental vehicle dynamics equations and resultant parameters in section 4.3 serve to highlight this fact. Further, it appears some or many of these design parameters are not explicitly addressed until lower levels (third and fourth level) of concept-form decomposition so the architect does not directly address them. Often, it appears architects, of even complex dynamic systems like automobiles, think about these parameters at a very abstract level, or in an intuitive sense, but they do not address them explicitly, as appears necessary. Therefore, the relevant design parameters have been placed within the concept map at the level, which seemed the most appropriate. See Figure 37 and Figure 38 below for the steering/cornering dynamics and straight-line acceleration concept mapping respectively.

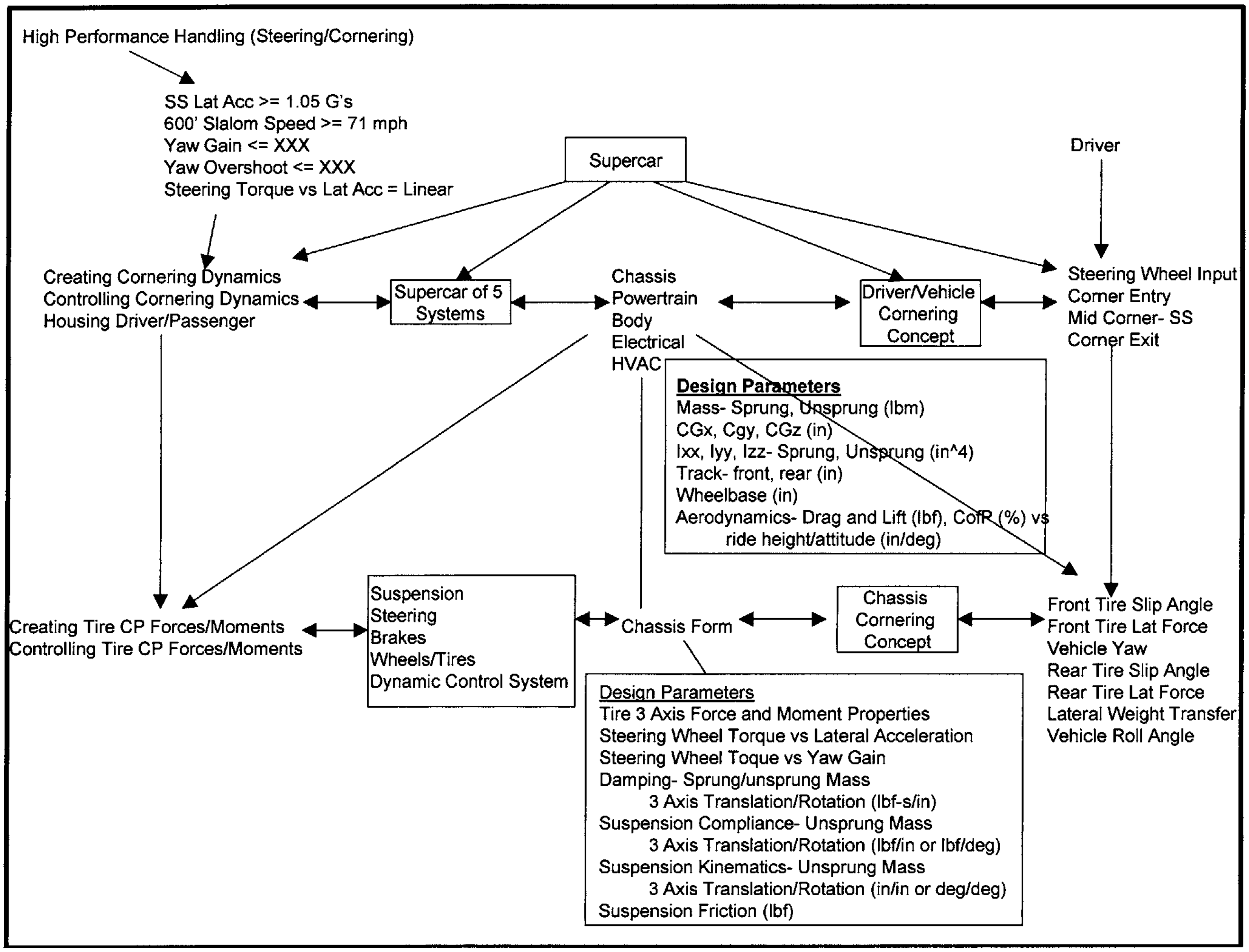


Figure 37: Supercar Steering/Cornering Dynamics Concept Mapping with Relevant Design Parameters Listing.

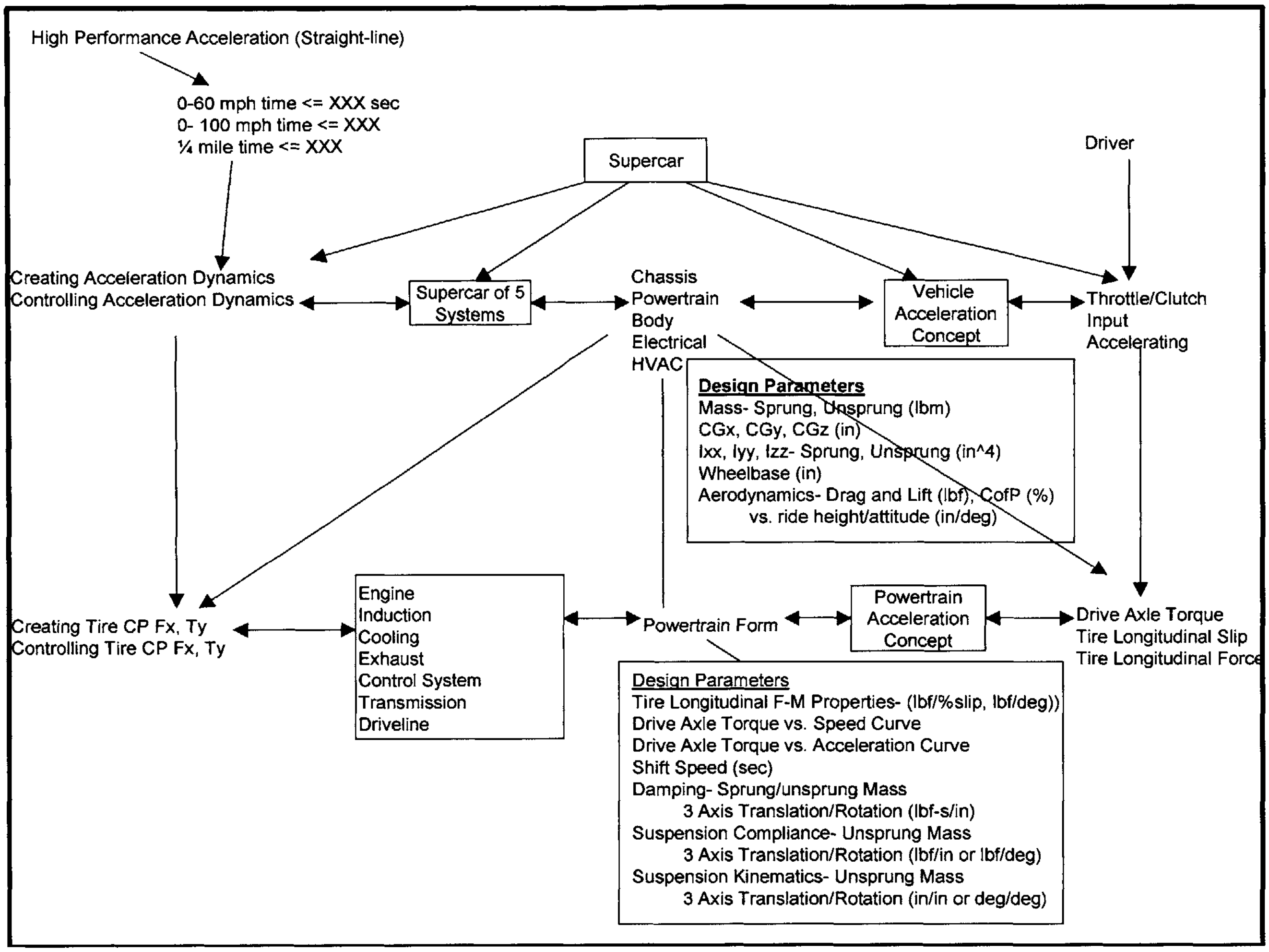


Figure 38: Supercar Straight-line Acceleration Dynamics Concept Mapping with Relevant Design Parameters Listing.

The above design parameters are listed in a rank order from most important to least based on experience and knowledge of the fundamental equations. However, a true ranking and understanding of the system and resultant interactions is better served through more a detailed DOE on parametric models. The results (relative importance of each parameter) can vary depending upon the allowable range for each of the parameters and the particular dynamic event.

Quick inspection of the design parameters in Figure 37 and Figure 38 for these two aspects of the overall vehicle dynamic performance identifies a considerable degree of overlap, as one might expect. Design parameters in similar concept mapping for braking performance, primary and secondary ride also would show considerable overlap, highlighting the importance of these parameters during architecture and detailed design decisions. Ideally, one completes a similar functional requirements cascade through concept mapping for all of the high level functional requirements. The above concept maps for vehicle cornering and straight-line acceleration requirements cascade and resultant design parameters are used in the following sections for the Supercar-A system architecture assessment.

4.5 Application of System Architecture Principles for the Supercar-A Architecture

The system architecting principles described in section 2.4 are used to evaluate the systems identified in Figures 35 and 36. The five major principles identified for application are as follows:

1. Minimize Complexity
2. Form, Function and Laws of Physics Union (known as "Form and Function Union" from here forward)
3. Balanced Architecture
4. Synergy
5. Balanced External Forces

Application of these five system architecture principles signals the start of explicit architecture evaluation process in this methodology. As a reminder, the principles application serves to complete final assessment on some aspects of the architecture, while highlighting the need for additional, more focused analysis in others.

The qualitative nature of the following principles application and QFD steps for architecture evaluations warrants the use of a classic architecting and design process focused principle. This process-focused principle is stated as follows: "Input by many, design by few". "Input by many," describes the use of information and influence from many perspectives, as opposed to a singular one. Multiple perspectives include professional, life experience, gender, age and so on. The "design by few" portion, however, describes the necessity for only a few to complete the final architecture and design, to maintain a singular holistic vision. The following principles and QFD application certainly embodies analysis from a singular vision, my own, but does not necessarily encompass the desired range of perspectives. While my background cuts across many disciplines in automotive engineering, my perspective is certainly different than the powertrain systems engineers, for example. However, I did spend considerable time interviewing and discussing the engine/induction system and transmission/driveline systems with Supercar-A and non-Supercar-A powertrain design and development engineers. Their perspective is represented heavily in the application of "Balanced External Forces" principle for the powertrain systems assessment as well as the challenges presented in development of a new powertrain. In addition, recall of our actual discussions and decisions during Supercar-A's chassis system architecture determination is also called upon. Ultimately, the qualitative nature of this analysis, even grounded in the basic laws of physics, leaves plenty of room for interpretation during system architecture assessment. The following application of principles and QFD for evaluation of the Supercar-A architecture is not intended as the final authority, but instead a strong example for future use of CD-SAAM. Therefore, the principles analysis is not all-inclusive.

The primary goal of the following application is meant to assess the merits of CD-SAAM, while evaluation of the Supercar-A system architecture is secondary. The analysis highlights some of the more obvious strengths and weaknesses and aspects expected to have a noticeable impact on the system constraints and goals. However, my experience contains a considerable void with respect to the Federal Regulations and corresponding safety, emissions and CAFÉ (Corporate Average Fuel Economy) elements. Consequently, the following analysis does not directly address the Federal Regulations constraints.

The following application, which does highlight some potential for improvement regarding Supercar-A's system architecture, is not meant to slight the extreme efforts put forth by the Supercar-A program team. The entire team's performance and results to date has far exceeded outsiders' expectations, not including the very difficult constraints, most notably timing, highlighted in section 3.7. Further, one of the seemingly "simple" systems I lead in chassis design of Supercar-A demonstrates a fair degree of potential for improvement.

Evaluation against the principles requires some degree of direct comparison to alternatives. The comparisons are heavily utilized for application of the synergy principle and a lesser degree to the rest. Comparison of specific examples of architectures does pose a potential challenge with respect to evaluating an overall concept versus the specific execution of an architecture. One's implementation of a concept may add complexity or hurt the marriage of form and function that may be superior otherwise. This aspect is kept in mind in the following analysis.

At this stage, the primary comparisons are made to the two chosen benchmarks for Supercar-A. However, there are some aspects of the architecture, which have their options narrowed to a large extent due to core competency, timing and resource considerations. This consideration then limits comparison to the benchmarks for some aspects of the architecture and is discussed in portions of the following sections.

Although the following principles application to the Supercar system architecture in sections 4.6 to 4.12 is abbreviated in potential scope, it still remains extremely long. This is partially due to the need for additional explanation of background and reasoning for particular assessments, which is more than necessary in real world application. For those more interested in CD-SAAM and application of principles than the Supercar-A architecture evaluation itself, I recommend reading at least through the end of section 4.7, the engine/induction system architecture assessment through principles application. One certainly gets a strong flavor of the principles portion, its strengths and weaknesses as well as its fit in the proposed synthesis of tools. Then skip to section 4.13 where the QFD application begins.

4.6 Overall System Architecture (first level decomposition) Versus Principles Analysis

Table 18 below depicts some of the overall system architecture aspects of Supercar-A and its benchmarks, the 360 Modena and the Viper. The overall supercar system architecture is represented again in the following decomposition.

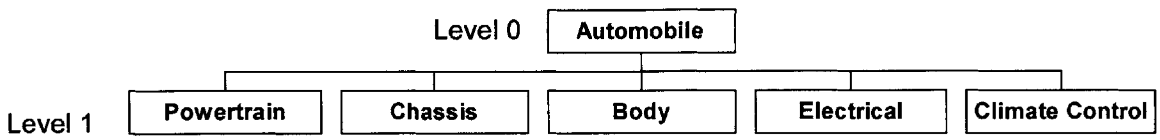


Figure 39: Supercar Overall System Architecture Decomposition.

In reality, the elements listed in this table are design parameters rather than concepts. However, they describe the architectural concepts to a degree in that these parameters demonstrate the overall size of the vehicles. For example, a fairly long, yet low vehicle architecture was chosen for Supercar-A as compared to its two primary benchmarks and many other cars in its class. Supercar-A is also on the heavier side of the weight range in its class, which is a function of its overall size and other system architecture decisions including the powertrain and chassis.

Table 18: Supercar-A, 360 Modena and Viper Overall Architecture Comparison.

Architectural Element	Supercar-A	2003 Ferrari 360 Modena	2003 Dodge Viper
Overall Vehicle			
Curb Weight (lbf) (Reference)	3348	3241	3357
Weight Dist. % Front (Reference)	43/57	43/57	48/52
CG Height (in) (Reference)	17.7	17.7	17.5
Wheelbase (in)	106.7	102.4	98.8
Track front/rear (in/in)	63/63.7	65.7/63.7	57.8/60.9
Length (in)	182.8	176.3	175.5
Width (in)	76.9	75.7	74.8
Height (in)	45.0	47.8	47.6
Ground clearance (in)	5.0	5.0	5.0
Estimated Shadow Area (ft^2)	97.6	92.7	91.2

Also, as noted in the concept mapping above in Figure 37 and Figure 38, many of these parameters related to size and mass impact the goals for the vehicle and ultimately, the constraints as well. The five identified system architecture principles are applied to this level of overall architecture with these aspects in mind. One reminder, aspect(s) of an architecture demonstrating weakness relative to a principle as compared to alternatives does not mean it is deficient overall. As noted earlier, one may choose higher complexity, for example, to gain performance in another aspect of the architecture. Finally, many of the principle evaluations note the need for further information based on other principles and analysis as well as design parameter importance quantification.

1. **Minimize Complexity Principle Applied to Supercar-A's Overall Architecture**

   There is little that can be evaluated at this level with regard to complexity, with the exception of noting that the Supercar-A architecture is comprised of five major systems. These five primary systems exist for the Supercar-A's competitors and do not appear overly complex, at this level. Meaning the concept of a powertrain, chassis, body, electrical and HVAC appears to exhibit the smallest degree of complexity to achieve the goals of the system.

2. **Form and Function Union Principle Applied to Supercar-A's Overall Architecture**

   The fact that the Supercar-A exterior concept and resultant dimensions was conceived by the design studio with limited input from engineering leads one to believe the vehicle demonstrates more of a function follows form principle. However, the vehicle visually meets expectations for a high performance vehicle of this nature. In addition, the brief synergy analysis below is not completely conclusive at this stage with respect to the laws of physics; therefore it is difficult to completely assess Supercar-A with respect to this principle as well.

3. **Balanced Architecture Principle Applied to Supercar-A's Overall Architecture**

   While the brief application of vehicle dynamics judgment in the Synergy Principle analysis is inconclusive, the wheelbase and overall length appear on the extreme side (4% longer than the 360 Modena and 8% longer than the Viper) for a vehicle of this class. Further, its overall height appears extremely low (6% lower than the 360 Modena). The percentages appear small but they are significant differences for a vehicle of this nature. Beyond potential dynamics impact, the height alone may forecast challenges to packaging the five systems of the vehicle and passengers.

4. Synergy Principle Applied to Supercar-A's Overall Architecture

The concept of overall size and mass of the vehicle allows for a fair amount of discussion with regard to synergy for the Supercar-A. Many of the key resultant design parameters including wheelbase, track width, mass and CG location have a direct impact on many of the goals and constraints for the system. However, the true performance impact and overall dynamic behavior sensitivity to these parameters in the Supercar-A system architecture is unclear at this stage and requires further analysis utilizing DOE methods in parametric models. The following is a summary of the overall concept's directional impact on relevant constraints and goals that are affected most, either positive or negative.

- Overall Vehicle Dynamics (track) Performance- Difficult to completely assess at this level due to conflicting trends.
  - Handling Performance (steering, cornering, braking)
    - Vertical Tire Loading- long wheelbase and wide track serve to reduce weight transfer as desired and highlighted in the vehicle dynamics section, but the resultant mass increase may offset the improvement. At the same time Supercar-A's low roof height and profile may force the CG height down and reduce weight transfer again.

      Utilizing the parameters in Table 18 above and the equations for weight transfer, Supercar-A exhibits 6% more lateral weight transfer than the 360 Modena in a 1G cornering event signifying a potential cornering capability deficit to the Ferrari. At the same time Supercar-A exhibits 1% less longitudinal weight transfer during braking or acceleration as compared to the 360 Modena, denoting a very small potential for improved longitudinal capability. However, the total weight and CG position include other architecture decisions beyond the overall size, including the chassis and powertrain decisions, so this is not a direct comparison of the overall architecture.

    - Yaw Dynamics- Supercar-A's long wheelbase by itself yields a higher yaw natural frequency and damping levels, which are desired. However, the actual yaw natural frequency and damping tend to end up very similar to a smaller vehicle with a shorter wheelbase due to trends in mass and radius of gyration with size for a similar weight distribution. Further, Supercar-A's overall weight distribution is the same as the Ferrari, which means it has the potential for a similar understeer gradient. Therefore, the overall Supercar-A architecture most likely results in similar inherent yaw dynamics to the shorter 360 Modena, all else being equal- especially tire dynamics.

- Straight-line Acceleration Performance- The increased vehicle mass due to size by itself serves to degrade straight-line acceleration performance. However, at higher speeds, improved aerodynamic drag due to the low roof height and corresponding competitive frontal area improve straight-line performance as a function of speed squared. Also, Supercar-A's rearward weight bias serves to improve straight-line acceleration capability due to improved rear tire vertical loading. Therefore, further analysis is required to understand the final impact on straight-line performance.

    - Primary Ride Dynamics- increased size, resultant mass and inertia tend to degrade ride performance with all else being equal, yet Supercar-A's longer wheelbase serves to reduce the pitch mode, for example, and therefore it is very difficult to assess the true performance at this level.
- Seating Package- Supercar-A's low roof height tends to hurt the occupant seating package but the increased vehicle length exhibited by Supercar-A potentially offsets the low roof height constraint.
- SVA- Supercar-A's greater length and width requires more material (structural and otherwise) resulting in increased weight, with all else equal. And weight begets weight, meaning increased weight trends to build upon itself. Eliminating this weight penalty costs more in the following:
    - Lower weight/strength materials and processing
    - Greater engineering optimization time

5. Balanced External Forces Principle Applied to Supercar-A's Overall Architecture

Maintaining Supercar-A's showcar concept exterior and resultant overall dimensions reduces risk with respect to customer approval from an aesthetic point, as there was an overwhelming positive response to the concept exterior when shown to the public. Also, maintaining the concept car exterior potentially reduces risk further because it reduces the lengthy time and effort spent styling the exterior. However, its impact on some of the performance goals and resultant synergy of the system is unclear at this stage of the analysis; therefore, the complete balance of risk against the constraints and goals is also unclear at this point.

This concludes the principles application to Supercar-A's overall system architecture. Some aspects of the architecture are due to direct decisions on the overall such as wheelbase, length, height and width. However, other aspects like mass, weight distribution and moments of inertia are heavily biased by powertrain and chassis system architecture decisions. Therefore, it is difficult to directly assess the merits of the overall architecture at this stage in addition to the fact that it demonstrated a combination of position and negative aspects.

Completion of the overall system architecture evaluation through principles application leads to the following analysis on Supercar-A's powertrain architecture. Figure 40 below once again shows the Supercar-A powertrain systems to be analyzed.

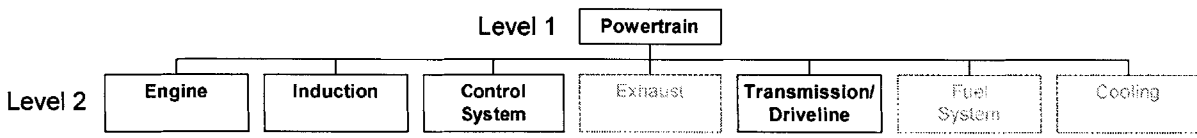


Figure 40: Supercar-A Powertrain System Architecture for Evaluation: Engine, Induction, Transmission and Driveline excluding the Exhaust, Fuel and Cooling Systems

4.7 Powertrain: Engine and Induction System Architecture (2nd level decomposition) versus Principles Analysis

The engine and induction system are analyzed together against the five principles in this section because they are closely linked. A vehicle's powertrain system's primary purpose involves creation and control of drive torque to the vehicle's drive axle(s) to produce acceleration and control the vehicle's speed. However, as is demonstrated below, this large and important system impacts a considerable portion of the system goals and interfaces with a high degree of the system architecture.

Table 19 and Table 20 cover the major highlights of the engine and induction system architectures for Supercar-A, 360 Modena and the Viper. Arguably, elements such as the powertrain location and orientation could be discussed or included in the overall architecture analysis. However, these aspects fit just as well into the powertrain discussion as they can impact other elements of the engine and transmission/driveline architecture. This includes a linkage between displacement, configuration and orientation for the engine as well as the resultant interface with the transmission/driveline system.

In addition, one may note a few output variables of the engine including horsepower, torque and redline (max) rpm that can be used as a reference for the architectures. However, at a high level they can describe portions of the engine/induction concept as well. Two concept examples include: a small displacement, high revving, high horsepower 360 Modena engine/induction concept versus the large displacement, low revving, high torque and horsepower Viper engine/induction architecture.

Table 19: Supercar-A, 360 Modena and Viper Engine System Architecture Comparison.

Architectural Element	Supercar-A	2003 Ferrari 360 Modena	2003 Dodge Viper
Powertrain- Engine			
Location	Mid-engine (in front of rear axle)	Mid-engine (in front of rear axle)	Front-engine
Orientation	Fore-Aft (north-south)	Fore-Aft (north-south)	Fore-Aft (north-south)
Displacement (cc)	5400	3600	8300
Configuration	90 deg V8	90 deg V8	V10
Valvetrain, type	Quad OHC	Variable Valve Timing Quad OHC	OHV
Valvetrain, #	4 valves/cylinder	5 valves/cylinder	2 valves/cylinder
Block and Head Material	Aluminum	Aluminum	Aluminum
Lubrication	Dry Sump	Dry Sump	Dry Sump
Max. Power (hp / rpm)	500/5,500	395/8500	500/NA
Max. Torque (lb-ft / rpm)	500/5,500	275/4750	500/NA
Redline (rpm)	6,500	8,500	6,000 (estimated)
Vehicle Weight: Power (lbf/bhp)	6.7	8.2	6.7
Specific Power (bhp/Liter)	93	110	60

Table 20: Supercar-A, 360 Modena and Viper Induction System Architecture Comparison.

Architectural Element	Supercar-A	2003 Ferrari 360 Modena	2003 Dodge Viper
Powertrain- Induction			
Induction Type	Lysholm Supercharged with Intercooler	Normally Aspirated	Normally Aspirated

For clarification, a normally aspirated engine induction system simply uses ambient airflow for combustion while a forced induction system utilizes a compressor system to increase the air density prior to combustion. The increased air density allows additional fuel introduction for a given combustion volume producing a larger "explosion" and greater resultant torque. Most compressor systems are driven off of the engine crank mechanically (known as a supercharged system) or by the waste exhaust gas via a turbine (known as a turbo charged system).

Prior to analysis, a brief discussion on engine and induction system design and development is warranted. Internal combustion engine system design and development is as difficult and perhaps more difficult than any other major system in an automobile. The difficulty arises from its complexity and hard to predict emergent properties. Internal combustion engine dynamics includes the disciplines of fluid dynamics, thermodynamics, heat transfer and mechanical dynamics. Many tools exist to model each area of discipline and some are able to combine multiple disciplines. However, much of the modeling and analysis include considerable assumptions. One assumption often made in modeling the engine's mechanical dynamics includes the use of rigid bodies for elements like the crankshaft. However, the crankshaft is not truly rigid and this assumption can lead to unpredicted modal alignment issues and inaccurate main bearing loading, for example, leading to failure. Therefore, just changing cylinder bore spacing for a new engine creates additional failure and development risk due to the required changes to the crankshaft. The complicated nature of this system and all of its interactions leads to a wide range of opinions and competency regarding predictive capabilities for internal combustion engine performance and reliability. Some claim 80% confidence in engine architecture and design prior to system integration and development, while others predict much less. Therefore, engine architecture decisions can be heavily biased by a company's core competencies and corresponding ability to predict its behavior. This was noted during the description of the Balanced External Forces architecture principle in section 2.4. These described considerations of engine and induction system design and development are included in the fifth principle analysis.

1. **Minimize Complexity Principle Applied to Supercar-A's Engine and Induction System Architecture**

   A few aspects of Supercar-A engine architecture as listed above provide for reduced complexity. First, Supercar-A has the identical engine system orientation and layout as on the 360 Modena. Their longitudinal orientation and mid-engine layout in a rear wheel drive system facilitates improved integration of form and function, thereby reducing apparent as well as actual complexity as compared to a front-engine, rear wheel drive architecture like the Viper. Although it should be noted that a rear-engine layout mated to a rear wheel drive, as demonstrated by the Porsche 911, also provides a similar level of form integration and complexity reduction as the mid-engined Supercar-A. In addition, a transverse oriented engine mated to an integral transverse transaxle (like most front wheel drive architectures) in a mid-engine layout, as demonstrated by the Acura NSX, exhibits the highest degree of form and function integration and corresponding lowest amount of complexity in its supercar class.

Second, the Supercar-A engine does not include a variable valve timing system, which reduces complexity as compared to some of its competitors, including the 360 Modena. However, there are a few major aspects of Supercar-A engine and induction system that demonstrate a fair degree of increased apparent (and actual) complexity as compared to both of its normally aspirated benchmark vehicles. Some of the additional complexity is demonstrated in Supercar-A's forced induction system and the engine's front-end accessory drive (FEAD). Visually compare Supercar-A's FEAD versus the 360 Modena in Figure 41 and Figure 42 below.

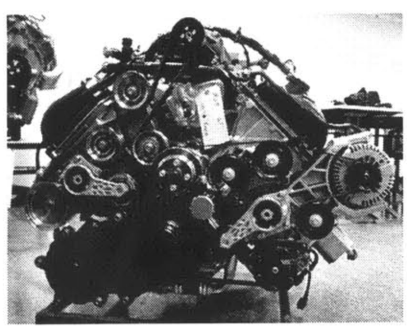


Figure 41: Supercar-A Engine/Induction FEAD.

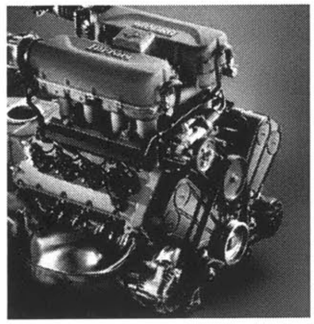


Figure 42: 360 Modena Engine/Induction FEAD.

Supercharged induction systems typically involve more complex FEADs due to the fact that they are mechanically driven off of the crank. The supercharger and its pulley are shown at the top and center of the FEAD system. Arguably, a supercharged architecture does not necessarily call for this degree of FEAD complexity but it is representative of the increase as compared to a normally aspirated counterpart. Beyond the FEAD complexity, the supercharged induction system adds the complexity of the supercharger itself (in essence a compressor) and intercooler (cools the "charged" air prior to introduction to the engine's intake runners) in this case as compared to a normally aspirated engine. In addition, the supercharged forced-induction system is apparently more complex (and arguably actual complexity) than perhaps even a twin turbo system. As described above, the turbo and the supercharger are both compressors with the turbo compressor driven by exhaust gases and the supercharger mechanically driven off of the crank. The compressors themselves are perhaps similar in complexity, but the drive system for a turbo entails a turbine versus the additional pulleys and idlers interfacing with the crank accompanying the supercharger. View an example twin turbo system in Figure 43 below.

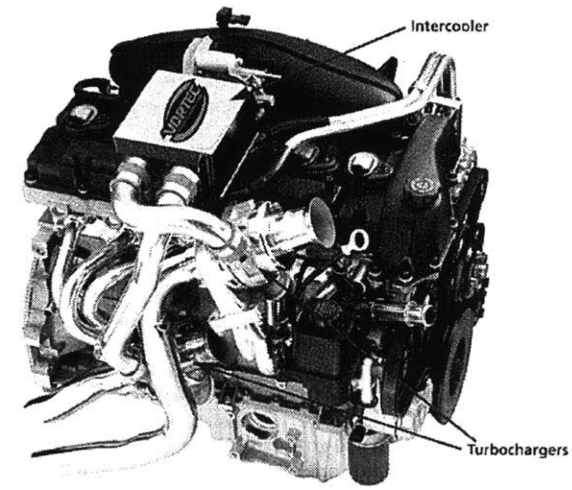


Figure 43: Twin Turbo Charged Engine and Induction System Example. [Car, April 2003]

Further, some have reduced turbo charger system complexity to a greater extent by integrating the turbine and compressor housing into the exhaust manifold as shown in Figure 44.

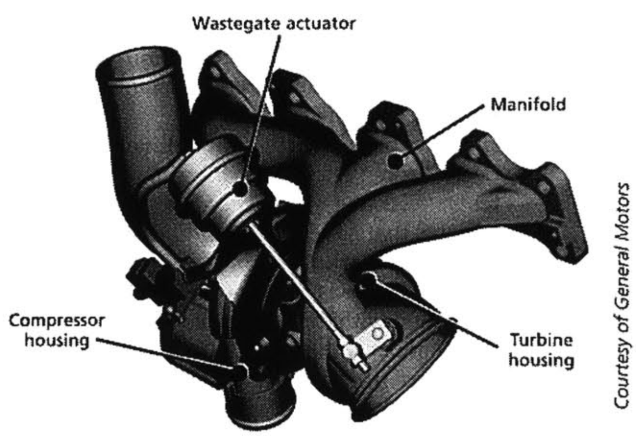


Figure 44: Turbo Charger with the Turbine and Compressor Housing Integrated into the Exhaust Manifold. [Car, April 2003]

The twin turbo charged systems are visually less complex externally and facilitate integration of form and function. However, to some they pose a higher degree of interface sophistication and resultant complexity as compared to the supercharged system. This highlights the fact that complexity is often dependent on one's perspective and is difficult to quantify.

2. Form and Function Union Principle Applied to Supercar-A's Engine and Induction System Architecture

As noted above in the "Complexity" principle, Supercar-A's mid-engine location allows for better integration of form. It also leads to improved function. First, the improved form integration facilitates reduction in system mass, improving all aspects of dynamics. Second, Supercar-A engine and induction system mounted longitudinally in front of the rear axles also provides a better static tire loading distribution for braking and accelerating performance than a front-engine architecture (i.e. Viper). Note, the size and placement of this system always has a considerable impact on the vehicle weight distribution. Contrary to some manufacturers advertisements, 50/50% front to rear weight distribution is not ideal for all aspects of vehicle dynamics. Perhaps this provides the best balance for some vehicle segments like family sedans, but this is not the case for a supercar biased toward handling performance. Some rearward weight bias (~2-6%) is preferable due to vertical tire loading dynamics during braking and accelerating. However, tire sizing and its dynamic behavior must be properly matched to the weight distribution. The rearward weight bias allows more efficient use of all four tires during braking, while that same bias provides better traction during acceleration as compared to its front-engined counterparts. One then may conclude the rear-engined architecture to be better yet, but the greater bias of weight rearward creates additional challenges in ride and yaw dynamics as highlighted below. The same can be said for the transverse engine orientation in a mid-engine layout (NSX), which results in fore-aft weight distribution in between Supercar-A's longitudinal mid-engine and the Porsche 911 rear-engine architectures.

In addition to favorable vertical tire loading, Supercar-A's mid-engine layout provides the best yaw dynamics when compared to front, rear and even transverse mid-engine architectures. This is due to its reduced radius of gyration in yaw as compared to these three alternatives. Reduced yaw radius of gyration, with all else equal, increases the vehicle's yaw natural frequency yielding improved yaw dynamics.

Finally, the supercharged forced-induction system creates are very flat and full torque curve from extremely low engine speed up the maximum RPM. The resultant torque versus RPM curve provides very strong acceleration performance from a standing start. A turbo charged system has potential to create similar peak torque, but typically suffers from some degree of "turbo lag" at lower RPM as it takes time to spin them up to the necessary rotational speed to produce boost. Therefore, a supercharger is superior for standing starts and drag racing due to its nearly instantaneous boost if implemented properly.

However, like the complexity principle analysis, there are some aspects of Supercar-A's engine and induction system architecture that detract from the union of form and function for the system. First, the engine and induction system is fairly tall, with about 1/6 of its mass sitting at the top in the form of the supercharger. This height results in a higher CG for the engine and induction system than its counterparts and resultant increased total vehicle CG with all else being equal. As covered earlier, an increase in the vehicle's CG height increases weight transfer and degrades handling performance. Second, while Supercar-A's forced induction supercharger adds up to 20% more horsepower and torque at the flywheel, it actually provides double that potential to the combustion chamber. This means the losses in the supercharger drive and compressor system is equal to the final gain in the system as it is driven off of the engine crank to which it is boosting power. This in turn means the engine cooling system must be capable of removing the heat created for the full 40% increase in power at the combustion chamber, while only yielding a 20% true gain in power and torque to drive the rear axle. Therefore, the cooling system for a normally aspirated or even turbocharged engine/induction system is smaller than that of the less efficient supercharged system for the same power and torque output to the drive axle. Turbo charged systems, for example, do create additional heat over normally aspirated systems, but it is typically contained in the turbocharger units themselves running off of the spent exhaust gases. This allows the turbo units to be air-cooled by ducting, which adds little in extra weight (or complexity) for the same power and torque.

3. Balanced Architecture Principle Applied to Supercar-A's Engine and Induction System Architecture

The Supercar-A's engine displacement of 5.4 L lies just below the midrange between the 3.6 L 360 Modena and the 8.3 L Viper. This number itself appears to exhibit a good balance in trying to embody the large displacement straight-line performance of the Viper, while it must have the dynamic prowess of the small displacement 360 Modena. However, despite this apparent balance, Supercar-A's engine, induction and resultant cooling system weigh substantially more than the rival 360 Modena's corresponding system. Supercar-A's system rivals the Viper's large displacement engine, induction and cooling system weight and represents a potential extreme when compared to the goals for Supercar-A.

4. Synergy Principle Applied to Supercar-A's Engine and Induction System Architecture

The following analysis highlights the significant degree of influence the engine and induction system have on the overall system performance with respect to its constraints and goals. The following is a summary of Supercar-A's engine and induction concept impact on relevant constraints and goals that are affected most, either positive or negative.

- Overall Vehicle Dynamics (Track) Performance- This is difficult goal to assess at this level in full. This is due to the following, which demonstrates conflicting trends and requires further, more detailed analysis to predict the ultimate performance impact.

- Handling Performance (steering, cornering, braking) is weakened as compared to the 360 Modena benchmark.
  - Vertical Tire Loading- Supercar-A's longitudinal engine orientation and mid-engine layout is very good with respect to vertical tire loading and positive impact on handling dynamics.

    However, the benchmark 360 Modena has an identical mid-engine layout, but Supercar-A's engine/induction system and corresponding cooling system yield considerably greater mass than the 360 Modena's system. This alone leads to degraded handling performance due to increased lateral and longitudinal weight transfer with all else being equal. Further, Supercar-A's powertrain with top mounted super charger also exhibits a higher center of gravity than the 360 Modena. The higher vehicle CG position again increases lateral and longitudinal weight transfer, degrading handling performance further.
  - Yaw Dynamics- In addition to favorable vertical tire loading, Supercar-A's mid-engine layout provides the best yaw dynamics when compared to front and rear-engine architectures as analyzed in principles one and two above.

    However, once again the benchmark Ferrari has an identical mid-engine layout, but increased mass of Supercar-A engine and induction system mass serves to increase its yaw radius of gyration yielding reduced yaw dynamic performance.
- Straight-line acceleration performance appears strong with respect to its benchmark, the Viper, and alternatives. Supercar-A's engine and induction system provides identical horsepower and torque numbers as its straight-

line acceleration benchmark, the Viper. While, Supercar-A's engine and induction system architecture are heavy for its displacement, its system weight is still very comparable to the Viper's. Therefore, Supercar-A's engine and induction system should provide the necessary performance to achieve its straight-line acceleration objectives, with all else being equal. However, an inertia comparison of Supercar-A's engine and induction system versus the Viper's is difficult to complete, which may hamper 0-60 mph and even quarter mile times. It is not clear if Supercar-A's smaller displacement engine mated to the supercharger results in more or less rotating and reciprocating inertia, which impact acceleration. Further analysis is required to understand the impact degree of rotating and reciprocating inertia on acceleration times.

- Primary ride is degraded as compared to the 360 Modena benchmark due Supercar-A engine, induction and corresponding cooling system's higher weight and fore-aft weight distribution as well as increased pitch inertia.
- Secondary ride is degraded in comparison to the 360 Modena benchmark due to Supercar-A's higher engine and induction system mass. The engine and induction systems of passenger cars are isolated from the rest of the vehicle at its mounts. This isolation turns the engine and induction system into an additional sprung mass, in which larger mass affects the rest of the dynamic system more during secondary ride events. Some utilize the engine and induction system as a tuned mass damper for the rest of the vehicle system and believe more mass may actually help. However, the negatives of greater engine mass outweigh the positives with respect to secondary ride.

- <u>Maintain Concept Integrity-</u> Supercar-A's 5.4 L Aluminum Supercharged V8 certainly maintains Supercar-A concept car integrity because it is the engine and induction system included in the showcar. However, the engine and induction system were not specifically a portion of this goal in that they were sub exterior.

- Craftsmanship- This goal entails fairly subjective measures and is difficult to truly judge. Supercar-A's engine and induction system are certainly a central focus visually of the rear half of the car, with or without the engine cover in place. Therefore, they plays a considerable role in craftsmanship. To some, the big V8 and supercharger are works of art; while to others the supercharger and corresponding lines are unappealing.
- Seating Package- Supercar-A's engine and induction system meets this goal since Supercar-A concept car's dimensions included it and the resultant overall dimensions achieved this goal.
- Powertrain NVH- Supercar-A's engine and induction system add difficulty to achieving this goal due to the addition and proximity of the supercharger system to the occupants as compared to its benchmark, the 360 Modena. Supercar-A's induction system most likely requires additional NVH "treatment" to even achieve its degraded goal with respect to the 360 Modena.
- SVA and Timing- Aspects of these two constraints are included in Balanced External Forces principle assessment below.
- Reliability- Supercar-A's engine and induction system meets this constraint. This system architecture is heavily based on another, which is well proven in testing and the field.
- Manufacture and Assembly- Supercar-A's engine and induction system meets this constraint. Again, this system architecture is heavily based on another, which is well proven to meet high volume needs. In addition, the chosen architecture is biased toward design for manufacture and assembly. However, the additional forced induction systems do present some degree of disadvantage as compared to normally aspirated systems.

- Maintainability- Supercar-A's engine and induction system meets this constraint. Again, this system architecture is heavily based on another, which meets the maintenance requirements.

5. **Balanced External Forces Principle Applied to Supercar-A's Engine and Induction System Architecture**

As shown in Figure 29, section 3.7, the Supercar-A's product development timeline was severely compressed, especially in the first half where architecture decisions were made. This timeline and difficulty in emergent property prediction for the engine and induction system heavily biased the decision for Supercar-A. While a great deal of the chosen engine system was all new, it was heavily based on one of OEM-A's well proven supercharged, iron block V-8 architectures. This allowed, for example, the use of a common, well-proven crank for the new engine. The powertrain team viewed the chosen architecture as their only real option to achieve Supercar-A's goals within its constraints. However, a couple of other options may have existed, including one notable normally aspirated all aluminum V-10 engine and induction system. The V-10's design and development team vigorously promoted this new option a little way into Supercar-A's product development process. The V-10 team advertised very similar power and torque numbers to the chosen V-8, and at least 20% less system weight as well as the ability to fit the Supercar-A requirements. Supercar-A's V-8 overall was longer than normal due to its supercharged FEAD package and the V-10 team claimed very similar overall length. My analysis of the full engine packages including the FEAD demonstrated that the V-10 option was about five percent longer. It still sounded very promising. Reduced, system weight, CG height and polar moments of inertia along with the strong power of the V-10 would have improved performance in the synergy analysis above. However, the V-10 architecture included two major challenges or increased difficulty and increased risk with respect to Supercar-A's chosen engine and induction architecture. The aluminum V-10 was a new concept that was based off another iron block V-8 architecture in which they added two cylinders at one end. First, the V-10 required an all-new crank design. Second, the V-8 architecture it was based upon was on the edge for properly cooling its own high output engine versions. The two additional cylinders and lengthened cooling passage in the same area presented additional risk. These two hurdles were viewed as substantial within the program's timing constraints.

Alternative engine and induction system options definitely posed different and added risk from the powertrain design team perspective. Nonetheless, reflection on Supercar-A's chosen supercharged aluminum V-8 engine and induction system and the above analysis, it appears the risk was balanced primarily against powertrain related goals and constraints, as opposed to all of the system goals. The risk saved by Supercar-A's chosen engine and induction system architecture versus the V-10 was arguably pushed to the rest of the system as well as the powertrain design team itself. For example, considerable time, effort and financial means were spent on the rest of Supercar-A's architecture to offset the weight penalty of the fairly heavy engine and induction system architecture because weight is key to so many of its goals. In addition, the powertrain engineering team spent additional effort to reduce the weight penalty of the architecture through materials, processing choices and engineering optimization. The weight reduction was completed on other systems through architecture decisions, materials and processing choices as well as considerable engineering optimization. Therefore, making up for a heavy architecture in this case is very time consuming and costly. Does the displaced risk equal the risk involved in the V-10 architecture choice? Which provides a better balance of performance with respect to all of the goals and constraints? This thesis can't truly answer the question with regard to the risk aspect alone, but further analysis in the following QFD and DOE sections shed light on total system synergy and some aspects of risk.

This concludes the principles application to the Supercar-A engine and induction system architecture. The true performance impact and overall dynamic behavior sensitivity to these parameters in the Supercar-A system architecture is incomplete at this stage and requires further analysis utilizing DOE methods in parametric models. Further, the degree of conflicting trends with respect to the most affected goals and constraints highlight the need for additional analysis in the form of QFD.

4.8 Powertrain: Control System Architecture (2^{nd} level decomposition) versus Principles Analysis

Engine control systems base function involves control of the fuel delivery and ignition to insure proper performance based on numerous inputs including the throttle position dictated by the driver. These systems can also control automatic transmission function and any other systems direct interaction with the powertrain. Current engine control systems additionally interact with modern braking ABS and many vehicle's yaw stability systems that act through ABS. Further, some new engine control architectures enable and control the use of electronic throttle control (ETC), active axle differentials and the new semi-automatic paddle shift capabilities. However, the OEM-A proprietary engine system chosen for the Supercar-A did not allow direct capability for ETC, an active rear axle differential or semi-automatic shifting. Further, modifying ignition, fuel, turning work cylinders on and off and adding brake torque on traction control systems compatible with OEM-A's proprietary control system is inferior to ETC based versions, especially for very high power and torque applications. Therefore, the inability to run ETC was a notable consideration in the choice to avoid traction control as well on Supercar-A.

Table 21: Supercar-A, 360 Modena and Viper Control System Architecture Comparison.

Architectural Element	Supercar-A	2003 Ferrari 360 Modena	2003 Dodge Viper
Powertrain- Control System			
Control System Type	OEM-A Proprietary	Ferrari Proprietary	Dodge Proprietary

1. **Minimize Complexity Principle applied to Supercar-A's Engine Control System Architecture**

   I am unable to evaluate the lines of code for the chosen control system and the total number of inputs and outputs with respect to alternatives. However, as noted, Supercar-A's control system architecture eliminated options like ETC, an active differential and semi-automatic paddle shifting. It also weighed heavily in the decision to eliminate traction control. Supercar-A team's avoidance of the additional systems significantly reduced overall vehicle complexity. It also reduced complexity within the control system itself, as compared to competitors like the 360 Modena.

2. **Form and Function Union Principle Applied to Supercar-A's Engine Control System Architecture**

   I am unable to evaluate Supercar-A's engine control system architecture with respect to this principle.

3. **Balanced Architecture Principle Applied to Supercar-A's Engine Control System Architecture**

   I am unable to evaluate Supercar-A's engine control system architecture with respect to this principle.

4. **Synergy Principle Applied to Supercar-A's Engine Control System Architecture**

   The following is a summary of Supercar-A's engine control system architecture impact on relevant constraints and goals that are affected most, either positive or negative.

   - <u>Overall Vehicle Dynamics (track) Performance-</u> Supercar-A control system strategy potentially reduced performance with respect to this goal. This is primarily due to the lack of ETC and traction control.

- Track performance is potentially degraded on corner exit (mainly low speed) during application of the high horsepower and torque of Supercar-A as compared to its benchmark, the 360 Modena.
- Straight-line acceleration, especially from a standing start could have benefited from traction control. Traction control mainly would have improved performance consistency, controlling wheel spin during launch.

- SVA and Timing- Aspects of these two constraints are included in Balanced External Forces principle assessment below.
- Reliability- Supercar-A's engine control system is superior to alternatives with respect to this constraint due to its well-proven architecture and minimal complexity noted earlier in the complexity principle analysis.
- Maintainability- Supercar-A's engine control system is superior to alternatives with respect to this constraint due to its long history and wide spread use of its diagnostic systems.

5. Balanced External Forces Principle Applied to Supercar-A's Engine Control System Architecture

Supercar-A's control system choice was arguably biased by the core competency of the group charged with design and development of the system and their confidence with regard to emergent property prediction, similar to the engine and induction system. Other, more advanced choices that would have facilitated ETC, traction control, active differential and so on, required a fair amount of training for the calibrators. However, the base OEM-A proprietary code that was well-proven for a similar engine existed already, providing more insurance for achieving Supercar-A's constraints and goals. The alternatives were new, less developed, advanced systems that demonstrated potential issues with regard to robust operation. The alternatives required starting from scratch on complex code that is not trivial, as highlighted by numerous modern system failures due to control system programming issues. While it is easy for those of us used to hardware design to view this as "simply writing new code"; it is far more difficult than it appears from the outside. Experienced programmers can relate well to the following example of how quickly complexity builds in software and the inability to test robust operation of all potential combinations. Nancy Leveson, an Advanced Software Professor at MIT, utilizes the "simple" example shown in Figure 45 to describe how quickly the complexity of software expands to unimaginable proportions. In addition, the complexity shown does not cover logic paths that might be missing.

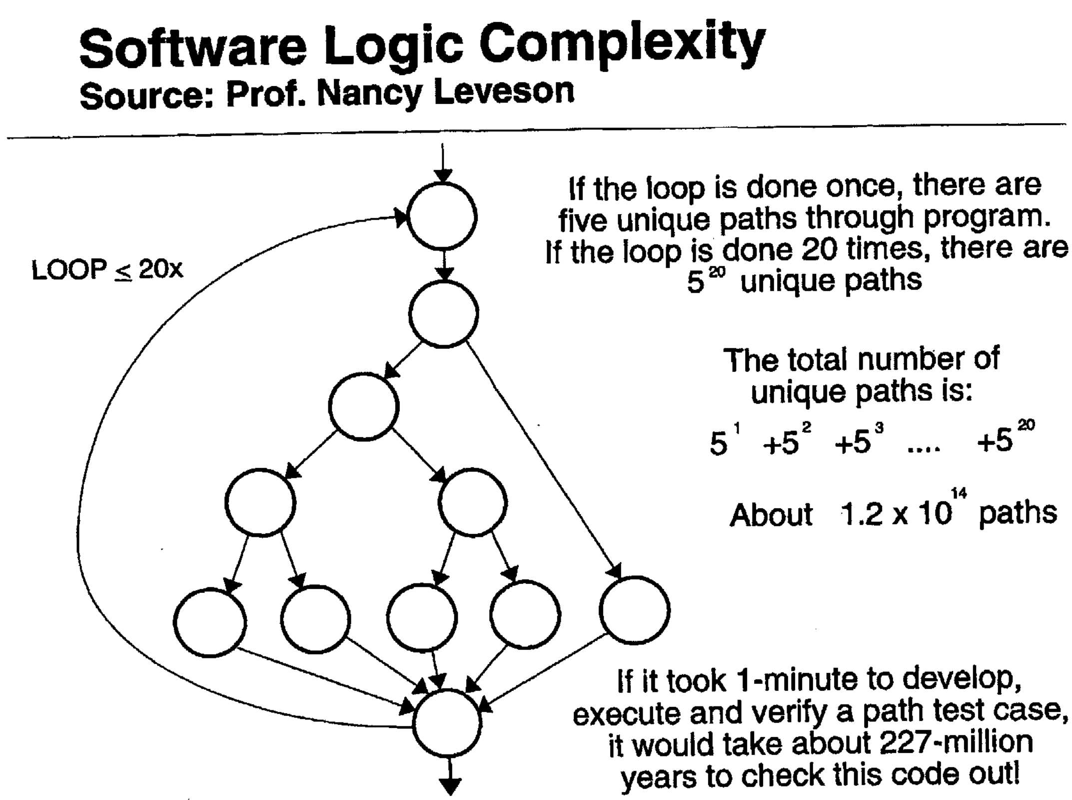


Figure 45: Leveson's Software Logic Complexity Example. [Bop]

The balance of risk against the goals and constraints initially appears biased again toward one's ability to predict the behavior of a system to avoid serious issues in the development phase and meet the given objectives. For sure, Supercar-A's timing played a considerable role in this risk assessment. However, the above considerations demonstrate risk of enormous proportions. In addition, the decision did not push considerable risk onto the other systems as the engine and induction system may have done. Supercar-A's engine control system and resultant elimination of additional active systems reduced complexity for all as opposed to increasing it. Also, it did not add weight; only reduce it, which is key to the vehicle's dynamic performance as highlighted numerous times above. Finally, Supercar-A's overall weight distribution provided a large advantage for straight-line acceleration over its benchmark Viper, rendering traction control, for example, less important. The potential areas for improvement noted above in the synergy analysis are small, especially when compared to the risks. This is supported by the fact that many of the active systems, like active differentials, are band-aids for poor passive vehicle dynamics, as noted in an earlier active yaw dynamics discussion. Therefore, Supercar-A's proprietary control system also served to reduce costs to improve SVA as well as save precious design and development time.

This concludes the powertrain control system architecture evaluation through principles application and leads to assessment of Supercar-A's transmission/driveline system architecture.

4.9 Powertrain: Transmission/Driveline Architecture (2nd level decomposition) versus Principles Analysis

The Supercar-A's transmission/driveline system is responsible for transmitting the engine system torque to the rear wheels. Supercar-A's longitudinal mid-engine layout essentially dictated the integrated form of a transaxle. A transaxle that met Supercar-A's package requirements and was capable of transmitting the necessary torque did not exist in the OEM-A system. Therefore, Supercar-A required an all-new transaxle, allowing flexibility in its architecture definition, as it was not constrained by past designs. While a transaxle is a complex system in itself, it does not present the degree of challenge the engine and induction system does with regard to emergent property prediction. For comparison, note Supercar-A's transmission and driveline architecture is nearly identical to the benchmark 360 Modena, with the exception of the differential and traction control. Architecture elements including clutch and differential type are not included in the following analysis due to the lengthy nature of this section of the thesis and their secondary impact on the goals as compared to rest of the transmission driveline architecture.

Table 22: Supercar-A, 360 Modena and Viper Transmission and Driveline System Architecture Comparison.

Architectural Element	Supercar-A	2003 Ferrari 360 Modena	2003 Dodge Viper
Powertrain- Transmission/Driveline			
Type	Manual Transaxle (integral differential)	Manual Transaxle (integral differential)	Manual Transmission mated to a driveshaft coupled to the rear axle differential
In Vehicle Gear Set Orientation	Longitudinal (north-south)	Longitudinal (north-south)	Longitudinal (north-south)
Speeds	6	6	6
Case/Structure Material	Aluminum	Aluminum	Aluminum
Drive	RWD	RWD	RWD
Traction Control System	NA	Traction Control System through ETC	NA

1. **Minimize Complexity Principle Applied to Supercar-A's Transmission/Driveline System Architecture**

   Supercar-A's longitudinal mid-engine layout facilitates form integration and minimizes complexity, as highlighted in the engine and induction system discussion. This layout facilitates the use of the highly efficient, form integrated, transaxle that encompasses the transmission and driveline in a single unit, as opposed to separate transmission, driveshaft and axle subsystems demonstrated by the front-engine, rear wheel drive layout of the Viper. Figure 46 shows the 360 Modena's transaxle mated to the engine, which is a very similar layout to the transaxle of Supercar-A.

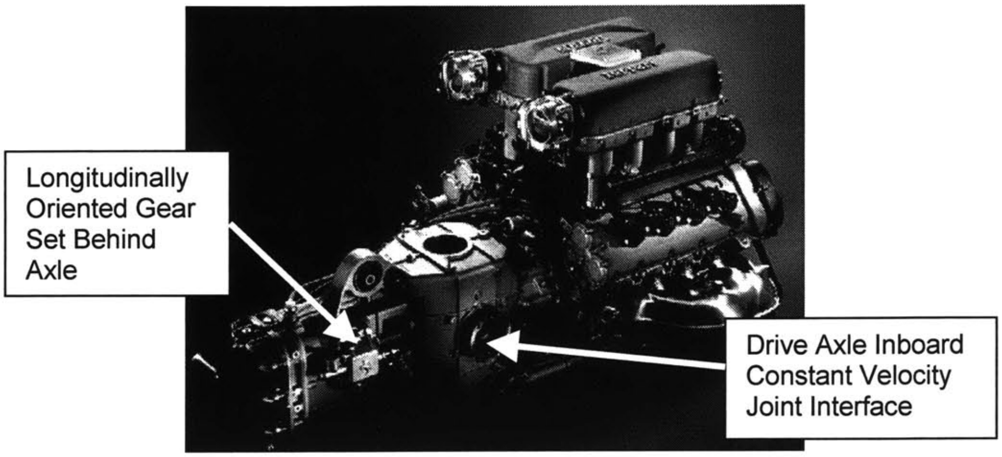


Figure 46: Ferrari 360 Modena Engine and Longitudinal Transaxle. Source: www.ferrari.com.

2. Form and Function Union Principle Applied to Supercar-A's Transmission/Driveline System Architecture

The longitudinal mid-engine layout of Supercar-A and its resultant longitudinal transaxle yields a very good marriage of form and function. The benefits of the mid-engine layout and transaxle discussed in the engine and induction system architecture with respect to tire loading and yaw dynamics apply here as well. The integration of the transmission, differential and driveline in a single compact unit certainly provides packaging, weight and efficiency advantages over less integrated alternatives. Only one alternative may have provided better marriage of form and function. The potential alternative was another transaxle unit with its gear set oriented transverse in car versus longitudinal. The transverse transaxle would have been wider, with less overhang beyond the rear axle where the gear sets are placed as demonstrated in Figure 47. The reduced overhang of the transverse box would have reduced rear weight distribution bias (too much is as great an issue as too little for overall vehicle dynamics) as well as yaw radius of gyration. The result potentially providing improved vertical tire loading as well as yaw and pitch dynamics for enhanced overall vehicle dynamic performance.

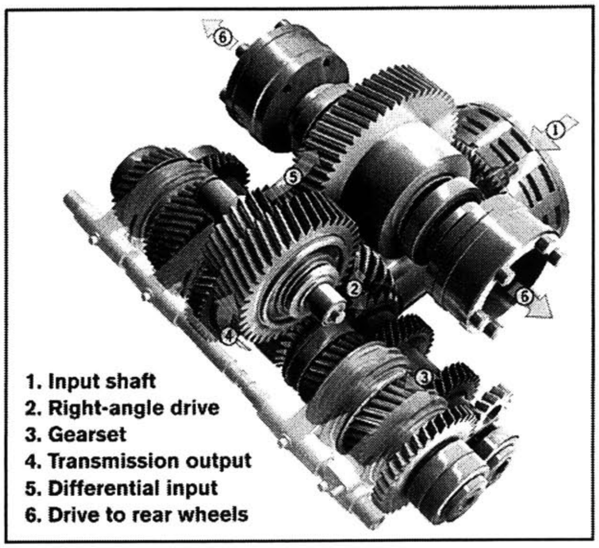


Figure 47: 2004 Porsche Carerra GT Transverse Gear Set Layout. [CnD]

Further, the transverse transaxle as utilized in the McLaren F1 may have reduced the critical distance (up to 2 inches) from the rear face of engine block to the rear axle centerline, providing additional space for the occupant and/or engine package. However, it is not clear if Mclaren's patent on their transverse transaxle covered this aspect, eliminating its potential. In addition, the total width of the transverse transaxle and impact on frame and suspension package is not perfectly clear, although it appears it would stay well within the engine package width, limiting its impact on the rest.

3. **Balanced Architecture Principle Applied to Supercar-A's Transmission/Driveline System Architecture**

The Supercar-A's transmission/driveline system does not exhibit any apparent extremes.

4. **Synergy Principle Applied to Supercar-A's Transmission/Driveline System Architecture**

As demonstrated earlier, Supercar-A transmission/driveline system exhibits good characteristics with respect to complexity, form and function marriage and is almost identical to the primary benchmark 360 Modena. The only potential architecture option was a transverse transaxle layout that may have provided an improvement to overall vehicle dynamic performance with little side affect. The only obvious side effect has been related to gear noise or rattle in the transverse architecture, affecting powertrain NVH performance.

5. Balanced External Forces Principle Applied to Supercar-A's Transmission/Driveline Architecture

There were very limited architecture options to analyze the balance of risk against the constraints and goals. The option chosen for Supercar-A exhibits considerable strengths. The potential for a transverse gear set layout was very briefly investigated but quickly dismissed. The reasoning was not clear, but the potential gains are also not clear at this level of analysis. Quick calculations exhibit a few percent reduction in pitch and yaw polar moment of inertia as well as a very slight (0.2%) increase on percent front weight. The true performance gain and overall dynamic behavior sensitivity to radius of gyration and weight distribution in the Supercar-A system architecture is unclear at this stage and requires further analysis utilizing DOE methods in parametric models.

This completes the principles application to the Supercar-A powertrain systems. Principles application to the Supercar-A chassis systems follows in the next section. Figure 48 below once again shows the Supercar-A chassis systems to be analyzed.

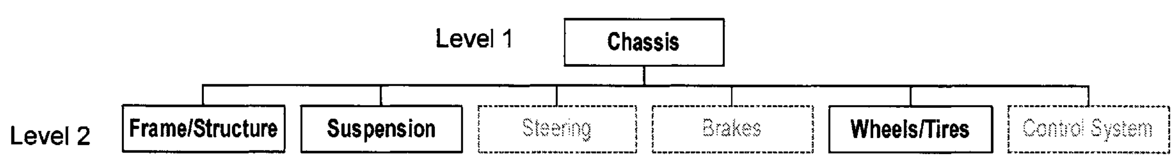


Figure 48: Supercar-A Chassis System Architecture for Evaluation: Frame/Structure, Suspension and Wheels/Tires excluding the Steering, Brakes and Control System

4.10 Chassis: Frame/Structure System Architecture (2nd level decomposition) versus Principles Analysis

The chassis system frame acts as the foundation for an automobile, analogous to the airframe in an airplane. The chassis system frame connects and supports all of the major systems for the automobile. Further, the frame is critical to proper function of the chassis system including the suspension, steering, brakes and the all-important wheels/tires. The suspension's intended function, for example, includes isolating the sprung mass and occupants from imperfect road disturbances as well as minimizing vertical load variations at the wheel/tire to ground interface due to these disturbances. While isolating the vehicle, the suspension system must maintain the desired wheel/tire attitude with respect to the road. Functionally, this requires the frame to be "rigid" with respect to the suspension system stiffness to allow predictable and controlled behavior. If the frame is not rigid with respect to the suspension stiffness and becomes part of the suspension system, it is much more difficult to predict and control its behavior and the system response is likely much less damped.

An additional primary function of the frame includes its attributes, which create structure for energy absorption and occupant isolation during an accident resulting in impact. Therefore, a frame structure requires anisotropic stiffness behavior as a whole. It must be stiff in certain loading for proper suspension performance yet "soft" enough to absorb rather than transmit energy to the occupants in other loading conditions. However, as noted earlier, I do not attempt to predict safety performance in this analysis due to inexperience in the dynamic discipline of vehicle safety design and analysis.

Table 23: Supercar-A, 360 Modena and Viper Frame/Structure System Architecture Comparison.

Architectural Element	Supercar-A	2003 Ferrari 360 Modena	2003 Dodge Viper
Chassis- Frame			
Primary structure type	Hybrid space frame featuring extruded tubular construction with cast nodes and limited shear panels	Hybrid space frame featuring extruded tubular construction with cast nodes and limited shear panels	Tubular space frame and limited shear panels
Primary structure material	6061/6063-T6 Aluminum (Extrusions)	6061/6063/6260-T6 Aluminum (Extrusions)	HSLA Steel

Architectural Element	Supercar-A	2003 Ferrari 360 Modena	2003 Dodge Viper
Chassis- Frame			
	A356-T6 Aluminum (Castings) Aluminum shear panels	A356-T6 Aluminum (Castings) Aluminum shear panels	
Suspension Interface Type	Cast aluminum nodes with post machined mounts	Cast aluminum nodes with post machined mounts	Pre-machined clevis tabs welded to Tubular members
Primary load carrying member placement	Primary-Tunnel with aid from Rockers	Rockers/tunnel/roof cant rails	Primarily tunnel and rockers
Joint Type	Primarily MIG Welded extrusion to extrusion and extrusion to cast node. Some adhesive bonding and mechanical fastening.	Primarily MIG Welded extrusion to extrusion and extrusion to cast node	Primarily MIG Welded tube to tube

1. Minimize Complexity Principle Applied to Supercar-A's Frame/Structure System Architecture

Supercar-A and its primary benchmark, the 360 Modena embody very similar frame architecture as listed above in Table 24. View of Supercar-A versus the 360 Modena frames in Figure 49 and Figure 50 demonstrate similarity in apparent complexity. It is more difficult to judge the actual complexity, especially with respect to sophistication of joints, for example. The use of adhesive bonding in conjunction with mechanical fastening, in addition to MIG welding of aluminum in Supercar-A is arguably more complex than strictly welding aluminum or the typical steel space frame shown in Figure 51.

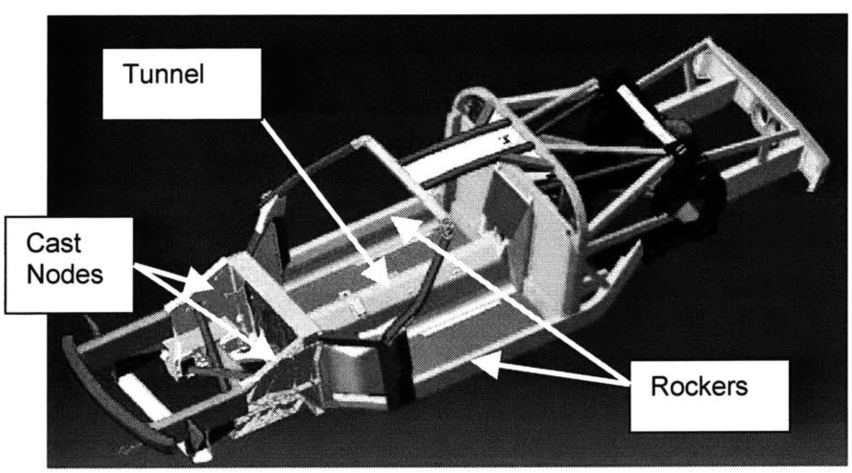


Figure 49: Supercar-A Frame.

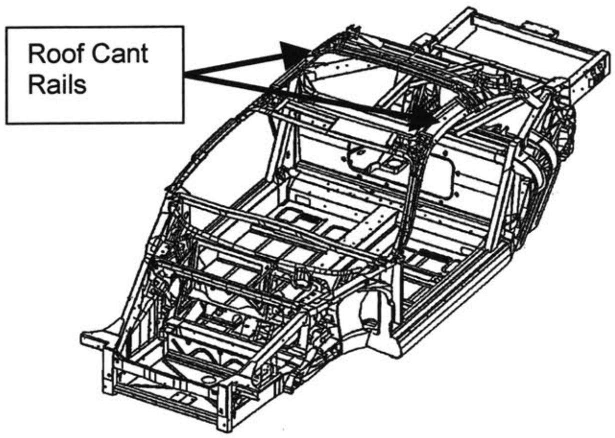


Figure 50: Ferrari 360 Modena Frame. [Nov]

However, the use the four large cast nodes in Figure 49 for suspension mounting serve to reduce joint sophistication and complexity in addition to structural and manufacturing accuracy benefits noted below. This is especially true at the rear of the car, where many extrusions are joined. Supercar-A's use of the cast nodes and potential complexity reduction is highlighted by comparison to a typical tubular space frame structure utilized in racing and other high performance car applications. View Figure 51, which shows the tubular space frame for a kit car in Europe. Space frames of this nature are manually MIG or TIG welded at the joints. Note the interconnections and apparent complexity of some of the joints where many members join. Is this truly more complex? It is difficult to accurately judge, but apparent complexity is often as important as actual complexity because it relates to one's ability to successfully execute a concept.

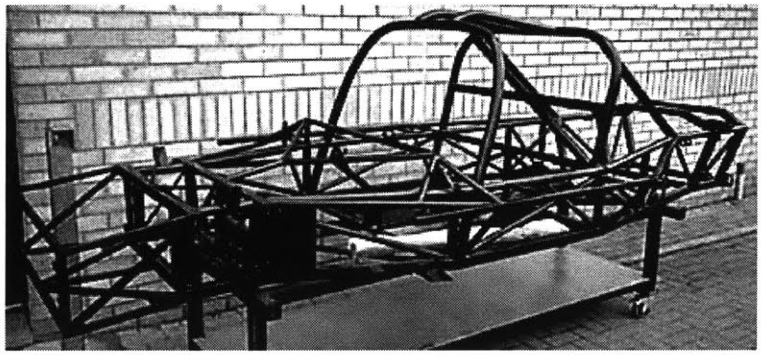


Figure 51: Ultima Kit Car Space Frame. Source: www.ultimacars.com.

2. Form and Function Union Principle applied to Supercar-A's Frame/Structure System Architecture

The use of high strength aluminum extrusions and castings in Supercar-A frame architecture represent a positive aspect with respect to marriage of form and function. Optimized 6000 series aluminum structures yield about 2/3 the weight of optimized HSLA steel structures providing the same strength (including fatigue) and stiffness. However, the aluminum structure typically requires larger sections to achieve this savings so more space is typically required. Note the large sections utilized on Supercar-A and 360 Modena frame versus the kit car's tubular space frame. In addition, the use of extrusions allows considerable flexibility in section shapes including interior stiffening ribs, for very low investment cost as compared to standard tubular or stamped steel alternatives. These brief statements on aluminum's superiority lead one to ask, "Why haven't aluminum structures been utilized more in the automotive industry?" Aluminum frames in the automotive world have been slow to take off for multiple reasons including material expense and greater joining expenses that are being reduced through continued development in the industry.

In addition to taking advantage of the aluminum construction for superior stiffness and strength to weight, the Supercar-A frame architecture employs the use of adhesive bonding in critical areas to improve its efficiency. It also stresses a few key body panels in the roof area, which is greatly needed as roof section details noted below challenge the structure's efficiency.

Supercar-A's and the 360 Modena's cast nodes and suspension mounting pads surrounded by ribbed structures represent another advantage for stiffness to weight as compared to the typical clevis joints employed for suspension control arm and damper attachment. The standard clevis joint is cantilevered off of the primary frame structure to allow machining or stamping of the mounting hole as well as well bolt insertion access for assembly. The cantilevered nature of the clevis joint requires additional structure and resultant mass to achieve a similar stiffness in the fore-aft, lateral and vertical joint loading. The fore-aft direction is important due to reaction of impact loading square edges and potholes in the road. The lateral local stiffness is required to react the cornering loads and typically requires increased local reinforcement in the standard clevis joint as it is often attached to an open section member, in which its wall is too compliant without additional reinforcement. Vertical stiffness with respect to weight for damper and spring loads is also a notable challenge for the cantilevered clevis structure. Example pictures of clevis mounts and the Supercar-A mounting scheme are located in section 4.11, Figure 59.

Further, Supercar-A's cast nodes and suspension mounting scheme facilitate post machining of the complete frame structure and its critical suspension mounting holes, yielding improved positional accuracy. This positional accuracy is important for proper wheel and tire kinematic and compliant behavior. Post machining of clevis joints is nearly impossible due to their orientation. Post machining of the completed frame structure improves accuracy due to the joining methods (welding), which impart heat and yield some distortion in the process. Note, the cast node machined pad as compared to the clevis joint does create a slight penalty with regard to joint complexity that is addressed in section 4.12, the suspension system architecture assessment.

However, Supercar-A frame structure architecture exhibits one notable deficiency with respect to marriage of form and function. Supercar-A's major load carrying structure placement at the center of the vehicle versus the rockers and roof cant rails yields considerable lower overall torsional and bending stiffness for a given weight. As discussed earlier, adequate frame stiffness is key to suspension and resultant vehicle dynamic performance. Note the size of the tunnel versus the rockers in Figure 52. Bending and torsional stiffness are a function of the area moment of inertia for the same material, length and loading. Area moment of inertia is maximized as material is placed the greatest distance possible from the neutral axis for bending or torsional loading. Therefore, placement of primary structure at the perimeter of the frame as opposed to the center yield far greater area moment of inertia for the same cross sectional area. Figure 52 below depicts a cross sectional view Supercar-A's primary load carrying structure as viewed fore-aft in vehicle in the center section passenger compartment. Figure 53 demonstrates an optional layout that improves structural efficiency.

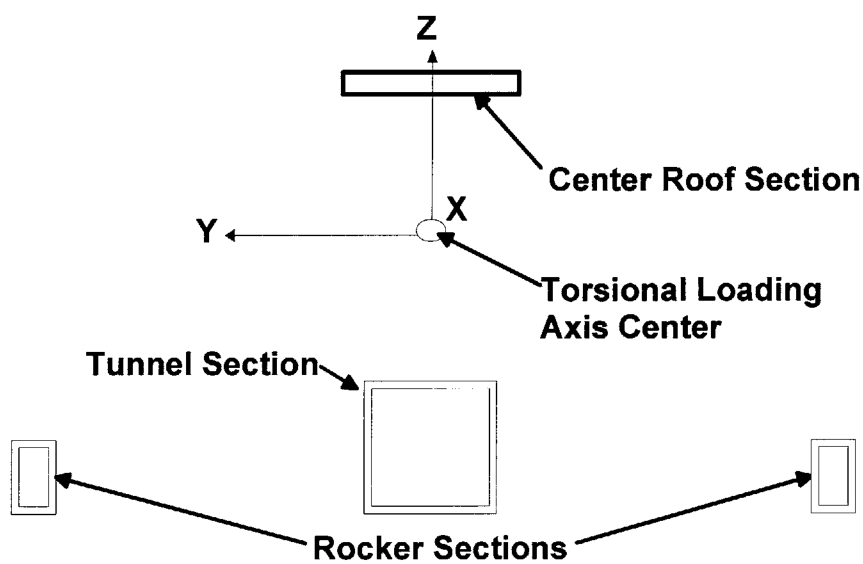


Figure 52: Supercar-A's Primary Load Carrying Member Cross Sectional Layout in the Center Section (Passenger Compartment) of the Vehicle as Viewed Fore-Aft.

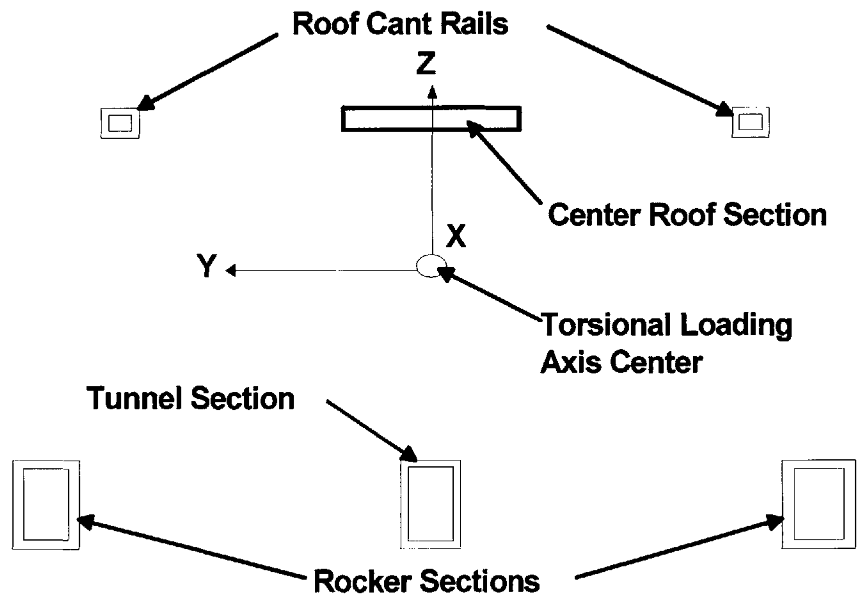


Figure 53: Optional Load Carrying Member Cross Sectional Layout in the Center Section (Passenger Compartment) of the Vehicle as Viewed Fore-Aft

The following brief analysis and rough calculations on torsional and bending stiffness are based on the cross sectional layouts shown in Figure 52 and Figure 53. First rough calculations for torsional stiffness.

Torsional Stiffness for a Rectangle

$$\text{Torque / Angle (lbf-in/deg)} = c_2 * a * b^3 * G / L$$ [Bee, Equation 3.44]

Where:

$c_2 * a * b^3$ = Polar moment of inertia for an area about the rectangle center (in^4)

(c_2 is based on the ratio of the rectangle's (long side) / (short side))

G = Shear Modulus (lbf/in^2)

L = Length (in)

The following calculations assume identical lengths and material (shear modulus); therefore, torsional stiffness is proportional to the polar moment of inertia. In addition, the total polar moment of inertia for each section is dependent on the distance from the torsional load axis, which adds the cross sectional area * distance^2. Table 24 demonstrates the differences in cross sectional layout and resultant polar moment of inertia for an area and weight. The "Baseline" refers to Figure 52, while the "Option" refers to Figure 53. The torsional load axis height utilized for the polar moment calculations is based on the average of the front and rear upper damper mounts. The upper damper mounts represent the position of primary torsional and bending loading. Also, note that the optional example maintained (actually increased slightly) the baseline spacing between the tunnel and rockers. Finally, the cross sections for the baseline example are rough equivalents, as they are not truly rectangular and the material assumed for weight calculations in 6061-T6 Aluminum. This brief and rough analysis demonstrates 31% greater polar moment of inertia (proportional to torsional stiffness) for an area with the same overall weight. This is a considerable margin of improvement. Yes, it is not completely accurate as the members actually see combined bending and pure torsion in this mode. In addition, it assumes one is able to create adequate load paths from the upper damper mounts to these members to allow them to carry the necessary load. However, it does serve to show potential for improvement in torsional stiffness efficiency. However, vertical bending stiffness follows, which again shows improvement by the option but not nearly as significant.

Table 24: Baseline and Option Primary Load Carrying Member Polar Moment of Inertia for an Area and Weight Calculations for Rough Torsional Stiffness Efficiency Comparison.

	Member Name	a-outside (in)	b-outside (in)	Wall thickness (in)	Member Only Polar Moment of Inertia for an Area- Ix = c2*a*b^3 (in^4)	Cross Sectional Area (in^2)	Distance from Neutral Axis (in)	Area * Distance^2 (in^4)	Total Polar Moment of Inertia= Ix + Area * Distance^2 (in^4)	Percent of Total Inertia	Length (in)	Weight (lbf)
Baseline	Rocker Left	6	3.5	0.16	14.4	2.9	39.7	4621	4635	38%	44	12.7
Baseline	Rocker Right	6	3.5	0.16	14.4	2.9	39.7	4621	4635	38%	44	12.7
Baseline	Tunnel	12	12	0.16	312.2	7.6	17.0	2190	2502	20%	44	32.7
Baseline	Roof Center	12	1.5	0.079	2.9	2.1	15.3	490	493	4%	33	6.8
								Total	12266	100%		64.8
Option	Rocker Left	7	6.5	0.16	52.7	4.2	38.1	6127	6180	38%	44	18.2
Option	Rocker Right	7	6.5	0.16	52.7	4.2	38.1	6127	6180	38%	44	18.2
Option	Tunnel	7	5	0.16	33.2	3.7	19.5	1421	1454	9%	44	16.1
Option	Roof Center	12	1.5	0.079	2.9	2.1	15.3	493	496	3%	33	6.8
Option	Roof Cant Rail Left	2	2	0.11	0.9	0.8	32.6	886	887	6%	33	2.7
Option	Roof Cant Rail Right	2	2	0.11	0.9	0.8	32.6	886	887	6%	33	2.7
								Total	16086	100%		64.7

Bending stiffness for the following rough calculations is based strictly on the area moment of inertia for the members in Figure 52 and Figure 53. It is based on the Moment-Area Theorem for Beam Deflection where the beam deflection is proportional to the total area moment of inertia if loading and member length is identical. [Ber] The neutral axis vertical position is again based on the average of the front and rear upper damper mounts. Bending stiffness efficiency is improved roughly seven percent in this case based on the area moment of inertia and weight for the optional layout. The results are shown in Table 25. This is a much smaller margin of improvement than the torsional case, as one might expect by visual inspection of the cross-sectional layout.

Table 25: Baseline and Option Primary Load Carrying Member Area Moment of Inertia and Weight Calculations for Rough Vertical Bending Stiffness Efficiency Comparison.

	Member Name	Height-outside (in)	Base-outside (in)	Wall thickness (in)	Area Moment of Inertia- Iy ($1/12*base*h^3$)	Cross Sectional Area (in^2)	Distance from Neutral Axis (in)	Area * $Distance^2$ (in^4)	Total Area Inertia= Iy + Area * $Distance^2$ (in^4)	Percent of Total Inertia	Length (in)	Weight (lbf)
Baseline	Rocker Left	6	3.5	0.16	14.4	2.9	20.0	1175	1189	23%	44	12.7
Baseline	Rocker Right	6	3.5	0.16	14.4	2.9	20.0	1175	1189	23%	44	12.7
Baseline	Tunnel	12	12	0.16	177.1	7.6	17.0	2190	2367	45%	44	32.7
Baseline	Roof Center	1.5	12	0.079	1.0	2.1	15.3	490	491	9%	33	6.8
								Total	5237	100%		64.8
Option	Rocker Left	7	6.5	0.16	32.3	4.2	19.5	1604	1636	26%	44	18.2
Option	Rocker Right	7	6.5	0.16	32.3	4.2	19.5	1604	1636	26%	44	18.2
Option	Tunnel	7	5	0.16	26.7	3.7	19.5	1421	1448	23%	44	16.1
Option	Roof Center	1.5	12	0.079	1.0	2.1	15.3	490	491	14%	33	6.8
Option	Roof Cant Rail Left	2	2	0.11	0.5	0.8	15.0	187	188	6%	33	2.7
Option	Roof Cant Rail Right	2	2	0.11	0.5	0.8	15.0	187	188	7%	33	2.7
								Total	5586	100%		64.7

Finally, the following covers rough lateral bending stiffness efficiency calculations, which are based on the same fundamentals as the vertical bending stiffness numbers. Lateral bending stiffness efficiency shows the greatest advantage for the option based on its area moment of inertia. Table 26 demonstrates a rough estimate of a 48% improvement in lateral bending stiffness efficiency. This is significant, like the torsional case, but again assumes that one is able to create adequate load paths from the upper damper mounts to these members. Visual inspection of the two diagrams and base frame layout does not demonstrate any major challenges to proper loading of the optional member layout.

Table 26: Baseline and Option Primary Load Carrying Member Area Moment of Inertia and Weight Calculations for Rough Lateral Bending Stiffness Efficiency Comparison.

	Member Name	Height-outside (in)	Base-outside (in)	Wall thickness (in)	Area Moment of Inertia- Iz (1/12*base*h^3)	Cross Sectional Area (in^2)	Distance from Neutral Axis (in)	Area * Distance^2 (in^4)	Total Area Inertia= Iz + Area * Distance^2 (in^4)	Percent of Total Inertia	Length (in)	Weight (lbf)
Baseline	Rocker Left	3.5	6	0.16	6.2	2.9	34.3	3446	3452	49%	44	12.7
Baseline	Rocker Right	3.5	6	0.16	6.2	2.9	34.3	3446	3452	49%	44	12.7
Baseline	Tunnel	12	12	0.16	177.1	7.6	0.0	0	177	2%	44	32.7
Baseline	Roof Center	12	1.5	0.079	30.3	2.1	0.0	0	30	0%	33	6.8
								Total	7112	100%		64.8
Option	Rocker Left	6.5	7	0.16	28.8	4.2	32.8	4524	4552	43%	44	18.2
Option	Rocker Right	6.5	7	0.16	28.8	4.2	32.8	4524	4552	43%	44	18.2
Option	Tunnel	5	7	0.16	15.9	3.7	0.0	0	16	0%	44	16.1
Option	Roof Center	12	1.5	0.079	30.3	2.1	0.0	0	30	0%	33	6.8
Option	Roof Cant Rail Left	2	2	0.11	0.5	0.8	28.5	675	676	6%	33	2.7
Option	Roof Cant Rail Right	2	2	0.11	0.5	0.8	28.5	675	676	6%	33	2.7
								Total	10503	100%		64.7

Again, while these are rough calculations, they do serve to show trends. Ultimately, this shows that the Supercar-A frame structure is probably less efficient than possible and therefore carries more weight than necessary.

Supercar-A's frame design team was well aware of this fact but the lack of cant rails in the roof across the door openings were dictated due to an exterior element of the body structure, which had to be preserved to maintain Supercar-A concept integrity. Also, the large tunnel versus large rocker decision was another legacy of the engine/induction system chosen. Supercar-A's engine package did not allow space for placement of the fuel tanks directly behind the passenger bulkhead on either side of the engine, as done in the 360 Modena and other vehicles in this class. Therefore, the tunnel was chosen for the best and only real position for the fuel tank, forcing its large size and negating the ability to utilize the scheme shown in Figure 53. One may note that the optional larger rockers shown in Figure 53 hurt driver and passenger ingress/egress to the vehicle, but ingress/egress, for example, did not make the top 25 goals. Consequently, it is a far lower consideration than the potential weight impact on vehicle dynamic performance. Ultimately, the optional case is not feasible, unless a different engine package facilitated fuel tank placement change. The roof cant rail members are even less likely as they would change the theme of the concept. Therefore, this structural efficiency analysis demonstrates primarily a deficiency to the 360 Modena frame/structure architecture.

3. Balanced Architecture Principle Applied to Supercar-A's Frame/Structure System Architecture

The Supercar-A's frame/structure only appears to exhibit an extreme with respect to the tunnel size versus the rockers as discussed. This highlights potential challenges noted regarding stiffness to weight efficiency.

4. Synergy Principle Applied to Supercar-A's Frame/Structure System Architecture

The following is a summary of Supercar-A's frame/structure concept impact on the relevant constraints and goals that are affected most, either positive or negative. However, the true performance impact and overall dynamic behavior sensitivity to weight, CG position and polar moment of inertias in the Supercar-A system architecture is unclear at this stage and requires further analysis utilizing DOE methods in parametric models.

- <u>Overall Vehicle Dynamics (Track) Performance-</u> Supercar-A's frame/structure architecture demonstrates numerous aspects that serve to improve stiffness to weight efficiency and resultant impact on mass and moments of inertia. However, the 360 Modena exhibits similar strengths. At the same time, the Supercar-A's primary load carrying placement represents a notable weakness as compared to the 360 Modena and its ultimate structural efficiency.

- Maintain Concept Integrity- Supercar-A's frame/structure exhibits strength with respect to this goal as it fully maintained the concept integrity.
- Craftsmanship- Supercar-A's frame structure architecture exhibits strength with respect to this goal due to the sculpted, appealing nature of its exposed elements.
- SVA- As noted earlier, the low production volume of Supercar-A causes great emphasis on fixed cost reduction. Supercar-A frame/structure architecture appears equal to the 360 Modena with respect to variable and fixed costs. Additionally, it yields far lower investment cost than the typical BFI architecture, like the Porsche 911 and Honda NSX, which typically contains numerous stampings with high tooling costs. However, a standard tubular space frame as depicted by the kit car in Figure 51, yields the lowest investment cost by a considerable margin. The kit car's investment cost is basically non-existent due to the usage of standard tubing. In addition, the primary load carrying members of Supercar-A frame/structure and resultant reduced efficiency with regard to stiffness and weight yields increased variable and fixed costs as the team works to achieve weight targets based on the 360 Modena frame. The increased expense comes in the form of more expensive materials and processes as well as increased engineering costs for additional optimization work.
- Timing- Supercar-A frame/structure appears to allow flexibility in design with relatively short-lead time and cost for extrusion tooling, but the cast nodes on the other hand require a fair amount more lead-time, which is potentially problematic. Also, the less efficient stiffness with respect to weight architecture requires more time than otherwise necessary to achieve its targets.

5. **Balanced External Forces Principle Applied to Supercar-A's Frame/Structure System Architecture**

   Supercar-A frame structure/design team incurred additional risk with respect to the system goals and constraints (primarily vehicle dynamic, cost and timing) due to one exterior concept mandate and an artifact of the powertrain architecture. The Supercar-A frame architecture included numerous novel aspects to counteract the mandated challenges, taking on greater risk in the process. The frame architecture itself does not appear to displace risk to other systems; instead incurring more to help the entire system achieve its goals within the given constraints.

This concludes frame/structure principles analysis and leads to the suspension system architecture analysis.

4.11 Chassis: Suspension System Architecture (2nd level decomposition) versus Principles Analysis

As briefly covered in the prior frame/structure discussion, the suspension's primary function includes isolating the sprung mass and occupants from imperfect road disturbances as well as minimizing vertical load variations at the wheel/tire to ground interface due to these disturbances. Road disturbance loading from gentle dips and bumps create primarily vertical input and resultant loading. Potholes and other forms of "square edges" impart longitudinal input and loading in addition to vertical, which the suspension system must absorb as well. While isolating the occupants from road imperfections the suspension system must maintain the proper wheel/tire attitude with respect to the road. The wheel/tire attitude is dictated by the chassis/suspension system's kinematics and compliance (stiffness) characteristics. The wheel/tire ground interface vertical load variation is dominated by the chassis/suspension system stiffness, damping and the sprung and unsprung mass.

There are innumerable suspension configuration options, but the few analyzed here represent the range utilized in high performance applications of the Supercar-A nature. The following four options are all variations on a four-bar linkage:

- Independent, unequal length, Double A-Arm (360 Modena, Viper)
- Independent, unequal length, Upper A-Arm, Lower L-Arm (Supercar-A)
- McPherson Strut (Porsche 911 front suspension)
- Multi-link (Porsche 911 rear suspension)

Example pictures are shown of each, where applicable in the following analysis. Note, the first two options listed are the primary architectures chosen in high performance vehicle applications of this nature. Also, the McPherson Strut alternative was only feasible at the rear of Supercar-A. It would not physically fit in the front and achieve the necessary wheel travel due to the very low front hood line.

In addition to suspension system overall configuration, other specific architecture differences, including interfaces to frame structure are analyzed. Once again the following assessment covers the strengths and weaknesses of the Supercar-A architecture that appear to impact the goals and constraints the most as opposed to every aspect. Supercar-A and its two benchmark vehicles' suspension architectural elements are listed in Table 27. This table demonstrates considerable similarity as well as notable differences. Many argue that all of these options provide very similar results, given proper implementation. However, there are still notable tradeoffs to assess.

Table 27: Supercar-A, 360 Modena and Viper Suspension System Architecture Comparison.

Architectural Element	Supercar-A	2003 Ferrari 360 Modena	2003 Dodge Viper
Chassis- Suspension			
Front Suspension Configuration	Independent, Unequal Length, Lower L-Arm, Upper A-Arm	Independent, Unequal Length, Double A-Arm	Independent, Unequal Length, Double A-Arm
Front Suspension Configuration	Independent, Unequal Length, Lower L-Arm, Upper A-Arm	Independent, Unequal Length, Double A-Arm	Independent, Unequal Length, Double A-Arm

Architectural Element	Supercar-A	2003 Ferrari 360 Modena	2003 Dodge Viper
Chassis- Suspension			
Control Arm Material	Cast Aluminum	Cast Aluminum	Cast Aluminum
Frame Interface Type	Bar Pin Style, Grippy Bushings bolted to machined mounts	Bar Pin Style, Slippery Bushings bolted to machined mounts	Standard Clevis Style, Grippy Bushings bolted to frame clevis
Front Damper/Spring Configuration	Outboard coil-over spring/damper	Outboard coil-over spring/semi-active damper	Outboard coil-over spring/ damper
Rear Damper/Spring Configuration	Outboard coil-over spring/damper	Outboard coil-over spring/semi-active damper	Outboard coil-over spring/ damper
Front/rear anti-rollbar configuration	Standard torsion anti-rollbar attached to the knuckle on the KPI	Standard torsion anti-rollbar attached to the lower control arm	Standard torsion anti-rollbar attached to the lower control arm

1. Minimize Complexity Principle Applied to Supercar-A's Suspension System Architecture

The unequal length A-Arm (Figure 54) and L-Arm (Figure 55) architectures represent a fairly low number of components and interfaces. In this aspect of complexity they are superior to the typical multi-link (Figure 56) option, which has two additional joints. However, the McPherson Strut (Figure 57) suspension architecture represents the least number of components and interfaces of the four architectures analyzed. This is due to the fact that the damper/spring strut replaces the upper control arm(s) yielding maximum integration of form. However, the McPherson Strut does exhibit a considerable increase in interface sophistication as the strut resists all load paths, including bending moments, not resisted by the coil-overs in the other three architectures. The integration of form debatably increases the complexity for prediction of kinematics, compliance and friction behavior as well. Therefore, it is not perfectly clear, which is superior with regard to complexity. The multi-link suspension kinematics and compliance behavior is also slightly more difficult to predict than the double A-Arm or A-Arm/L-Arm concepts. The A-Arm/L-Arm architecture provides the least complexity of all with respect to difficult compliance behavior prediction as it decouples lateral and longitudinal characteristics. This advantage is discussed further in the form and function union principle analysis.

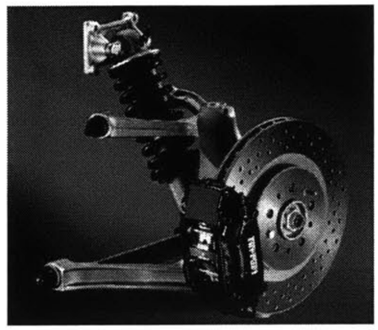


Figure 54: 2003 Ferrari 360 Modena Right Front Suspension and Foundation Brakes. Independent, Unequal Length, Double A-Arm Architecture. Source: www.ferrari.com.

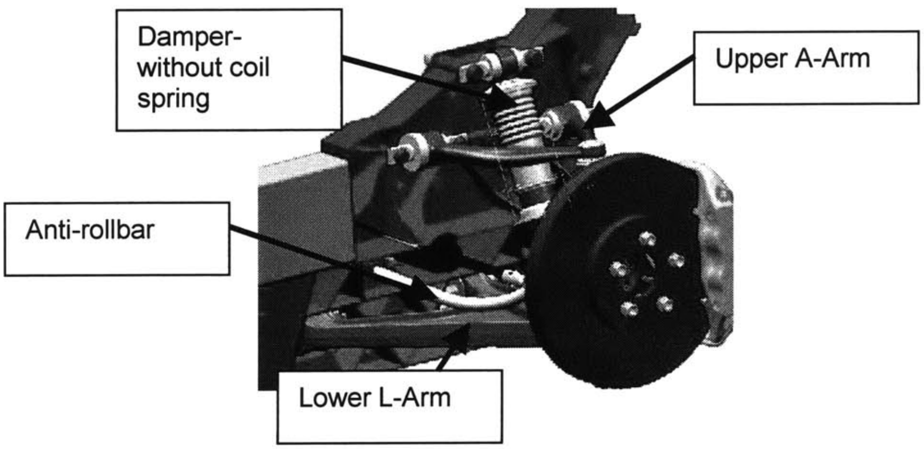


Figure 55: Supercar-A Left Front Suspension, Steering and Foundation Brakes. Independent, Unequal Length, Upper A-Arm, Lower L-Arm Architecture.

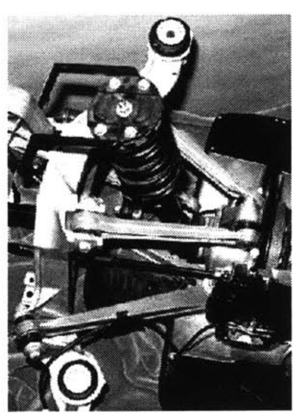


Figure 56: 1995 Porsche 911 Rear Suspension and Subframe. Multi-link Architecture.

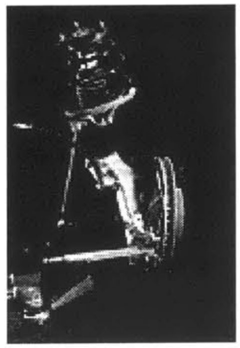


Figure 57: 2003 Porsche 911 Turbo Left Front Suspension. McPherson Strut Architecture. Source: www3.Porsche.com.

Another aspect of the suspension system involves sub-frames, which many use to create necessary structure and isolate the suspension loads. This can add considerable complexity with regard to the number parts, interfaces and prediction of behavior. Supercar-A and its two benchmarks do not utilize sub-frames.

At the same time, Supercar-A and the 360 Modena utilize bar pin style bushings and two bolts interfaced to machined holes as opposed to the typical clevis joint. These bolts see shear and tensile loading. The standard bushing and clevis joint utilizes a singular bolt loaded in shear. This aspect of the Supercar-A architecture represents an aspect of increased complexity as compared to typical alternatives. The bushing becomes more complex and requires an additional mounting bolt.

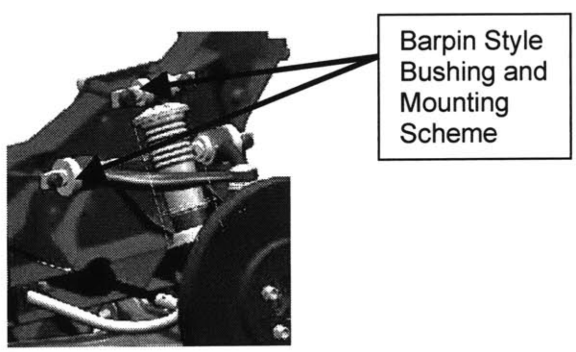


Figure 58: Barpin Style Bushings Mounted to Frame Structure with Two Bolts Each.

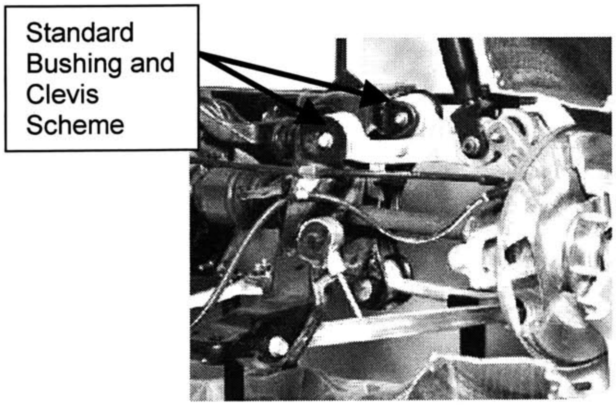


Figure 59: Standard Bushings Mounted to a Clevis Style Frame Structure with a Single Bolt.

2. Form and Function Union Principle Applied to Supercar-A's Suspension System Architecture

This section first covers a brief comparison of the Supercar-A and McPherson Strut and Multi-link control arm configurations with respect to this principle. The union of form and function analysis then focuses on assessment of the Supercar-A versus the more common Double A-Arm layout as well as other architecture aspects.

While the McPherson Strut architecture provides superior form integration within the suspension system itself, it exhibits some functional downsides as well frame structure integration challenges. Functionally, the McPherson Strut is the most deficient with respect to camber (the tire's front view vertical angle with respect to a plane normal to the road surface) control as compared to the other three architectures listed. Camber control is one of the most important aspects of the suspension system kinematics. At the same time, the McPherson Strut does provide superior damper and spring travel to wheel travel, increasing sensitivity to inputs and decreasing loading on the system. However, the superior motion ratio does not come for free. The McPherson Strut requires a fairly large, cantilevered tower that requires considerable frame structure to achieve proper stiffness. Therefore, the resultant stiffness to weight efficiency for the system is degraded a fair amount with respect to the Supercar-A suspension architecture and other alternatives. Further, it is difficult (or impossible) to package in vehicles of this nature due to its height.

Conversely, the Multi-link suspension configuration allows for very similar kinematics and compliance characteristics and resultant system mass (a small amount heavier) to the unequal length A-Arm/L-Arm architecture. However, the multi-link does it with additional complexity in components and prediction of behavior as noted above. Therefore, unequal length A-Arm/L-Arm is deemed superior with regard to this principle.

While the unequal length double A-Arm and the unequal length A-Arm upper and L-Arm lower appear very similar, there are considerable differences with respect to the union of form and function. First and foremost, the highly loaded lower L-Arm provides for superior ride and handling balance as it decouples lateral and longitudinal compliance. Lateral compliance characteristics (camber, steer, lateral displacement) are key for cornering while longitudinal compliance behavior (caster wind-off, steer, longitudinal displacement) affects braking, accelerating and impact isolation. The upper A-Arm, lower L-Arm architecture also provides for superior stiffness to weight due to the standard double A-Arm architecture utilized by the 360 Modena. This is due to the L-Arm's primary control structure placement directly in-line (tension/compression) with the wheel forces during highly loaded cornering events. The same wheel forces in a double A-Arm yields compressive/tensile and bending loading that attempts to separate the two legs, requiring added structure due to combined loading. Supercar-A's use of a new semi-solid cast aluminum process also improved its structural efficiency, although very similar to the 360 Modena's in this respect.

The last advantage of the L-Arm architecture itself in Supercar-A's specific case involves the fact that lower L-Arm is swept forward, facilitating greater passenger compartment foot space. Once again improving function through its form.

The last major positive aspect of the suspension architecture worth noting with respect to this principle involves the usage of the barpin style bushings as opposed to the standard through-hole bushing. As noted in the frame/structure analysis, this style bushing provided for improved system structural efficiency as well as facilitates improved mounting location accuracy. Compare Figure 58 and Figure 59, noting the cantilevered nature of the clevis joint versus the corresponding structure for the barpin concept. Note the clevis type joint requires one "ear" to be relatively soft in bending to allow proper joint closure, so it relies heavily on the other cantilevered ear for fore-aft stiffness. However, the 360 Modena embodies the same barpin architecture; therefore, it is not an advantage for Supercar-A as compared to its primary competitor.

3. Balanced Architecture Principle Applied to Supercar-A's Suspension System Architecture

The Supercar-A's suspension architecture does not appear to exhibit any extremes.

4. Synergy Principle Applied to Supercar-A's Suspension System Architecture

The following is a summary of Supercar-A's suspension concept impact on the relevant constraints and goals that are affected most, either positive or negative.

- <u>Overall Vehicle Dynamics (Track) Performance-</u> Supercar-A's suspension architecture demonstrates superiority with respect to this goal as compared to the 360 Modena and other options. This is due to advantages with respect to structural efficiency (mass) and kinematics and compliance (lateral and longitudinal) characteristics.
- <u>Maintain Concept Integrity-</u> Supercar-A's suspension architecture maintains the show car concept integrity.
- <u>Craftsmanship-</u> The Supercar-A suspension system is clean and uncomplicated in appearance and consistent with a vehicle of this class.

- Seating Package- As noted earlier, the forward swept lower L-Arm provided for additional footwell space in the passenger compartment as compared to alternatives.
- SVA- Similar investment and variable cost with respect to the 360 Modena. Both vehicles utilized identical suspension architectures front to rear, which facilitates commonization and reduced investment cost. The 360 Modena commonized knuckles on the diagonal (left front was identical to right rear and vice versa). Supercar-A utilized one upper control arm at all four corners and only three separate castings for all eight control arms. Superior structural efficiency also serves to reduce engineering and material costs. However, the use of barpin style bushings represent a measurable piece cost increase as compared to standard alternatives as well as greater assembly cost as discussed briefly below.
- Manufacturing/Assembly- Supercar-A's barpin style bushings and resultant frame facilitates manufacturing accuracy. However, installation and proper indexing of the bar pin bushings in the control arms represent an additional challenge not exhibited in other options. The indexing is important in the Supercar-A suspension architecture as the bushing style and indexing affect the vehicle's static ride height. Further, the barpin style bushings require two bolts instead of one and increased difficulty regarding bolt head access during control arm assembly. Finally, the Supercar-A (and 360 Modena) suspension architecture and barpin interface utilize shims instead of cams to adjust alignment, causing additional difficulty during final assembly. The additional manufacture and assembly challenges involved in the Supercar-A suspension system represent its primary deficiency as compared to alternatives.
- Timing- The Supercar-A unequal length upper A-Arm and lower L-Arm architecture reduces required design and development time due to its decoupled longitudinal and lateral compliance characteristics. This improves ones ability to determine the proper geometry and stiffness combinations in design as well as development.

Further, identical control arm architecture front to rear and resultant commonality serves to reduce design and manufacture time. Finally, Supercar-A's suspension system architecture and resultant structural efficiency serves to reduce engineering time and optimization with regard to weight. However, the barpin style bushing and resultant interface requires more design and analysis time as compared to the standard clevis interface due to increased complexity and different bolt loading.

5. Balanced External Forces Principle Applied to Supercar-A's Frame/Structure System Architecture

The Supercar-A suspension architecture exhibits some additional risk with respect to "standard" unequal length A-Arm/L-Arm alternatives. First, the barpin bushing design and resultant interface was fairly new to OEM-A, requiring additional analysis and effort as opposed to reliance on experience and rules of thumb for the standard design. This is especially true for the interface to frame design. Additionally, the architecture employed the use of a semi-solid casting process, which was originally developed at MIT in the 1960's and has evolved considerably since. However, the suspension control arms represent a fairly new application of this technology.

Upon reflection, the barpin style bushing interface did transfer some risk to teammates creating the frame architecture and completing its design and development. The new casting process, however, kept the risk within the suspension design team. Ultimately, both examples of additional risk are countered by their improvement in structural efficiency and resultant weight savings in critical unsprung mass and well as sprung mass.

This concludes the Supercar-A suspension system architecture analysis through principles application. This analysis demonstrated strengths primarily with little conflict in trends. Therefore, only additional assessment of the importance of mass and wheel control with respect to the system goals in the DOE analysis can completely validate or refute the usage of the barpin style bushing, which added cost and manufacturing/assembly difficulty.

4.12 Chassis: Wheel/Tire Architecture (2nd level decomposition) versus Principles Analysis

As briefly discussed earlier, the wheel and tire assembly is responsible for creating, transmitting and controlling all of the vehicle dynamic forces. The tire itself is the vehicle's interface to the road and is paramount to the dynamic behavior of the system. Therefore, this seemingly simple subsystem warrants separation from the other chassis systems.

The Supercar-A relevant wheel and tire information is shown in Table 28. While these dimensions are second level decomposition design parameters, they also represent aspects of concept and resultant impact on structural efficiency, unsprung mass and moments of inertia. Further, these dimensions represent aspects of the chosen wheel/tire architecture selected early in a program as they all involve considerable tooling and lead-time. Therefore, these parameters are not "tunable". For purposes of this thesis the basic dimensions represent a considerable portion of the wheel/tire concept. For example, the tire's aspect ratio is the tire's sidewall height as a percentage of its width. In Table 28 the Supercar-A front tire is a 235/45 ZR18. This means the tire is 235 mm wide and its sidewall height is 45 percent of 235 mm, which equals 106 mm. The "Z" is the speed rating of the tire, where "Z" is the highest speed rating available for a tire. The "R" stands for radial construction and the "18" is the rim diameter in inches.

The choice of a "small" wheel and tire combination versus a "large" one, or a low aspect ratio versus a high aspect ratio tire, can have considerable impact on the vehicle's goals and constraints as shown below.

The following assessment covers the strengths and weaknesses of the Supercar-A wheel/tire architecture that are believed to impact the goals and constraints the most as opposed to every aspect.

Table 28: Supercar-A, 360 Modena and Viper Wheel/Tire System Architecture Comparison.

Architectural Element	Supercar-A	2003 Ferrari 360 Modena	2003 Dodge Viper
Chassis- Wheels and Tires			
Front Wheel Size	9" x 18"	7.5" x 18"	11" x 18"
Rear Wheel Size	11.5" x 19"	9.5" x 18"	14" x 19"
Wheel Material	Cast Aluminum	Cast Aluminum	Forged Aluminum
Front Tire Size	235/45ZR18	215/45ZR18	305/35ZR18
Rear Tire Size	315/40ZR19	275/40ZR18	345/30ZR19

1. **Minimize Complexity Principle Applied to Supercar-A's Wheel/Tire System Architecture**

   The standard radial tire is more complex than one may assume. A cross section of its primary elements is shown in Figure 60. This is not identical to the Supercar-A tire makeup but is representative to give one the understanding of the level of complexity involved.

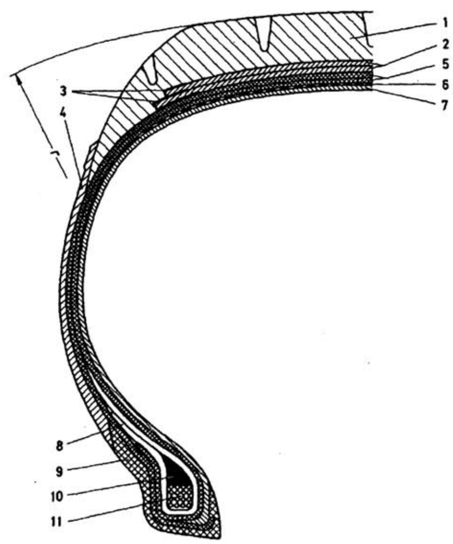


Figure 60: Standard Radial Design Passenger Car Tire Cross-Section ("T" Speed Rated). The components are: 1- running tread; 2- steel belt; 3- edge protection for the belt (nylon or rayon); 4- sidewall; 5- substructure with two layers; 6- cap; 7- inner lining; 8- flipper; 9- bead profile; 10 core profile; 11- bead core. [REI, p. 92]

However, the single piece cast aluminum wheels and radial tires for Supercar-A do not exhibit additional complexity as compared to its competitors or known options.

2. Form and Function Union Principle Applied to Supercar-A's Wheel/Tire System Architecture

The Supercar-A exhibits a fairly large diameter wheel and tire package. Again, basic external dimensions of the wheel and tire combination are fixed at the beginning of vehicle design and development due to the long lead and costly tooling required for both. The diameters were dictated by the Supercar-A concept. Larger diameters have become a trend for aesthetic reasons, but also have some functional advantages as well as potential disadvantages. Large diameter wheels facilitate the use of larger diameter, more efficient brake rotors and improved braking performance. At the same time the larger diameter wheels include increased unsprung mass and rotational inertia. Increased unsprung mass hurts ride, while increased rotational inertia (shown in Figure 61 below) hurts acceleration. A rough estimate of unsprung mass and rotational polar moment of inertia follows utilizing the Supercar-A rear wheel/tire assembly as the 19-inch example. A 17-inch wheel tire combination of the same width and aspect ratio yields approximately a 12 percent reduction in weight simply based on a ratio of circumferences with all else being equal. At the same time, the 17-inch wheel and tire combination roughly provides a 50 percent reduction in polar moment of inertia about its axis of rotation (Iyy) on the road based on mass * (radius of gyration^2). Further dynamic analysis in the DOE RSE phase of CD-SAAM is required to better understand the tradeoffs.

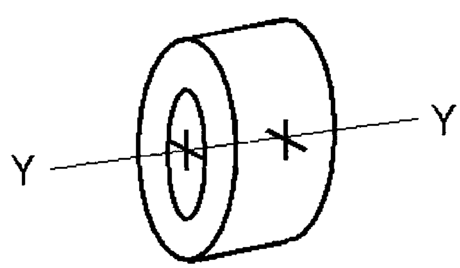


Figure 61: Unsprung Mass (wheel and tire) Axis of Rotation: Y-Y.

At the same time, the Supercar-A tire exhibits fairly tall sidewall heights, based on its width and aspect ratio, as compared to much of its competition, including the 360 Modena. This is especially true at the rear. Supercar-A's front tire sidewall is nine percent taller than the

360 Modena's while the rear is 15% taller. This aspect of the tire exhibits potential for advantages and disadvantages over alternatives. First, the taller sidewall heights can provide superior secondary ride performance through better isolation of road impacts. Second, the taller sidewall heights facilitate improved wheel durability in rougher road conditions. At the same time, the taller sidewall heights can create added difficulty in achieving the desired cornering stiffness and resultant steering/vehicle response discussed in the vehicle dynamics fundamentals section. Simply reviewing the ratio of sidewall heights gives one a feel for structural efficiency under lateral loading. In simplest terms, a lateral force at the contact patch multiplied by the tire's sidewall height provides a very rough estimate of this efficiency. Therefore, additional or stiffer materials and construction may be required for the taller sidewall tire to achieve the same lateral and cornering stiffness. This may lead to increased cost and/or weight. Figure 62 below shows the rear Supercar-A wheel tire combination versus an option with one step down in aspect ratio, which provides the same sidewall height as the 360 Modena. However, this method of sidewall height reduction shown was infeasible for Supercar-A due to the considerable outer diameter change. This change ruins the tire to fender opening gap or else requires an enormous tear up to the body, which was infeasible. At the same time, there was another potential option, which I did not think of during the final wheel/tire architecture establishment. Perhaps the design studio would have been agreeable to increasing the wheel diameters one size, decreasing aspect ratios one step and maintaining overall diameter. Further dynamic analysis in the DOE RSE phase of CD-SAAM is required to better understand the tradeoffs and whether or not the change is justified.

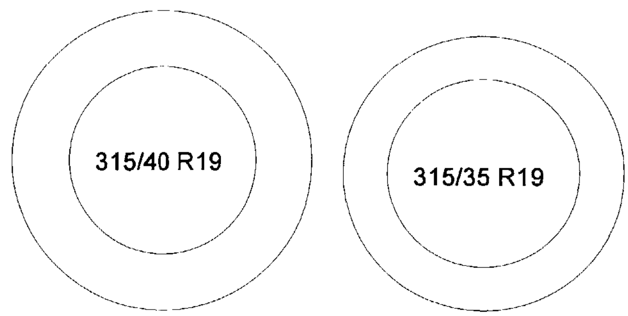


Figure 62: Supercar-A's Rear Wheel/Tire Combination Scaled Against the Next Step Down in Aspect Ratio Tire For Comparison.

The final aspect to discuss regarding the union of form and function regarding the wheel and tire package involves their width. This was the only dimensional aspect of the tire open for us to choose at the beginning of the program. Some, like the 360 Modena, attempt to make a "narrow" tire act like a "wide" one, with different tradeoffs. The general tire width and the ratio of the tire width front to rear as they relate to the vehicle's CG location and overall weight are critical to all aspects of the vehicle's handling dynamics in this class of vehicle. Considerable effort and DOE analysis were utilized to determine the proper widths and find a reasonable balance.

3. **Balanced Architecture Principle Applied to Supercar-A's Wheel/Tire System Architecture**

   For this class of vehicle, Supercar-A's tire sidewall heights represent an extreme highlighting potential challenges to meeting handling and steering targets.

4. **Synergy Principle Applied to Supercar-A's Wheel/Tire System Architecture**

   The following is a summary of Supercar-A's wheel/tire concept impact on the relevant constraints and goals that are affected most, either positive or negative.

   - <u>Overall Vehicle Dynamics (Track) Performance-</u> Supercar-A's wheel/tire architecture demonstrates a combination of strengths and weaknesses with respect to this goal as compared to the 360 Modena and other options as highlighted in the Form and Function Union Principle application.

- <u>Maintain Concept Integrity-</u> Supercar-A's wheel/tire architecture maintains the show car concept integrity.
- <u>SVA and Timing-</u> Similar investment and variable cost with respect to the 360 Modena, but a potential for increased design and development costs and time if the Supercar-A's tire sidewall height proves to impact its handling and steering in a negative sense.
- <u>Quality/Reliability-</u> The Supercar-A wheel/tire package demonstrate an advantage over its competitors in this department due to its tall sidewall heights.

5. **Balanced External Forces Principle Applied to Supercar-A's Wheel/Tire System Architecture**

   The potential element of additional risk in the Supercar A's wheel/tire architecture involves the tire's sidewall height that was dictated by the Showcar Concept in conjunction with the wheel diameter, which may not balance well against the all of the goals and constraints. It is not clear at this stage of analysis. It requires further analysis on the potential impact on the tire's cornering stiffness and resultant vehicle handling performance in the DOE RSE phase of CD-SAAM.

This completes the principles analysis section. Final conclusions regarding the five principles application to complex dynamic system architecture are found in section 6.3. Corresponding recommendations for improvement to the principles application are also found in the same section.

4.13 QFD Analysis of Supercar-A Engine/Induction System Architecture

Completion of the principles application of Supercar-A system architecture rendered final evaluation of many aspects. For example, Supercar-A's transmission/driveline architecture assessment is fairly complete at this stage, with the exception of quantification of an option that impacts the vehicle's yaw inertia and weight distribution. The principles analysis also highlighted multiple facets of concepts, which required further analysis for final assessment. Supercar-A's engine/induction system architecture appears the most apparent example of one requiring additional analysis to fully evaluate its merit. This need is highlighted in the application of the Synergy principle in which there existed a considerable degree of conflicting trends of architecture performance over a wide range of constraints and goals affected. The potential for displaced and unbalanced risk versus the system goals and constraints described in the Balanced External Forces principle application further justifies additional analysis.

QFD is the next tool chosen to evaluate system architecture merits from a qualitative perspective. QFD appears tailor made for further assessment of Supercar-A's engine/induction system due to its ability to transform a complicated collection of conflicting trends into an organized array, resulting in a final score for each option. The usage of a weighting system for each constraint and goal, as well as a score selected for the impact of a particular concept on each constraint and goal provides a more rigorous system for evaluation of architecture. In this process the score selected can and should be based on the arguments posed in the principles section. As noted in section 2.5, the scores in the following example maintain standard QFD practice and utilize either a "9", "3" or "1" with regard to the level of positive impact on a particular constraint or goal. A "9" represents the most positive affect, while a "1" the least, relative to the competing concepts. This large separation emphasizes differences in concepts and forces one to identify considerable gain or deficiency when scoring. Goals or constraints that are not affected by the architecture options or inability to differentiate impact between the options are left blank and do not influence the result.

The QFD analysis requires the inclusion of competing architectures for evaluation. The following Supercar-A engine/induction system architecture analysis compares four different concepts. The four concepts, which are assumed to have dry sump oiling systems include the following:

1. *Aluminum 5.4 L, quad OHC, inter-cooled, supercharged V-8*. This is the actual Supercar-A engine/induction system.

2. *Aluminum 5.4 L, quad OHC, inter-cooled twin turbo charged V-8.* This is the Supercar-A engine with an inter-cooled twin-turbo charged induction system, which appeared to exhibit potential in the principles analysis.
3. *Aluminum, 6.4 L, quad OHC, normally aspirated V-10.* This is the V-10 engine/induction system architecture option briefly discussed in the five principle application analyses.
4. *Aluminum 5.8 L, pushrod actuated OHV, normally aspirated V-8.* This final option was not discussed in prior analysis but appears to be a strong potential option for Supercar-A, which was overlooked by the Supercar-A program for multiple reasons. This alternative engine is an architecture from a prior generation of engines at OEM-A that have been primarily phased out of production. However, its architecture has been and continues to be used in many high performance applications, especially motorsports. Other engines from this lineage (larger and smaller displacement) could have been selected for this analysis, but this one intuitively appeared to embody the best balance with respect to Supercar-A's goals and constraints based on the prior analysis. Although, the marketing implications of this engine architecture is unclear and would require further investigation if this option proved advantageous.

A comparison chart of these four different engine and induction system architectures is located below in Table 29. This table includes relevant information for the QFD analysis including the following: engine dimensions, engine mass, resultant vehicle mass, engine CG location, resultant vehicle CG location, resultant vehicle polar moments of inertia, resultant vehicle weight transfer, yaw natural frequency and yaw damping. Ideally, the engine system rotating and reciprocating inertia is included in the following comparison, but it was not available for each option. This information is utilized for QFD scoring of vehicle dynamics and package related goals. Note engine CG information is estimated based on the engine dimensions. The engine CGx position is based on half of the length of the engine and the front of the engine block. The deeper FEAD of the supercharged engine moves the front of the engine block an extra three inches beyond the other alternatives. The CG height is simply based on half of the engine height for each. This is probably an overestimation, especially for the pushrod V-8 option number four, but it is a reasonable approximation. In addition, the cooling pack weight has been simply scaled by the horsepower provided to the combustion chamber. Not perfect, but a reasonable estimate. Note Table 29 demonstrates the comparison in percent difference terms relative to the baseline engine to highlight contrast and protect a few proprietary elements.

Table 29: Supercar-A Engine/Induction System Architecture Comparison Table.

	Supercar-A Engine/Induction System Architecture Options			
Relevant Engine/Induction System Information for Supercar-A's Vehicle Dynamics and Package Related Goals	**#1- Aluminum 5.4 L, quad OHC, inter-cooled super-charged V8**	**#2- Aluminum 5.4 L, quad OHC, inter-cooled twin turbo charged V8**	**#3- Aluminum, 6.4 L, quad OHC, normally aspirated V10**	**#4- Aluminum 5.8 L, pushrod actuated OHV, normally aspirated V8**
Engine Length % Difference from Baseline (%)	Baseline	-12%	5%	3%
Engine Height % Difference from Baseline (%)	Baseline	0%	0%	-20%
Engine Width % Difference from Baseline (%)	Baseline	0%	0%	-27%
Engine/Induction Weight % Difference from Baseline (%)	Baseline	-7%	-18%	-18%
Cooling Pack Weight % Difference from Baseline (%)	Baseline	-17%	-20%	-36%
Engine CGx Position % Difference from Baseline (%)	Baseline	-3%	-1%	-2%
Engine CG Height % Difference from Baseline (%)	Baseline	-2%	-2%	-15%
Peak HP % Difference from Baseline	Baseline	0%	6%	-22%
Peak Torque % Difference from Baseline	Baseline	0%	-2%	-20%
Peak RPM % Difference from Baseline	Baseline	0%	11%	0%
Vehicle Weight/Peak HP % Difference from Baseline	Baseline	-2%	-10%	22%
Vehicle Weight % Difference from Baseline (%)	Baseline	-2%	-4%	-5%
% Front Weight Distribution % Difference from Baseline (%)	Baseline	2%	2%	0%
Vehicle CG Height % Difference from Baseline (%)	Baseline	0%	0%	-3%
Vehicle Yaw Moment of Inertia % Difference from Baseline (%)	Baseline	-4%	-4%	-6%
Vehicle Pitch Moment of Inertia % Difference from Baseline (%)	Baseline	-5%	-5%	-7%
Vehicle Roll Moment of Inertia % Difference from Baseline (%)	Baseline	0%	0%	0%
Total Lateral Load Weight Transfer @ 1 G % Difference from Baseline (%)	Baseline	-3%	-5%	-8%
Total Longitudinal Load Weight Transfer @ 1 G % Difference from Baseline (%)	Baseline	-3%	-5%	-8%
Yaw Natural Frequency % Difference from Baseline (%)	Baseline	1%	0%	1%
Yaw Damping Ratio % Difference from Baseline (%)	Baseline	0%	0%	0%
Understeer Gradient (deg/G) % Difference from Baseline (%)	Baseline	5%	10%	10%

Originally, I intended to only have engine/induction system architecture options in this comparison that embodied a (vehicle curb weight (lbf)) / (horsepower (Hp)) ratio of 6.7 or better. However, I found that I was initially overestimating the horsepower potential of the fourth option and so it does not directly meet this criterion as shown above. I have left this option in the analysis though as one notes its considerable size advantage in width and height, which could have facilitated improved structural efficiency and overall performance.

For reference, (vehicle weight) / (horsepower) is a rule of thumb ratio relating the total vehicle weight to horsepower, where engine horsepower is work done over time. This ratio then gives one an estimate of the vehicle's acceleration capability as compared to another. The 6.7 ratio utilized here is based on option one above with a projected vehicle curb weight of 3350 lb and predicted horsepower of 500 Hp. Therefore, if an engine/induction system is projected to reduce system weight by 200 lb, then it need only produce 470 Hp (3150/6.7). Obviously, this horsepower is only a peak number and area under the curve is a more accurate representation of engine performance, but this simple ratio is sufficient at this stage of analysis. The actual QFD analysis comparing the four described engine/induction system architecture options is covered directly below in Table 30. Reasoning for each score is found in Table 31 directly after the QFD table.

Table 30: Supercar-A Engine/Induction System Architecture QFD.

		Weighting	Supercar- A	Engine/Induction	Architecture	Options
			#1- Aluminum 5.4 L, quad OHC, inter-cooled super-charged V8	#2- Aluminum 5.4 L, quad OHC, inter-cooled twin turbo charged V8	#3- Aluminum, 6.4 L, quad OHC, normally aspirated V10	#4- Aluminum 5.8 L, pushrod actuated OHV, normally aspirated V8
Constraints	1- Federal Regulations- Emissions only	10	9	3	9	1
	2- Timing- J123, Production	10	9	3	1	1
	3- SVA impact- Fixed Cost	10	3	3	9	9
	4- SVA impact- Variable Cost	10	3	3	9	9
	5- Quality/Reliability	10	9	3	1	3
	6- Manufacture/Assembly	10	3	1	9	9
	7- Maintainability- No specialty Tools	10				
Live or Die Goals	8- Overall Vehicle Dynamic/Track Performance	10	3	9	9	3
	9- Handling Performance	9	1	3	3	9
	10- Straight-line Acceleration Performance	9	9	3	9	1
	11- Aesthetic Appeal- Maintain GT Concept Integrity	9	9	3	3	1
	12- Braking Performance	8	1	3	3	9
	13- Steering Performance	8	1	3	3	9
	14- Craftsmanship	8	3	9	9	9
	15- Exhaust Tone/Note	7	9	3	9	9
	16- Drivability	7	9	3	9	9
	17- Shift Quality	7				
	18- Primary Ride Performance	6	1	3	3	9
	19- Seating Package	6	3	9	1	1
Other Goals	20- Powertrain NVH Performance	5	1	3	9	9
	21- Wind NVH Performance	5				
	22- Secondary Ride Performance	4	1	3	9	9
	23- Road NVH Performance	4				
	24- Vehicle Range	2	1	9	3	3
		Score	762	610	962	938
		Rank	**3**	**4**	**1**	**2**

Prior to discussion of the final results of the QFD it is worth including examples of the notes for the scores found in Table 30, which are heavily based on the information provided in Table 29. The following format in Table 31 for documenting specific scoring reasoning is suggested in which the first number represents the goal or constraint (row) and the second number represents the architecture option (column).

Table 31: Supercar-A Engine/Induction System Architecture QFD Scoring Specifics Example.

Row-Column	QFD Scoring Specifics
1-2	Turbo charger's negative impact on catalytic converter light-off as it absorbs heat.
1-4	Pushrod historic emissions performance and OEM-A's departure from development of this architecture.
2-2	Core competency is not as strong with regard to turbo charged systems; therefore, increased design/development time is predicted with respect to option 1.
2-3	Noted V10 challenges including crankshaft and cooling; therefore, a considerable increase in design/development time is predicted with respect to option 1.
2-4	Emissions challenges and OEM-A's departure from development of this architecture; therefore, a considerable increase in design/development time is predicted with respect to option 1.
3-1 to 3-2	Additional forced induction systems, which contain a fair number of additional parts to the normally aspirated counterparts. In addition, the extra engine weight (especially for option 1) as compared to the other two options forces additional material and engineering costs to offset the weight penalty.
4-1 to 4-2	Additional forced induction systems versus normally aspirated options.
5-2 to 5-3	Quality and reliability downgraded due to reduced core competency and/or predictive capability challenges resulting in inability to meet the requirements within timing. Otherwise options 3 and 4 are equal to or better than option one for this goal.
6-1	Downgraded with respect to options 3 and 4 due to additional components utilized for forced induction.
7-1 to 7-4	Left blank due to inability to differentiate between the four options.
8-1	Downgraded with respect to options 2 and 3 due to similar horsepower to system weight but greater vehicle weight, polar moment of inertias and weight transfer.
8-4	This option is far superior to all in weight, polar moments of inertia and weight, but it is at a considerable weight/horsepower disadvantage.
9-1	Downgraded the most as it is the heaviest, with the largest polar moments of inertia, greatest weight transfer.
9-2 to 9-3	Downgraded as they are in between options one and four regarding weight, polar moment of inertia and weight transfer.
10-2	This option should embody similar peak horsepower to option one, but it is probably not as flat so it is downgraded. Although, potential advantage in engine/induction system inertia may counteract this penalty.
10-4	Downgraded heavily for its considerable weight/horsepower disadvantage. Although, potential advantage in engine/induction system inertia may counteract a portion of this penalty.
11-2 to 11-3	These two fit the image of the vehicle (in my opinion), but are downgraded as option one was the actual engine/induction system shown in the concept.
11-4	Downgraded the most due to its horsepower rating versus the alternatives as well

Row-Column	QFD Scoring Specifics
	as it may be considered "old technology" as compared to the alternatives.
12-1	Downgraded the most due to longitudinal weight transfer.
12-2 to 12-3	Downgraded as they are in between options one and four longitudinal weight transfer.
13-1	Downgraded the most due to lateral weight transfer and yaw polar moment of inertia.
13-2 to 13-3	Downgraded as they are in between options one and four for lateral weight transfer and yaw polar moment of inertia.
14-1	Downgraded due to a less "clean" appearance of the supercharger and resultant plumbing as well as its FEAD.
15-2	Downgraded due to the muffled exhaust note of a turbocharged engine.
16-2	Downgraded due to turbo lag.
17-1 to 17-4	Left blank due to inability to differentiate between the four options.
18-1	Downgraded the most due to the greatest engine/induction system weight and pitch moment of inertia.
18-2 to 18-3	Downgraded as they are in between options one and four for engine/induction system weight and pitch moment of inertia.
19-1	Downgraded as it is in between options two and three/four for overall engine length.
19-3 to 19-4	Downgraded the most due to the greatest overall engine length.
20-1	Downgraded the most due to supercharger noise and vibration and proximity of supercharger to the passenger compartment.
20-2	Downgraded due to turbine noise and vibration.
21-1 to 21-4	Left blank due to lack of impact on the goal.
22-1	Downgraded the most due to the greatest engine/induction system weight making it more susceptible to secondary shake.
22-2	Downgraded as it is in between options one and three/four for engine/induction system weight.
23-1 to 23-4	Left blank due to lack of impact on the goal.
24-1	Downgraded the most due to the least operating efficiency of the options.
24-3 to 24-4	Downgraded as they are in between options one and two for operating efficiency.

The final scoring exhibited in Table 30 predicts that engine/induction system option three, the aluminum 6.4 L V-10, provides the best synergy with respect to the affected goals and constraints, as compared to the other three concepts. Option four, the aluminum 5.8 L V-8, is a close second, while option one finishing third and option two a distant fourth. Note option one is the Supercar-A's chosen engine/induction system architecture. While prior principles analysis noted multiple challenges and areas of opportunity in this option, it is surprising that the QFD results are this dramatic. Further, prior analysis in the principles section indicated that the twin turbo charged option might fair better than the supercharged concept. This was not the case and demonstrates an advantage of QFD and its ability to organize a large collection of conflicting trends and reduce engineering judgment (intuition) bias.

While engine/induction system architecture options three and four demonstrate superiority over the chosen architecture, some would argue that only option one in this analysis was feasible within the given timing constraints. Therefore, some may argue this is not a fair comparison. Also, the V-10's additional length poses another challenge to its implementation due to potential impact on the seating package, within the wheelbase constraints. The infeasibility of the other engine concepts may be true within the given resource and system architecture assumptions for the Supercar-A program, but it is also worth arguing that this analysis is completely valid. The analysis demonstrates that the engine/induction system chosen has a high potential of displacing risk, and ultimately hurting the synergy and overall performance of the vehicle with respect to its all of its goals and constraints. In addition, a few heavily weighted constraints including timing were downgraded considerably with respect to option one and still showed superiority. Further, the ultimate timing risk to the program for options three and four may actually be less than option one for the overall system. This is due to the increased time required for additional weight, weight distribution and resultant vehicle dynamic performance optimization for the rest of the systems required in concert with option one.

However, while QFD analysis is more rigorous and less biased than the prior principles application or other approaches based on engineering judgment, it still is primarily qualitative. The numerous vehicle performance scores above, for example, are based soundly on the basic laws of physics. However, they still do not include true quantification of the sensitivities of the specific design parameters affected by the options. Therefore, it is sometimes difficult to justify downgrading a score from a "9" to a "3", for instance. QFD analysis is heavily based on predicted trends as opposed to actual quantification. Specifically, quantification of design parameters like vehicle weight, weight distribution, CG height and polar moment of inertia's impact on every aspect of vehicle performance is still marginal at this stage of analysis. Most would agree that increasing weight or CG height of the vehicle, for example, is detrimental to virtually all aspects of Supercar-A's vehicle dynamic performance; however, quantifying the level of importance or impact for tradeoff decisions is difficult. Is a tradeoff decision that increases overall vehicle weight by three percent considerable? Is it worth downgrading from a score of "9" to a "3" in the above analysis? Experience says, "yes" for this class of vehicle. Ultimately, it is dependent on the nominal settings for all of the important design parameters and the respective constraints and goals for the system. A three percent increase in overall vehicle weight on a family sedan may be inconsequential as compared to the same increase in Supercar-A due to very different constraints and goals as well as very different nominal design parameters.

In addition, while this engine/induction system QFD analysis includes considerable effort to represent the input and concerns of the Supercar-A powertrain engineers, it is still the work of a single person. Had the Supercar-A engine/induction system demonstrated superiority in the QFD analysis shown in Table 30, one could argue for completion of the engine/induction system architecture evaluation at this phase of CD-SAAM. However, this specific engine/induction system analysis, as well as much of the prior principles application analysis in phase two, warrant further analysis in phase four of CD-SAAM to quantify the true importance of numerous design parameters. The final DOE RSE methodology phase and resultant design parameter sensitivity analysis provides the ability to finalize assessment of multiple aspects Supercar-A's system architecture, which is incomplete at this stage.

5 Quantitative Analysis Application of the Supercar-A System Architecture

5.1 Chapter 5 Scope and Objectives

Chapter Five involves the fourth and final phase of CD-SAAM application to the Supercar-A system architecture. As noted earlier, the fourth phase is quantitative in nature and includes the utilization of DOE RSE methodologies in parametric models to calculate and provide true design parameter to vehicle behavior relationships (sensitivities) as shown again in Figure 63.

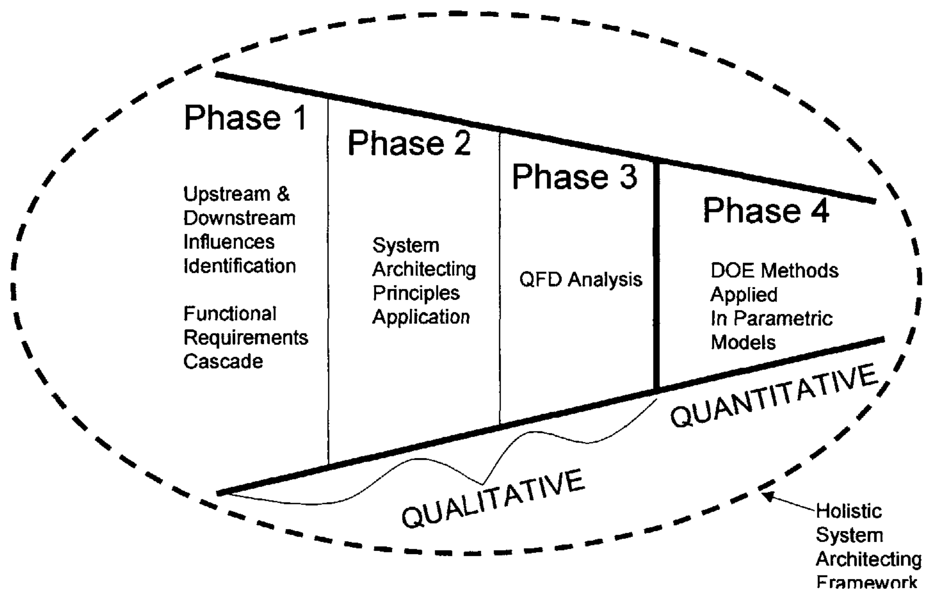


Figure 63: CD-SAAM Framework.

The design parameters and vehicle behavior analyzed are those highlighted in the prior phases of evaluation, which require further assessment. Quantification of the identified design parameters facilitates final assessment of remaining aspects of a system architecture, which are inconclusive up to this stage of CD-SAAM. Analysis in the three prior stages of CD-SAAM highlighted numerous high level design parameters, which impact Supercar-A's goals. The following sections of Chapter Five complete analysis of two DOEs. The first DOE covers Supercar-A's straight-line acceleration performance, while the second covers its handling performance. These two specific vehicle behaviors are chosen for potential conflict of needs, especially with respect to Supercar-A's goals, as well as their ability to cover a majority of the top ranked overall vehicle dynamic performance.

The resultant RSE's for each DOE provide the sensitivities as well as direct comparison ability to finalize assessment of Supercar overall, powertrain and chassis system architectures. The following analysis includes background information on the DOE setup, including high level specifics about the models used. The analysis for each vehicle response includes direct observations on the relative importance of the design parameters, while conclusions about open aspects of the Supercar-A system architecture are left until the completion of all the DOE results.

5.2 Supercar-A's High level Design Parameters Chosen for DOE Application Summary

As briefly discussed, the two DOE analyses chosen for the final system architecture assessment of Supercar-A involve its straight-line acceleration and handling dynamics capability. The potential performance conflict between the two corresponding goals for Supercar-A is underscored in the following discussion. Supercar-A's straight-line acceleration goals require considerable powertrain torque characteristics, for example. However, system architecture decisions made to achieve high torque often add measurable weight to the system and resultant increase in CG height, weight distribution and polar moments of inertia. Some of these increases may actually help straight-line acceleration, while increases of these parameters are predicted to hurt handling performance. A considerable portion of the prior analysis highlighted numerous Supercar-A system architecture decisions impact on the following design parameters in generic terms requiring further quantification of relative importance:

- Driveline torque versus speed and acceleration characteristics
- Total vehicle weight
- Total vehicle three axis CG location
- Total vehicle three axis polar moments of inertia
- Unsprung mass rotational polar moment of inertia
- Aerodynamic drag characteristics
- Tire three axis force and moment properties
- Driveline ratio change time

These generic design parameters are broken down further in some cases in the following straight-line acceleration a handling performance DOE's and are mapped directly to show their relationship.

5.3 Straight-line Acceleration DOE Background

The straight-line acceleration analysis comprises a nine factor, three level DOE completed in a parametric full vehicle dynamic model. The full vehicle dynamic model utilized, VDANL [Aln], is fairly specific to automotive application. Representation of subsystems, components and interfaces are represented by singular parameters, lookup tables or polynomial curves making it parametric for purposes of this thesis. For example, the suspension kinematics and compliance are represented by second order polynomial curves in VDANL, as opposed to the specific use of components and linkages (Double A-arm versus McPherson strut architecture, for example) utilized in more detailed models. The more detailed component based models actually determine the kinematics and compliance behavior of the system. However, the level of fidelity and accuracy in VDANL is appropriate for the following straight-line acceleration analysis, which does not warrant the use of a component based, more detailed model. Although as noted in the brief parametric model discussion in section 2.4, one must be aware of parameter settings and their relevance to the physical system.

Straight-line Acceleration Factors

The actual factors chosen for analysis are a function of the above generic parameters highlighted for further analysis in prior phases of CD-SAAM and assumed specific to straight-line acceleration performance. For example, engine architecture choices directly impact the following high level design parameters listed above: driveline torque versus speed and acceleration, total vehicle weight, total vehicle CG location and total vehicle polar moments of inertia. The factors for the straight-line acceleration DOE represent a combination of the highest level design parameters from the first and second level form/function decomposition. The specific parameters chosen as factors are directly mapped to the corresponding high level generic factor in Table 32 below. Range of adjustment explanation and level setting for each factor in the DOE is located afterward in detail.

Table 32: Straight-line Acceleration DOE Factors Mapped to Corresponding Design Parameters.

Factors	Corresponding "Generic" High level Design Parameter
1- Engine Torque vs. RPM Curve (lb-ft vs. rpm)	Driveline torque versus speed and acceleration characteristics
2- Engine rotating/reciprocating Inertia- (lb-ft-s^2)	Driveline torque versus speed and acceleration characteristics
3- Unsprung Mass Rotational Inertia- Iyy front/rear (lb-ft-s^2)	Unsprung mass rotational polar moment of inertia
4- Tire Peak Longitudinal Capability (Coefficient of Friction)	Tire three axis force and moment properties
5- Aero Drag (Cd)	Aerodynamic drag characteristics
6- Total Vehicle Weight with Driver (lbf)	Total vehicle weight
7- Total Shift Time (s)	Driveline ratio change time
8- Total Vehicle Fore/Aft Weight Distribution (% Front Weight)	Total vehicle three axis CG location
9- CG Height- Total Vehicle at Design from Ground (in)	Total vehicle three axis CG location

Review of Table 32 demonstrates that a few of the factors are identical or nearly identical to the high level design parameter so the relationship requires little explanation. These particular factors, including total vehicle weight are identical due to the fact that they are full vehicle (first level decomposition) based. However, others are not as direct and require brief explanation because they are based on the 2nd level architecture. For example, the engine torque versus rpm curve represents the highest level design parameter of the engine architecture performance with respect to driveline torque versus speed and acceleration. Engine rotating and reciprocating inertia (the sum of the engine inertias from the flywheel, crankshaft, pistons, rods, auxiliary drives, etc) directly impacts the highest level driveline torque versus acceleration characteristics. The unsprung (wheel and tire) rotational inertia factor represents only one axis of rotation, which is its primary axis of rotation during acceleration as shown in Figure 64.

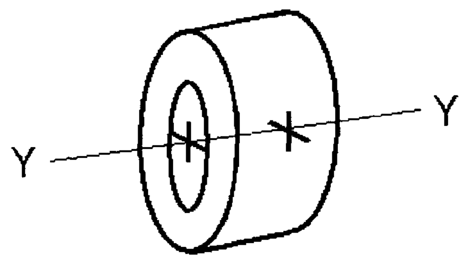


Figure 64: Unsprung Mass (wheel and tire) Axis of Rotation: Y-Y

The tire's peak longitudinal capability (thrust) factor is represented by its coefficient of friction at the interface with the road surface in the fore-aft direction (X-direction in vehicle coordinates) for accelerating and braking. This coefficient of friction is a single element, although important, of the tire's three axis force and moment properties. The force and moment properties are described in more detail in the handling DOE section below.

The total shift time factor includes the driver and the total time for a gear ratio change to occur including throttle lift, driveline disengagement (clutch) and return to original speed and acceleration trajectory. Therefore, this factor combines the architecture efficiency, the typical driver capability and the basic inertia of the system.

The factor adjustment range or levels chosen for each are based primarily on the architecture options described during the prior qualitative analysis. The range for each factor does not, however, encompass the entire scope of architecture possibility for the supercar class. The factor levels chosen due encompass a majority of the architecture possibilities and resultant design parameters in some cases, like unsprung mass rotational inertia. Other cases, like the range for percent front weight distribution, are more limited to the realm of the mid-engine car. An estimate of the ability to change aspects of the architecture was also a factor in the appropriate range for this analysis, in addition to the prior qualitative evaluation. As an example, there was no chance of Supercar-A changing from its mid-engine layout in this particular case. A reduced range of factor adjustment is advantageous as it tends to improve the accuracy of the resultant RSE's utilized for analysis. This is especially true for systems with high interactions and non-linear behavior.

Table 33 shows the factor setting specifics for the straight-line acceleration DOE. A few of the wider ranges deserve further comment. The two inertia ranges demonstrate a very wide range of adjustment as compared to the others. However, the nature of polar moment of inertia calculations (function of mass and distance squared) make them very sensitive to typical architecture changes in the wheel and tire. The total range shown for the unsprung rotational inertia corresponds to approximately a 10% change in wheel/tire diameter for the Supercar-A, in which its wheel/tire diameters are shown at the top end of the range. Shift time, not discussed in the prior phases of evaluation, is included because of its wide range performance due to heavy interaction between the driver and the shift mechanisms.

Table 33: Supercar-A Straight-line Acceleration DOE Factors and Levels

	Level		
Factors	**Low**	**Nominal**	**High**
1- Engine Torque vs. RPM Curve (lb-ft vs. rpm)	-5%	500	+5%
2- Engine rotating/reciprocating Inertia- (lb-ft-s^2)	-20%	0.34	+20%
3- Unsprung Mass Rotational Inertia- Iyy front/rear (lb-ft-s^2)	-25%	.83/1.2	+25%
4- Tire Peak Longitudinal Capability (Coefficient of Friction)	-5%	1.05	+5%
5- Aero Drag (Cd)	-10%	0.39	+10%
6- Total Vehicle Weight with Driver (lbf)	-5%	3522	+5%
7- Shift Time (s)	-30%	0.2	+30%
8- Total Vehicle Fore/Aft Weight Distribution (% Front Weight)	40	43	46
9- CG Height- Total Vehicle at Design from Ground (in)	-5%	17.5	+5%

Straight-line Acceleration Responses

Specific straight-line responses for this analysis are based on Supercar-A's goals. The four vehicle responses related to straight-line acceleration utilized to complete the desired sensitivity analysis are as follows: zero to sixty mph acceleration time, quarter mile elapsed time, 80 to 160 mph acceleration time and top speed. The 80 to 160 mph acceleration time is the only response not explicitly stated in Supercar-A's goals. The specific reasoning for usage of this response is included in discussion below on "model assumptions/limitations".

Straight-line Acceleration DOE Design

Numerous years of experience with regard to analysis of this nature have demonstrated the merit of a specific matrix design algorithm that provides the fidelity required and proper representation of vehicle dynamic systems with far fewer runs than a full-factorial matrix. The matrix design algorithm utilized in this analysis is called "D-Optimal". OEM-A proprietary scripts run in Matlab generate the matrix that specifies the factor settings and the number of runs. This nine factor, three level DOE resulted in a 100 run matrix. For reference, a full factorial run for the same experiment requires 19,683 runs. Even though the DOE analysis is run in a parametric model as opposed to the physical world, and consequently, requires much less time and effort, the savings of the D-Optimal design versus the full-factorial by almost a factor of 200 is worth it.

Straight-line Acceleration Response Surface Equations (RSE's)

The resultant RSE's for the straight-line acceleration DOE take on the same form as the one described in section 2.4, except this specific equation encompasses 55 separate terms and is as follows:

$$Y = B0 + B1 * X1 \ldots B9 * X9 + B10 * (X1 * X2) \ldots B45 * (X8 * X9) + B46 * X1^2 \ldots B54 * X9^2$$

Once again showing the coefficients for the first order effects (B1...B9), non-linearities (B46...B54) and first order interactions (B10...B45), ignoring higher-level interactions. OEM-A proprietary scripts run in Matlab were utilized to complete the regression and corresponding RSE's.

Straight-line Acceleration Modeling Assumptions/Limitations

There are a few notable assumptions/limitations in the modeling of this vehicle dynamic system and straight-line acceleration events that deserve mention. First, standing start acceleration is difficult from a modeling perspective as well as reality in high torque vehicles of this nature. Minimizing wheel-spin and maximizing traction is difficult for the driver in an actual supercar and arguably represents the greatest variation in elapsed time results for standing start acceleration runs. Running simulations from a standing start exhibit the same challenge as well as additional difficulty with regard to numerical stability starting from zero speed. Starting the simulation at zero speed is a difficult numerical problem that also adds a small degree of variability to the results. The following acceleration analysis utilizes a simple closed loop "traction control". The simulation simply ramps from zero to "full throttle" over 0.1 seconds and the traction control system in the model compares wheel slip (percent longitudinal slip) against a threshold value and effectively reduces the torque versus rpm curve accordingly until wheel-spin drops below the given threshold. The simulation quickly returns to "full throttle" operation once acceptable longitudinal slip is achieved. The percent longitudinal slip utilized in this case is eight percent, based on tire performance knowledge. While this is analogous to the control of an experienced driver of these vehicles, it is not identical. However, the sensitivities from the acceleration analysis do exhibit characteristics that appear to differentiate setups with regard to their impact on wheel-spin. Also, the 80 to 160 mph metric added for this straight-line acceleration analysis provides sensitivity analysis without the wheel-spin challenges. However, 80 to 160 mph is simply part of the run to top speed as opposed to starting at 80 mph steady state and then accelerating to 160 mph. Therefore, this is not completely analogous to a real world example like acceleration from the exit of a medium speed corner at a racetrack.

The second major assumption/limitation of the following straight-line acceleration analysis involves the engine torque versus rpm curve utilized. The nominal engine torque curve represents that of Supercar-A, while the low and high settings for engine torque merely include a +/-5% shift. This is reasonable, but certainly not completely accurate as the engine/induction architectural options described earlier do not all exhibit the same curve shape. Figure 65 represents the 5.4 L V-8 supercharged engine torque versus rpm curve utilized in Supercar-A. It also shows the curve of one of the prime alternatives; the 6.4 L V-10 normally aspirated engine discussed earlier in the principles and QFD analysis.

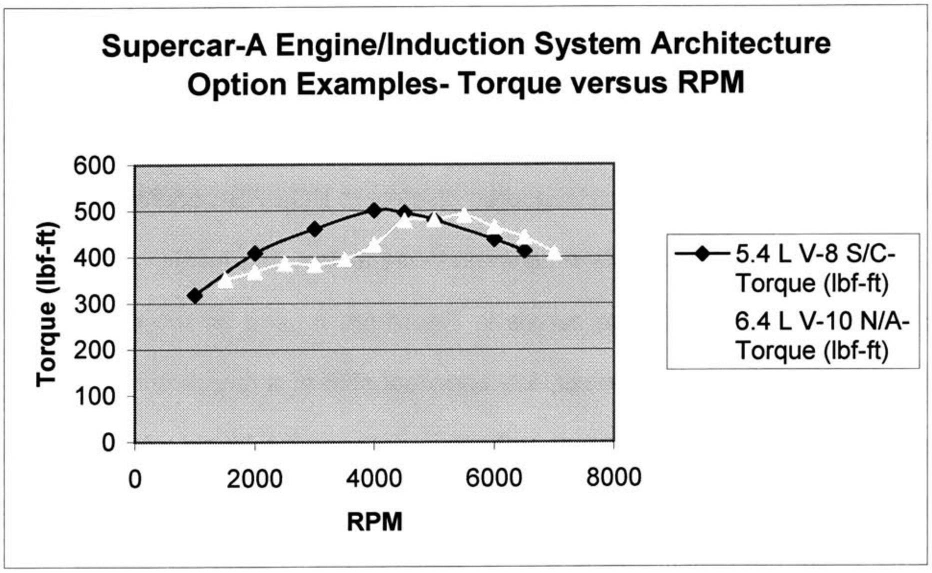


Figure 65: Supercar-A Engine/Induction System Architecture Option Examples- Torque versus RPM.

Supercar-A's supercharged torque curve is the flattest of the options. However, while the shift may overestimate the "flatness" of lower torque options, it also underestimates the rpm range of the slightly lower torque alternative shown, which would increase the area under the curve and gain performance back. However, different strengths are assumed, even if the two curves exhibited the same area under the curve. Presumably, the V-8 supercharged engine would exhibit better acceleration from a standing start while the V-10 makes it up on the top end. However, proper gearing may equalize these two examples. Mention of gearing raises the other limitation of this analysis, which was a mistake on my part that was not caught until after the fact and too late to change. Typically, the powertrain engineers would review peak horsepower versus vehicle weight and adjust the final gear multiplication accordingly for lower or higher horsepower options. Unfortunately, this analysis does not adjust the final torque multiplication with engine torque adjustment, so it can over estimate higher engine torque's advantage over a lower one by a small degree. Therefore, the adjustment of engine torque in this analysis is not ideal but is still useful as long as the potential discrepancies from reality are kept in mind while drawing conclusions.

The different engine torque versus rpm curve shapes discussion brings up a potential challenge with the usage of DOE RSE methods in system architecture analysis as prescribed in CD-SAAM. System architecture concepts are fairly discrete in nature as opposed to the continuous factors utilized in this analysis. If something is considered discrete in DOE RSE analysis, one cannot make inferences about performance at points in between those tested. The levels in between are invalid. For example, the two separate torque curves in Figure 65, if used as two different levels in the DOE, would be discrete factors. However, the non-ideal shift of a torque curve +/- five percent is continuous and allows for valid analysis at settings in between the levels tested. In addition, most relevant design parameters affected by architecture options, as demonstrated in this straight-line acceleration DOE and the handling DOE can be analyzed in a continuous fashion. Single number design parameters like mass, stiffness, moments of inertia, etc. are all prime examples of continuous factors. Different curve shapes, like the engine torque versus rpm are not. However, there are methods to transform a seemingly discrete factor like torque versus rpm into a set of continuous parameters. For example, engine torque versus rpm curves can be fit fairly well with third order polynomials as shown in Figure 66. Each term in the polynomial could be a continuous factor and allow DOE RSE analysis to include different curve shapes and a better representation of the discrete architectures. Unfortunately, it is difficult to make sense of changes to the polynomial terms and understand their impact on the curve shape and level. Therefore, the engine torque versus rpm example could benefit from a custom curve fit with terms that make more sense as demonstrated by the tire model discussed below for the handling DOE. Perhaps terms that represents initial torque, max torque, final torque, final RPM and area under the curve. At the same time, some point out the significant chance of optimizing toward a combination of parameters and resultant curve that is physically infeasible to meet by current concepts. On the other hand, this scenario provides potential for narrowing focus of R&D work to gain a competitive advantage in the future.

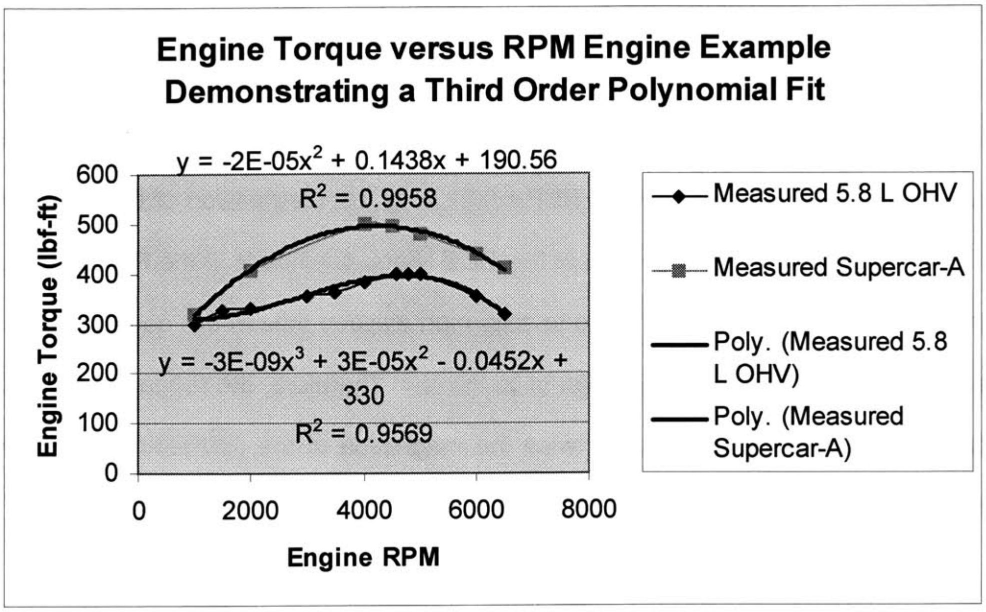


Figure 66: Engine Torque versus RPM Examples Demonstrating a Third Order Polynomial Fit Over the Measured Data.

Of course, an easier but more time consuming method for dealing with discrete factors involves completion of multiple DOE's with the different discrete factors held fixed in each. This is more difficult to compare results and truly understand the system but is an approach utilized often.

A final limitation includes the fact that all vehicle parameters, other than those utilized as factors, are fixed at a level, which corresponds to the actual setting in Supercar-A. This includes the parameters like transmission gearing and suspension vertical stiffness (spring rates). Therefore, the results potentially exhibit a bias based on the vehicle parameters held constant. However, the prior qualitative analysis, based on sound fundamentals highlighted the design parameters chosen as factors, which are first order effects. The other numerous design parameters held fixed are assumed to play a reduced role or are not deciding factors in the remaining architecture decision. In addition, items like gearing and suspension spring rates are primarily considered tunable as opposed to architectural decisions. Further, the analysis is intended to understand and quantify gross vehicle behavior for system architecture decisions as opposed to refinement.

5.4 Straight-line Acceleration DOE Sensitivity Analysis

The straight-line acceleration run sensitivity analysis includes the four stated events, starting with review of the zero to sixty mph acceleration results to quantify the relative importance of each factor. The sensitivity analysis utilizes the RSE coefficients from regression of the responses as a function of the factor settings for each run of the DOE. Each coefficient in the RSE represents the magnitude of change in the response (zero to sixty mph elapsed time in this case) if a given factor is adjusted from its nominal level to the high or to the low. Therefore, the range of impact from the low setting to high setting for a factor is twice the magnitude of the coefficient. Table 34 shows abbreviations for each factor description in the following bar charts.

Table 34: Straight-line Acceleration DOE Analysis Factor Name Abbreviation for Bar Charts

Factors	**Factor Name Abbreviation**
1- Engine Torque vs. RPM Curve (lb-ft vs. rpm)	Eng-Torq
2- Engine rotating/reciprocating Inertia- (lb-ft-s^2)	Eng-Inertia
3- Unsprung Mass Rotational Inertia- Iyy front/rear (lb-ft-s^2)	US-Iyy
4- Rear Tire Peak Long Capability (Coefficient of Friction)	rTire-PLong
5- Aero Drag (Cd)	Drag
6- Total Vehicle Weight with Driver (lbf)	Wt
7- Shift Time (s)	Shift-ET
8- Total Vehicle Fore-Aft Weight Distribution (% Front Weight)	%FW
9- CG Height- Total Vehicle at Design from Ground (in)	CG-h

Figure 67 depicts the top 12 coefficients in a bar chart (pareto), based on their magnitude, for Supercar-A's zero to sixty mph elapsed time analysis.

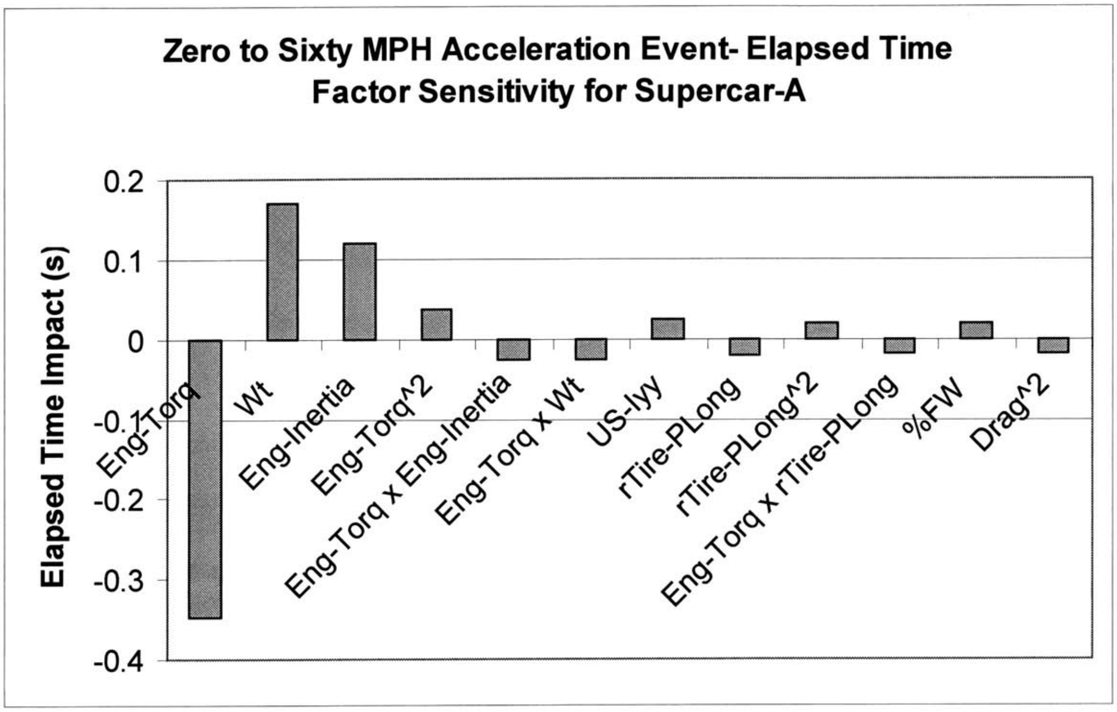


Figure 67: Zero to Sixty MPH Acceleration Elapsed Time Factor Sensitivity for Supercar-A.

Factors whose bar goes positive in Figure 67 represent an increase in elapsed time (performance degradation) as the factor is adjusted from the nominal setting to the high setting. A bar that goes negative depicts the opposite trend. The cutoff in coefficient magnitude for the following sensitivity curves is any term within 5% of the greatest coefficient magnitude, in this case engine torque. Therefore, the other 42 terms in this RSE are viewed as inconsequential. The regression of coefficients for the four straight-line acceleration DOE's resulted in an R-Squared Adjusted fit of 0.99. This means the analysis and regression fit the relationship between the factors and response very well and should provide a very good representation of trends. However, the resultant standing start elapsed times for Supercar-A in this analysis may be a little slow compared to actual times. For example, the simulation predicts a 4.5 second elapsed time while preliminary testing of the car demonstrates times closer to 4 seconds flat, while the quarter mile elapsed time prediction is 12.5 seconds versus test times closer to 11.8 seconds. This discrepancy is most likely due to different traction conditions (coefficient of friction) as well as better control over the vehicle launch from a standing start in the actual vehicle. This conclusion is backed up by the reduction in percent difference between predicted performance and actual as the event length increases. Further, analytical models are best utilized for analysis of trends as opposed to absolutes.

Multiple observations relevant to the Supercar-A system architecture assessment can be made from review of Figure 67. The ones that standout the most are as follows:

- Engine torque, vehicle weight and engine inertia are the overwhelming key contributors to Supercar-A's zero to sixty mph elapsed time performance.
- A five percent upward shift of the engine torque curve results in a 0.34 second reduction in elapsed time, while a five percent reduction in vehicle weight yields only a 0.17 second reduction in elapsed time for Supercar-A. This observation leads one to believe that the standard ratio of (total vehicle weight) / (engine horsepower) for comparison of powertrain/vehicle architecture options and resultant acceleration performance is invalid in this case. However, engine inertia is not necessarily inseparable from architecture options that provide notable changes in torque characteristics. This is discussed in the next point.
- Engine inertia is a measurable contributor to Supercar A's zero to sixty mph elapsed time performance. For the most part, a reasonable increase in engine torque results in an increase in engine rotating and/or reciprocating inertia. The range of engine inertia chosen for this analysis corresponds to the range of engine options and torque given.
- Table 35 demonstrates a direct comparison of Supercar-A nominal settings versus an optional setup with a 5% decrease in engine torque, a corresponding decrease in 20% engine inertia and a 5% decrease in vehicle weight. Note the nearly identical zero to sixty mph elapsed time prediction for the two different setups. This demonstrates potential for achieving this portion of the straight-line acceleration goal with a lower torque, lower weight option.

Table 35: Straight-line Acceleration Factor Settings and Predicted Elapsed Time for the Supercar-A Baseline Setup versus an Optional Setup.

	Vehicle Setup		Valid Range	
Factor Name	**Base**	**Option**	**Min**	**Max**
1- Engine Torque vs. RPM Curve (lb-ft vs. rpm)	500	475	475	525
2- Engine rotating/reciprocating Inertia- (lb-ft-s^2)	0.34	0.272	0.272	0.408
3- Unsprung Mass Rotational Inertia- Iyy front/rear (lb-ft-s^2)	1.6	1.6	0.8	1.6
4- Tire Peak Long Capability (Coefficient of Friction)	1.1	1.1	1	1.1
5- Aero Drag (Cd)	0.39	0.39	0.35	0.428
6- Total Vehicle Weight with Driver (lbf)	3522	3346	3346	3698
7- Shift Time (s)	0.2	0.2	0.14	0.26
8- Total Vehicle Design Weight Distribution (% Front Weight)	43	43	40	46
9- CG Height- Total Vehicle at Design from Ground (in)	17.5	17.5	16.625	18.375

Response	**Base**	**Option**
1- Zero to Sixty ET (seconds)	4.48	4.51

- The two largest interaction terms are engine torque * engine inertia and engine torque * vehicle weight. The combination or interaction of increasing engine torque and increasing engine inertia or vehicle weight actually serve to reduce elapsed time to a small degree. This seems counterintuitive at first, but is most likely due to the increased engine inertia or vehicle weight reducing wheel spin and improving the vehicle launch performance.
- The rest of the factors not mentioned have a small, but fairly limited impact on the results. The limited impact of tire peak friction, weight distribution and CG height is a little surprising yet believable as compared to the other factors; the range of adjustment and their absolute values are fairly low. Aerodynamic drag and unsprung mass rotational inertia were not expected to affect this metric measurably due to the low speeds. Note, the gearing for this Supercar-A analysis was set such that it did not require a shift up to 60 mph; therefore, it does not show up as a factor that impacts the response.
- The zero to sixty mph elapsed time behaves fairly linearly with respect to changes in the design parameters within the given range of adjustment.

This completes the major observations for the zero to sixty mph elapsed time analysis and leads to the quarter mile distance elapsed time results. Figure 68 depicts the top eight coefficients in a bar chart, based on their magnitude, for Supercar-A's quarter mile distance elapsed time analysis. Similar to the zero to sixty mph bar chart, the cutoff in coefficient magnitude for this chart is any term within 100% of the greatest coefficient magnitude, in this case engine torque.

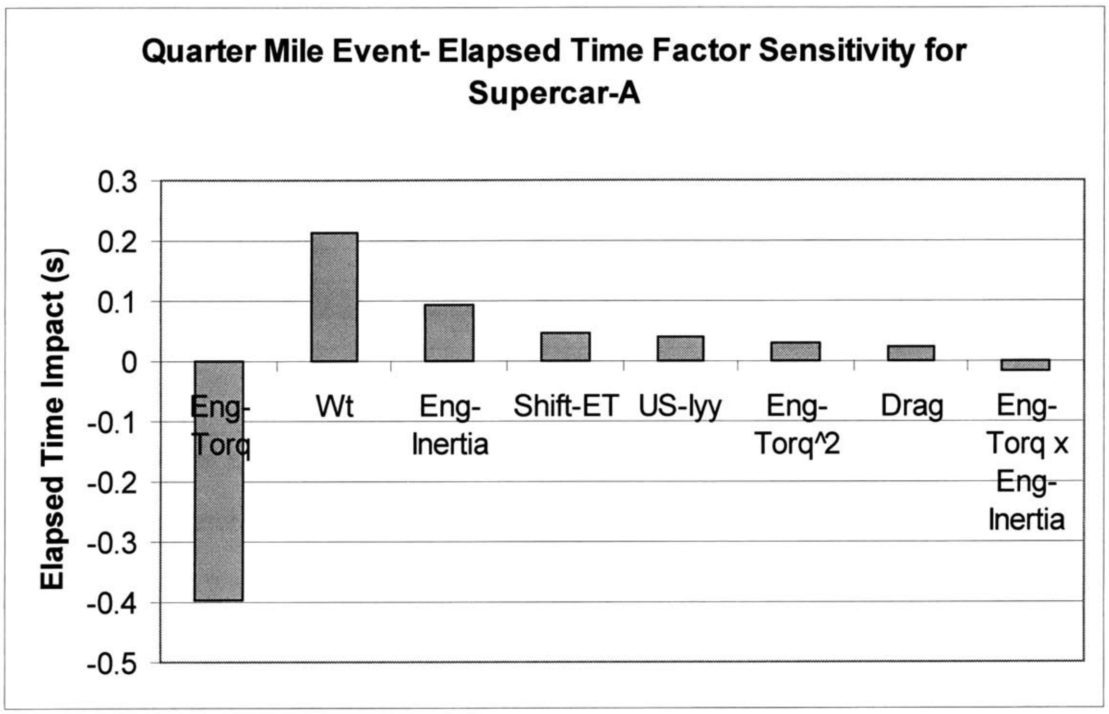


Figure 68: Quarter Mile Acceleration Distance Elapsed Time Factor Sensitivity for Supercar-A.

The quarter mile elapsed time analysis provides more information for a few additional observations to those highlighted for the zero to sixty mph analysis based on review of Figure 68. The ones that standout the most are as follows:

- Engine torque, vehicle weight and engine inertia are again the top three factors with respect to magnitude and impact on the response, which are the same as those demonstrated in the zero to sixty mph analysis. The relative magnitudes of these three are also very similar to those found in the lower speed analysis. For reference, the quarter mile top speed is about 120 mph for this vehicle.

- The necessity to shift gears in the quarter mile shows as a small factor on performance.
- Unsprung rotational inertia and drag terms gain a small degree of importance as speeds increase, as expected.

This completes the major observations for the quarter mile distance elapsed time analysis and leads to the 80 to 160 mph acceleration elapsed time results as shown in Figure 69. It depicts the top eight coefficients in the bar chart based on their magnitude.

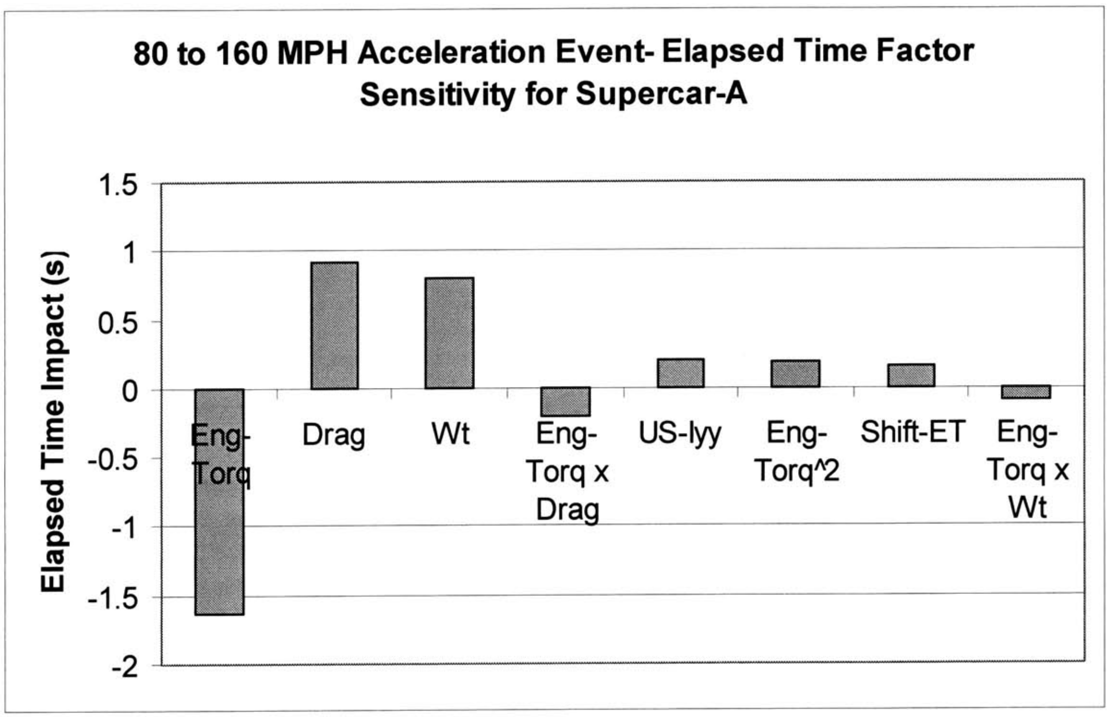


Figure 69: 80 to 160 mph Acceleration Elapsed Time Factor Sensitivity for Supercar-A.

The 80 to 160 mph acceleration elapsed time factor sensitivities demonstrate considerable difference from the two prior standing start acceleration analysis, with the exception of the fact that engine torque is still the most important factor. In this instance, the vehicle's aerodynamic drag displaces vehicle weight to the third most important factor due to the high-speed nature of this event. Drag force increases as a function of speed squared. Unsprung mass rotational inertia changes still only impact the results by a small degree, which seems a little counterintuitive. This may highlight that the nominal setting and range relationships for the supercar system architecture results in different sensitivities versus other vehicle classes.

The last response for straight-line vehicle performance, top speed, is primarily completed as an additional "sanity" check for the parametric model results. Top speed analysis represents a steady state behavior in which the vehicle's final drive torque (including final drive ratio, which is not shown) reaches equilibrium with its inherent aerodynamic drag properties. Figure 70 shows the model predicted sensitivities for top speed performance, which is in line with this statement as it demonstrates the dominance of drag and engine torque.

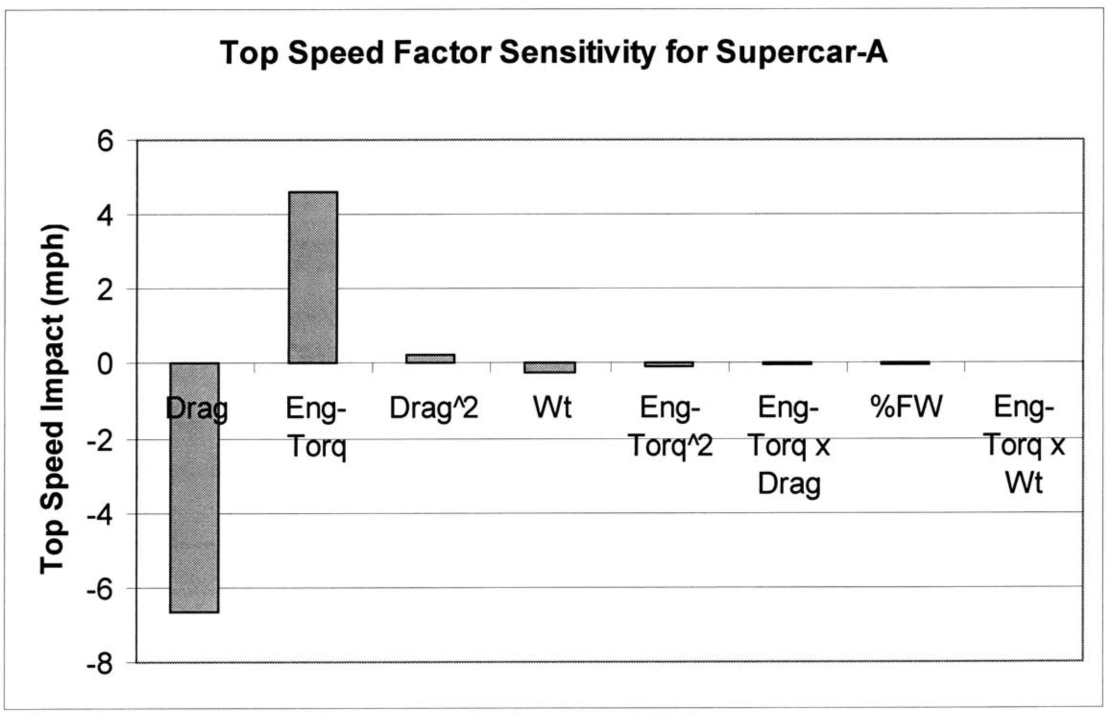


Figure 70: Top Speed Factor Sensitivity for Supercar-A.

This completes the observations for the Supercar-A straight-line acceleration performance sensitivity and leads to the handling performance DOE analysis. Note, the direct application of the above straight-line acceleration RSE's, sensitivity charts and observations for remaining Supercar-A system architecture evaluation takes place after the handling DOE discussion.

5.5 Handling DOE Background

The full vehicle handling analysis comprises a 15 factor, three level DOE completed in a component based full vehicle dynamic model using the ADAMS simulation program. ADAMS has fairly generic capability for detailed dynamic systems analysis; however, the version utilized in this analysis is very specific to automotive vehicle dynamics. For those interested, further details on ADAMS models and analysis capability can be located at www.adams.com. The component-based nature of the model means that suspension kinematics and compliance characteristics, for example, are outcomes of the specific suspension geometry/linkages as well as bushing and member stiffnesses. The parametric based VDANL model utilized for straight-line acceleration is sufficient for the following handling analysis, but important details, like tire properties already existed in Supercar-A chassis team's ADAMS model. In addition, the complicated tire data and resultant formats are not directly compatible between the two models. Ideally both sets of DOE's would be completed in the same model. However, the design parameters in both models are essentially equivalent with respect to producing identical subsystem behavior.

Handling Factors

The actual factors chosen for analysis are a function of the majority of above generic parameters highlighted in the prior phases of CD-SAAM and assumed specific to full vehicle handling performance. Ideally, the following analysis for Supercar-A includes its wheelbase and front and rear track width. However, those three parameters were fixed based on the original show car, with no ability to change. Therefore, they have been left out of the analysis. The factors chosen for the handling DOE represent a combination of the highest level design parameters from the first and second level form/function decomposition. The specific parameters chosen as factors are directly mapped to the corresponding high level generic factor in Table 36 below. A range of adjustment explanation and level setting for each factor in the DOE is explained in detail afterward.

Table 36: Handling DOE Factors Mapped to Corresponding Design Parameters.

Factors	**Corresponding "Generic" High level Design Parameter**
1- Total Vehicle Weight with Driver (lbf)	Total vehicle mass
2- CG Height- Total Vehicle from Ground (in)	Total vehicle three axis CG location
3- Total Vehicle Fore-Aft Weight Distribution (% Front Weight)	Total vehicle three axis CG location
4- Front Static Camber (deg)	Tire three axis force and moment properties and suspension kinematics and compliance characteristics
5- Rear Static Camber (deg)	Tire three axis force and moment properties and suspension kinematics and compliance characteristics
6- Front Tire Peak Lateral Capability Scaling Factor	Tire three axis force and moment properties
7- Front Tire Cornering Stiffness Scaling Factor	Tire three axis force and moment properties
8- Rear Tire Peak Lateral Capability Scaling Factor	Tire three axis force and moment properties
9- Rear Tire Cornering Stiffness Scaling Factor	Tire three axis force and moment properties
10- Front Tire Peak Long Capability Scaling Factor	Tire three axis force and moment properties
11- Rear Tire Peak Long Capability Scaling Factor	Tire three axis force and moment properties
12- Rear Tire Longitudinal Stiffness Scaling Factor	Tire three axis force and moment properties
13- Front Tire Longitudinal Stiffness Scaling Factor	Tire three axis force and moment properties
14- Front Lateral Load Transfer Distribution (% Front)	Not directly applicable
15- Total Vehicle Yaw Polar Moment of Inertia (lbf-ft-s^2)	Total vehicle three axis polar moments of inertia

Like the straight-line acceleration example, review of Table 36 demonstrates that a few of the factors are identical or nearly identical to the high level design parameter so the relationship requires little explanation. These particular factors, including total vehicle weight, CG height, fore-aft weight distribution and yaw polar moment of inertia are essentially identical to the high level generic design parameters due to the fact that they are full vehicle (first level decomposition) based. However, others are not as direct and require brief explanation because they are based on the second level architecture. For example, all of the tire force and moment related terms require further explanation. A wheel/tire's camber angle, as described earlier in the vehicle dynamics analysis section 4.3, is one of the primary factors that affect a tire's three-axis force and moment characteristics in addition to vertical load, slip angle (for lateral dynamics) and slip ratio (for longitudinal dynamics). The other tire factors (numbers 6 to13) utilized in this DOE and shown in Table 36 require more explanation as they represent specific portions of the tire's force and moment relationships. Figure 71 below depicts an example for a tire's lateral force versus slip angle relationship and the four major elements of the curve. This figure presents two of the factors and example changes as well as two of the curve's characteristics, which are held constant in the DOE. The tire's peak lateral capability as shown in Figure 71 represents one factor and its cornering stiffness represents the other. Cornering stiffness and its importance was discussed in section 4.3 and peak lateral capability is more obvious. Note, these two factors are utilized at the front and rear and are analogous to the corresponding longitudinal factors. Note these two factors are continuous in nature; therefore, settings in between in post analysis are valid.

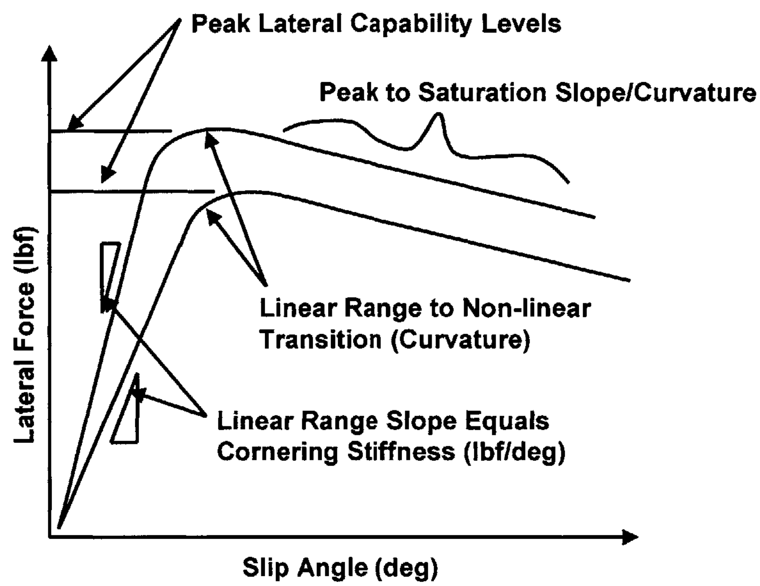


Figure 71: Tire Lateral Force versus Slip Angle Example for Factor Description.

At the same time, two important features of the tire's character are held fixed in this analysis. The fixed features, based on the Supercar-A tire, are its linear range to non-linear range curvature and its peak to saturation slope/curvature. In addition, the curves in Figure 71 represent a single load case and camber angle. In reality, there is a separate plot for each camber angle and a separate curve for each load case. These aspects of the tire's lateral force versus slip angle are also fixed and a function of the Supercar-A tire architecture. Potential limitations of these fixed parameters are located below in the handling model assumptions/limitations discussion.

Front lateral load transfer distribution is the only factor, which does not map directly to one of the generic high level design parameters. However, indirectly it does. It is chosen as a factor due to its impact on vertical tire loading as well as review of a factor's impact on the responses, which is a tunable. Comparison of a "tunable" versus hard to change architecture serves to demonstrate the relative importance and the ability or inability to counteract system architecture deficiencies.

The factor adjustment range or levels chosen for each are based primarily on the architecture options described during the prior qualitative analysis. The range for each factor does not, however, encompass the entire scope of architecture possibility for the supercar class. The factor levels chosen do encompass a majority of the architecture possibilities and resultant design parameters in some cases, like tire cornering stiffness. Other cases, like the range for percent front weight distribution, are more limited to the realm of the mid engine car, as described in the straight-line acceleration section.

Table 37 shows the factor setting specifics for the handling DOE. The ranges for the tire properties are actually adjusting scaling factors and not the actual design parameters themselves, as they are more complicated than single values. However, this does not detract from the usefulness of the analysis.

The two static camber factors found in Table 37 also are primarily "tunable" aspects of the Supercar-A chassis system. Similar to front lateral load transfer distribution, camber is included to understand its effect on the response relative to the system architecture related factors. Camber, as briefly described earlier, is the tire's front view vertical angle with respect to a plane normal to the road surface. Tire performance is sensitive to camber angle, especially in this class of vehicle and tire. Camber is adjusted through static alignment changes of the geometry, which are feasible on the actual car. While camber is only adjusted statically, results from the DOE analysis with respect to camber sensitivity also serve to provide some information regarding the importance of camber kinematics and compliance characteristics of the suspension system.

The other tunable parameter, front lateral load transfer distribution, reflects the bias of lateral weight transfer, and resultant vertical tire loading, at the front versus the rear of the vehicle. This distribution is dictated by the vehicle's track width, weight distribution, spring rates and anti-rollbar rates. For this example, the front lateral load distribution is adjusted through the anti-rollbar rates, while track width, weight distribution and springs rates remain constant.

Table 37: Supercar-A Handling DOE Factors and Levels.

	Level		
Factors	**Low**	**Nominal**	**High**
1- Total Vehicle Weight with Driver (lbf)	-5%	3522	+5%
2- CG Height- Total Vehicle from Ground (in)	-5%	17.5	+5%
3- Total Vehicle Fore/Aft Weight Distribution (% Front Weight)	40	43	46
4- Front Static Camber (deg)	-0.25 deg	-0.5	+0.25 deg
5- Rear Static Camber (deg)	-0.25 deg	-1.25	+0.25 deg
6- Front Tire Peak Lateral Capability Scaling Factor	-5%	1	+5%
7- Front Tire Cornering Stiffness Scaling Factor	-10%	1	+10%
8- Rear Tire Peak Lateral Capability Scaling Factor	-5%	1	+5%
9- Rear Tire Cornering Stiffness Scaling Factor	-15%	1	+15%
10- Front Tire Peak Long Capability Scaling Factor	-5%	1	+5%
11- Rear Tire Peak Long Capability Scaling Factor	-5%	1	+5%
12- Rear Tire Longitudinal Stiffness Scaling Factor	-15%	1	+15%
13- Front Tire Longitudinal Stiffness Scaling Factor	-10%	1	+10%
14- Front Lateral Load Transfer Distribution (% Front)	-5%	47	+5%
15- Total Vehicle Yaw Polar Moment of Inertia (lbf-ft-s^2)	-5%	1800	+5%

Handling Responses

Specific handling responses are a little more difficult to describe than the straight-line acceleration metrics utilized in the prior analysis. However, the following responses fall into three of the major categories briefly described earlier in the vehicle dynamics background section. The three categories are as follows: ultimate lateral acceleration capability, the balance level or degree of understeer and the vehicle's yaw response. These three primary categories are far from inclusive regarding a vehicle's handling performance, but the do represent considerable importance for the supercar class and relevance to system architecture decisions. The three primary response categories are analyzed through three separate events. The complexity of the vehicle events and responses deserves structured explanation, which is covered below in the handling sensitivity analysis section. The event name, event description, response name and response description are located below the relevant charts and analysis.

Handling DOE Matrix Design

The "D-Optimal" algorithm for the matrix design is also employed for the handling DOE, for the same reasoning given in the straight-line acceleration analysis. However, the resultant design for the handling analysis is completed in an ADAMS software package named Insight. This fifteen factor, three level DOE resulted in a 200 run matrix. For reference, a full factorial run for the same experiment requires over 14 million runs. The D-Optimal again provides incredible reduction in time and effort, while achieving the same level of fidelity in the analysis.

Handling Response Surface Equations (RSE's)

The resultant RSE's for the handling DOE take on the same form as the one described in section 2.4, except this specific equation encompasses 136 separate terms and is as follows:

$$Y = B0 + B1 * X1 \ldots B15 * X15 + B16 * (X1 * X2) \ldots B121 * (X14 * X15) + B122 * X1^2 \ldots B135 * X15^2$$

Once again showing the coefficients for the first order effects (B1...B15), non-linearities (B122...B135) and first order interactions (B16...B121), ignoring higher-level interactions. ADAMS Insight is utilized to complete the regression and corresponding RSE's. The responses analyzed in the handling DOE resulted in R-Squared Adjusted fits of 0.97 or better during the regression of the responses as a function of the factors. Many responses actually exhibited 0.999 R-Squared Adjusted fits after regression. Therefore, the RSE's utilized in the following analyses represent the complex dynamic systems well.

Handling Modeling Assumptions/Limitations

There are a few notable assumptions/limitations in the modeling of this vehicle dynamic system and the handling events that deserve mention. First, while the tire models utilized in ADAMS are fairly advanced, the tire parameters are primarily steady state based as opposed to the inclusion of transient behavior. There are very few tire models in existence that represent the tire's true transient behavior due to great difficulty in measuring a tire's dynamic three axis force and moment characteristics as well as simulating them. However, the tire model used for this analysis has proven to yield accurate results for the full vehicle dynamic events and responses utilized here.

An additional potential limitation of the handling DOE analysis includes the fact all fixed (not adjusted in the DOE) vehicle parameters correspond to the actual setting in Supercar-A. The largest potential issue with this fact comes from the tires utilized in this analysis and bias around their base characteristics. While four key force and moment parameters are adjusted for both the front and rear tires, there are still considerable characteristics specific to the chosen tire that remains fixed. The transition from the linear range of the tire to the non-linear limit characteristics is fixed in this example. Further, the tire's saturation behavior at the limit is also fixed. Finally, the tire's sensitivity to vertical load and camber, especially near its limit of capability also remain constant through this analysis. These "constants" are important due to their interaction with the vehicle performance and must be kept in mind when drawing conclusions. However, considerable analyses with regard to tire characteristics and their interaction with the high level vehicle parameters like weight, weight distribution and CG location was completed outside of this thesis. Therefore, the tire and its fixed force and moment parameters utilized in the following sensitivity study represents a very good baseline for the analysis.

Finally, aerodynamic lift and center of pressure analysis is not included in the following handling DOE as it is limited to low speed events (~60 mph to 80 mph). High-speed behavior should be analyzed for a vehicle of this nature, but it is heavily weighted toward aerodynamic performance and is beyond the scope of this paper.

5.6 Handling DOE Sensitivity Analysis

The Supercar-A handling DOE sensitivity analysis utilizes the RSE coefficients from regression of the responses as a function of the factor settings for each run of the DOE. Identical to the straight-line acceleration sensitivity analysis, each coefficient in the RSE represents the magnitude of change in the response if a given factor is adjusted from its nominal level to the high or to the low. Therefore, the range of impact from the low setting to high setting for a factor is twice the magnitude of the coefficient. Table 38 shows abbreviations for each factor description in the following bar charts.

Table 38: Handling DOE Analysis Factor Name Abbreviation for Bar Charts

Factors	Factor Name Abbreviation for Paretos
1- Total Vehicle Weight with Driver (lbf)	Wt
2- CG Height- Total Vehicle from Ground (in)	CG-h
3- Total Vehicle Weight Distribution (% Front Weight)	%FW
4- Front Static Camber (deg)	fCamber
5- Rear Static Camber (deg)	rCamber
6- Front Tire Peak Lateral Capability Scaling Factor	fTire-Plat
7- Front Tire Cornering Stiffness Scaling Factor	rTire-CS
8- Rear Tire Peak Lateral Capability Scaling Factor	rTire-Plat
9- Rear Tire Cornering Stiffness Scaling Factor	rTire-CS
10- Front Tire Peak Long Capability Scaling Factor	fTire-Plong
11- Rear Tire Peak Long Capability Scaling Factor	rTire-Plong
12- Rear Tire Longitudinal Stiffness Scaling Factor	rTire-LS
13- Front Tire Longitudinal Stiffness Scaling Factor	fTire-LS
14- Front Lateral Load Transfer Distribution (% Front)	FLLTD
15- Total Vehicle Yaw Polar Moment of Inertia (lbf-ft-s^2)	Yaw-Inertia

The 200 foot constant radius skid pad is the first event in the handling DOE factor sensitivity analysis. The following charts and corresponding observations are grouped based on the three handling response categories mentioned. The three categories repeated again are as follows: ultimate lateral acceleration capability, the vehicle "balance" level or degree of understeer and the vehicle's yaw response. Unlike the straight-line acceleration analysis, the following bar charts only contain the top ten rather than those whose magnitudes are within 5% of the largest term magnitude. This is due to the large number of terms, mostly factor interactions, which demonstrate reasonable importance in the handling events. Often up to 30 or more terms for responses fit within the 5% threshold. Therefore, they have been artificially been limited to ten to facilitate review and discussion.

Ultimate Steady State Lateral Acceleration Capability

The 200 foot constant radius event (also known as the " 200 foot skid pad") is a steady state event in which the vehicle slowly steps from 0.1 G lateral acceleration to its maximum lateral capability on a 200 foot radius circle in 0.1G increments. A vehicle of this nature achieves its lateral acceleration limit between 1.0 and 1.1 G's, which corresponds to approximately 55 mph on the 200 foot radius. The response below in Figure 72 simply represents the vehicle's ultimate steady state lateral acceleration capability and the top ten factors' impact on the response. This particular response displayed a large degree of factors exhibiting magnitudes beyond the threshold, which is five percent of the largest factor magnitude. Therefore, they have been limited to ten artificially to keep them the number of factors shown within a reasonable limit.

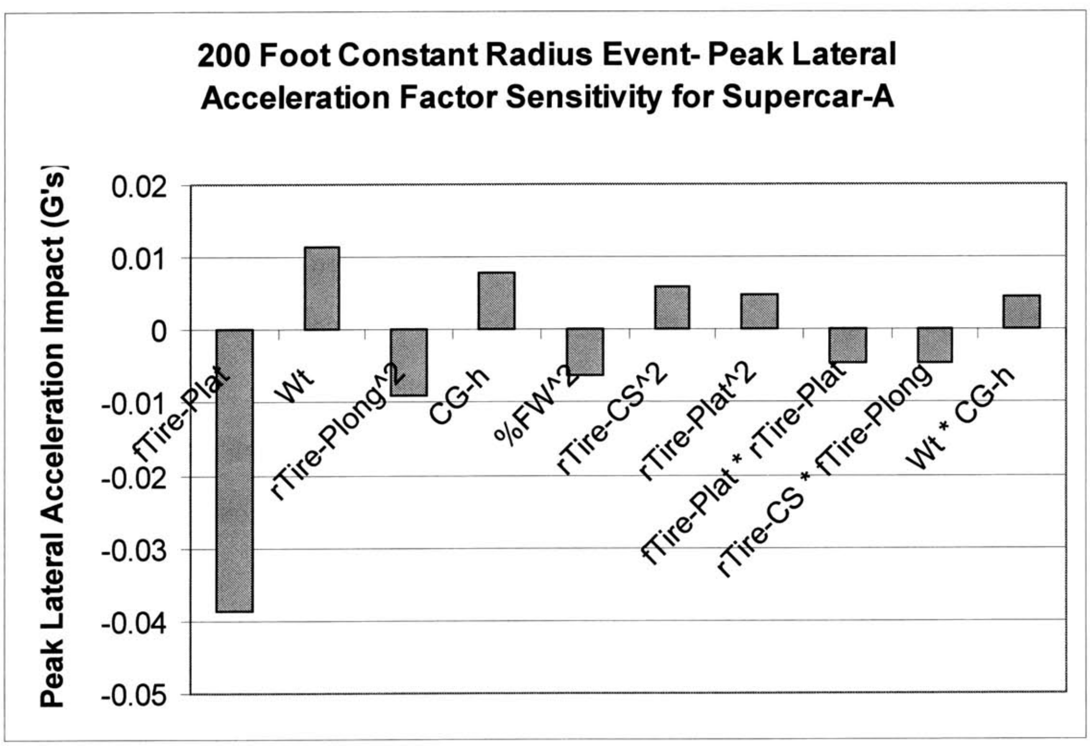


Figure 72: 200 Foot Constant Radius Event- Steady State Peak Lateral Acceleration Capability Factor Sensitivity for Supercar-A.

For this particular chart, increasing lateral acceleration is negative in this simulated event. Consequently, a factor that goes positive in Figure 72 actually demonstrates decreasing lateral acceleration capability. For instance, the figure demonstrates that increasing vehicle weight from its nominal level reduces the vehicle's ultimate lateral acceleration capability. The relative sensitivities are plainly shown in Figure 72; however, some of the less obvious observations are as follows:

- Increasing the front tire peak lateral coefficient of friction five percent from nominal demonstrates nearly a four percent (0.039 G / 1.03 G) improvement in steady state lateral acceleration capability in its linear term alone. While this improvement appears small, it is significant in a vehicle of this class, where every percentage counts. For example, a supercar's merits are often judged in the enthusiast magazines by lap time around a racetrack. A reduction of 0.5 seconds in lap time over a 60 second lap is viewed as significant. This reduction represents less than one percent improvement. This then highlights the importance of tire performance on the vehicle's ultimate lateral acceleration capability. Note the other peak lateral tire factors and interaction terms shown in Figure 72. As one expects the tire's peak capabilities are more important than its linear range cornering stiffness terms.
- Rear tire peak longitudinal capabilities second order term shows up as a reasonable sized term in the RSE. The appearance of a longitudinal term in the pure cornering event seems counterintuitive at first, but it is due the tractive effort required to maintain speed during the high G cornering event, which detracts from the tire's cornering capability.
- Weight and CG height, including an additive interaction term also serve as the remaining significant non-tire contributors shown in Figure 72. Again their contribution to the vehicle's steady state lateral acceleration capability seems small, but every percentage improvement is considered worthwhile in the supercar class.

This concludes high level observations regarding the vehicle's inherent steady state peak lateral acceleration capability. While this response is a metric many use to gauge a vehicle's cornering performance, the results must be tempered with the reminder that it is only steady state behavior.

Adjustments and changes to the vehicle (especially regarding steady state balance), which achieve superior results for this metric often lead to unacceptable behavior in transient events. An increase in front tire lateral capability, as shown above, improves the steady state lateral acceleration capability due to improved grip at the front and corresponding reduction in understeer. The reduced understeer allows for improved utilization of all four tires in steady state handling in a moderately understeering vehicle, but can result in unforgiving behavior in transient maneuvers. In this vain, representative transient events are discussed after the steady state understeer analysis.

Steady State Understeer

The 200 foot constant radius event also provides the ability to review the Supercar-A's inherent understeer gradient from low G levels up to the limit. As discussed, the level of understeer in a vehicle represents its balance (or heading) through an event, which has implications regarding the vehicle's response in addition to affecting its ability to utilize all four tires. Prior to the sensitivity analysis it is worth revisiting the basic understeer gradient equation from the vehicle dynamics fundamentals section.

Understeer Gradient or Bundorf's Cornering Compliance (deg/G) = 180/PI * (Wf / Cf – Wr / Cr)

Where:

Wf = front axle vertical load (lbf)

Wr = rear axle vertical load (lbf)

Cf = front axle cornering stiffness (lbf/rad)

Cr = rear axle cornering stiffness (lbf/rad)

Note the fact that this simple equation basically involves the vertical load on the tires at a given axle as well as the cornering stiffness of the axle, which is dominated by the tire's cornering stiffness characteristics. Figure 73 below demonstrates the chosen factors' impact on the vehicle's low lateral acceleration level, linear response range understeer gradient for the 200 foot constant radius event. Figure 74 demonstrates the factors' effect on the instantaneous understeer gradient at 0.9 G's lateral acceleration (near limit) for the same event.

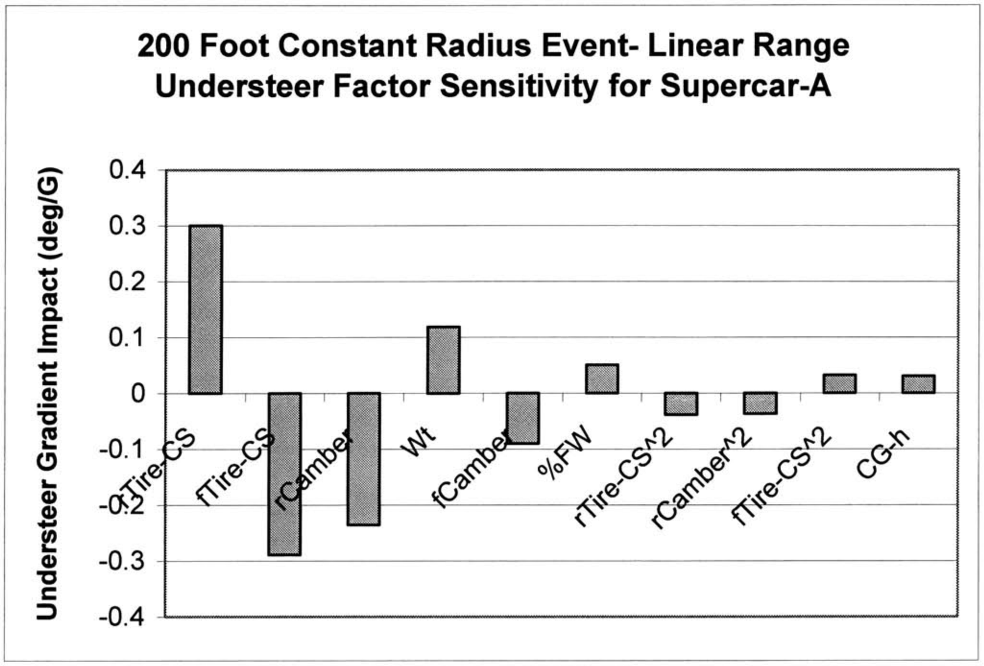


Figure 73: 200 Foot Constant Radius Event- 0.3 G (Linear Range) Steady State Lateral Acceleration Understeer Gradient Factor Sensitivity for Supercar-A.

The appearance of the camber factors in this chart requires clarification regarding sign convention for the term as it is adjusted from its nominal level to a high one. The front and rear nominal camber angles are both negative, so the high level for these terms actually reduces the degree of negative angle. This is a little confusing, but is shown correctly in Table 37 earlier as each camber factor has a positive 0.25 degrees added to the negative nominal value to represent the high factor level. For example, the front nominal camber is –0.5 degrees and its corresponding high and low values are –0.25 degrees and –0.75 degrees respectively. An additional note about camber angle involves its heavy influence on the tires cornering stiffness and overall force and moment properties. Adding negative camber angle increases cornering stiffness. Therefore, the third term in Figure 73, rear camber angle, shows the correct trend as it reduces understeer due to a reduction in its resultant cornering stiffness at the rear axle. Other less obvious observations about the sensitivities demonstrated in Figure 73 are as follows:

- Similar adjustment of camber at the front and rear yields triple the impact on understeer at the rear versus the front. This is likely due to the width of the rear tire with respect to the front and its resultant camber sensitivity. This trend shows up in additional responses below. Unfortunately, the front camber trend in Figure 73 and Figure 74 appears to be the sole error in all of the DOE analysis covered in this thesis. An increase from the nominal to high level of front camber should serve to decrease front axle cornering stiffness and yield increased understeer, the opposite trend of the rear camber. However, the figures show that this increase in front camber level reduces understeer, incorrectly. Further investigation of this anomaly found a modeling issue in which adjustment of camber results in various static equilibrium points with regard to the tires starting slip angle. Increasing slip angle increases the tires lateral force capability in this range. Therefore, the adjusted static equilibrium point was increasing its starting slip angle as camber angle was made less negative. This produced the errant trend result in both sensitivity analyses.
- The two understeer responses follow the simple understeer equation, except the noted front camber term. Figure 73 and Figure 74 are dominated by tire properties (axle cornering stiffness) with contribution from vehicle weight, weight distribution and CG height, which affect each axle's vertical tire loading. The rear tire cornering stiffness adjustment alone of 5% changes the linear range understeer by 20%.

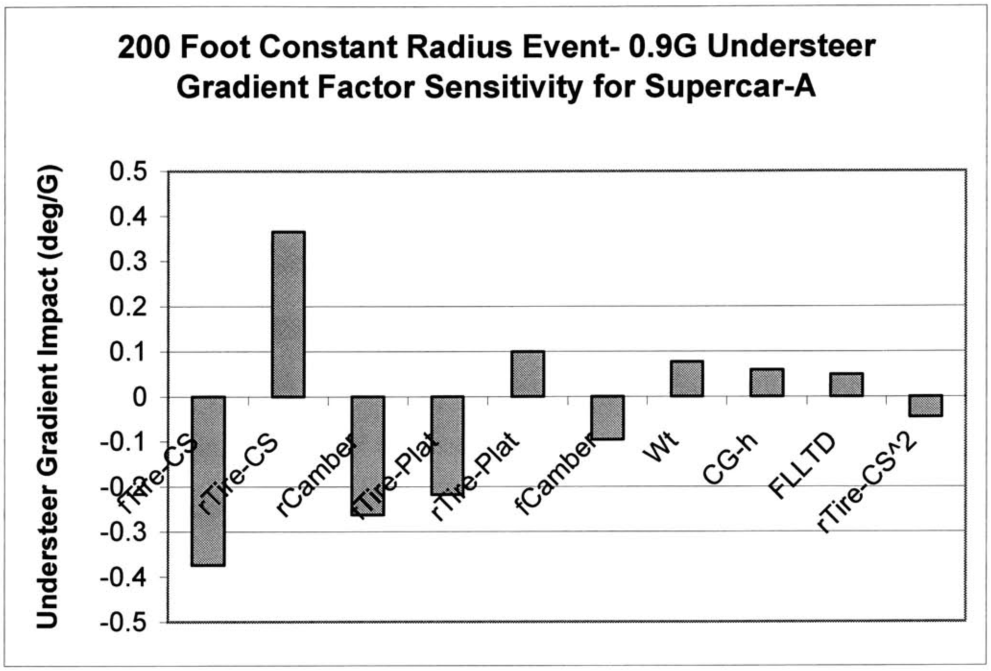


Figure 74: 200 Foot Constant Radius Event- 0.9 G Steady State Lateral Acceleration Instantaneous Understeer Gradient Factor Sensitivity for Supercar-A

The 0.9 G lateral acceleration figure wraps up the steady state analysis and leads to the final handling DOE RSE analysis involving Supercar-A's its yaw response in transient events. In the end, understeer, like most things should be set at a moderate level, not too much or too little, although likely less in a vehicle of Supercar-A nature than a family sedan. Ultimately, understanding these trends and relative sensitivities are what matters for the architect of this complex system, to allow better quantification of options.

Vehicle Yaw Response in Transient Behavior

Two full vehicle transient handling events are employed in the following analysis to better understand the vehicle's crucial yaw dynamic behavior. The first event is a linear range (less than 0.5 G lateral acceleration) frequency response event. The specific event run for this analysis utilizes a cosine pulse input through the steering wheel that covers entire frequency span of human input capability, which is zero to three Hertz. The specific peak steer angle utilized is vehicle dependent and corresponds to a 0.3 G peak lateral acceleration during the event. The vehicle speed during the event is held constant at 60 mph. The output and following response is calculated in the frequency domain through the use of frequency response functions.

The specific response analyzed from this event is equivalent to the vehicle's yaw natural frequency discussed in the vehicle dynamic fundamentals section earlier in this paper. As described earlier, increased yaw natural frequency reduces the driver's effort for vehicle control and leads to improved performance. This is due to increased vehicle bandwidth yielding reduced lag between the driver input and vehicle response. Figure 75 exhibits the yaw natural frequency response factor sensitivity results for Supercar-A. For reference, Supercar-A's nominal yaw natural frequency in this analysis is 2.7 Hz. This is fairly high for a passenger car and represents another aspect of the high performance nature of these vehicles.

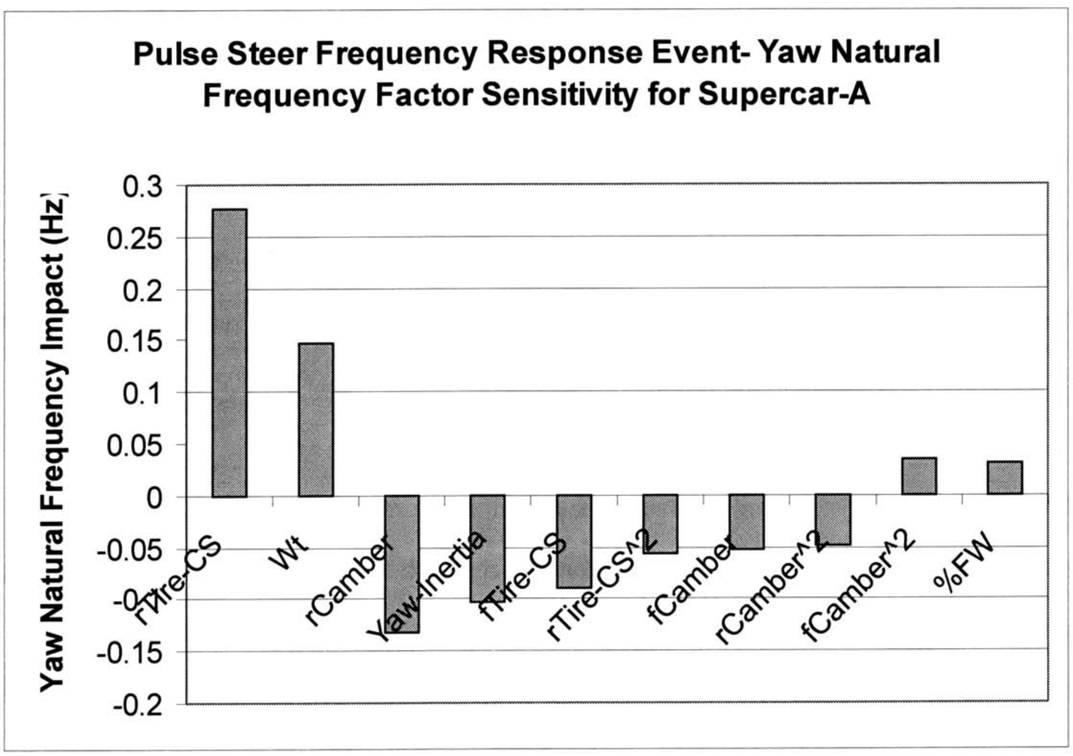


Figure 75: Pulse Steer Frequency Response Event at 60 MPH- Yaw Natural Frequency Factor Sensitivity for Supercar-A

Supercar-A yaw natural frequency response factor sensitivity trend observations, which are less obvious, include the following:

- The 20% increase in rear cornering stiffness from its nominal value yields a 10% increase in yaw natural frequency.
- Camber once again impacts the tire cornering stiffness terms and therefore all terms in Figure 75 correspond to the yaw natural frequency equation from section 4.3, except the weight term shown to rank second in importance. It demonstrates that increasing vehicle weight (mass) should increase yaw natural frequency, which is counter to all basic natural frequency equations! However, this apparent error is actually correct due to the vertical loading impact on the tire's cornering stiffness. The increase in vehicle weight produces a greater percentage increase in the tire's cornering stiffness terms (a tire's cornering stiffness increases with vertical load) at this low lateral acceleration and loading condition. It also is compounded by the fact that increasing mass isn't linked to increasing the vehicle's yaw inertia as it tends to do in reality, which would serve to decrease its yaw natural frequency and make more sense.

Resultant trends for Supercar-A's yaw natural frequency response demonstrate the dominance of the tire cornering stiffness characteristics, especially the rear; while yaw inertia and percent front weight play a smaller although measurable role.

The final dynamic handling event involves braking within a turn. It is a limit-handling event in which the vehicle starts in a 0.8 G lateral acceleration steady state turn and then the brakes are applied ramping to 0.6 G longitudinal acceleration over 0.5 seconds. The response analyzed and demonstrated in following involves the vehicle's peak yaw rate during the event. An increase in peak yaw rate (yaw velocity) primarily signals increased difficulty with respect to vehicle control during this transient event. Therefore, reductions in peak yaw rate are typically desired. However, understanding the sensitivities below in Figure 76 is almost more important for the architect(s) to compare and tradeoff against steady state behavior as well as frequency response. In this case, the factors that increase cornering and braking capability at the front or detract from the rear dominate increases in yaw rate. This makes intuitive sense. Further, CG height plays a considerable role due to its impact on load transfer and resultant vertical tire loading effects. Based on factors below, a three percent increase in percent front weight yields a one percent increase in yaw rate. Once again, this sounds negligible, but it is not as discussed earlier.

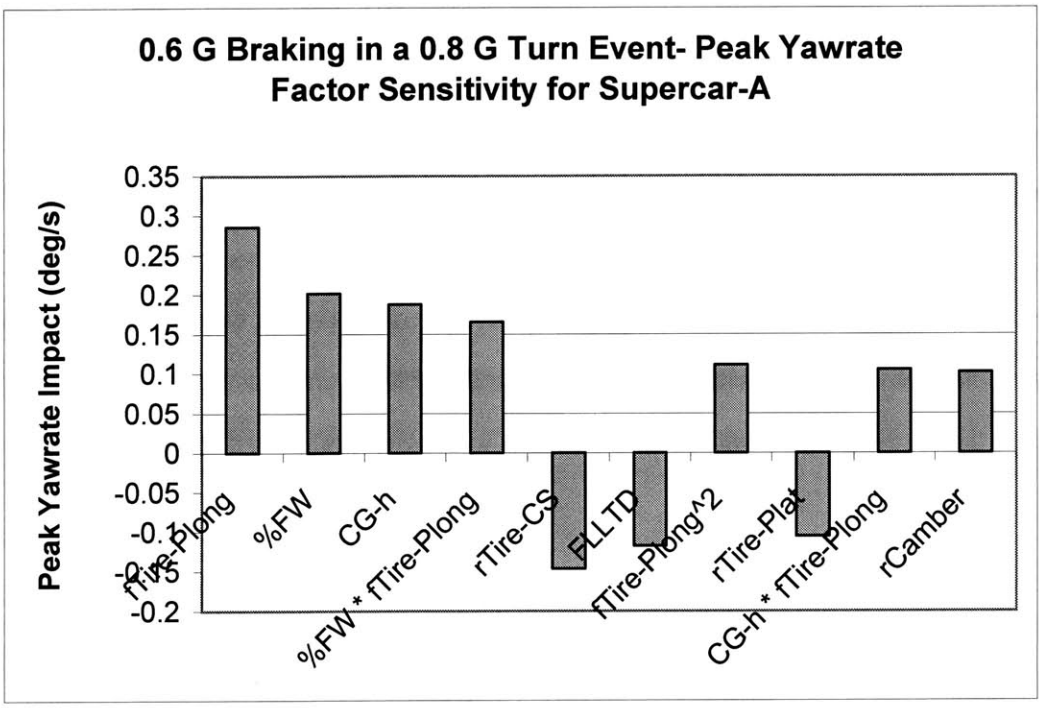


Figure 76: 0.6 G Braking in a 0.8 G Turn Event- Peak Yaw Rate Factor Sensitivity for Supercar-A

The brake in turn event concludes the handling portion of the DOE RSE factor sensitivity analysis. A review of all of the handling events, factors and their sensitivities demonstrates a few high level themes. First, all vehicle responses and corresponding factor trends corresponded well to the fundamental vehicle dynamics equations put forth in Section 4.3, with the one noted exception in the understeer response due to a modeling issue. Second, tire characteristics, often dominated by the rear camber adjustment proved to be fairly universal in their high degree of importance for all demonstrated responses. Third, vehicle weight, CG height, and percent front weight distribution were also notable contributors. Finally, the handling events definitely demonstrate a fair degree of interaction between factors and second order effects, as those experienced in vehicle dynamics expect. As described earlier, all of the handling response sensitivity charts were limited to ten factors artificially as they all demonstrated a large degree of significant factors, primarily interactive terms.

Review of the straight-line acceleration and handling together highlights one primary overlap with regard to vehicle weight showing consistent importance throughout. Increasing vehicle weight almost always served to detract from vehicle dynamic performance by a measurable margin. This makes perfect sense in the world of dynamics where Newton's Second Law of F = MA dominates. The only result that does not make complete sense is the lack of the rear tire coefficient of friction sensitivity during the straight-line acceleration events. This requires further investigation outside of this thesis, but is likely due to the range of tire friction versus torque and weight, resulting in a high degree of involvement and interaction with the simple traction control system. Completion of the DOE RSE factor (design parameter) analyses leads to the final system architecture evaluation step in CD-SAAM.

5.7 Final Analysis of System Architecture Attributes Still Requiring Evaluation

While evaluation of numerous aspects of the analyzed Supercar-A system architecture were finalized in an earlier phase of CD-SAAM, many others were not. The following is a final analysis of a majority of architectural attributes still requiring assessment. The assessments are based both on the quantified trends from the sensitivity analysis as well as some absolute quantification of performance improvement or degradation. The trends from the sensitivity plots give the architect(s) a true understanding of the system and allow them the ability to quickly assess the merits of a concept and balance system tradeoffs. However, absolute comparison through input of relevant design parameters into the RSE's for comparison is ideal in many cases. This is actually required when conflict arises in trends for a factor on different responses. For example, increasing CG height can serve to improve straight-line acceleration performance but hurt the vehicle's cornering capability. An example case of this conflict and resolution through normalized responses, with weighting factors in an objective function is found below. Nevertheless, the following analysis only gives examples for a portion of the whole picture, although an important one with respect to Supercar-A's goals. Therefore, the following final analysis serves as an example of DOE RSE usage in CD-SAAM as opposed to the ultimate judge of the Supercar-A architecture.

Engine/Induction System- Supercar-A's engine induction system exhibits the desired flat torque characteristics to drive the rear wheels aggressively. The straight-line acceleration DOE highlighted engine torque consistently as the single largest factor to improve straight-line performance, as one expects. Therefore, this represents a notable strength of the chosen engine/induction system. However, the same analysis demonstrated significant importance of minimizing overall vehicle weight as well as the engine/induction system rotating and reciprocating inertia. Supercar-A's engine/induction system architecture is at the higher end of the spectrum for both parameters as compared to the discussed alternatives representing a weaker attribute of its architecture. The supercharged induction system architecture alone has a considerable negative impact on both.

Actual placement of relevant design parameters into the RSE's for comparison of the 5.4 L supercharged V-8 and the 6.4 L V-10 demonstrates a few lessons. The torque for the V-10 is only two percent less than the baseline engine. Once again, the baseline torque curve was merely shifted with the final gear multiplication unchanged. However, as shown earlier in Figure 65, the V-10's curve shape is not as flat as Supercar-A's, but it exhibits an advantage in the higher rpm range. Therefore, input of the actual curve produces different results shown afterward. The relevant factor settings for each engine/induction system architecture and resultant responses are shown in Table 39. Explanation of the results shown and an objective function follow this table.

Table 39: Straight-line Acceleration and Handling DOE Factor and Response Comparison. Aluminum 5.4 L Supercharged V-8 Engine/Induction System versus the Aluminum 6.4 L Normally Aspirated V-10 with the Base Engine Torque Curve Shifted Down 2 % for the V-10.

Factors	5.4 L V-8 S/C (Baseline)	6.4 L V-10
Engine Torque (lbf-ft)	Baseline	-2%
Engine Inertia (lbf-ft-s^2)	Baseline	Baseline
Front/Rear Wheel Inertia (lbf-ft-s^2)	Baseline	Baseline
Longitudinal Tire Friction	Baseline	Baseline
Aero Drag (Cd)	Baseline	Baseline
Total Vehicle Weight with Driver (lbf)	Baseline	-4%
Shift Time (s)	Baseline	Baseline
Total Vehicle Fore/Aft Weight Distribution (%)	Baseline	+2%
Total Vehicle CG Height (in)	Baseline	0%
Front Camber (deg)	Baseline	Baseline
Rear Camber (deg)	Baseline	Baseline
Front Tire Lateral Peak Scaling Factor	Baseline	Baseline
Front Tire Cornering Stiffness Scaling Factor	Baseline	Baseline
Rear Tire Lateral Peak Scaling Factor	Baseline	Baseline
Rear Tire Cornering Stiffness Scaling Factor	Baseline	Baseline
Front Tire Longitudinal Peak Scaling Factor	Baseline	Baseline
Rear Tire Longitudinal Peak Scaling Factor	Baseline	Baseline
Rear Tire Longitudinal Stiffness Scaling Factor	Baseline	Baseline
Front Tire Longitudinal Stiffness Scaling Factor	Baseline	Baseline
Front Lateral Load Transfer Distribution (%)	Baseline	Baseline
Total Vehicle Yaw Inertia (lbf-ft-s^2)	Baseline	-4%

Straight-line Acceleration and Handling Responses	5.4 L V-8 S/C (Baseline)	6.4 L V-10	% Difference	QFD Weighting	Cost Function = (% Difference) x (QFD Weighting)
Zero to 60 mph ET (s)	4.5	4.5	-0.2%	-10	0.02
Quarter Mile Distance ET (s)	12.5	12.5	-0.2%	-10	0.02
Top Speed (MPH)	193	191	-0.9%	5	-0.04
80 to 160 mph ET (s)	16.5	16.5	-0.1%	-5	0.00
Max Ay (G's)	-1.03	-1.05	1.9%	10	0.19
Lin U/S (deg/G)	0.51	0.5	-2.0%	3.33	-0.07
0.9 G U/S (deg/G)	1.1	1.04	-5.5%	-3.33	0.18
Yaw Natural Frequency (Hz)	2.7	2.7	0.0%	10	0.00
Peak Yaw rate (deg/s)	21	21	0.0%	-3.33	0.00
				Total Cost Function	0.31

One lesson from this example involves the use of an objective function or cost function to compare competing trends and find which option is superior overall.

Table 39 shows the use of a cost function utilizing percent difference between the V-8 supercharged engine/induction system and optional V-10 architecture in concert with the QFD weighting factors. Responses that should be minimized have a negative sign in front of the weighting factor. For example, peak lateral acceleration and yaw natural frequency should be maximized, while the difference between linear range understeer and 0.9 G understeer should be minimized and achieve a moderate level of understeer. In this case the linear range understeer is showing a low level of understeer, while the 0.9 G understeer is reasonable, but a little high. Finally, yaw rate during brake in turn should be minimized.

In addition, one has to be careful here as there are multiple responses for acceleration as well as handling. Both of these overall responses are supposed to be weighted equally; therefore, the total weighting for the individual responses must maintain this relationship. Note the reduction in weighting for three of the handling responses and two of the straight-line acceleration responses. This was done because they were considered less important than the other responses and some had to be reduced to maintain equal overall weighting. The total cost function is positive if the option is superior. In this case it is positive, signaling that 6.4 L V-10 is superior overall, but not by a lot. Further, while covering two of the highest ranked goals, dynamic or otherwise, results must be factored in with the rest of the impact on goals and constraints.

Another straight-line acceleration run was completed with the actual 6.4 L V-10 curve and an 11 percent increase in the final drive ratio to compare against the prior results. The final drive ratio increase corresponds to the higher rev range of the V-10. All other design parameters were held fixed as shown in Table 40. This example shows a small improvement in the V-10's standing start performance as well as considerable improvement in the 80 –160 mph performance, as one might expect. Therefore, the V-10 demonstrates superiority for these two high ranked goals.

Table 40: Straight-line Acceleration and Handling DOE Factor and Response Comparison. Aluminum 5.4 L Supercharged V-8 Engine/Induction System versus the Actual Aluminum 6.4 L V-10 Torque Curve and Final Drive Ratio Increased 11%.

Factors	5.4 L V-8 S/C (Baseline)	6.4 L V-10
Engine Torque (lbf-ft)	Baseline	V-10 Curve and 11% Increase in Final Gearing
Engine Inertia (lbf-ft-s^2)	Baseline	Baseline
Front/Rear Wheel Inertia (lbf-ft-s^2)	Baseline	Baseline
Longitudinal Tire Friction	Baseline	Baseline
Aero Drag (Cd)	Baseline	Baseline
Total Vehicle Weight with Driver (lbf)	Baseline	-4%
Shift Time (s)	Baseline	Baseline
Total Vehicle Fore/Aft Weight Distribution (%)	Baseline	+2%
Total Vehicle CG Height (in)	Baseline	0%
Front Camber (deg)	Baseline	Baseline
Rear Camber (deg)	Baseline	Baseline
Front Tire Lateral Peak Scaling Factor	Baseline	Baseline
Front Tire Cornering Stiffness Scaling Factor	Baseline	Baseline
Rear Tire Lateral Peak Scaling Factor	Baseline	Baseline
Rear Tire Cornering Stiffness Scaling Factor	Baseline	Baseline
Front Tire Longitudinal Peak Scaling Factor	Baseline	Baseline
Rear Tire Longitudinal Peak Scaling Factor	Baseline	Baseline
Rear Tire Longitudinal Stiffness Scaling Factor	Baseline	Baseline
Front Tire Longitudinal Stiffness Scaling Factor	Baseline	Baseline
Front Lateral Load Transfer Distribution (%)	Baseline	Baseline
Total Vehicle Yaw Inertia (lbf-ft-s^2)	Baseline	-4%

Straight-line Acceleration and Handling Responses	5.4 L V-8 S/C (Baseline)	6.4 L V-10	% Difference	QFD Weighting	Cost Function = (% Difference) x (QFD Weighting)
Zero to 60 mph ET (s)	4.5	4.3	-3.1%	-10	0.31
Quarter Mile Distance ET (s)	12.5	12.3	-1.8%	-10	0.18
Top Speed (MPH)	193	199	3.2%	5	0.16
80 to 160 mph ET (s)	16.5	14.5	-12.3%	-5	0.61
Max Ay (G's)	-1.03	-1.05	1.9%	10	0.19
Lin U/S (deg/G)	.45	0.44	-2.0%	3.33	-0.07
0.9 G U/S (deg/G)	1.1	1.04	-5.5%	-3.33	0.18
Yaw Natural Frequency (Hz)	2.7	2.7	0.0%	10	0.00
Peak Yaw rate (deg/s)	21	21	0.0%	-3.33	0.00
				Total Cost Function	1.58

This measurable change in results utilizing the actual V-10 torque curve and appropriate gearing demonstrate the limitation of trying to shift somewhat "discrete" factors like an engine torque curve. It appears advantageous to work toward representation of the curve characteristics as separate and continuous, yet meaningful, parameters to utilize as factors in a DOE.

Ultimately, this DOE analysis shows a measurable advantage for the V-10 option in the straight-line acceleration and handling metrics analyzed. Although, the handling metrics analyzed do not all show improvement. Mainly, the handling analysis shows ultimate lateral capability improves and a reduction of balance difference between sub-limit and limit steady state cornering. However, braking and ride dynamics, which are not analyzed, should improve as well with the option due to reduced weight. Again, this analysis does not cover all of the dynamic goals of the system, but it does encompass two of the top goals. The results reinforce earlier qualitative analysis and the potential for future improvement in powertrain selection for a vehicle of this nature at OEM-A.

Transmission/Driveline System: Longitudinal versus Transverse Gear Orientation

Supercar-A's longitudinally oriented transaxle system architecture demonstrated considerable strengths in the prior phases of assessment. Only the assessment of a transverse gear set versus the chosen longitudinal remained. The transverse gear orientation serves to move weight forward and reduce yaw inertia. Quick calculations estimate a potential for a one percent reduction in the vehicle's total yaw inertia with the transverse gear layout and only a 0.2% increase in total vehicle percent front weight distribution. Supercar-A's yaw natural frequency above shows sensitivity to the vehicle yaw inertia with little impact on other metrics. This trend is backed up in Table 41, where the only metric changes from the baseline transaxle is a one percent increase in the vehicle's yaw natural frequency. Percent front weight distribution sensitivity analysis shows some impact on responses but such a small change provides no affect on results as shown in Table 41. The transverse gear set layout's impact on the reviewed responses provides a very small advantage over the longitudinal transaxle, although a one to one relationship with respect to yaw inertia reduction. Therefore, based on this analysis, the transverse gear set layout is only worthwhile if it does not require extra time, effort, cost and does not exhibit, reduced performance with respect to other goals not analyzed. However, one must keep in mind dynamics, which are not analyzed including ride (one percent pitch inertia impact), as well the fact that multiple small gains can add up to a measurable advantage.

Table 41: Straight-line Acceleration and Handling DOE Factor and Response Comparison. Baseline Longitudinal Gear Set Transaxle versus a Transverse Gear Set Transaxle.

Factors	Baseline Transaxle	Transverse Gear set Transaxle
Engine Torque (lbf-ft)	Baseline	Baseline
Engine Inertia (lbf-ft-s^2)	Baseline	Baseline
Front/Rear Wheel Inertia (lbf-ft-s^2)	Baseline	Baseline
Longitudinal Tire Friction	Baseline	Baseline
Aero Drag (Cd)	Baseline	Baseline
Total Vehicle Weight with Driver (lbf)	Baseline	Baseline
Shift Time (s)	Baseline	Baseline
Total Vehicle Fore/Aft Weight Distribution (%)	Baseline	+0.2%
Total Vehicle CG Height (in)	Baseline	Baseline
Front Camber (deg)	Baseline	Baseline
Rear Camber (deg)	Baseline	Baseline
Front Tire Lateral Peak Scaling Factor	Baseline	Baseline
Front Tire Cornering Stiffness Scaling Factor	Baseline	Baseline
Rear Tire Lateral Peak Scaling Factor	Baseline	Baseline
Rear Tire Cornering Stiffness Scaling Factor	Baseline	Baseline
Front Tire Longitudinal Peak Scaling Factor	Baseline	Baseline
Rear Tire Longitudinal Peak Scaling Factor	Baseline	Baseline
Rear Tire Longitudinal Stiffness Scaling Factor	Baseline	Baseline
Front Tire Longitudinal Stiffness Scaling Factor	Baseline	Baseline
Front Lateral Load Transfer Distribution (%)	Baseline	Baseline
Total Vehicle Yaw Inertia (lbf-ft-s^2)	Baseline	-1%

Straight-line Acceleration and Handling Responses	Baseline Transaxle	Transverse Gear set Transaxle	% Difference	QFD Weighting	Cost Function = (% Difference) x (QFD Weighting)
Zero to 60 mph ET (s)	4.5	4.5	0.0%	-10	0.00
Quarter Mile Distance ET (s)	12.5	12.5	0.0%	-10	0.00
Top Speed (MPH)	192	192	0.0%	0	0.00
80 to 160 mph ET (s)	16.4	16.4	0.0%	-10	0.00
Max Ay (G's)	-1.03	-1.03	0.0%	10	0.00
Lin U/S (deg/G)	.45	.45	0.0%	-3.33	0.00
0.9 G U/S (deg/G)	1.1	1.1	0.0%	-3.33	0.00

Factors	Baseline Transaxle	Transverse Gear set Transaxle			
Yaw Natural Frequency (Hz)	2.70	2.73	1.1%	10	0.11
Peak Yaw rate (deg/s)	21	21	0.0%	-3.33	0.00
				Total Cost Function	**0.11**

Wheel/Tire Diameters

Supercar-A's wheel and tire package are at the large end of the scale diameter wise with respect to its competitors. The rear wheel and tire package is also fairly wide. Therefore, its wheel and tire overall size results in fairly large rotational polar moment of inertia as described earlier, which would seem to impact straight-line acceleration performance. However, the straight-line acceleration sensitivity analysis above demonstrated that its impact on acceleration performance is small as compared to the other factors. Actual adjustment of the rotational polar moment of inertia from the baseline 18 inch front and 19 inch rear diameter wheel/tire combination down to a 16 inch front and 17 inch diameter rear in the RSE's, with all else fixed, does not demonstrate a considerable impact on straight-line acceleration performance. This is demonstrated in Table 42 in which the 80 to 160 mph time is affected the most, as one might expect, demonstrating an opportunity for improved race track performance and a small improvement at lower speeds.

Table 42: Straight-line Acceleration DOE Factor and Response Comparison. Baseline Wheel/Tire Diameters (18 inch front, 19 inch rear) versus a Reduced Diameter Option (16 inch front, 17 inch rear).

Straight-line Acceleration Factors	Baseline- 18 inch / 19 inch Diameter Wheel/Tire	16 inch / 17 inch Diameter Wheel/Tire
Engine Torque (lbf-ft)	Baseline	Baseline
Engine Inertia (lbf-ft-s^2)	Baseline	Baseline
Front/Rear Wheel Inertia (lbf-ft-s^2)	Baseline	-50%
Longitudinal Tire Friction	Baseline	Baseline
Aero Drag (Cd)	Baseline	Baseline
Total Vehicle Weight with Driver (lbf)	Baseline	Baseline
Shift Time (s)	Baseline	Baseline
Total Vehicle Fore/Aft Weight Distribution (%)	Baseline	Baseline
Total Vehicle CG Height (in)	Baseline	Baseline

Straight-line Acceleration Responses	Baseline- 18 inch / 19 inch Diameter Wheel/Tire	16 inch / 17 inch Diameter Wheel/Tire	% Difference
Zero to 60 mph ET (s)	4.50	4.46	-1.1%
Quarter Mile Distance ET (s)	12.5	12.4	-0.7%
Top Speed (MPH)	192	192	0.1%
80 to 160 mph ET (s)	16.4	15.9	-2.6%

The larger wheels were dictated for Supercar-A by the concept, which are always appealing aesthetically and facilitate the use of large diameter brake rotors for improved braking capability and efficiency. Further analysis would be required to regarding resultant gains in braking versus this incremental improvement. Further, ride analysis and unsprung mass sensitivity are also useful.

Tire Aspect Ratio and Resultant Sidewall Height

As discussed earlier, Supercar-A's tall tire sidewall may reduce cornering stiffness for a given construction and require additional material and unwanted weight and cost to achieve the same lateral stiffness as a lower profile tire. Its rear tire sidewall height especially is at an extreme for this class of vehicle. Changes to cornering stiffness of the front and rear tire are completed in the following according to the ratio of sidewall height between Supercar-A and the 360 Modena, nine and fifteen percent respectively. This is a very rough estimate of difference with everything else being equal. The results in Table 43 show that yaw natural frequency and understeer levels are affected in a positive sense with the increased cornering stiffness, as expected. The yaw natural frequency has increased as well as small increase in linear range understeer. Both desirable. At the same time, the vehicle's understeer near the steady state limit has decreased slightly. The change in understeer near the limit versus the linear range reduces the change in balance, which is advantageous.

Table 43: Handling DOE Factor and Response Comparison. Baseline Front and Rear Tire Cornering Stiffness Comparison.

Factors	Supercar-A (Baseline)	Increased Tire Cornering Stiffness
Total Vehicle Weight with Driver (lbf)	Baseline	Baseline
Total Vehicle Fore/Aft Weight Distribution (%)	Baseline	Baseline
Total Vehicle CG Height (in)	Baseline	Baseline
Front Camber (deg)	Baseline	Baseline
Rear Camber (deg)	Baseline	Baseline
Front Tire Lateral Peak Scaling Factor	Baseline	Baseline
Front Tire Cornering Stiffness Scaling Factor	Baseline	+9%
Rear Tire Lateral Peak Scaling Factor	Baseline	Baseline
Rear Tire Cornering Stiffness Scaling Factor	Baseline	+15%
Front Tire Longitudinal Peak Scaling Factor	Baseline	Baseline
Rear Tire Longitudinal Peak Scaling Factor	Baseline	Baseline
Rear Tire Longitudinal Stiffness Scaling Factor	Baseline	Baseline
Front Tire Longitudinal Stiffness Scaling Factor	Baseline	Baseline
Front Lateral Load Transfer Distribution (%)	Baseline	Baseline
Total Vehicle Yaw Inertia (lbf-ft-s^2)	Baseline	-4%

Handling Responses	Supercar-A (Baseline)	Increased Tire Cornering Stiffness	% Difference	QFD Weighting	Cost Function = (% Difference) x (QFD Weighting)
Max Ay (G's)	-1.03	-1.03	0.0%	10	0.00
Lin U/S (deg/G)	0.45	0.47	4.4%	3.33	0.15
0.9 G U/S (deg/G)	1.1	1.08	-1.8%	-3.33	0.06
Yaw Natural Frequency (Hz)	2.7	2.86	5.9%	10	0.59
Peak Yaw rate (deg/s)	21	21	0.0%	-3.33	0.00
				Total Cost Function	**0.80**

Ultimately, one requires better quantification of the cornering and lateral stiffness impact of sidewall height to truly judge its merits for handling. However, the rough comparison of sidewall heights through a simple ratio and the noticeable impact on important handling metrics represents an opportunity for improvement in the future.

The tire sidewall height assessment concludes the final aspects of Supercar-A's system architecture assessment. While the final analysis highlighted multiple areas of opportunity for future improvement, it also resulted in validation of other aspects of the car's system architecture, which appeared potentially problematic during qualitative analysis. This leads to final conclusions and recommendations with regard to CD-SAAM as well as final high level comments regarding Supercar-A's system architecture.

6 Final Conclusions and Relevant Recommendations

6.1 Chapter 6 Scope and Objectives

This chapter covers final conclusions regarding the merits of the proposed methodology, CD-SAAM, for assessment of complex dynamic system architecture. The conclusions include the perceived value of each phase of the proposed approach as well as the overall value of CD-SAAM. The following conclusions also include relevant recommendations for improvement to aspects of CD-SAAM based on the application analysis completed. Chapter Six ends with a final high level assessment of the Supercar-A system architecture with respect to its goals and stringent constraints.

6.2 CD-SAAM Phase One (Influences Identification and Concept Mapping) Value, Final Conclusions

The influences identification step of CD-SAAM returned high value for the effort due to a combination of elements that lay a strong foundation for architecture evaluation without considerable time and effort. First the holistic nature of the chosen influences framework by Crawley, which encompasses CD-SAAM provides the proper scope of analysis and combats "tunnel vision" with regard to architecture decisions. Next, the direct mapping of constraints and goals to the influences insures they are accounted for and places the influences into the language of the specific system architecture analyzed. Further, ranking and explicitly listing the goals and constraints provides a simple reference for the architects and design team to continually review to insure the proper and intended balance. Completion of this explicit list of constraints and goals for the Supercar-A improved tradeoff decisions and allocation of valuable time and resource throughout the program. Even such a "focused" vehicle as Supercar-A benefited from this approach.

The functional requirements cascade through concept mapping also returns high value for the effort in the first and critical phase of CD-SAAM. Crawley's concept map is intuitive and covers all of the relevant elements of system architecture requirements cascade to the second level decomposition with the exception of a new element introduced in this thesis. The new element, explicit definition of the highest level solution neutral design parameters within the concept map is a key contributor to successful application of CD-SAAM. This addition appears extremely important in complex dynamic system architecture determination, although is addressed typically by architects in an implicit sense at best. The explicit definition of the highest level design parameters forces the architects and primary participants involved in the system design to truly understand the basic laws of physics for their system. This seems basic, but as noted, is uncommon.

The functional requirements cascade through concept mapping to the second level for each Live or Die Goal and Other Goals appears time consuming, but it provides the "map" from which to create the architecture. This step would certainly benefit from an "input by many design by few'" approach to complete it in a timely and accurate manner. Ultimately, the first phase of CD-SAAM serves to narrow the range of reasonable concepts considerably, as well as provide the foundation for the explicit architecture assessment.

6.3 CD-SAAM Phase Two (Five System Architecture Principles) Value, Final Conclusions and Recommendations

Phase two of CD-SAAM and the specific five principles applied provides a very good tool for the first and highest level of explicit system architecture analysis. The principles application yields a narrowed focus or lens to complete the assessment yet the specific principles utilized are "system neutral" and do not over constrain the analysis. This means the principles were not specific to automobiles or even complex dynamic systems, as well as being holistic in their coverage.

The principles worked well for the first level evaluation of a system architecture's strengths and weaknesses as well as highlighting aspects requiring further analysis in following phases. The principles application also served to demonstrate the first assessment of the importance or lack of importance for the design parameters identified in phase one of CD-SAAM.

The identified principles for CD-SAAM application included the introduction of a new "risk" and the balance against the system constraints and goals. The novel aspect of risk introduced here regards one's ability to predict the emergent properties of a system. This new element of risk is fairly specific to complex systems, especially ones of a dynamic nature. One's assessment of their ability to predict the resultant system behavior for a given architecture can heavily bias their ultimate direction chosen. This bias is due to often severe consequences with respect to the system goal achievement if unforeseen issues arise in the integration phase of product development of a complex dynamic system like an automobile. This important element of risk and potential decision bias is exhibited during assessment of the Supercar-A system architecture.

The principles application to the Supercar-A system architecture in stage two of CD-SAAM is very valuable, but it is also extremely lengthy in the form utilized in this thesis. This is partially due to the expansive nature of the complex system analyzed, which is unavoidable. It is also due to the need to write somewhat lengthy reasoning for each evaluation at a more detailed level than is required in reality to provide better clarity for the reader. Therefore, the following discussion includes multiple recommendations for improving the level of time and effort expended on this important phase of CD-SAAM.

The first suggestion for improvement of the principles analysis involves establishment of a shorthand method for analyzing and documenting the corresponding assessment. Ideally it is graphical in nature, or even tabular to allow everyone to view readily the results and see areas of overlap for all of the systems analyzed. The long hand form utilized in this thesis does not facilitate either of these aspects. However, the actual analysis and format utilized to complete the long hand form of principles application in this thesis provides a strong example of implementation of this tool. I utilized Mind Mapping to outline and depict the actual principles analysis, which was quick, graphic and provided all of the necessary information, including visual demonstration of recurrent themes. Mind Mapping utilizes key words, pictures and association to represent thoughts and ideas quickly. A small example of the synergy portion of the principles application to the Supercar-A suspension system architecture Mind Map is shown in Figure 77.

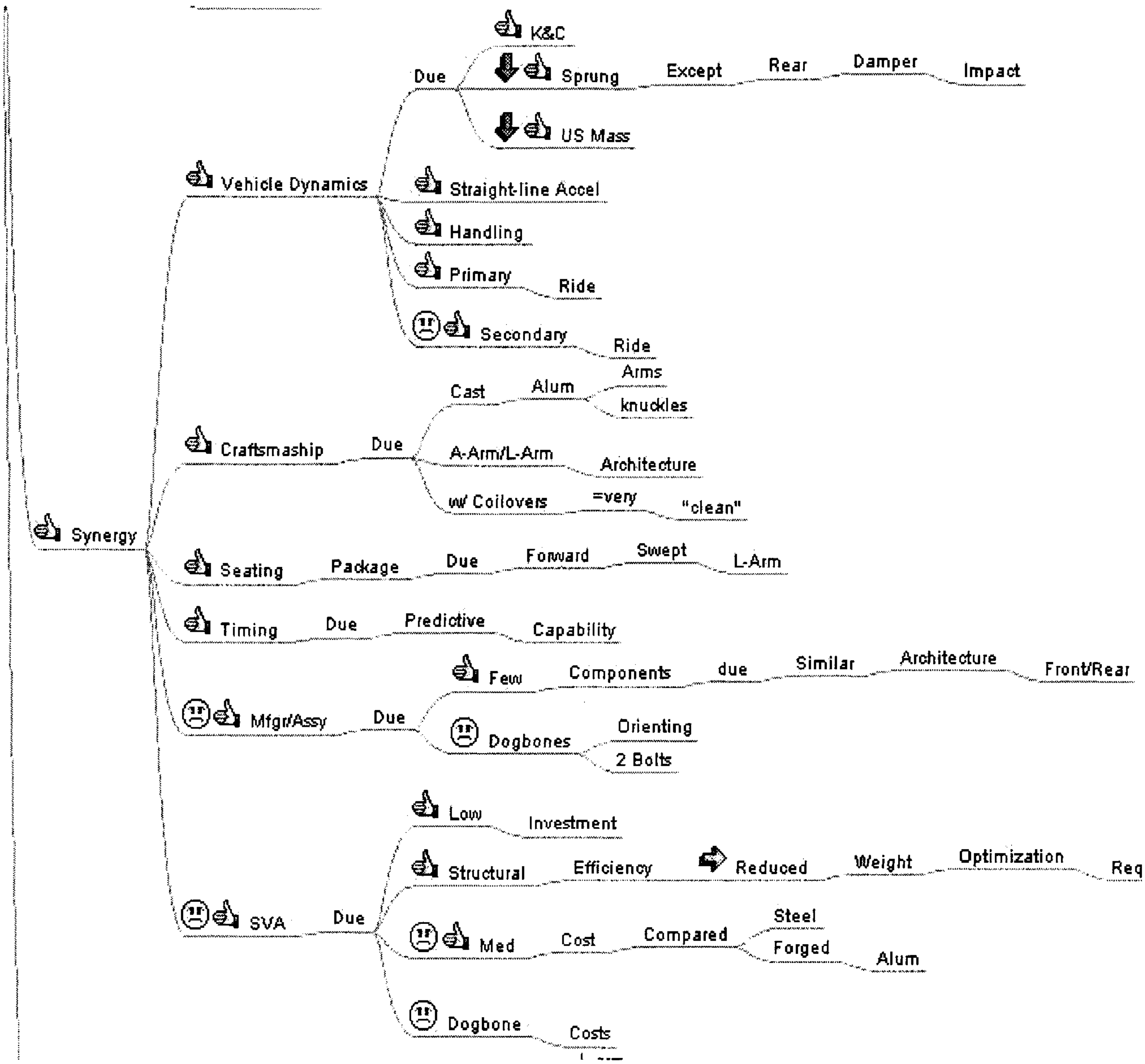


Figure 77: Example Usage of Mind Mapping for the Synergy Principle Analysis of the Supercar-A Suspension System Architecture

Certainly a method of this nature requires agreement on notation, but it serves to vastly improve efficiency of the analysis.

Reflection on the principles application provided additional potential for improvement of the process exhibited in Chapter Four. Ultimately, four of the principles (Complexity, Form and Function Union, Balanced Architecture and Balanced External Forces) feed the fifth principle; Synergy. Therefore, it may be more efficient, but just as useful, to simply apply these four principles while completing the synergy analysis instead of a separate analysis for each. Finally, another potential improvement involves the application of the Synergy principle. It may prove advantageous to jump straight to the QFD format for Synergy principle analysis in specific circumstances. This approach could improve efficiency and results if one is able to detect a high potential for an aspect(s) of a system architecture to exhibit a considerable degree of impact on the system goals and constraints, along with conflicting trends. This could shortcut the additional step that would have demonstrated the need for further analysis in the QFD phase of CD-SAAM and provide a more organized, rigorous answer in a timely fashion.

6.4 CD-SAAM Phase Three (QFD Analysis) Value, Final Conclusions and Recommendations

The QFD analysis appears to be positioned well in the CD-SAAM process and provides a very good value with respect to the effort expended and results achieved. QFD's ability to build upon evaluations and reasoning from the prior principles analysis results in fairly low effort for significantly improved assessment performance. QFD worked very well in its application to organize a large degree of conflicting trends uncovered in the prior principles analysis step. The weighted constraints and goals combined with the individual scoring often produces surprising but believable results in a structured approach. Often surprising or counterintuitive results from QFD analysis highlights potential biases and one's inability to keep track of more than nine basic chunks of information through standard inspection of trends and the use of "engineering judgment". In addition to the standard QFD, the proposed "reasoning" table utilized to keep track of the logic applied for each score provides a good reference for future discussion and trace-ability of the scoring, which may evolve as relevant information is updated. Otherwise, the standard QFD process exhibited minimal potential for improvement in its application in CD-SAAM. Further, QFD is still judged to be a better fit into CD-SAAM than other matrix tools investigated, including Design Structure Matrices (DSM).

6.5 CD-SAAM Phase Four (DOE RSE Methodology) Value, Final Conclusions and Recommendations

The DOE RSE phase of CD-SAAM provides good value for the effort. This final phase and non-typical application of rigorous DOE RSE methods fit well into CD-SAAM providing quantification of the high level design parameters importance. This step does represent a fair degree of additional work as compared to standard system architecture evaluation but is deemed worthwhile in this analysis. The RSE's ability to complete thorough judgment of remaining aspects of the architecture still requiring evaluation in a timely manner is invaluable. I know of no other method that can cover such a large design space and provide the true factor sensitivities including the typically ignored interaction terms. Typical one-factor-at-a-time methodologies do not produce the true factor sensitivities in a system that contains interactions between subsystems and components. Complex dynamic systems are known for considerable interactions although often overlooked. Feeding architecture decisions with applicable DOE RSE results provides considerable insurance regarding proper prediction of a system's emergent properties, thereby facilitating avoidance of considerable issues during the integration phase of product development.

The RSE's and resultant sensitivities plots provided a strong graphical tool to rapidly assess the relative importance of design parameters and facilitate extremely educated decisions with respect to corresponding system architecture elements. The application example demonstrated multiple interaction examples and the presence of counter-intuitive results that do not make sense without additional reasoning. In addition to sensitivities, the RSE's also provided the ability to complete rapid "A" to "B" comparisons, which can be cumbersome in the full system models.

Application of phase four in CD-SAAM to finalize assessment of the Supercar-A system architecture highlighted two potential challenges, but was addressed with strong solutions. First, the discrete nature of architectural concepts can be perceived as a roadblock to assessment with DOE methods. However, as demonstrated, a majority of the relevant design parameters affected are continuous in nature. In addition, those that are not initially continuous can be transformed into a continuous set of design parameters to allow determination of the best concept. This challenge also highlighted the ability to utilize CD-SAAM and the final phase to focus R&D efforts toward specific design solutions not yet invented.

The second challenge in application of DOE RSE methods for system architecture assessment involved the potential for conflicting trends regarding a design parameter's impact on the system constraints and goals. This hurdle was appropriately cleared through application of standard multi-disciplinary optimization methods. The usage of normalized responses in an objective function with infusion of the QFD weightings successfully resolved this issue.

Ultimately, this final quantitative analysis phase of CD-SAAM does not eliminate the need to understand the fundamental dynamics of the system. Instead it actually reinforces the need for strong knowledge of the background physics as they are crucial in proper functional requirements cascade and heavily bias the design parameters reviewed throughout the analysis, including phase four.

6.6 CD-SAAM Overall Value, Final Conclusions and Recommendations

Overall, CD-SAAM worked very well to evaluate complex dynamic system architecture strengths and weaknesses through its holistic approach and hierarchical synthesis of tools and methods. Starting from a high level and working methodically to a more detailed level of analysis in CD-SAAM maximizes assessment value as it utilizes the appropriate level of tool fidelity, at the right point in the process. Yes, CD-SAAM requires greater time and effort up front than the loose architecture framework and engineering judgment methods utilized now at OEM-A in the concept development phase of the product development process. However, application of CD-SAAM in this thesis reinforces my belief that this methodology provides considerable improvement to achieve consistent positive performance with respect to all of the system goals for complex dynamic systems. It also demonstrates the capacity to ultimately reduce product development cycle times for complex dynamic systems as it is intended to heavily reduce the occurrence of costly, time consuming and synergy detracting changes to an architecture late in the process.

In addition, the application of CD-SAAM to the Supercar-A system architecture revealed additional lessons and recommendations. Further, reflection of the process denoted a potential feedback loop in CD-SAAM that involves the ability to uncover inconsistent or unattainable goals within the stated constraints due to its quantitative nature. This information could feed back into the system goals to adjust them and/or the constraints and assumptions accordingly. Finally, application of CD-SAAM to Supercar-A reinforced the need for implementation of the architecture and design process principle of "input by many, design by few". Application of this principle yields improved ability to achieve a holistic solution with a singular vision.

Ultimately, CD-SAAM is a very rigorous, organized method for complex dynamic system architecture assessment. However, it still contains a considerable degree of subjectivity in the analysis and consequently does not eliminate the art of architecting.

6.7 CD-SAAM Supercar-A System Architecture Assessment General Conclusions

The application of CD-SAAM highlights both strengths and areas for opportunity in Supercar-A's system architecture. Areas of weakness in some cases were due to multiple key architecture mandates outside of the program team's control. In addition, extremely tight constraints, especially timing, biased some system architecture decisions toward minimization of risk with respect to prediction of dynamic behavior and one's core competencies. In some cases the reduced risk did not balance well against the full system constraints and goals. However, other examples of lower risk bias were certainly justified.

The resultant implementation of CD-SAAM reinforced the difficult nature of some of the key system architecture aspects and influenced design parameters that the Supercar-A design and development team has experienced first hand. Battling vehicle mass/inertia and noted tire property characteristics represent some of the greatest challenges for the Supercar-A design and development team throughout the program. A majority of the team was well aware of the importance of vehicle mass minimization, but numerous aspects of the Supercar-A system architecture are heavy with respect to noted alternatives. The heavy nature of the system architecture forced considerable additional effort and resultant cost with regard to weight reduction through implementation of lighter weight materials and methods as well as significant optimization work. Fortunately, in spite of a reasonable degree of improvement potential in Supercar-A's system architecture, Supercar-A results to date demonstrate a strong ability to achieve or exceed a majority of its goals within its stated constraints. This fact is a tribute to the entire Supercar-A program team's extraordinary efforts.

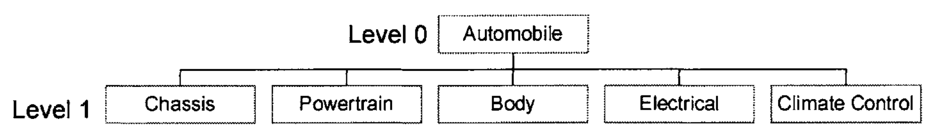
Glossary

Abstraction

Formation of an idea apart from concrete things, situations, etc. [Lex] A simulation or mathematical model is a good example of an abstraction of reality.

Architecture

The embodiment of concept, and the allocation of physical informational functionality and definition of structural interfaces among the elements. It is the form and function of the system. [Cr2, Lecture 1, p.14] For example, the form of a modern automobile may be decomposed into five major systems at the

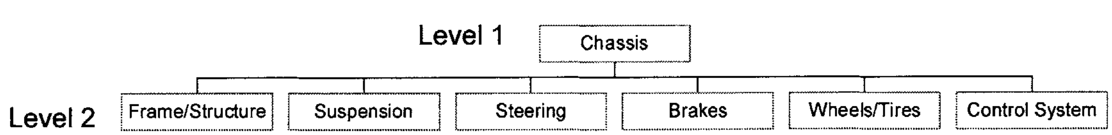


first level as shown in Figure 1.

Figure 1: Automobile Form Decomposition- Level 0 and 1

It is at this level and the next level of decomposition, where the vehicle architect works and defines the architecture. The chassis, for example, is comprised of 6 chunks at the 2nd level as shown in Figure 2:

Figure 2: Automotive Chassis Form Decomposition- Level 1 and 2



Frame/structure architectural elections could include the following elements:

- Overall *configuration*:

- Body Frame Integrated (unit body- typically utilized in passenger cars)
- Body on frame (often utilized for trucks)
- Tubular space frame (often used in automobile racing)
- Monocoque (fabricated shear plate/panel construction- historically used in airframes for airplanes. The fuselage of an airplane is a good example of a monocoque configuration)

- *Materials*:
  - Steel
    - Mild
    - HSLA
    - Chrome-moly
  - Aluminum
  - Composite
    - Carbon fiber
    - Kevlar
    - Aluminum or nomex honeycomb
- *Joint types*:
  - Welded
    - MIG
    - TIG
    - Friction stir
  - Adhesive bonded
  - Riveted
- *Suspension interconnection types*:
  - Cast nodes with machined bosses

        - Shear panels and clevis
        - Isolated sub-frame
    - *Primary structural load paths*:
        - Rockers/sills (lower, outboard edge of frame)
        - Tunnel (lower, central section of frame)
        - Roof/cant rails (upper, outboard edges of frame)

Any combination of the above types describes the frame/structure architecture. For example, "an all aluminum, tubular membered space frame, with TIG welded joints, cast nodes for suspension interface and its primary load carrying structure in the rockers and roof/cant rails".

Complexity	The level of interfaces or interconnectedness in a system. Complexity typically increases when multiple attributes or situations exist simultaneously. [Bop, Section 3]
Essential (Ideal)	The minimum or essential complexity required to achieve the desired functionality. [Cr1, Lecture 7, p. 21, paraphrased] Systems whose essential complexity exceeds human capacity is complicated.
Actual	The actual level of interconnectedness of a system.
Perceived	The perceived level of interconnectedness of a system.
Complicated	Difficult to understand. [Cr1]
Concept	A system vision, which maps form to function and embodies working principles and is in solution-specific vocabulary - it is the solution. It is created by the architect and must allow for the

	execution of all required functions. It specifies the vector of design parameters, which, when selected, will establish the design. It is an abstraction of form or form is the specification of the concept. [Cr1, Lecture 1, p. 27]
Decomposition	A method to group or break elements of a system down into smaller, more manageable chunks. For purposes of this thesis it refers to decomposition of an architecture, its form and its function.
DOE	Design of Experiments (DOE)- a statistical method to system understanding through analytical models or physical testing. See Chapter 2.6 for much greater detail on this subject.
Dynamic(s)	The branch of mechanics (opposite statics) that deals with matter in motion (kinematics) and the forces that produce or change such motion (kinetics). [Lex] For purposes of this paper, it is not simply changes in state over time, as described by Crawley respect to dynamic behavior. [Cr1, Lecture 1, p. 36] Instead, for the purpose of this paper "dynamic(s)" only refers to objects whose primary function involves motion. For example: automobiles, motorcycles, airplanes, trains, etc.
Hierarchy	Any arrangement of principles, things, etc. in an ascending or descending order. [Lex]
Holistic	Of the whole. To think holistically is to encompass all aspects of the task at hand, taking into account the influences and

	consequences of anything that might interact with the task. [Cr2, p. 20, Lecture 1]
Methods	The organization of approaches and tasks to achieve an end, which should be grounded on principles.
Part	A part which cannot be taken apart without destroying its functionality. For example: screw, microprocessor, spring, etc. However, if details of the part combine to produce a larger functionality (microprocessor), then the part is a system. [Cr1, Lecture 7, p.10]
Principle	Underlying and long enduring fundamentals, which are always (or almost always) valid. [Cr2, Lecture 1, p. 25]
QFD	Quality Functional Deployment (QFD)- a graphical tool utilized in Systems Engineering to aid requirements cascade. See section 2.4 of this thesis for more background on this tool.
Sprung Mass	The vehicle mass supported by a vehicle's suspension system springs
Synthesis	Assembling various parts into a whole
System	Collection of components or subsystems that provide one or more functions through their relationships. [SA1]

SVA	Shareholder Value Added (SVA) is a financial metric utilized at OEM-A and numerous corporations. The SVA calculation is fairly straight-forward: SVA = Net Income – Asset Charge However, to understand this equation, it is important to understand its components: Net Income = Revenue – Costs (including Taxes) Asset Charge = Net Operating Assets X Cost of Capital Net Operating Assets are net receivables, inventories, plant, property, equipment and tooling assets required to run the business and directly supported by shareholders and lenders' capital. Cost of Capital is the minimum acceptable return required by investors.
Track Width	The lateral distance between the centers of the left and right tires on an axle for a vehicle.
Unsprung Mass	The vehicle mass that is not supported by a vehicle's suspension system springs. This typically includes tires, wheels, brake rotors, brake calipers, hubs, knuckles and portions of the control arms and spring damper system.

Wheelbase	The longitudinal distance between the centers of the front and rear axles of a vehicle.

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