Common Global Architecture Applied to Automobile Electrical Distribution Systems

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

January 2010
[February 2010]

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Abstract

Electrical and electronic components have a prominent role in today's vehicles. Particularly during the last two decades, functionality has been added at an exponential rate, resulting in increased complexity, especially of the Electrical Distribution System (EDS), which is the backbone of the Electrical and Electronic System (EES).

Increased content and complexity of electrical systems, together with pressure to reduce the design cycle time – to bring a larger variety of products to the market and at a faster pace – are forcing car companies to re-evaluate their existing electrical development processes. One of the ways that car makers have devised to accomplish this is a common EES architecture strategy, which consists in combining communization, standardization, reusability and best practices to create flexible EES architectural concepts that will be used in a higher number of derivative vehicles. This common architecture has several benefits, the most important being: reduction of development costs and time, which translates in less time for putting the products in the market; architecture, concepts and components reuse; rapid platform modifications, to adapt to market changes and regional preferences.

The EES architecture choice for a vehicle is the result of the implementation of the desired functions in hardware and software. Many considerations need to be taken into account: costs, network capabilities, modularity, manufacturing, energy management, weight, among several others. The present work aims to explain these considerations, as well as the elements of the common EES, and in particular their impact on the EDS.

Another important aspect for the successful implementation of the common architecture is the EDS development process. Despite the availability of a wide range of software tools, the current EDS approach is intensely manual, relying on design experts to define and maintain the interrelationships and complexities of the core design definition. There is a need to redefine the process, from concept to manufacture using a systems engineering approach, which would yield key benefits, like shorten development time, produce accurate harness manufacturing prints, reduce wiring costs by synchronizing all input and output data. An analysis of the tools and methods for design and validation of wire harnesses will be presented in the last two chapters of this thesis.

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List of Acronyms

2D	Two-Dimensional
3D	Three-Dimensional
ABS	Anti-lock Braking System
AMIC	Automotive Multimedia Interface Collaboration
BCI	Bulk Current injection
BSM	Blind Spot Monitor
CAD	Computed-Aided Design
CAE	Computed-Aided Engineering
CAFE	Corporate Average Fuel Economy
CAN	Controller Area Network
CD	Compact Disc
CHMSL	Center High Mounted Stop Lamp
CID	Centerstack Information Display
CPM	Critical Path Method
CUV	Crossover Utility Vehicle
DFMEA	Design Failure Mode Effect Analysis
FMET	Failure Mode Electrical Test
DNA	Deoxyribonucleic Acid
DRL	Daytime Running Lights
DTC	Diagnostic Trouble Code
DV	Design Verification
DVD	Digital Versatile Disc
ECU	Electronic Control Unit
EDS	Electrical Distribution System
EES	Electrical and Electronic System
EMC	Electromagnetic Compatibility
EOL	End-of-Line
FFC	Flexible Flat Cable
FPC	Flexible Printed Circuit
FSS	Full Service Supplier
HIL	Hardware In the Loop
HMI	Human-Machine Interface
HS-CAN	High-Speed CAN
HUD	Heads-Up Display
HVAC	Heating Ventilating and Air Conditioning

I/O	Inputs / Outputs
IVD	Interactive Vehicle Dynamics
IVHS	Intelligent Vehicle Highway Systems
MCAD	Mechanical Computer-Aided Design
MS-CAN	Medium-Speed CAN
NVH	Noise, Vibration and Harshness
OEM	Original Equipment Manufacturer
PCM	Powertrain Control Module
PDB	Power Distribution Box
PERT	Program Evaluation Review Technique
PV	Process Validation
RCM	Restraints Control System
RKE	Remote Keyless Entry
SAE	Society of Automotive Engineers
SIL	Software in the Loop
SPC	Statistical Process Control
SJB	Smart Junction Box
TPMS	Tire Pressure Monitoring System
RF	Radio Frequency
USB	Universal Serial Bus

1 Introduction

1.1 Motivation

Electrical and electronic components have a prominent role in today's vehicle performance and customer appeal. More than half of the comfort and convenience features that are available in a modern car today were simply not around ten years ago, while other features were only available in premium or luxury cars. For example, features like electric windows and seats, air bags and remote door opening are standard in most vehicles produced today for the U.S. market, while other systems like vehicle navigation, remote keyless entry and tire pressure monitoring are all becoming very popular and less expensive, making them attractive for the average car buyer.

These innovations make the interaction of the customer with the car more pleasant, but they also represent an advantage from the safety and reliability perspectives. Cars are safer because of the addition of innovations such as the restraints control module, which commands the deployment of the airbags and cuts the fuel flow to the engine when an accident occurs. The same way, cars are more reliable because of electric components like the traction control or the interactive vehicle dynamics modules, which helps the vehicle adapts to varying road and driving conditions. Therefore, competition among car makers is focusing highly on offering more customization options, in-vehicle electronics compatibility and safety features, all of which are to help keep passengers entertained and safe, as well as to enhance the customer-vehicle experience. Of course, these factors pose challenges that the automobile manufacturers must resolve in order to keep themselves at the top of their game in satisfying the rapidly evolving consumer demands.

One of the biggest challenges is the increase in wire content, which has the inevitable components of cost and weight increase, both acting in detriment of the car's performance and price competitiveness. Everything, from controlling the engine functionality to providing safety through the restraint systems, interacts with the Electrical Distribution System (EDS), so it is no surprise that this is one of the fastest growing systems within a car. For instance, the new modern automobile possesses up to 2 km of wire and nearly 2000 terminals, compared with the vehicles of the 1950s which had only 100 terminals and 75 meters of wire[1]. In fact, electronics constitutes approximately 35% of the content and cost of today's average vehicle, and the percentage is even higher for luxury vehicles. As a consequence, the modern vehicle electrical system is becoming more and more complicated.

This massive electrification of the car has forced automobile makers to commonize and standardize at all levels: system, subsystem, part and component. However, the optimal solution should be developed at a higher level. Until now, electrical architectures had differed amongst the regional organizations around the world due to a lack of a global EES engineering standard, which makes it extremely difficult to optimize material and intellectual resources; thereby, deriving in the inability to migrate features back and forth or source at higher volumes.

One of the initiatives that has been devised to address these concerns is the creation of a common electrical architecture strategy, which will be explained in greater detail in one of the chapters of this thesis. This strategy emerged as an effort to commonize architectural elements to enable various levels of sharing between regional organizations, as well as reduction of engineering development costs. The strategy only defines the elements that need to be common, but does not define the entire architecture. Not only will this common electrical architecture help reduce costs by taking advantage of the economies of scale, but it will also promote communication among the regional organizations, facilitating the exchange of knowledge. Nevertheless, this huge modularization has some disadvantages, because it decreases flexibility between different hardware and software strategies, hindering the development of more ad-hoc systems according to the market needs and demands.

A clear understanding of how this new common electrical architecture strategy works in an electrical and electronics systems engineering organization is a crucial element in identifying its specific implications for the EDS. This understanding will make it possible to realize the current and future needs from the design, manufacturing and validation perspectives, as well as other factors that are crucial for its successful implementation.

1.2 Objectives

Since first instated in automotive Original Equipment Manufacturers (OEMs), common electrical architecture guidelines have proved to be a very effective way to communicate and drive the design of electrical and electronic components within the electrical systems engineering division, and it is currently seen as an innovative way to shift into the future as car manufacturers become global organizations and as their product development divisions around the world begin collaborating more closely together.

However, there are still many challenges that need to be addressed in order to have a comprehensible, coherent and holistic process for the design of electrical distribution systems. By analyzing the most important factors, from the EES and EDS architecture perspective, this thesis intends to:

- Serve as a basis for understanding the current electrical architecture elements, EDS development processes and the role of the current validation methods;
- Identify the shortcomings or limitations, if any, in the existing EDS architectural design process, and suggest improvements on the recommendation section;
- To use a systems engineering approach to categorize the current engineering challenges that the architectural strategy poses, and identify potential issues that will emerge when

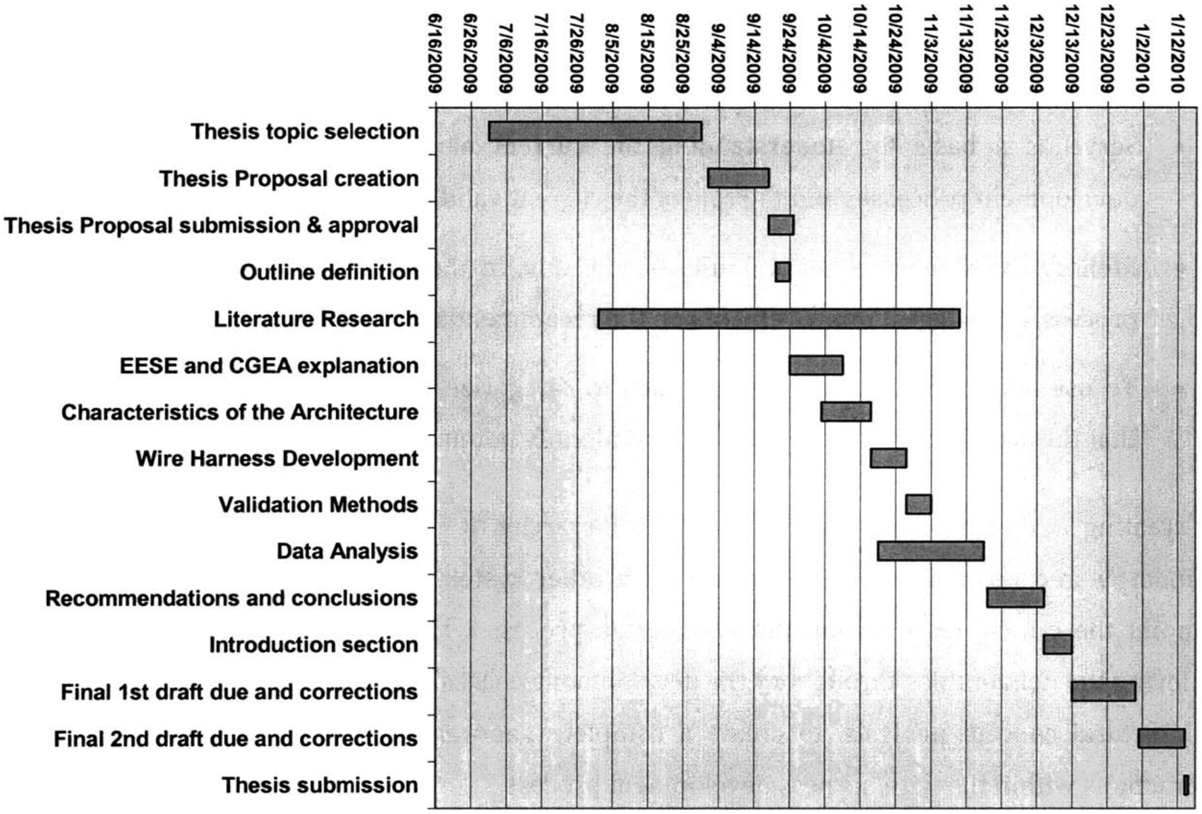
By creating a sketch of the current system's hierarchy, it will be possible to define the EES boundaries and recognize the interactions with other systems. A Critical Path map will help to pinpoint the critical tasks within the EDS design process which have the greatest influence for achieving the deliverables throughout the development phases. This should be done along with the architectural concept analysis, to create a complete panorama of all the relevant aspects and interactions within the wire harness development process.

1.3 Research Method and Approach

Research will be conducted by an Electrical and Electronics Systems Engineer who works for two distinct regional organizations. With the purpose of gaining insight of how the electrical distribution system engineering development process currently works, it is essential to look at it from the perspective of the internal stakeholders.

Specific information will be collected through literature research on the common electrical architecture strategy, EDS and electrical/electronic systems processes, global product development process, plus the latest tendencies in other automotive OEMs. A deep dive into the existing System Engineering literature will be carried out with the aim of identifying the fundamental elements that are present in the current EDS design process and practices, and recognizing those principles that have not yet been put into practice and that would benefit the regional organizations.

1.4 Timeline



1- Figure 1.4.1 Thesis Timeline

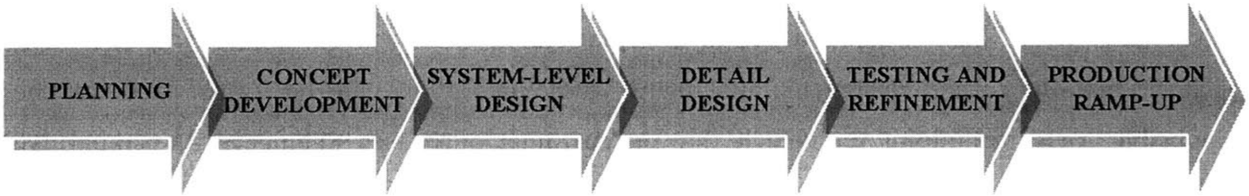
2 Vehicle Electrical and Electronic Systems

> *"A system is a network of interdependent components that work together to try to accomplish the aim of the system. A system must have an aim. Without an aim, there is no system."*
>
> *Dr. W. Edwards*

The primary objective of this chapter is to present an overview of some of the concepts that are relevant to understanding the vehicle subsystems in a car, their main characteristics and how they interact with the Electrical and Electronic System (EES) through the wiring, which is the main subject of study of this thesis.

2.1 Product Development Process

Like most product development projects, the product development process at the automotive OEMs consists of sequential phases. It includes the general phases of definition, design, development, validation and launch. Nearly all activities of the organization are part of the vehicle development, which makes it an interdisciplinary activity requiring contributions primarily from Marketing, Finance, Design, Manufacturing and Purchasing. The product development process essentially consists of six phases as shown in Figure 2.1.1.



2- Figure 2.1.1 Product Development Process[2]

During the *Planning* phase, product development opportunities are identified by various sources, including marketing, research, customers, current product development teams, and benchmarking of competitors. The OEM looks at these opportunities from marketing, design, financial and manufacturing standpoints, analyzes the business case, value proposals, market targets/segmentation, and decides which opportunities should be explored. During the *Concept Development,* these ideas are evaluated taking into consideration the customer, corporate, governmental, and social needs. The production feasibility is also assessed at this time. During the *System Level Design* phase, the product architecture is generated and the product is decomposed and its various systems/components are assigned to the respective technology teams. The key suppliers are also identified during this time. In the *Detail Design* phase the complete specification of all the parts in the product as well as all the parts are identified. The *Testing and Refinement* phase entails the construction of multiple pre-production versions of the product, or prototypes. These prototypes undergo reliability testing, life testing, and performance testing during this phase. In the *Production Ramp-up* phase the operation of the entire production and manufacturing system begins.

In order to execute the vehicle programs in a timely manner, the project management team defines *gateways* or *milestones* which are also used to assess the status of the project. For the vehicle program to move from one phase to the next, all aspects of the system must achieve a common level of readiness at the same time. Even when the systems and subsystems individually have separate timing requirements for certain gateways, they will have to meet the ultimate timing for the program collectively.

2.2 Vehicle Systems and Subsystems

A vehicle can be thought of as a system. On the largest scale, the inputs are the target market customer's wants and needs, business needs, and government regulations. The product development process consists of all the activities that occur at the automotive OEM to create a vehicle from these inputs. The output is information, in the form of engineering drawings, specifications and other design/manufacturing guidelines that will be transferred to the responsible areas for building the vehicle that the customer purchases. Engineering a competitive product in the current dynamic and changing market is a challenge that requires an organized systematic approach focusing on the whole.

The overall vehicle behavior depends upon several and sometimes complicated interactions between the numerous elements that comprise it. At the end, they all come together to deliver a system function that is greater than the sum of the functions of the individual elements. Managing the interactions and interfaces between the various components is essential to creating exciting products that will satisfy the needs of the customers with the least number of defects.

One of the ways to reduce the complexity when dealing with such a big system is partitioning, which is the process of hierarchically decomposing or dividing the vehicle into elements based on one or more criteria. The reasons for partitioning vehicles are mainly:

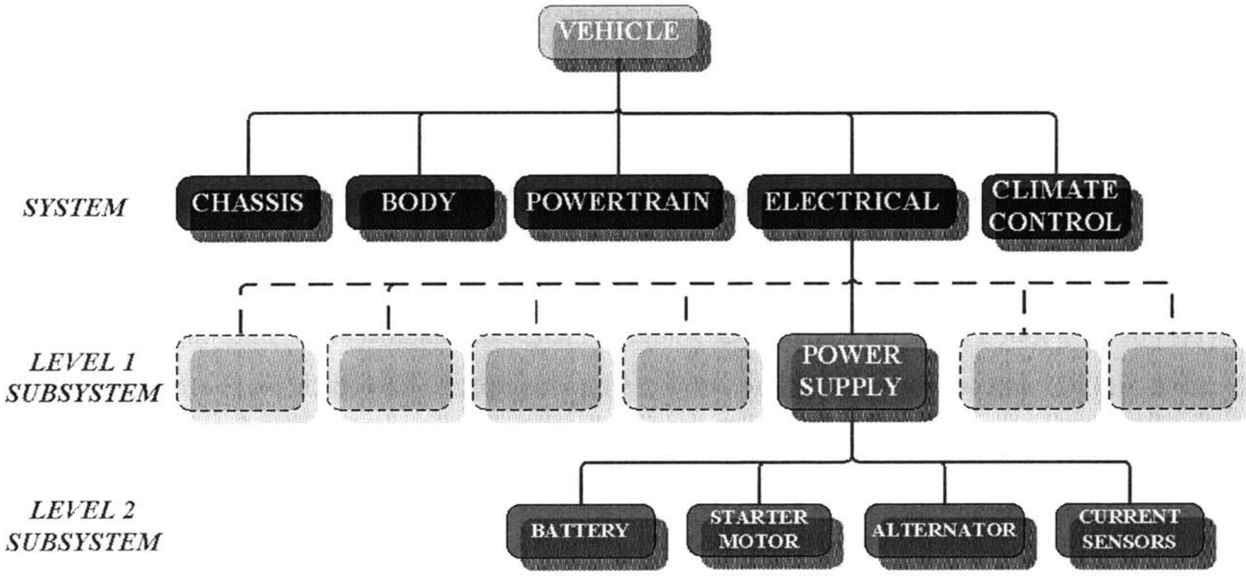
a) To organize a complex system in a way that can be understood and managed.

b) To focus the teams on comprehensible, lower-scope project objectives.

In the automotive lingo, 'vehicle level' is a term used to define tasks or attributes that can only be carried out or applied with reference to a whole vehicle. For instance, ride and handling, noise, vibration and harshness (NVH), durability, and craftsmanship, are all vehicle level attributes since they apply to and can only be assessed with a whole vehicle. Vehicle level engineering is concerned with building and verifying characteristics of the whole vehicle such as interior lighting harmony, exterior and interior style themes, acoustics, etc.

People within the automotive industry utilize the concept of 'system' to refer to a set of connected parts or elements within the vehicle that share common attributes and can be characterized in some way. Within automotive OEMs the partitioning of the vehicle into systems has been carried out mainly by the grouping together of functions. The highest levels subdivision in which the total vehicle can be partitioned into are the following five vehicle systems: Body, Electrical, Powertrain, Climate Control, and Chassis.

Figure 2.2.1 represents a real world example of vehicle partitioning or high level subdivision in systems and subsystems of the vehicle. As explained by Flower[3], the term *'Body system'* is used as a system level partitioning to describe those elements of the vehicle that are typically structural, static, and are related to the exterior and interior styling of the vehicle, like body panels, trim, instrument panels and sheet metal. In the same way, the term *'Electrical system'* is used as a system level partitioning to describe those elements of the vehicle that use electrical/electronic power and information technology, like relays, electronic modules, and batteries. *'Powertrain system'* is used as a system level partitioning to describe those elements of the vehicle that are involved with providing automotive power to make the vehicle move, like the engine and transmission. In the case of the *'Climate Control system'*, it is comprised by those elements that serve to control heating, ventilating and air conditioning, with the purpose of providing environmental comfort inside the cabin. Finally, the term *'Chassis system'* is used to denote the elements that bring support to the car, where all other elements fasten to, like the frame and suspension, which also to provide steering, shock absorption and smooth handling.

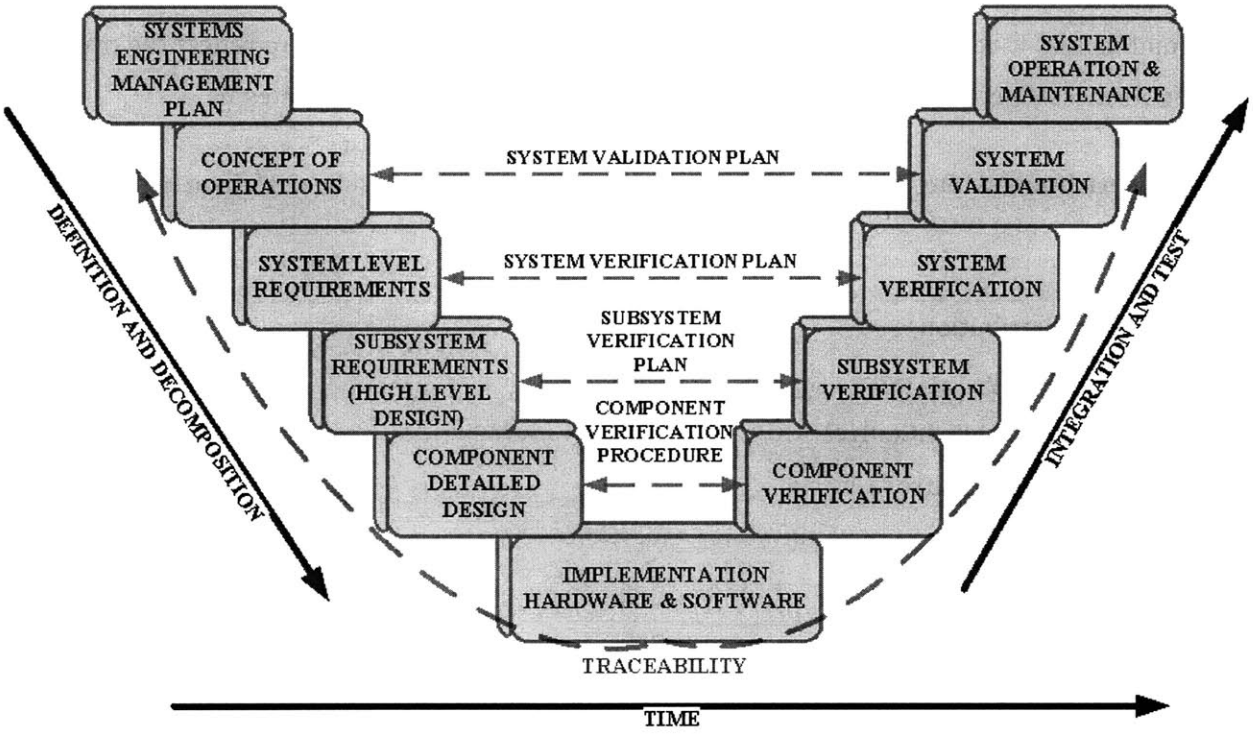


3- Figure 2.2.1 Vehicle Systems

The term 'subsystem' is used to mean those smaller elements of the system that can be broken further down into another characteristic. Normally the characteristic that is used is the function that the entire group of interconnected components is aiming to provide. A typical example of a small electrical sub-system is the power supply subsystem. This is a part of the electrical system, but remains a smaller system in its own right, for the reason that it consists of a group of components all working together to provide two discrete functions: starting and charging. Hence, it is a system that is below a system level partitioning and therefore is denoted as a subsystem that now can be broken down even further into constituent components such as alternator, starter motor, battery, current sensors, wires, etc.

The idea of breaking the vehicle down into subsequent smaller systems is considered to best enable the customer wants and needs to be cascaded downwards from high level vehicle requirements to detailed components requirements. Once this is completed, OEMs use the process model illustrated in Figure 2.2.1 below that shows the engineering V – the cascade of customer wants to component design – to help visualize the aspects of the design that are being developed and when they are being developed.

In concept, the engineering V model takes the timeline of the specific system development plan, and folds it into a "V" shape at the point of product realization. It acknowledges that information relevant to the completion of the later test phases is derived from the earlier development phases and aligns these to show relevant information flows.



4- Figure 2.2.4 Systems Engineering V Diagram[4]

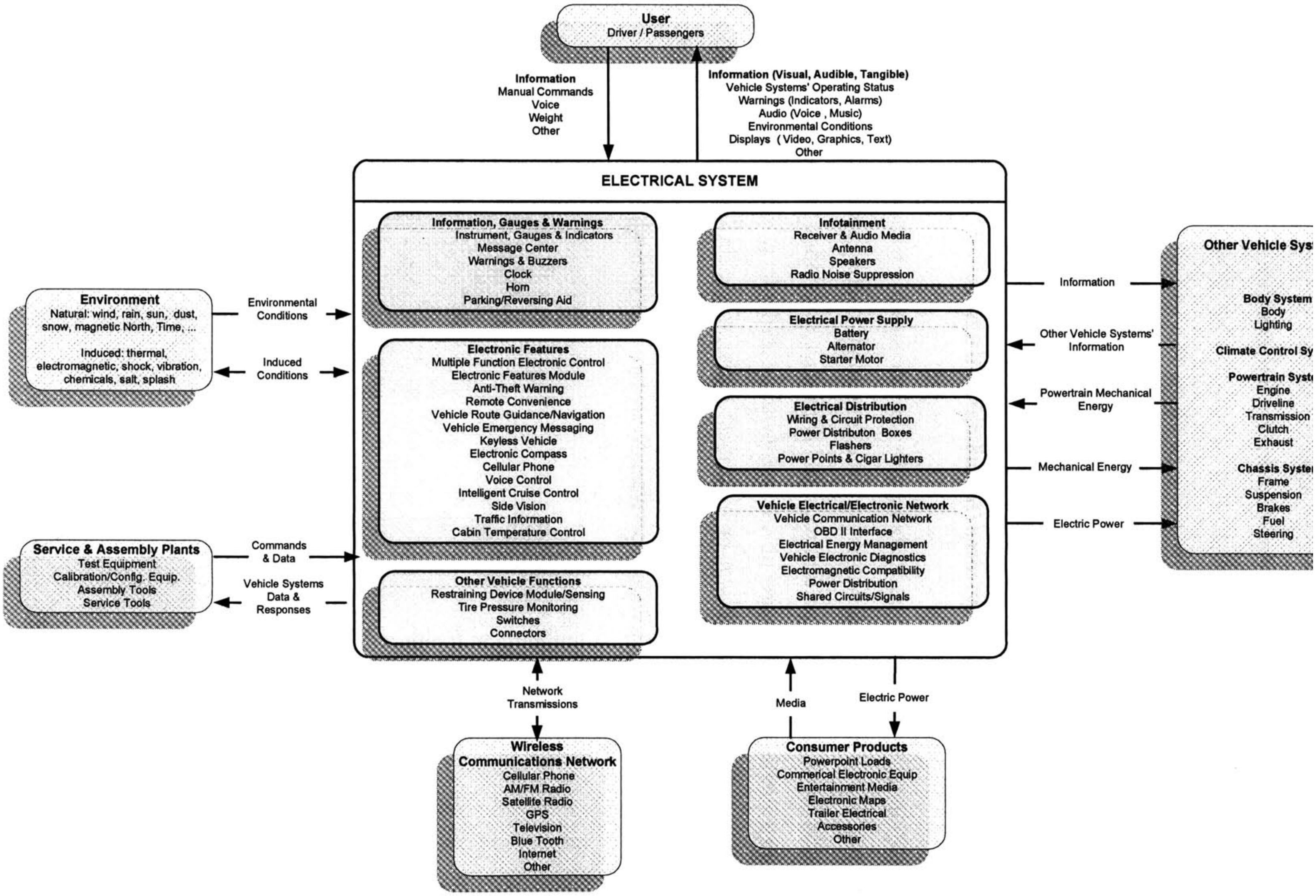
2.3 Vehicle Electrical and Electronic System

The vehicle's EES, which is the foundation of this study, is the brains and nervous system of an automobile. In its early days, the electrical system in a car was comprised of only basic wiring technologies that were almost exclusively used for distributing power to a few parts of the vehicle: ignition system and interior/exterior lighting components. Over the years, the EES has gradually evolved and nowadays, it includes all sorts of sensors (mechanical, optical, pressure, temperature, current etc.), actuators (hydraulic, stepper motors), switches, relays, Electronic Control Units (ECU), among other components. These electrical and electronic components interface with all the other systems in a car.

The scope the EES, as defined by automotive OEM's program management team, comprises components and subsystems designed and released by the EES department, including shared signals, network messages, link based diagnostics, electromagnetic compatibility (EMC), and the vehicle EES architecture. The EES interfaces with the other systems as shown in Figure 2.3.1. With added customer wanted features like drive-by-wire, traction control, tire pressure monitoring system, reverse park aid, navigation system, infotainment system, and active anti-theft system, it is evident that there is a high level of interaction between the EES with all the other systems in the vehicle. This generic boundary diagram serves to demonstrate the extent of the EES and the most important factors that affect it. This is a generic version that can be adapted to reflect the program specific electrical/electronic content, features and design implementation strategies.

The EES is partitioned into the following subsystems, some of which will be described in succeeding chapters:

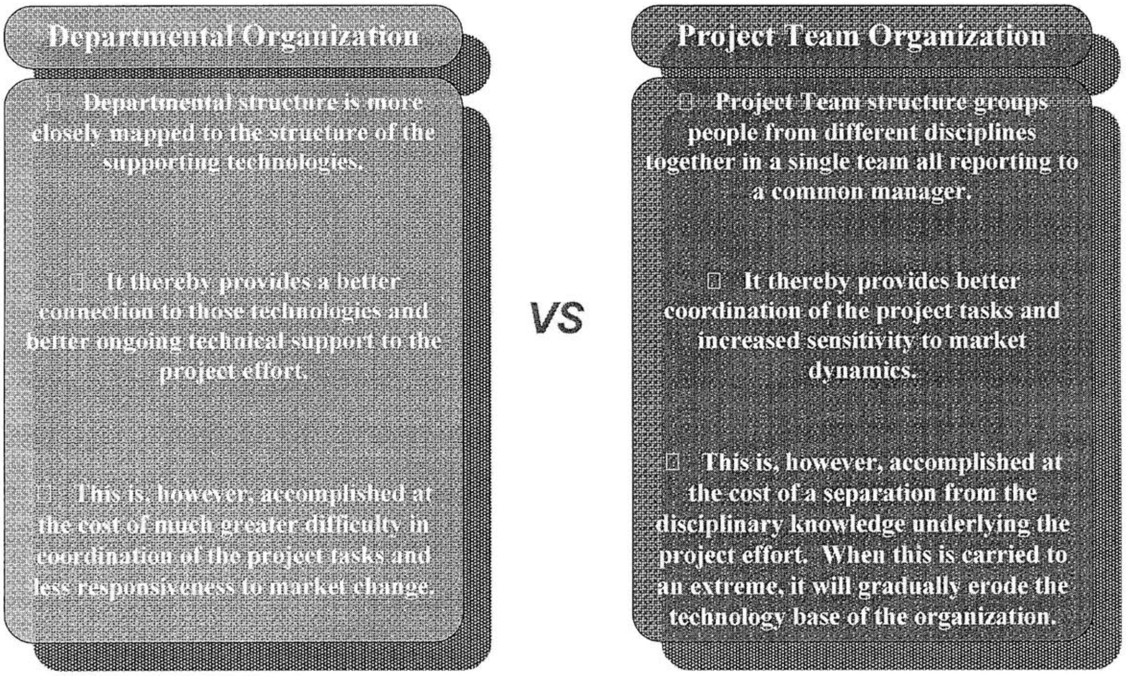
- Power Distribution
- Power Supply
- Powertrain Engine Control
- Transmission Control
- Exterior Lighting
- Interior Lighting
- Visibility
- Horn
- Restraints
- Interactive Vehicle Dynamics (IVD)
- Driver Information and Warnings
- Climate Control
- Power Convenience Electronics
- Security
- Infotainment and Multimedia
- Intelligent Vehicle Highway Systems (IVHS)
- Communications/Telematics
- Navigation Systems
- Special Vehicle Features


User
Driver / Passengers
Information
Manual Commands
Voice
Weight
Other
Information (Visual, Audible, Tangible)
Vehicle Systems' Operating Status
Warnings (Indicators, Alarms)
Audio (Voice , Music)
Environmental Conditions
Displays (Video, Graphics, Text)
Other
ELECTRICAL SYSTEM
Information, Gauges & Warnings
Instrument, Gauges & Indicators
Message Center
Warnings & Buzzers
Clock
Horn
Parking/Reversing Aid
Electronic Features
Multiple Function Electronic Control
Electronic Features Module
Anti-Theft Warning
Remote Convenience
Vehicle Route Guidance/Navigation
Vehicle Emergency Messaging
Keyless Vehicle
Electronic Compass
Cellular Phone
Voice Control
Intelligent Cruise Control
Side Vision
Traffic Information
Cabin Temperature Control
Other Vehicle Functions
Restraining Device Module/Sensing
Tire Pressure Monitoring
Switches
Connectors
Infotainment
Receiver & Audio Media
Antenna
Speakers
Radio Noise Suppression
Electrical Power Supply
Battery
Alternator
Starter Motor
Electrical Distribution
Wiring & Circuit Protection
Power Distributon Boxes
Flashers
Power Points & Cigar Lighters
Vehicle Electrical/Electronic Network
Vehicle Communication Network
OBD II Interface
Electrical Energy Management
Vehicle Electronic Diagnostics
Electromagnetic Compatibility
Power Distribution
Shared Circuits/Signals
Environment
Natural: wind, rain, sun, dust, snow, magnetic North, Time, ...
Induced: thermal, electromagnetic, shock, vibration, chemicals, salt, splash
Environmental Conditions
Induced Conditions
Service & Assembly Plants
Test Equipment
Calibration/Config. Equip.
Assembly Tools
Service Tools
Commands & Data
Vehicle Systems Data & Responses
Information
Other Vehicle Systems' Information
Powertrain Mechanical Energy
Mechanical Energy
Electric Power
Other Vehicle Sys
Body System
Body
Lighting
Climate Control Sy
Powertrain Syst
Engine
Driveline
Transmission
Clutch
Exhaust
Chassis Syste
Frame
Suspension
Brakes
Fuel
Steering
Network Transmissions
Media
Electric Power
Wireless Communications Network
Cellular Phone
AM/FM Radio
Satellite Radio
GPS
Television
Blue Tooth
Internet
Other
Consumer Products
Powerpoint Loads
Commerical Electronic Equip
Entertainment Media
Electronic Maps
Trailer Electrical
Accessories
Other

As a result, designing a vehicle's EES is a tremendous job with a high level of complexity. The vehicle's entire EES needs to be considered and all constraints understood in order to facilitate the cascading of the customer wants and needs accurately into the design and to create a system that achieves cost, timing and quality objectives. If the entire system is not considered, one subsystem/module may be optimized at the expense of the rest of the system, jeopardizing its intrinsic harmony. For this reason, a comprehensible interpretation of the elements that form the EES and the interactions between these elements and the other subsystems is compulsory to facilitate the analysis of the EDS, which is the main focus of this study.

2.4 Electrical and Electronic Systems Department Structure

Vehicle partitioning must also be consistent with the corporate structure that is responsible for delivering function. Hence, in order to reflect the functional partitioning of the vehicle electrical systems outlined previously, the automotive OEM product development organization should be structured in a similar way. There are, however, inevitable tradeoffs when deciding how to arrange any organization. Either by *department* or by *project teams*, the main question of which one best enables the exchange of information and collaboration is always present. As Professor Tom Allen explains, there are important differences between these two approaches:



Departmental Organization

- Departmental structure is more closely mapped to the structure of the supporting technologies.
- It thereby provides a better connection to those technologies and better ongoing technical support to the project effort.
- This is, however, accomplished at the cost of much greater difficulty in coordination of the project tasks and less responsiveness to market change.

Project Team Organization

- Project Team structure groups people from different disciplines together in a single team all reporting to a common manager.
- It thereby provides better coordination of the project tasks and increased sensitivity to market dynamics.
- This is, however, accomplished at the cost of a separation from the disciplinary knowledge underlying the project effort. When this is carried to an extreme, it will gradually erode the technology base of the organization.

6-Figure 2.4.1 Dilemma in Product Development Organization[5]

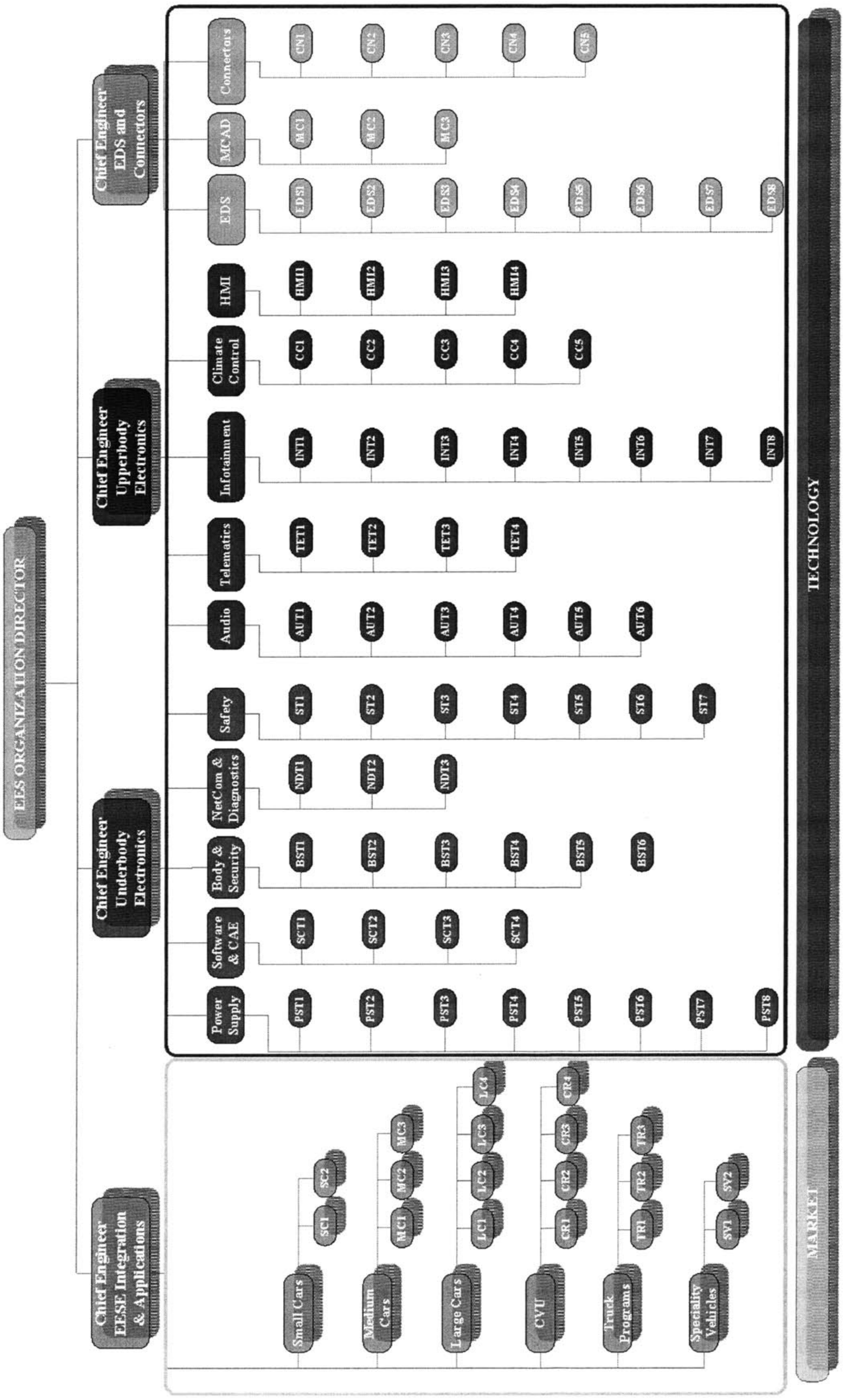
Figure 2.4.1 highlights the most important characteristics of each type of organization. It condenses the options and tradeoffs that every management team in any organization faces when setting the foundation for a new department or whenever re-organization of the current department is needed. In many cases, engineering organizations fall somewhere between the fully departmental and pure project team, or are a mix of these two.

Within the EES organization, the engineering process is deployed at all levels using a matrix management structure to balance the functional and project requirements of the product development process. The EES matrix structure is shown in Figure 2.4.2, which represents the high level EES organizational charts. All *chief engineers* report to the EES *director*, who is the most highly ranked employee within the EES organization. It can be seen from this diagram that there are four chief engineers: one of them is responsible for the application and integration of technologies in specific projects or *programs*, while the other three are in charge of the *technology* departments. The program groups are divided by the size of the vehicle: small cars, medium cars, large cars, crossover utility vehicles (CUV), trucks and specialty vehicles. A *manager* leads each of these groups, which are further divided into platform derivatives. A *supervisor* responsible for integrating all electrical technologies leads each platform derivative. This high level chart lists the manager's direct reports (supervisors) but does not show each supervisor's group in detail. The program supervisor groups have been listed simply as 'SC1' (small car 1), 'MC2' (medium car 2), 'TR3' (truck program 3), and so forth.

The technology groups are divided in a way that resembles more the EES partitioning: power supply, body and security modules, audio, infotainment, climate control, power distribution, etc. Just as in the case of the program groups, technology groups are led by a manager, who is responsible for various technology components and subsystems. Hence the technology groups are broken down into smaller groups, principally by type of technology, led by a supervisor. These technologies have been listed just as 'AUT5' (audio technology 5), 'CC2' (climate control technology 2), 'CN1' (connector technology 1), and so on.

It is pertinent to mention that there are other classifications within both technology and program groups that help differentiate the engineering roles. The terms system, subsystem and component (or commodity) have been described before, and simply denotes the level at which the engineer works. However, the term *application engineer* and *core engineer*, which are widely used within EES organizations, need to be defined. 'Application engineer' is used to describe an engineer delivering or applying electrical technologies to a specific project, i.e. an engineer working for a technology group but applying the technology to a specific project. The term 'core engineer ' is used to describe those engineers that do not work on specific projects but work across all car lines ensuring that the applications of electrical systems and subsystems are controlled and that lessons learned are carried across all projects. For some larger or more technical groups the post of technical specialist is also used to control core technology. This position is a lower-lever management position designed to keep highly skilled engineers within certain teams.

A matrix organizational method of this kind has clearly several advantages over organizing purely by department or by project. Instead of working in isolated groups, this kind of organization allows team members to exchange specialized knowledge, best practices and lessons learned across groups. For instance, we can think of the case of a cluster applications engineer who is assigned to different programs and reports to a cluster technology supervisor. This engineer must interact with the core cluster engineer to understand the functionality of the component, which also helps him/her to be aware of how new technologies develop. Besides, the cluster applications engineer must work closely with the applications electrical systems engineer and the network communications engineer for each of the programs to make sure that the cluster is electrically compatible with the rest of the system and to add the cluster-specific messages to each program's configuration specification and message's list. As we can see, the cluster engineer works indirectly under several managers to get his/her job done. This allows him/her to take into account the interdependencies in project work. This has the advantage that the engineer gains in depth knowledge of his component, but on the other hand sometimes he/she can be under al lot of pressure because of prioritization discrepancies between managers. However, this disadvantage can be minimized with a properly managed cooperative environment.



7- Figure 2.4.2 EES Matrix Organization

3 Common Electrical Architecture

"Architecture depends on Order, Eurhythmy, Symmetry, Propriety, and Economy."

Vitruvius Pollio [The Ten Books on Architecture]

3.1 Description and Objective

Like in almost any other industrial sector, competition among automobile makers has gotten tougher and tougher as customers demand better products at a competitive value. Hence, automobile companies are launching new vehicle models which meet the consumer preferences in various niches for their numerous products all around the globe. As a result, developing different vehicles simultaneously is a *must* for car manufacturers, but doing so may lead to increased production costs in case no appropriate development, cost and launching strategies are applied. To avoid this scenario, the common platform strategy[i] has been in use by car makers for decades and has promoted both standardization and reuse of vehicle components and systems. In consequence, common platforms represent an advantage from a couple of standpoints:

- Reduction of the overall project cost by purchasing large scale volumes of shared components and systems.
- Reduction of the overall project lead-time by keeping a base platform and making the changes/upgrades required by the specific vehicle line, maintaining a high level of commonization[ii] among vehicle designs.

However, in recent years, a new concept in product development called *common architecture* strategy has emerged and has been put into practice by some of the world car makers. Through combining commonization[6] and standardization, the global architecture promises to become a better option and to provide greater benefits beyond what can be accomplished by the conventional common platform strategy.

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[i] The strategy of platform sharing is a practice that automakers have embraced with vigor which portions common design, engineering, and production efforts over a number of outwardly distinct models. Platform sharing mixes lower-volume differentiating technologies to increase market attractiveness with higher-volume standardized technologies to lower overall costs.

[ii] The core of a platform commonization strategy is a process of finding the potentially common elements (product and manufacturing processes) within a family of products and designing for commonization and standardization of them.

In this chapter, the implications of the implementation of the common electrical architecture will be analyzed, with the ultimate objective of identifying the relevant variables that have to be taken into consideration when selecting an appropriate strategy for developing a new global architecture for a car's EES.

3.2 Common Architecture

3.2.1 Definition

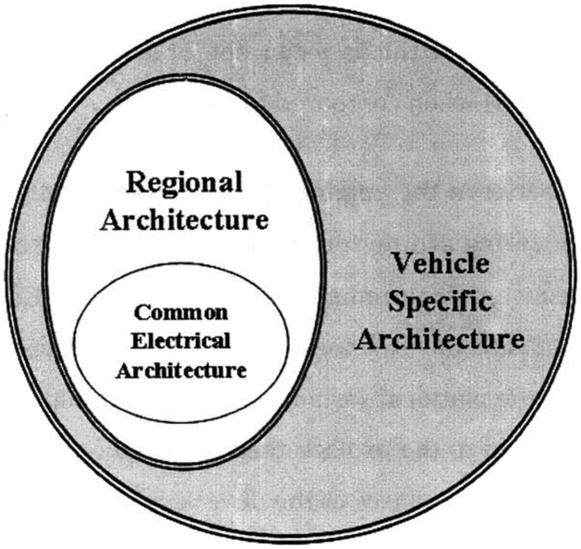
Architecture comprises the concept of the product, defined with boundaries, goals and functions that satisfy the customer needs, meets strategic business goals and incorporates appropriate technology. Unlike platforms, architecture is sustainable, can evolve and be modified as required.[22] *Platforms* are more specific, more rigidly defined from conception, and therefore less flexible. Car makers recognize the word architecture as a more flexible and wider notion than the word platform due to the fact that architectures can be the base concept for a larger number of derivative concepts (either at a vehicle or system level) when compared to a platform.

One of the main differences between the application of platform and architecture is certainly the way both planning and engineering are performed in each of these strategies. In the case of the architecture, all derivative concept requirements are taken into consideration from the earliest definition phase and cascaded into the engineering development phase from the very beginning. This is not necessarily true for the platform, because the company might decide that a derivative for a new market is going to be added to the project; therefore, the requirements for this new market have to be included somehow in later phases of the development process. Subsequently, this poses serious risks to the project, like:

- Cheapening high-end products or adding unnecessary cost to lower-end ones.
- Performing costly modifications to the product to make it technologically compatible with the new market requirements.
- Changing design requirements at a late development phase multiplies the risk across numerous derivative concepts, making recalls and redesigns potentially very expensive.

Following the notions of commonality and reusability, automotive OEMs have developed electrical and electronic architectures based on their experience and their knowledge of past efficient systems. They create numerous architecture concepts and assess them against each other. Based on the OEM's corporate objectives and all types of requirements (functional, corporate, governmental, environmental), they define evaluation criteria. After evaluation of all alternatives the best is chosen for the specific application and market. This methodology worked well enough in the past, but with today's pressure of development time and budget, OEMs are now looking for a better way to address these issues in a global manner as the volume of electronics and in-vehicle networking increases.

Experts have envisioned the common electrical architecture as a way to define only the elements that need to be common, not the entire architecture. The common architecture only defines a portion of the regional architecture just as the regional architecture defines only a portion of the vehicle specific architecture. This is represented in Figure 3.2.2 below.



8-Figure 3.2.2 Levels of EES Architecture

The motivations that the car makers have for implementing a common architecture strategy for the development of EES are listed next:

- Sharing a common electrical design to reduce re-engineering across platforms, brands and applications. As discussed in Chapter 2 of this thesis, not only does the electrical system deliver purely electrical features (audio, illumination, power windows, etc.), but it also controls and interconnects many other features in the vehicle (anti-lock braking system

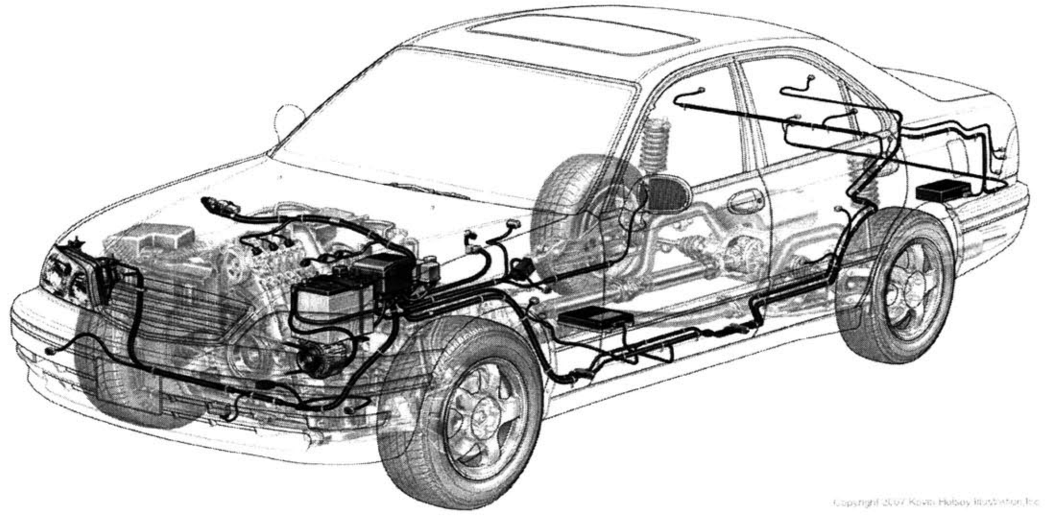
(ABS), remote start, restraints control system (RCM), tire pressure monitoring system (TMPS), etc.).

- Mechatronics solutions have emerged, where the power that drives electronics is no longer on the ECU's main board but moved to the actuator. Similarly, signal-conditioning electronics moves adjacent to the sensor itself. This way of putting electronics in the car coincides with a strong increase in electrically-driven actuators replacing the traditional belt-mechanics. By shifting to a common architecture, automotive manufacturers and suppliers can take advantage of these new technologies to increases design flexibility.[7]
- Currently, electrical architectures differ between the various regional organizations, leading to an inability to migrate features back and forth or source at higher volumes. Communization of architectural elements will enable various levels of sharing between these regional organizations, ultimately allowing to use global resources efficiently and to deliver innovation quickly at the lowest cost and best value to all regional partners.

3.2.2 EES Architecture Design Approach

When vehicle OEMs start the development of a model with major changes, they routinely have to make alterations to the vehicle structure, modifications to the internal and external sheet metal, and incorporate electrical- and electronic-based features. From a macro point of view, even though the electrical/electronic content is under development almost immediately, the structure and sheet metal aspects of the new platform are typically the primary focal point of the OEM. This non-EES focus is simply due to the history of the vehicle development process. Starting in the middle of the twentieth century, vehicle styling was the top concern of OEMs. Safety requirements brought more attention to the underlying vehicle structure starting around the 1980's. Only within the last decade has the importance of EES features as a product differentiator become prevalent.

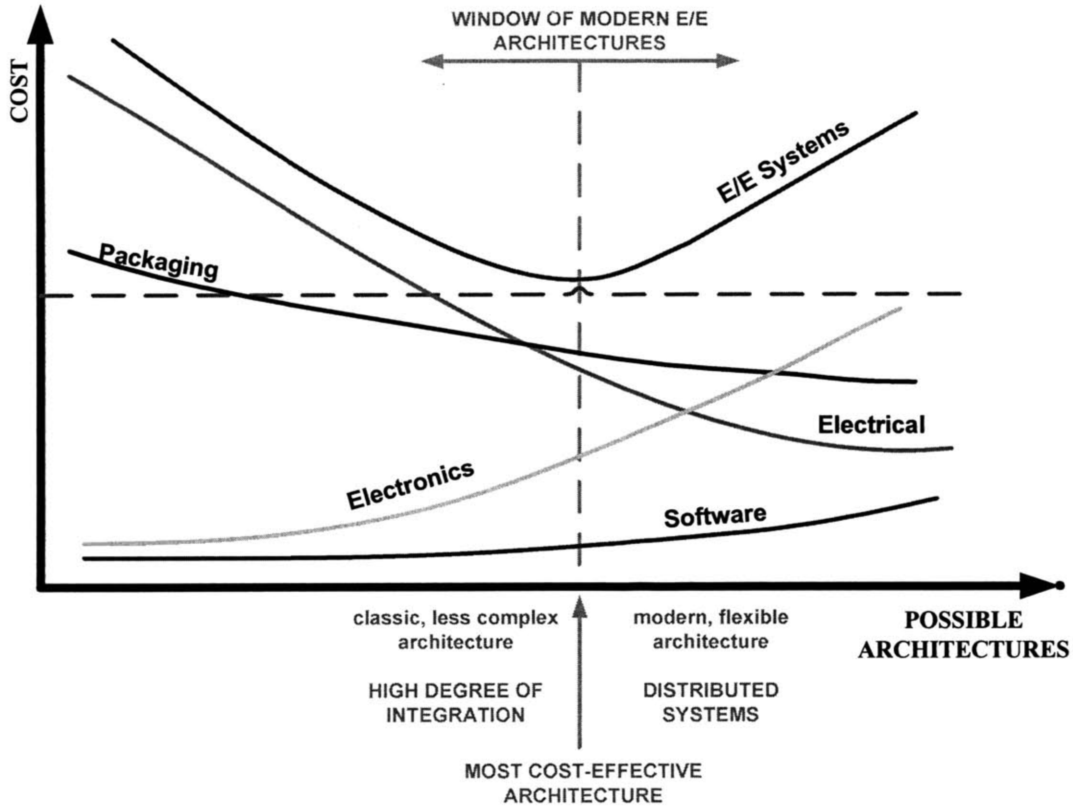
OEM metrics vary broadly around the world. For this reason, as Turner[9] explains, when performing the EES architecture analysis, a variety of specific OEM EES requirements may need to be balanced. In some cases, cost is the primary driving factor. Many other times, the impact of weight, packaging, and reliability may be critical metrics in addition to the cost metric. Finding the correct balance for the particular OEM is critical. The EES architecture must be correctly balanced based on the design direction data gathered early in the vehicle development process. As the vehicle design progresses, this same EES architecture must be able to continue to evolve and adapt throughout the development process according to updated design information.



9- Figure 3.2.3 Basic Car Electrical System[8]

Figure 3.2.4 serves as an example of how various elements that define the EES architecture are combined generating an EES system cost metric curve for multiple architecture solutions. While the knee of the curve indicates the optimal solution, it should be noted that this is a single point in time analysis. In reality, this point may not be the best solution for the OEM when looking at the long term plans for the vehicle platform. Consideration for future expansion of features may require a different point on the curve to be selected.

With the growing importance and sophistication of electronic features in a vehicle, the early definition of an EES architecture that balances all elements and critical design factors is required to achieve the optimal, lowest cost design.



10- Figure 3.2.4Balancing Architectural Alternatives[9]

3.3 Design Considerations

There are a number of factors that come into play when determining a vehicle's electrical architecture and partitioning of its EES. *Design constraints* are additional constraints on a specific design that are less formal in nature. These can be derived from business needs, corporate initiatives (e.g. commonality) and recognized best practices which are thought of as de facto standards. The typical constraints that affect the vehicles EES architectural components can be anything from allocating the functions to their physical space, identifying the possible trade-offs and complying with corporate and governmental regulations. The design constraints that have a major impact on the vehicle's EES, including some that have been identified by Rushton and Merchant[10], are discussed next.

3.3.1 Market Wants and Brand DNA

Vehicles must meet local customer's requirements with a consistent feel and sound that is unmistakably that of the car manufacturer. To do this, identification of market wants is the most important thing that OEMs must consider before determining a vehicle's balance and harmony attributes, which will ultimately define its DNA[iii]. The DNA[11] is a set of functional attributes of a system that are designed to be easily recognizable by the customers as a member of the OEM product family, which help ensure consistency of the brand, reinforces its character, and enhances harmony across its attributes. The goal of the car manufacturers should be to define the DNA elements which can be exactly the same globally. In a few instances it can be necessary to define DNA elements which deliver a similar character, however, tuned to meet either local, legislative or customer preferences. In the case of the EES, DNA elements such as the information strategy and switch functionality are relevant for the characterization of the human-machine interface (HMI) for a specific vehicle brand.

3.3.2 Cost and Timing

Like in any other industry and product development process, cost and timing are the two major factors that drive the design of a car. These will determine how much of the vehicle is carried over from the previous model year. For instance, when there is minor refreshment to the vehicle from the previous model year, minimal changes will be performed. In the case of a brand new vehicle model, major changes always occur. Whenever a program has a small budget, it is expected that it will use a lot of carry over components and modules. Although this may appear as a cost saving opportunity, it is not always the case, given that carry over components bring a lot of side issues with regard to interfaces (architecture and partitioning). Therefore, cost and cycle times play a big role in determining the architecture of the EES in the early stages of the development process.

The cost elements that occur during the phases of the EES architecture life-cycle are[12]:

- ***Design and development cost.*** This category encompasses the cost of developing and validating the hardware and software that is executed in embedded modules within the EES architecture. The cost items include OEM engineering activities (i.e. total system specification, documentation and validation) summed with supplier engineering activities,

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[iii] Deoxyribonucleic acid (DNA) is a nucleic acid that contains the genetic instructions used in the development and functioning of all known living organisms and some viruses.

such as design, development, and validation of the EES components and sub-systems. From the software point of view, cost is driven by items like coding, software licenses and office space (both for OEM and suppliers) - all items that are relatively independent of the architecture chosen.

- ***Part fabrication cost.*** This refers to the manufacturing cost for the parts and subsystems of the production version of the EES architecture. The current supply chain for EES components relies almost exclusively on suppliers for fabrication. The cost items in this category include the component's cost (tooling and piece cost) and packaging cost.
- ***Assembly cost.*** This is the cost related to the integration of the parts into the vehicle during production. The EES assembly cost includes the cost associated with connecting the parts and placing them into the vehicle body. The placement cost is comprised of the cost of inserting the system into the vehicle including fastening, attachment and labor to perform the operations. In this category, the most important items are: a) part maintenance cost, which is the engineering and production effort to keep track of new part numbers, and b) plant's internal module flashing cost.
- ***In-service cost.*** The cost of ownership resulting from repair and/or maintenance, which includes items like re-flashing modules, replacing parts, and labor costs.

There are basically two elements that need to be considered in regards to timing:

- ***Development time.*** This term refers to the time required to execute the new vehicle project, from its initial conceptual phase until the vehicle launch. OEMs keep shortening the development time with the aim of offering the latest technological advances and convenience options to the customers before the rest of their competitors. As a result, the lead time for developing electrical and electronic components has shrunk too, making it more challenging than ever to be ahead of the game in offering products that meet the different markets demand.
- ***Lifecycle.*** This is the time the new vehicle is kept in the market following the market trends. In the last decades, market tendencies have affected the vehicles' lifecycle, making it shorter, which requires car makers to renew their portfolios very often in order to satisfy customer wants. A vehicle's lifecycle has a direct relationship with its development strategy.

In most cases, the longer the vehicle's lifecycle, the larger the amount of changes that will be required to keep its appeal during the time it stays in the market.

3.3.3 Manufacturing and Assembly

What is the impact of a jumper harness from a system point of view when compared with the help it brings to the vehicle assembly process? Is vehicle assembly time/efficiency more important than the electrical system piece price? Does changing the routing of a harness or the location of an inline connector affect the reliability of the overall EES? What are the implications with respect to cost and ease of manufacturing of changing the location of a module in the vehicle to enable the assembly plant to construct their vehicle in a modular build fashion? These are all questions a design team must answer as it develops a system or subsystem architecture solution for the vehicle. Being able to address these tradeoffs and deliver results will allow the design team to make the correct decision for the vehicle.

Manufacturing and assembly constraints can be very restrictive on the design. Attributes such as ergonomics and EMC should be taken into consideration when choosing the physical location of any component within the car. For example, the size of a transmission control module, the type and size of its electrical connector and associated circuits can be affected by the manufacturing and assembly requirements.

The need to get more products to market faster has driven manufacturers to distribute production over many, often geographically remote, plants and contract manufacturers. The strategy to "plan anywhere, build anywhere" requires technologies and methodologies that allow manufacturers to efficiently author, simulate and manage manufacturing information throughout their organization and with each other.[13] For these reasons, when designing the EES, or any other system, automotive OEMs must ensure that the design is consistent with manufacturing practices and concepts globally. For instance, the Bill of Process has to be created based on global manufacturing standards, to ensure that the material logistics and assembly directions are concordant between regional manufacturing locations, regardless of whether the component is assembled in Korea or Brazil.

3.3.4 Flexibility and Scalability

When faced with the problem of developing an EES architecture for a new vehicle platform, the OEM does not start with all new features and components. The OEM will carry over numerous features to the new platform. These features utilize components that have been previously developed and tested. For an OEM to discard this previous engineering effort would be detrimental to the end cost of the new vehicle. Because of this requirement, the common EES architecture must be flexible enough to incorporate new features, and their associated components, while still supporting the carryover features with their required components. Additionally, the common architecture being designed needs to be flexible to support a new *standard* feature set while minimizing impact to the OEM metrics that the new *optional* feature set brings to the vehicle. An EES architecture analysis must be worked out within these constraints. By being able to quantify the impact of various alternative solutions for the new features and groupings of features, the best option for the vehicle can be selected.

In addition to flexibility, the EES architecture must also address the scalability requirements of several feature sets offered on a vehicle platform. The scalability techniques could include a family of modules ("de-contenting" common modules) or a base module that relies on additional modules to cover option content. By balancing the electrical and electronic costs versus option take rates and carryover requirements, various viable solutions can be found. It is this use of existing components or defining new electrical and electronic components that adds a level of complexity to the tradeoff analysis. Throughout the tradeoff analysis, an awareness of possible cross car/platform module commonality must be maintained. Commonality could exist for a single subsystem or cross multiple subsystems depending on feature bundling and optional content take rates.

3.3.5 Weight

Despite all attempts of reduction, the weight of modern cars is still increasing due to the large number of its additional features. It can be thought that the EES does not have as much impact on the weight of a vehicle as other systems, like Powertrain or Chassis, but the addition of new electrical and electronic technology to the modern vehicles has had a direct impact on the number of modules, circuits, fuses, connectors, and the overall EES weight. Therefore, even though the sum of all electrical and electronic components only represent a 3.8%[14] of the overall weight of the entire vehicle, the EES still has weight targets to meet.

Also, like in any other system, there are elements in the EES that do not add value to the product. These elements are needed for various reasons: to facilitate the assembly of harnesses, to ensure that parts don't get damaged during transportation, to facilitate serviceability, among others.

Certainly, these add cost and weight to the system, which impact the car performance and ultimately the customer's perception of the product. Therefore, it is important that these kinds of items are identified and minimized when architecting the EES.

Besides the impact on cost that the increase on weight represents per se, there are also other reasons to optimize and reduce the weight of the EES. Federal and state emission standards and federally mandated fuel economy requirements are also major constraints for the automotive manufacturer. For example, in United States the federal government sets the Corporate Average Fuel Economy (CAFE)[15] requirements for cars and trucks sold in the United States. These CAFE[iv] requirements determine the fuel economy requirements for the vehicle, which directly affect the weight requirements/targets.

3.3.6 Quality, Reliability and Serviceability

Other major considerations in the design of a vehicle's EES are the quality, reliability, and serviceability. Japanese vehicles set some standards for vehicle quality and reliability in the early 1980's. U.S. automotive manufacturers have since closed the gap and are now producing vehicles with equal and sometimes higher levels of quality and reliability. Nevertheless, with added electrical features comes added cost and complexity, which means there could be a trade off between cost and quality/reliability that needs to be managed and can affect the design of the vehicle's EES.

Service is also very important to the design of a vehicle's EES. If it takes a service technician twice as long to diagnose the problem or if the repair costs are too high, the consumer will not be completely satisfied and the automotive manufacturer will have additional warranty costs and low customer satisfaction ratings, leading to fewer sales of the company products and brand affectation. Even when a vehicle has an outstanding EES design, if it can not be serviced efficiently and affordably, it will not be very attractive to the automotive manufacturer as a plausible investment.

[iv] Corporate Average Fuel Economy (CAFE) is the sales weighted average fuel economy, expressed in miles per gallon (mpg), of a manufacturer's fleet of passenger cars or light trucks with a gross vehicle weight rating (GVWR) of 8,500 lbs. or less, manufactured for sale in the United States, for any given model year. Fuel economy is defined as the average mileage traveled by an automobile per gallon of gasoline (or equivalent amount of other fuel) consumed as measured in accordance with the testing and evaluation protocol set forth by the Environmental Protection Agency (EPA).

3.3.7 Industry Standards

Industry standards may also play an important role in determining the architecture and partition of the vehicle's EES. As an example, automotive OEMs recognize that human factors and ergonomics can affect the physical location of functions. SAE standards recommend boundaries of hand control locations that can be reached by a percentage of different driver populations in passenger cars, multi-purpose passenger vehicles, and light trucks (Class A vehicles), which in consequence drive the design specifications that the car manufacturers use during the development of components such as steering column switches, climate control and entertainment driver interfaces.

3.3.8 Brand Image

In the automotive industry brand image is very important. Brand image can set one vehicle apart from its competitors, and it can be at the vehicle level as well as at the component level. The perception of an OEM's products or brand is closely related to technological content or unique features that the company highlights through marketing campaigns or product positioning. Features such as a radio branded with the logo from a well-known audio equipment manufacturer can appeal to a specific kind of customers that pay close attention to sound fidelity. Or a voice recognition system that uses a platform created by a highly recognized software company is more able to serve as a marketing tool.

3.3.9 Functional Classification

The functional classification separates safety critical functions from non-safety related functions. Safety critical functions are classified as Class C functions and usually affect drivability or driver/passenger safety.

All Electrical/Electronic (E/E) functions shall be classified with respect their importance in affecting safe operation of the vehicle. Functions shall be categorized into one of 3 classifications:

- ***Class A*:** Any function that provides a convenience. In general, features like interior lighting (i.e. vanity mirror light, courtesy, puddle, glovebox lamps) audio system, remote door opening, which are not critical for operating the vehicle in a safe manner.

- ***Class B***: Any function that enhances, but is not essential to, the operation or control of the vehicle. Some of the climate control features, back-up lamps, fog lamps, traction control, heated backlight, traction control, fall inside this category.
- ***Class C***: Any function that is essential to the safe operation and control of the vehicle. Examples of Class C functions are headlamps low beams, brake lamps, front wipers, front windshield defrost, and airbags. Class C functions usually have dedicated power and ground signals, are fused separately, and have some built in redundancy for backup in case of failure. For example, if the headlamp switch fails, the headlamp low beams may default to *'on'*.

The separation of safety critical functions and non-safety critical functions usually prevents the integration of all of these functions into one module or the mixing of functional classes within a module. The brake signal, for instance, feeds one lamp on each side in the rear of the vehicle, and also a federally mandated center high mounted stop lamp (CHMSL), xare driven off of separate electrical signals and typically fused separately, as an effort to minimize the probability of failure of both at the same time.

3.3.10 Option Take Rates, Bundling and Volumes

Option take rates, bundling, and vehicle volumes play an important role in determining whether a function should be integrated with other functions into a module or should be a separate, stand alone module. Typically, if the option take rate is greater than 50%, then it is more cost effective to integrate the function. An example of this is with remote keyless entry (RKE). RKE has a very high take rate on most vehicles and is a very good candidate to integrate into a module with similar functions. However, when the total vehicle volume is considered, it may make more sense to leave as a separate standalone module. For example, daytime running lights (DRL) are federally mandated on vehicles sold in Canada. Thus, one may think that it makes sense to integrate the DRL function into a module with similar functions for vehicles sold in Canada. However, DRL is not federally mandated in United States and the volume of vehicles sold in Canada is far less than those sold in United States, for any particular vehicle. For that reason, when looking at the option take rates based on the total volume of vehicles sold for a particular vehicle, integration of DRL may not be cost effective, and consequently we may have to look for a different solution.

3.3.11 Distributed and Multiplexed

A distributed and multiplexed system design means that the electronics are closer to the actual input and/or output device, the function is distributed between multiple modules, and data is communicated between the modules via a multiplexed network. The distributed and multiplexed design of a vehicle's EES has advantages and disadvantages. A big advantage is cost and weight. The cost and weight savings come from the sharing of information by multiplexing the data over a serial data bus connected to multiple modules. A distributed and multiplex system can be cost effective and weigh less when designed correctly. However, a distributed and multiplexed system carries some disadvantages. It is more difficult to diagnose/service and can be harder to carry over to other vehicles, thus reducing the flexibility of cross-platform use.

3.3.12 Centralized and Hardwired

A centralized and hardwired system design typically has only a few electronic modules in the system with all of the input and output devices directly hardwired to the modules. This sort of system may cost more but is easier to diagnose. A centralized and hardwired design is very popular in the computer industry, but is not very popular in the automotive industry because of cost and flexibility constraints. In the case of a computer, most of the functions are centralized in the mother board, which is the hub of everything and manages all the different connections for the media devices (CD, DVD, USB flash drive, etc.), hard drives, graphics cards, sound cards, mouse, keyboard, monitor and anything else. A centralized and hardwired system works fine in this case, given the small number of modules and the limited number of combinations of peripheral elements. This is not the optimal solution for vehicles with several modules and constantly changing elements. On the other hand, in the case of lower content vehicles, this may still be a practical architectural approach.

3.3.13 Functional Isolation

A functionally isolated system design maximizes functional integration and minimizes the interactions between modules by separating functions into mutually separable modules. It allows the flexibility to add and delete functions from a vehicle very easily. A functionally isolated module may cost more for a given vehicle. Nonetheless, if the mutually separable modules are used across other vehicles lines, the functionally isolated system could be more cost effective for the automotive manufacturer, when the cost of multiple programs is considered, i.e., taking advantage of the economies of scale. There are many good examples in the automotive industry today of mutually separable modules: speed control system, climate control system, and audio system. Most of these examples are also defined as *optional features* in a vehicle, which means the function can be easily added or deleted without adversely affecting the rest of the vehicle system from either the cost or functional perspectives.

3.3.14 Hardware Capabilities

The hardware capabilities of a module/component contained within a vehicle can also affect the architecture of the EES. Physical factors like space constraints, risk of electromagnetic interference, environmental and safety constraints, and even appearance can influence the packaging location, size and other hardware requirements for the electrical and electronic components in a car. For instance, it is possible to equip every component with a smart system that provides safe operation and self-diagnosis, but at a great penalty on the cost, and risking the compliance of system requirements and design specifications. All components would be larger in size to accommodate and protect the electronics inside, posing additional challenges to the packaging and safety constraints. In a similar fashion, in order to reduce the cost of the vehicle's entire EES, one module may be equipped with battery backed up memory. However, the one module with battery backed up memory is now required to save all of the other modules critical information, rather than all modules being equipped with battery backed up memory. This may reduce cost, but it also adds complexity to the system and makes the system harder to diagnose and service.

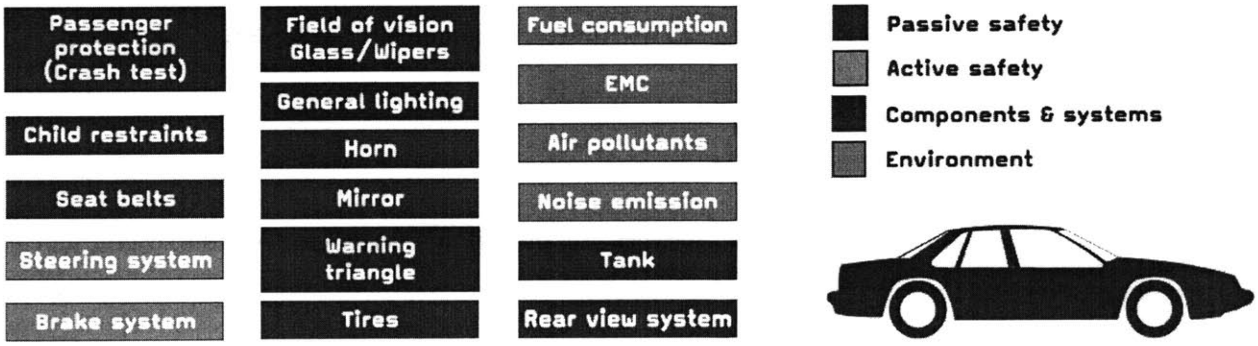
3.3.15 Vehicle Classification

Vehicles are classified by whether they carry passengers or commodities, the size of the vehicle or the market segment they are directed to. A vehicle's classification usually assumes certain functions to be standard. A luxury vehicle has more standard equipment than an economy vehicle. Also, a luxury vehicle usually contains much more additional/optional equipment than lower-end economy vehicles. Some examples of these features that are offered only on high-end vehicles are: passive entry and passive start systems, blind-spot monitoring, automatic parking, and rear-view camera. Therefore, these vehicles may have a different architecture and partitioning than an economy vehicle or even a truck.

3.3.16 Vehicle Homologation

Vehicles designed for North America, Europe, and Japan usually contain different functions and/or functions may operate differently. Prior to marketing and sales of motor vehicles, automotive systems and their components need to be approved according to the official standards of their destination countries. Homologation standards aim at improving active and passive car safety, environmental protection as well as the quality of products and production process.

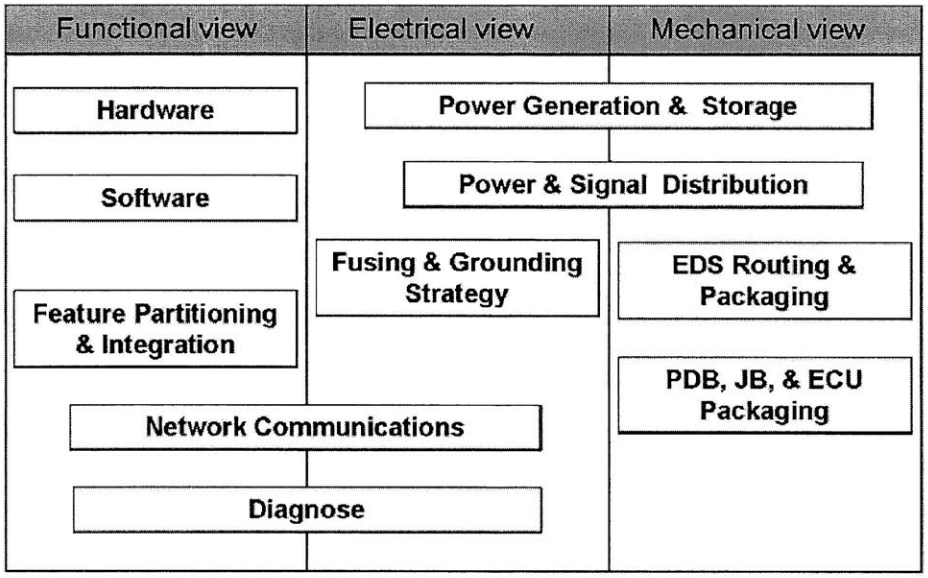
Depending on each country's regulations, a car can be tested for homologation compliance at different levels: component approval (e.g. lamps, mirrors, tires), component fitting to the vehicle (e.g. electric/electronic sub-assemblies, car audio systems), and system approvals (e.g. breaking, exhaust emission). For example, RKE and audio systems operate at different frequencies for different countries. Usually, the country differences can be contained within a component. However, the different functions may require a unique EES.



11- Figure 3.3.15 Example of Tested Items for Homologation[16]

3.4 Elements of the Electrical and Electronic System Architecture

The concept of electrical architecture has evolved by such an extent that it is often described in different views. The mechanical view describes mechanical interfaces to the vehicle including component packaging, wire harness routing, and protection provisions. The electrical view describes the generation and distribution of electrical power and signals, and the connection of components in the EES. The functional view provides an overview of the implementation and partitioning of feature functionality of the EES. Figure 3.4.1 shows this decomposition and how the specific elements are related to the architectural views. All these architecture elements have to be considered in order to achieve the most efficient integration.



12- Figure 3.4.1EES Architecture Elements[17]

These elements, suggested by de Oliveira[17], are described in more detail next.

3.4.1 Hardware and Software

Hardware and software elements are both critical for providing consistent, reliable, high quality electronic controls and interfaces.

Software is considered a key strategic architecture element that enables adding new features, feature upgradeability and serviceability. The main strategy in devising a software vehicle's architecture is *modularity*. Software modularity will allow maximum:

- *Portability*: The ability to use source code on various microprocessors/platforms.
- *Maintainability*: The ability to upgrade and modify software with ease.
- *Code reuse*: The ability to re-use same portions of the software in different projects.

Among other important considerations, modularity is the underlying characteristic that allows all of the above, as described by Maleki[18]. Regardless of the design methodology (object-oriented or data-flow based), the software architecture should be modular and structured in such way that defines the interfaces between each layer so that each layer is only coupled with its adjacent layers and as the data flows into higher layers, the data content becomes more abstract from the hardware.

3.4.2 Feature Partitioning and Integration

As discussed previously, partitioning is necessary in order to facilitate the management of a system, especially during the *Definition* phase of the design process, when the system is decomposed in subsystems and components (see Chapter 2, Figure 2.2.1). Once all the system's components have been defined, the integration of the subsystems commences. Here, modularity plays a prominent role, because an apposite design will lead to reusable modules or blocks. A good balance between integration and decomposition of features into ECUs is desired in order to create a physical layout that will facilitate the distribution and implementation of features in the vehicle. Furthermore, the creation of specific feature control logic from an architecture level, not a software level, is critical for the integration of features.

3.4.3 Network Communications and Diagnostics

It has never been so important to develop guidelines and strategies for the implementation and rollout of industry standard network communication and diagnostic technologies. These two elements are gaining importance in the automotive world as vehicles continue to become more complex, and grow in terms of total electronic value-added. Besides, their role for the implementation of redundant and fail detection systems is fundamental as these features are not a *plus* anymore but a *must* for today's industry standards. A few significant things to be considered when developing the network communications and diagnostics portion of the EES architecture are the development of tools, methods, list of approved protocols and gateway locations.

On the network communications aspect, as de Oliveira[17] describes in his analysis, there are several considerations that need to be addressed:

> "The design and optimization of the network requires the consideration of:
>
> - Number of signals to be communicated.
> - Speed, bandwidth, and physical layer of the bus.
> - Electromagnetic compatibility (EMC).
> - Fault tolerance or fail safety.

- Logistic costs due to ECU variants, usability of ECUs across one or even several vehicle platforms, system scalability.
- Cost and reliability of silicon and mechatronic integration.
- Availability of tools and software.

> (...) During the electrical architecture selection (...) it is important to consider the different classes of networks that are defined based network speed, cost, reliability, etc; these classes are:
>
> Class A: Normally is used for low-end, non-emission diagnostic, general purpose communication. Bit rate is frequently less or equals to 10 Kb/s and supports event-driven message transmission. Right now the leading for a Class A world standard is LIN.
>
> Class B: Used is for the vast majority of body control features and non-critical communication. Speed is between 10 Kb/s and approximately 125 Kb/s. Support event-driven and some periodic message transmission plus sleep/wakeup. The leading for a Class B standard is MS-CAN (125 Kb/s).
>
> Class C: Used for some safety-related, real-time controls such as engine ECUs and air bag ECUs. Speed is between 125 Kb/s and 1 Mb/s, and these networks support real-time periodic parameter transmission. The leading for C class is the HS-CAN (500 Kb/s)."

On the other side, this growth in network complexity, on a global scale, coupled with the need to diagnose problems quickly and accurately, is placing increasing challenges on the service and repair processes within the automotive workshop. Customer service surveys clearly identify "cost-of-repair" and "frequency of return visits to the dealer for the same issue" as major contributors to customer dissatisfaction with their service experience. Additionally, automotive service technicians are under increasing pressure to quickly and accurately repair vehicles and at the same time stay up to date on ever changing technology developments.

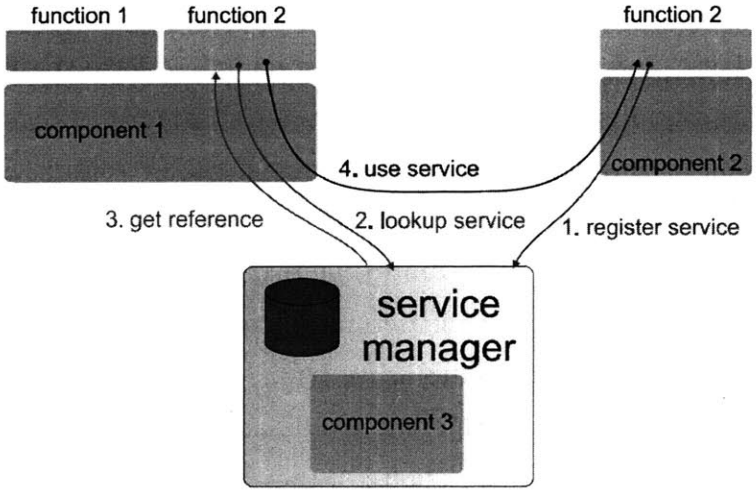
Network communications and diagnostics are architecture elements that deserve special attention due to the exponential rise of electrical parts or modules that exchange information with one or multiple components via the network bus for vehicle control and diagnostic purposes, without mentioning the emerging trend of adopting wireless technology for the reduction of wires and increase in component packaging flexibility.

3.4.4 Power Generation, Storage and Energy Management

Generating and storing power in a car is a critical element of the EES architecture. The power supply system directly affects numerous characteristics of other components in the car, from the engine torque to the connector and terminal size on the smallest sensor. Energy relevant components are alternator (power conversion), battery (power storage), capacitors, AC inverter, other functions which are attached to ECUs and thus able to be implemented into a digital energy control strategy, and the Energy Management Strategies for optimizing power conversion and consumption (e.g., load shedding, battery saver, sleep / wake-up, battery conservation during low-battery conditions, smart charging, etc.)

Until recent years, single power supply solutions were optimized for a certain EES architecture, which fitted into single platforms. Using them in different platform with different EES architecture resulted in a reduction of functionality or in a suboptimal energy control. A new approach for energy management proposes a distributed software function, which provides energy strategies and methods in order to realize generic control of real vehicle functions. Hence, the system software function regards both aspects, platform independence for energy management and components having different energy requirements on the power supply busses. It additionally provides scalability for the reuse in different platforms and supports easy communication configuration by service-oriented communication.

This new energy management approach, described by Beher and Werthschulte[19] in great detail in their paper, consists of system specific software and ECU specific software, which is spread over the vehicle EES architecture and thus generates the energy architecture for the vehicle electrical system. The system specific software is composed of centralized software components, which are hardware independent. This independence improves portability between ECUs, which is necessary to choose best configuration of software components and ECUs to carry the system software function. Additionally it enables the realization of the system specific software as a pure software function, that is totally independent of an own ECU. The decentralized ECU specific software is placed in energy relevant ECUs of the EES architecture and provides energy evaluation and interaction of the involved functions. These may be ECUs for solely one vehicle function, ECUs which control many consumers or ECUs with only measurement functionality. Typical vehicle functions that may be involved are chassis control, driver assistance or hybrid propulsion. The centralized system function system specific software determines and evaluates the system wide energy state and controls the energy in the vehicle EES architecture. Its algorithms for strategic behavior control the energy consumption and provide a flexible interface for optional functionality like cycling of energy storages. This approach of extending core functionality by optional functionality enables the exploitation of the energy resources available in the system and thus facilitates the realization of CO2-reduction strategies. Figure 3.3.4 below serves to illustrate the centralized software management strategy. The main module establishing the link is a common resource called service manager. The service manager's main task is to provide a database with all registered services in the network.



13- Figure 3.4.4Service Centric Software Architecture[19]

3.4.5 Power and Signal Distribution

This element should include the methods in which electric power and signals are physically partitioned and distributed within the vehicle. Distributing and interconnecting power, signals, and grounds is not an easy task, and there are some tools designed to aid the EDS engineers in optimizing and designing the wiring harnesses to accomplish the goals for which the system is designed.

Another important element herein is the Smart Junction Box[v] (SJB)[20], which can be used as communication gateway and to divide the EES, reducing the complexity and handling of the wiring harness. Some advantages of these smart power distribution boxes are:

- Consolidation of multiple functions and elements in a small space
- Commonality among several platforms
- Improved diagnostics, including system and component diagnostics
- Fail-safe functions
- Less use of fuses and relays
- Load and current management
- Plug-and-play to accommodate new features

For this element there is a big challenge to find an equation that brings all the advantages mentioned above with an affordable cost.

3.4.6 *Fusing and Grounding*

The main purpose of the fusing is to provide circuit protection for class A, B and C electrical wiring and loads through the use of protection devices (i.e., fuses, FETs, PTCs etc.). A properly defined fusing architecture should accommodate any changes on the fusing strategy, like when it is necessary to supply additional functions, either as a result of re-scaling or additional fuses. Depending on the functional requirements of protection options, the range covers: irreversible protection without a monitoring function, passive control with status recognition, and highly sophisticated monitoring with selective and current or voltage sensitive output control.

Providing appropriate subsystem grounding strategies aids to accommodate various signals and power classifications for the many electrical and electronic systems and components. Some of the considerations when designing the grounding strategy are: grounding topology (star, bus or ring), material of the cables and eyelets, EMC, physical and build constraints (restriction in number of grounds and number of cables).

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[v] Smart Junction Box technology is the main hub in a vehicle's electrical system, controlling and providing power to various electrical features such as power windows, power door locks, lighting (interior and exterior), instrumentation and the audio system. Current Smart Junction Box technology combines fuses, relays, a microcontroller and multiple (circuit board and fret) layers of interconnection into a single integrated assembly.

3.4.7 EDS Routing & Packaging

Routing and packaging wiring harnesses refers to creating the optimum lay-out for simplifying manufacturing and installation in the car, increasing flexibility, in addition to protecting them for ensuring their safe operation. Items contained in this element include:

- Division of the total vehicle EDS into wire harnesses; e.g., Body, Instrument Panel, Underhood, Engine, Door, etc.
- Routing strategies for each of the wire harnesses; e.g., H-pattern for Body Harness, dry-side routing for door wiring).
- Location of in-lines and pass-throughs.
- Component interconnect strategy; e.g., how the ECU, switches, sensors and actuators of a certain subsystem connect to the Body and Instrument Panel harnesses.

In Chapter 4, the EDS elements will be analyzed in further detail and a deep analysis will provide better insight of the implications of these for the entire EES architecture.

3.4.8 Packaging of Other Components

This architecture element provides guidelines and strategies for the packaging of major electric and electronic components, such as ECUs, Power Distribution Box (PDB) and other Smart Junction Boxes. Packaging requirements include location, orientation and electrical/mechanical interfaces. Given the fact that these requirements are going to be used across vehicle lines by different regional organizations, a strategy for optimizing and standardizing component packaging requirements should also be in place.

3.5 Validation of the EES

The development of any product requires verification of conformity to specifications and robustness in design. Testing allows the product development team to confirm that a component and/or system performs as intended and conforms to specifications. More specifically, it provides confirmation that it can execute the functionality it was created to provide, and that it will successfully accomplish its task over its entire lifetime and through all conditions for which it was designed.

The validation of vehicle EES and its components is critical, especially in these times where the offer of electrical and electronic features in the automotive marketplace has dramatically risen. In light of this expansion, traditional approaches to ECU and systems validation are being seriously challenged by pressures in different areas:

- ***Cost*** This is mainly driven by the cost of test equipment and labor costs related to testing. These two are the highest ever for the EES validation, mainly due to the costs associated with the expansion of number of ECU inputs/outputs and functionality in support of these features that need to be validated.
- ***Complexity.*** The evolution of multi-featured in-vehicle networking from its basis as multiplex wiring has also expanded systems complexity dramatically. Paradoxically, this new form of complexity can also reduce test requirements, hence test and validation costs, to a significant degree.
- ***Quality.*** Manufacturing of a high-volume product demands minimization of variability in order to ensure quality over the entire production line. Generating first-run quality out of a production line eliminates the costly inefficiencies arising from reworking products that do not meet quality standards, and scrapping products that cannot be reworked economically. Testing is included within the manufacturing process for maintaining quality control in production.

All development and production strategies rely on testing for the feedback required to improve and refine their products. In order to test the product thoroughly and in a timely fashion, the development methodologies should match the scope and depth of the test, i.e. these should be in concordance with the desired complexity and required robustness of the product. This process maximizes test efficiency while minimizing the cost of the required resources.

Staszel[21] has identified the traditional test strategies:

> "During the early part of the design effort, testing usually involves the simple confirmation that desired outcomes result when designs are run through their operating regimes. These early tests are very frequently ad hoc, informal, and not usually conducted according to a detailed time line.

The first formal testing event in most development programs occurs when the entire design is completed. At this point Design Verification (DV) tests are created and conducted according to a detailed formal plan established prior to beginning the development process.

The second formal testing event occurs with the startup of production. Process Validation (PV) tests confirm the ability of the manufacturing process to meet its target production goals. This is essential to the establishment of a controlled production environment. Since many aspects of the design of ECUs and electrical/electronic components have an effect on manufacturability, this test set also provides feedback on the design process.

The PV test suite is also important for the maintenance of the controlled production process after startup. In today's quality/cost-conscious environment, some production processes employ Statistical Process Control (SPC) as the means for managing the production process, and ensuring controlled production, in a cost conscious fashion. The initial PV suite is used to validate every ECU (also known as 100% Inspection) prior to and concurrent with startup. Afterward SPC allows it, or the relevant portions of it, to be applied to samples drawn at random from the production stream according to a pre-established plan, rather than testing every part. This reduces test expenses significantly, while simultaneously ensuring optimized quality.

Another formal testing event is known by the generic term End-of-Line (EOL). EOL tests are usually part of a 100% inspection program. By definition, 100% inspection is at odds with the premise within SPC that only random samples of production output need to be tested to verify conformance to specification in a well controlled production process. Thus, the existence of EOL testing is an admission that SPC is very difficult or even impossible.

Of the thousands of parts that make up a typical vehicle, experience has proven that ECUs exhibit this characteristic most often. As a result of the receipt of too many bad ECUs, i.e. those that made it past their respective production screening systems without being detected, OEMs frequently mandate EOL testing for most of the

> electronic components they buy. It is particularly true for complex ECUs that their inherent complexity makes it difficult for their manufacturing processes to hold all of their characteristics in control using SPC or by any other means. "

The process of validating automotive electrical and electronic components generally involves exercising their functional capabilities while attempting to place them under controlled conditions that represent those they will encounter in the target production vehicle, with a level of accuracy that is highly dependent on the complexity of the target system. This way the device under test can be scrutinized scientifically in a controlled environment. However, it is not possible to simulate all the interactions that the component will have with other systems until it is actually installed and validated on the vehicle. The reason behind this is that even for the simplest signal (e.g. a digital input that has only two possible values set at perhaps 12V and 0V), the application of these discrete voltages through a power supply has an analog component to it, which when driven by the interaction with other components can lead to problems. By expanding this case to each input or output (I/O) on each ECU in the vehicle, we can have an idea of the degree to which test systems must be meticulously designed in order to avoid a failure. The only certain method for minimizing the need for this level of detail is the reduction of I/O counts themselves.

The emergence of computer-like networking in vehicles has helped reduce the number of inputs and outputs, particularly those used to interconnect ECUs, leading to a significant reduction in the number of circuits, which has resulted in a decrease in wiring cost. Nonetheless, even when complexity has decreased for wiring, it has increased for in-vehicle networking, because the number of multiplexed signals per system has augmented as consequence. Successful implementation of in-vehicle networking requires a systems focus because it expands the level of interdependency between components on the vehicle. There is a clear need to test ECUs as part of the system in which it resides. One of the ways to verify functionality of an entire system is through a new validation method called Hardware in the Loop (HiL), which can also be integrated with the existing breadboard testing. These two are discussed in detail in Chapter 5.

As described in section 3.4.3 (Network Communications and Diagnostics), the utilization of in-vehicle networking is promising for diagnostics, process improvement and reduction of complexity in the EES. Nevertheless, this will be accompanied by some issues. For example, most test systems are currently configured to connect to network interfaces, but most engineers and technicians that work with ECUs are not typically trained in control networking techniques, hardware, systems or tools, since they typically regard them as simple inputs and outputs. Another problem is the haste of the auto industry to make components "smart"[vi]. Suppliers of the existing versions of these components are usually not inherently knowledgeable about the concepts and methods behind the networking technologies necessary to elevate their components to the smart category. This is not a trivial process, and it requires a higher level of interaction between the automotive OEM and its suppliers to make the evolution to these smart components possible.

Furthermore, test costs are a significant percentage of the cost of developing and producing electrical systems. Therefore, in order to reduce the cost of testing complex systems, OEMs should try to make each of the testable components in the system simpler. Simpler components are easier to test because they have fewer characteristics to monitor. Of course, reducing the complexity of the EES is the biggest challenge that engineers face when designing any electrical or electronic components or systems, and requires an architecture with the correct balance of distributed and centralized elements, as well as a significant reassignment from discrete I/Os to signals embedded in messages sent across the network.

3.6 Reusability

Reuse, in automotive jargon, is used in several different forms: it may refer to the reuse of architectures, best practices, knowledge, hardware and software designs, subsystems, and all the way down to actual parts across vehicles. The different levels in which an automotive EES can be reused following Bierzynski and Jackson's[25] approach are discussed next.

3.6.1 Architecture Reuse

Architecture reuse may be defined as the reuse of a vehicle platform in whole or in part, within or across regions, depending on the OEM. A specific architecture may be selected by the OEM for reuse based on certain characteristics for powertrain packaging, track, wheelbase, suspension geometry, seating configuration and electrical system, and can range from absolutely identical across models to a spread within the overall spectrum of the architecture elements. Examples of intensive platform reuse might be the 2012 Ford Focus execution or Nissan's V-Platform.

[vi] Sensors or actuators fitted with connections to the In-Vehicle Network, and a level of logic or programming that enables them to provide some measure of control autonomously.

Reusing architectures can lead to a reduction in engineering lead times and lower development costs, but savings are not necessarily obtained in investment or piece cost. If allowed to deviate widely within a possible range of options, each successive model within an architecture must still develop new specific part numbers, designs, release, validation and tools. This is potentially more likely to happen moving from region to region if not centrally controlled. Thus, reuse of an architecture depends highly on the implementation plan, and it may or may not be advantageous depending on the execution.

3.6.2 Design Solution Reuse

Design solution refers to the way of approaching a high-level design. In this context, reusing a design solution involves the reuse of a particular way of configuring a part, irrespective of the specific vehicle application. Design solution reuse is based on corporate knowledge, lessons learned, best practices and, in many occasions, some form of technical expertise. For example, in seat systems, there are many feature options including bench or captain seats, heated and/or cooled cushions, with/without knee airbags, etc. Customer preferences and market trends may indicate that the best option is indeed a captain seat although a bench seat might be viewed as having lower cost, higher reliability and less complexity. There are a number of factors to determine which design solution to use in a case like this: the product specification and DNA, cost and timing constraints, reliability and manufacturability, among several others. For electrical systems, design solution reuse it can extend to the basic approach for control system logic and standard algorithms. Obviously, this can result in reduced engineering lead times and higher quality, but may not significantly reduce engineering expense, investment or piece cost. In the aforementioned examples, executing an all new geometry will still require hardware validation, new tooling and will not add economies of scale to production. Just like in the case of the architecture reuse, the OEM's implementation strategy is fundamental for a successful execution of the design solution.

3.6.3 Detail Design Reuse

Detail design reuse is defined as the reuse of major elements of a specific design, including specific math data geometry or circuit board layouts. Detail design reuse is a way of approaching detail design in a "cut and paste" or replicate fashion. Some of the clearest examples are ECUs. To illustrate this, let's consider the case of a design engineer who has to choose among various existing

ECUs when selecting the right one for a certain vehicle's TPMS. Depending on several engineering constraints for that specific vehicle design, he/she may opt for one that has been extensively used in other vehicle platforms, and requires minor tuning to customize the software. For this example, there are definite savings in lead time, quality, and development, but some validation and re-tooling will be required. Piece cost reductions are possible depending on whether an original base part can work with the new electrical specifications.

3.6.4 Component Reuse

Component reuse can be defined as the use of the exact part number of a specific component across multiple car lines, models, platforms, or even OEMs. The ultimate case of reuse may be defined as component commonization. Examples within EES are abundant here, and include batteries, generators, starters, horns, connectors, bulbs, radios, Heating Ventilating and Air Conditioning (HVAC) controllers, sensors and actuators. For these components there is a clear advantage in every engineering metric. When weighing multiple alternatives among various options within a particular part category, the selection criteria is normally limited to cover a well-defined spectrum of vehicle loads, marketing requirements, trim/option levels, etcetera. By reusing components, OEMs drastically reduce development and validation costs, as well as piece cost because of economies of scale. The only incremental costs may come from tooling in case the supplier of the part is at top production capacity. Additionally, selecting an existing component of known capability and quality assures overall vehicle quality.

Another important consideration of reusability is the profound implications to the supply base. They include:

- The ability to decouple sourcing decisions from program timing for some components and defer others to take advantage of consumer trends.
- The need of OEMs for more design control.
- The demand by OEMs for suppliers to create and participate in these strategies, including work on standardization of components.

Once it has been understood how these reusability approaches can be applied to the EES, reuse opportunities can be categorized. Then, it can be determined which subsystems and components to reuse based on the overall vehicle architecture. A mature reuse strategy will lay out a comprehensive plan for components reuse with tight controls around the selection of variants for the vehicle program.

It may be apparent that the customer does not "see" or "touch" the electrical/electronic architecture, but the ultimate objective is to meet vehicle performance and customer requirements using a well-defined, validated electrical system. Command and control functions are transparent but impact customer satisfaction in many ways such as fuel economy, drivability and reliability, safety and convenience. Therefore, configuring with known subsystems, controls and vehicle powertrain interfaces guarantees performance and also begins to leverage volume within the architecture. Additionally, engineering development can be focused on the vehicle application more than on the basic development of the components.

3.7 Next Steps on Common Electrical Architecture

During these times of mass customization, markets seem to have a continuously growing desire for a larger variety of products. This added to the fact that competition has forced companies to shorten the time to bring products to the market and lower their costs, has positively impacted the customers, but has also posed a tremendous pressure on companies. The automotive market seems not to be an exception to this scenario. Global competitiveness and vehicles diversification have forced car makers to reduce their engineering development lead times, as well as reduce their development and manufacturing costs. All sorts of strategies such as a flexible and lean manufacturing system, optimized supply chain and product management have been implemented by most car makers aiming to become more and more competitive, and by some others to stay in business.

There are a few main challenges that are common to all automotive OEMs:

- Quick response to market needs.
- Vehicle launching in shorter periods of time.
- Product mix flexibility (portfolio spectrum).
- Structural cost reduction in product engineering development.

Automotive OEMs acknowledge that high-volume global architectures are the new strategic weapons in the war on vehicle development costs. However, moving from the traditional way of creating EES architectures to the common architecture approach represents a major challenge. This requires a change in the current culture of the different regional organizations. Working in a global environment is now a necessity, and the automotive OEMs need to acknowledge that in order to keep themselves competitive in this rapidly evolving business.

Then again, this cannot happen from one day to the other. Making a smooth transition is critical for reducing uncertainty for all the members of the organization. Thus, car makers are trying to migrate to the common electrical architecture in phases. Each phase of this transition process represents a greater level of commonality across regional organizations, vehicle platforms, systems, and components. In the first phase, the level of commonality occurs only for a few critical subsystems. During this time, processes are being defined, roles and responsibilities are acknowledged, and communication improves among the various players. For the second phase, it is expected that the major organizational and work roadblocks have been overcome, which enables an easier integration of the rest of the subsystems into the common architecture. Therefore, most of the major and more complicated systems migrate in this phase (e.g. Infotainment). Ideally, by the end of the third phase the transition of the remaining subsystems is finalized and working on a common architecture for a particular project occurs seamless between all design centers across regional organizations. To successfully accomplish all the above, the engineering teams have to agree on a common objective, be cooperative and supportive as well as work together as one team regardless of geographical or cultural differences. Also, competency development is a critical issue that must also be addressed during the first two phases. Not all regional organizations have the same capabilities, both from the knowledge base standpoint and from the experience standpoint. Some of these organizations need to be leveraged from phase one so the learning curve will start early on and they will be ready when the full transition to the common architecture occurs.

Understanding and analyzing all elements and requirements discussed in this chapter is a big challenge in itself. The task of integrating the increasing number of electrical/electronic functions into specific vehicle applications requires the use of a disciplined systems engineering methodology. All constraints and alternatives have to be considered when designing the architecture and partitioning of the vehicle's electrical/electronic system.

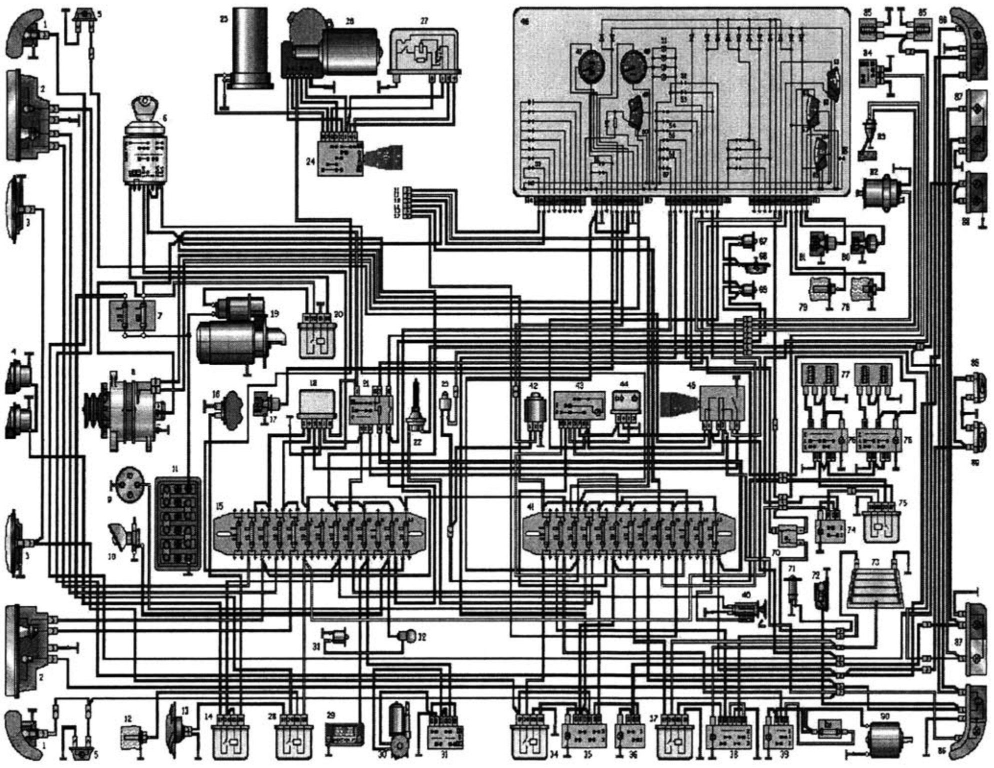
In the following chapters, all the elements formerly presented will serve to analyze the EDS architecture and provide a deeper understanding of the current industry situation within a structured systems engineering framework, which has to be consistent with the common electrical architecture strategy.

4 Electrical Distribution System Architecture

> *"[Architecture] is the embodiment of concept and the allocation of physical / informational function to elements of form, and definition of interfaces among the elements and with the surrounding context."*[22]
>
> *Ed Crawley*

4.1 Description and Objective

The vehicle's EDS, which is the focus of this study, is the nervous system of an automobile. It consists of the wiring harness and the associated connections to the various functions in the vehicle. EDS Full Service Suppliers (FSS) have estimated that there are some 3,000 electric wires built into a modern car. All of these electric wires and related parts are bundled into wiring harnesses to increase their efficiency and reduce their size for easy installation.



14- Figure 4.4.1Basic Car Electrical System: Layout of Volga GAZ-2110[23]

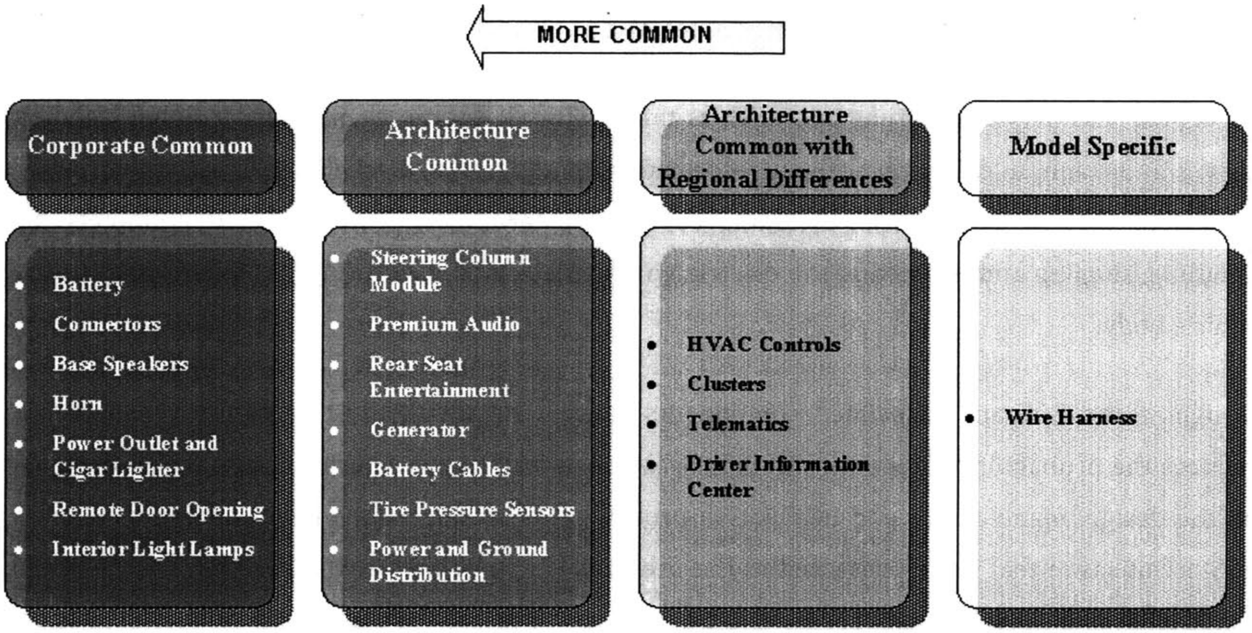
Wiring harnesses serve to electrically connect electrical and electronic components and to relay transmission of information and electric power between the components. Each electric wire in a wiring harness plays a different role, such as taking electric energy from power supplies, sending signals and communicating operational information. In addition to electric wires, wiring harnesses consist of various other parts, including connectors, terminals, protectors and grommets for bundling, shaping and protecting the electric wires and clamps for attaching the harnesses to the vehicle body.

Designing the EDS and associated components concurrently with the rest of the vehicle's EES reduces the probability of failures and improves the overall harness performance, which depends on the design, manufacture and installation process. The considerations for designing a vehicle's EES architecture that were presented in the previous chapters will set the base for analyzing the EDS design and development process and understanding its role in the overall common electrical architecture.

Like the electrical wiring in a home, the EDS provides the connectivity between all the electrical and electronic systems in the vehicle. It also ensures the integrity of the EES and other subsystems by protecting against critical electrical failure modes. Another important goal of the EDS is to protect the rest of the electrical and electronic components by minimizing the number of wires, terminals and connectors, as this reduces the opportunities for problems to occur.

4.2 Wire Harness Development

It has been discussed previously that the architecture and partitioning of the vehicle's EES defines the required functions and physical entities (modules) in the vehicle. The increase in the number of electrically controlled functions —and their complexity— leads to a corresponding increase in the number of electric and electronic modules, their associated communications requirements, and the number of circuits to perform each of these functions. The EDS contains the fuses, relays, power distribution and wire harnesses to support the vehicle electrical/electronic architecture and partitioning. It also contains all of the electrical interfaces between each of the modules within the vehicle's electrical and electronic system. Following Imrich's[24] idea of architecture, the EDS can be thought as the *'circuitry'* of the EES, the *'glue'*, connections and intersections of the concept, where the qualities of space and form are progressively revealed.



15- Figure 4.2.2Example of Electrical Architecture Commonization[25]

The EDS is constructed based on the EES architecture, but it remains unique for each specific vehicle program, given the differences in content, packaging and market requirements. The left-hand side of Figure 4.2.2 shows that components like batteries, power points, speakers and connectors are used by the automakers across platforms and regional organizations (and sometimes across OEMs). As we move to the right-hand side we can see that the components become more market- and vehicle-specific. Elements like cluster, Centerstack Information Display (CID), HVAC controllers are architecturally very similar, but they must be customized to meet the specific market requirements, aesthetically and functionally. At the end, the only model-specific electrical components are the wire harnesses. Given the fact that these are tailored for a specific vehicle body dimensions/shape and feature content, there is not a single EDS that can be used by another vehicle model, and there are only a few harnesses that can be used off-the-shelf for a different vehicle model.

The flexibility of wire harness enables different routes that meet the packaging space conditions. Thus, the EDS is generally determined after designing other subsystems that have a higher impact on the vehicle interior space and packaging attributes, so it requires constant design revisions and changes throughout the development process. In addition, many new functions and technologies in the vehicle's EES architecture are highly connected, which increases the interrelations and dependencies that need to be managed through the EDS. Subsequently, in the EDS design process a small modification to the design requirements of any electrical/electronic component often requires a full compatibility review of the subsystem design. EDS is also always the first item to be considered for revision over any other parts when a design change is required. This is because of the short lead time to make changes and the lower tooling cost compared to other parts in the vehicle. These design changes are more frequent for a brand new vehicle program especially when there are new added features and content.

The uniqueness of the wire harnesses development process along with other design factors make it extremely difficult to commonize and reuse during the EDS development process. The architectural target, according to Delphi[26], is to determine the correct balance between the electrical/electronic costs and the EDS design requirements. In this process, the following marginal conditions, for instance, must be taken into account: logistics, standardization, thermal behavior, humidity, installation space, interface requirements and diagnostics, communication costs and network management, and system-relevant demands such as energy management.

From concept to production installation, there are three main phases, or processes, which can have a large impact on the overall wiring harness performance. These phases are: wiring harness design, wiring harness manufacture, and vehicle installation. The following sections are intended to present some of the most important elements that the EDS team considers throughout the wire harness development process.

4.3 Design Considerations

The design method chosen to meet the physical and functional (basic electrical) requirements is mostly determined by the EES architecture. The design goal is to choose architecture solutions that minimize the number of wires, terminals, connectors, and other components. Fewer components mean less opportunity for failures to occur. An efficient EES architecture has the proper balance between wiring and electronics. Increasing a vehicle's electronic functionality can eliminate wires, but a cost/benefit analysis (wiring cost reduction vs. electronics cost add) should be performed to determine the best solution.

Wiring harness design consists of two main types: a) basic electrical and b) physical. The basic electrical design objective is to meet the functional requirements of the vehicle's EES. Process steps in this design phase include establishing power distribution and circuit protection, sizing cables, understanding and meeting subsystem mechanization requirements, and meeting device power requirements. The physical portion of wiring design includes the packaging, routing, covering, and attachment of the harnesses.

Basic Electrical Design Considerations

There are basically eight design elements in the basic electrical design. According to Abbuhl[27] some of the design considerations and recommended steps for these various design elements are as follows:

4.3.1 Overall EES Architecture Definition

The EES architecture needs to be determined before the EDS architecture design starts. As discussed in Chapter 3, the EES architecture is defined by such issues as the location of major devices, like electronic modules; the number, location, and types of distribution boxes; electronics as part of distribution boxes, or separated from them; the general wire routings; the number of harness; the major electrical content to be located within each harness; the available interior-to-exterior pass through locations; the locations of harness-to-harness inline connections. All these elements need to be generally defined before the next design steps can be executed.

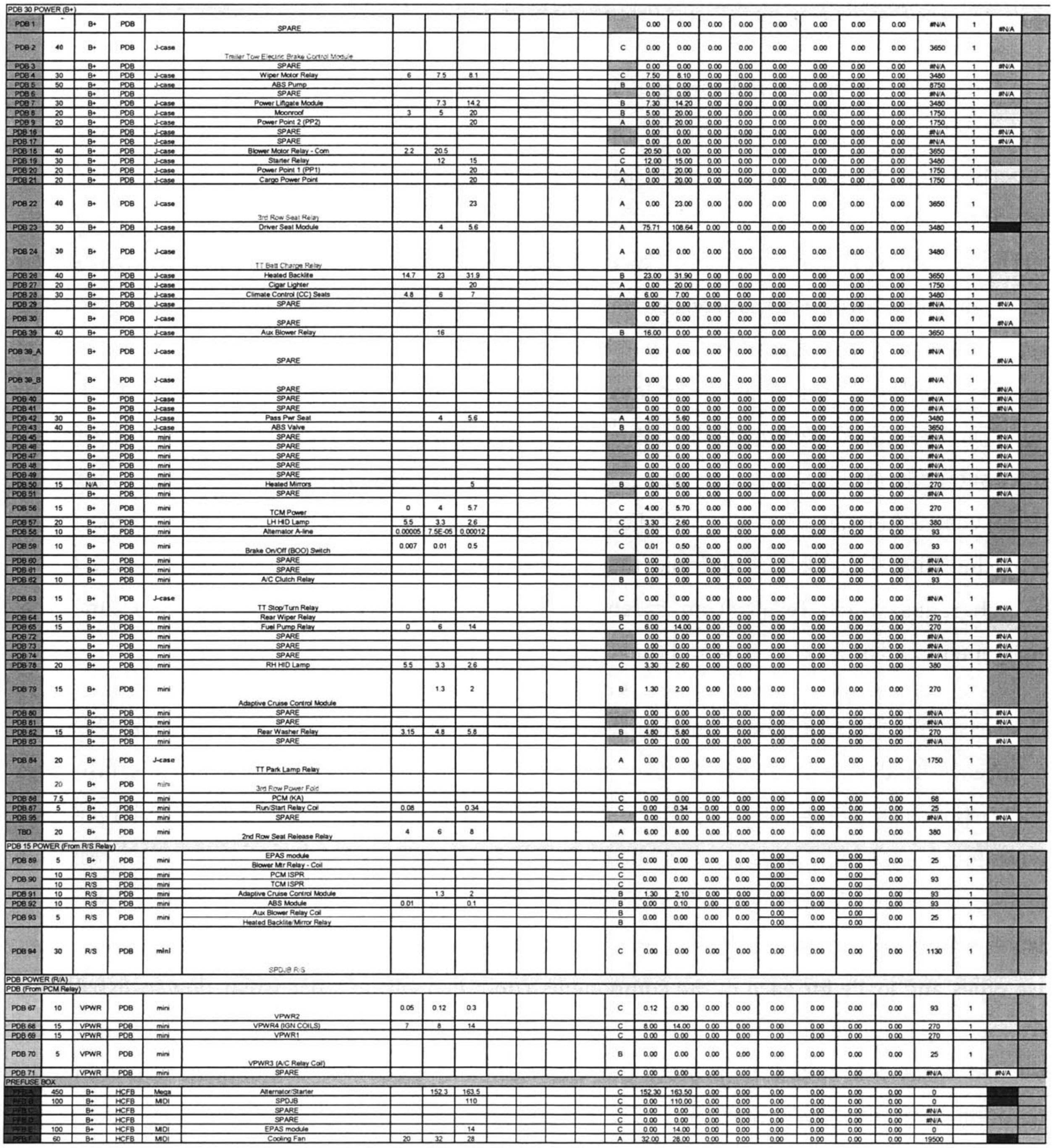
4.3.2 Electrical Subsystem Mechanizations

When reviewing the subsystem mechanizations, the emphasis should not be on just meeting the electrical requirements, but also on how to develop simplified, efficient solutions. There are basic questions that the EDS group must ask for each specific vehicle program: Can wires feeding direct battery voltage to relay contacts and coils in a distribution box be replaced by bussing copper traces or stamped metal to those locations? If multiple modules require an ignition run/start signal, can wires to those modules be replaced by putting the ignition run/start signal on a data bus? If modules are being redesigned, module partitioning should be considered. Partitioning means having connections to multiple electrical harnesses, and arranging the inputs/outputs in the module so the circuits physically route directly to the proper harness that contains those circuits. This eliminates the harness-to harness inline circuits required to transfer all circuits to a single harness connecting to the module. An example would be the Powertrain Control Module (PCM), which typically requires circuits from both the engine and transmission harnesses. If both harnesses can mate directly to a "partitioned" PCM, harness-to-harness inline circuits can be eliminated.

4.3.3 Power Distribution and Circuit Protection Scheme

In this stage, the team defines how the electrical power is to be distributed to the various loads. Battery power can be delivered through fuses, breakers, relays, diodes, and solid state devices. To properly design the power distribution scheme, accurate supplier-estimated loads are required for each of the electrical and electronic components in the vehicle. Load information includes inrush, continuous, and stall currents, as well as load duty cycles. Loads are then grouped by their power mode – meaning battery, accessory, run only, start only, etc. The loads within these mode groupings are then divided into subgroups that will be protected by circuit protection devices (fuses, circuit breakers, fuselinks). When assigning device loads to subgroups, critical and non-critical loads should not be mixed. For example, battery feeds to an electronic module and to a convenience outlet should be fused separately. This prevents a nuisance *open* on a shared fuse from impacting critical vehicle functions. Engine control circuits should be separated from non-critical loads, due to increasing federal regulations on reporting engine control related failures. These are just a few of the subgroups which result from careful consideration of regulatory, safety, and functional requirements, all of which are part of the EDS design toolkit.

When assigning fuses, or other circuit protection devices, the EDS engineer has to balance the fuses, i.e. spread the device loads evenly over a number of different fuses. This keeps the fuse sizes smaller (lower amperage ratings). More and smaller fuses, as opposed to fewer and larger fuses allows for smaller cable sizes, as it will be explained later in the *Cable Sizing* section. This results in smaller, more flexible wiring bundles which occupy less vehicle space and are therefore easier to install. Figure 4.3.3 is an example of an actual fusing assessment matrix. It contains fuse ratings, fuse types and loads for each of the components contained within a particular power distribution box for a specific vehicle model. Based on load current information, it calculates whether the assigned fuses are suited to protect the electrical and electronic components under normal operation conditions over time, such as inrush currents during start and stall currents if a motor fails.



PDB 30 POWER (B+)																									
PDB 1	-	B+	PDB		SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 2	40	B+	PDB	J-case	Trailer Tow Electric Brake Control Module								C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3650	1		
PDB 3		B+	PDB		SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 4	30	B+	PDB	J-case	Wiper Motor Relay	6	7.5	8.1					C	7.50	8.10	0.00	0.00	0.00	0.00	0.00	0.00	3480	1		
PDB 5	50	B+	PDB	J-case	ABS Pump								B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8750	1		
PDB 6		B+	PDB		SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 7	30	B+	PDB	J-case	Power Liftgate Module		7.3	14.2					B	7.30	14.20	0.00	0.00	0.00	0.00	0.00	0.00	3480	1		
PDB 8	20	B+	PDB	J-case	Moonroof	3	5	20					B	5.00	20.00	0.00	0.00	0.00	0.00	0.00	0.00	1750	1		
PDB 9	20	B+	PDB	J-case	Power Point 2 (PP2)			20					A	0.00	20.00	0.00	0.00	0.00	0.00	0.00	0.00	1750	1		
PDB 16		B+	PDB	J-case	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 17		B+	PDB	J-case	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 18	40	B+	PDB	J-case	Blower Motor Relay - Com	2.2	20.5						C	20.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3650	1		
PDB 19	30	B+	PDB	J-case	Starter Relay		12	15					C	12.00	15.00	0.00	0.00	0.00	0.00	0.00	0.00	3480	1		
PDB 20	20	B+	PDB	J-case	Power Point 1 (PP1)			20					A	0.00	20.00	0.00	0.00	0.00	0.00	0.00	0.00	1750	1		
PDB 21	20	B+	PDB	J-case	Cargo Power Point			20					A	0.00	20.00	0.00	0.00	0.00	0.00	0.00	0.00	1750	1		
PDB 22	40	B+	PDB	J-case	3rd Row Seat Relay			23					A	0.00	23.00	0.00	0.00	0.00	0.00	0.00	0.00	3650	1		
PDB 23	30	B+	PDB	J-case	Driver Seat Module		4	5.6					A	75.71	108.64	0.00	0.00	0.00	0.00	0.00	0.00	3480	1		
PDB 24	30	B+	PDB	J-case	TT Batt Charge Relay								A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3480	1		
PDB 26	40	B+	PDB	J-case	Heated Backlite	14.7	23	31.9					B	23.00	31.90	0.00	0.00	0.00	0.00	0.00	0.00	3650	1		
PDB 27	20	B+	PDB	J-case	Cigar Lighter			20					A	0.00	20.00	0.00	0.00	0.00	0.00	0.00	0.00	1750	1		
PDB 28	30	B+	PDB	J-case	Climate Control (CC) Seats	4.8	6	7					A	6.00	7.00	0.00	0.00	0.00	0.00	0.00	0.00	3480	1		
PDB 29		B+	PDB	J-case	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 30		B+	PDB	J-case	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 39	40	B+	PDB	J-case	Aux Blower Relay		16						B	16.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3650	1		
PDB 39_A		B+	PDB	J-case	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 39_B		B+	PDB	J-case	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 40		B+	PDB	J-case	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 41		B+	PDB	J-case	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 42	30	B+	PDB	J-case	Pass Pwr Seat		4	5.6					A	4.00	5.60	0.00	0.00	0.00	0.00	0.00	0.00	3480	1		
PDB 43	40	B+	PDB	J-case	ABS Valve								B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3650	1		
PDB 45		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 46		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 47		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 48		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 49		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 50	15	N/A	PDB	mini	Heated Mirrors			5					B	0.00	5.00	0.00	0.00	0.00	0.00	0.00	0.00	270	1		
PDB 51		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 56	15	B+	PDB	mini	TCM Power	0	4	5.7					C	4.00	5.70	0.00	0.00	0.00	0.00	0.00	0.00	270	1		
PDB 57	20	B+	PDB	mini	LH HID Lamp	5.5	3.3	2.6					C	3.30	2.60	0.00	0.00	0.00	0.00	0.00	0.00	380	1		
PDB 58	10	B+	PDB	mini	Alternator A-line	0.00005	7.5E-05	0.00012					C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	93	1		
PDB 59	10	B+	PDB	mini	Brake On/Off (BOO) Switch	0.007	0.01	0.5					C	0.01	0.50	0.00	0.00	0.00	0.00	0.00	0.00	93	1		
PDB 60		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 61		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 62	10	B+	PDB	mini	A/C Clutch Relay								B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	93	1		
PDB 63	15	B+	PDB	J-case	TT Stop/Turn Relay								C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 64	15	B+	PDB	mini	Rear Wiper Relay								B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270	1		
PDB 65	15	B+	PDB	mini	Fuel Pump Relay	0	6	14					C	6.00	14.00	0.00	0.00	0.00	0.00	0.00	0.00	270	1		
PDB 72		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 73		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 74		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 78	20	B+	PDB	mini	RH HID Lamp	5.5	3.3	2.6					C	3.30	2.60	0.00	0.00	0.00	0.00	0.00	0.00	380	1		
PDB 79	15	B+	PDB	mini	Adaptive Cruise Control Module		1.3	2					B	1.30	2.00	0.00	0.00	0.00	0.00	0.00	0.00	270	1		
PDB 80		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 81		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 82	15	B+	PDB	mini	Rear Washer Relay	3.15	4.8	5.8					B	4.80	5.80	0.00	0.00	0.00	0.00	0.00	0.00	270	1		
PDB 83		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PDB 84	20	B+	PDB	J-case	TT Park Lamp Relay								A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1750	1		
	20	B+	PDB	mini	3rd Row Power Fold																				
PDB 86	7.5	B+	PDB	mini	PCM (KA)								C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	68	1		
PDB 87	5	B+	PDB	mini	Run/Start Relay Coil	0.08		0.34					C	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	25	1		
PDB 95		B+	PDB	mini	SPARE									0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
TBD	20	B+	PDB	mini	2nd Row Seat Release Relay	4	6	8					A	6.00	8.00	0.00	0.00	0.00	0.00	0.00	0.00	380	1		
PDB 15 POWER (From R/S Relay)																									
PDB 89	5	B+	PDB	mini	EPAS module Blower Mtr Relay - Coil								C C	0.00	0.00	0.00	0.00	0.00 0.00	0.00	0.00 0.00	0.00	25	1		
PDB 90	10 10	R/S R/S	PDB PDB	mini mini	PCM ISPR TCM ISPR								C C	0.00	0.00	0.00	0.00	0.00 0.00	0.00	0.00 0.00	0.00	93	1		
PDB 91	10	R/S	PDB	mini	Adaptive Cruise Control Module		1.3	2					B	1.30	2.10	0.00	0.00	0.00	0.00	0.00	0.00	93	1		
PDB 92	10	R/S	PDB	mini	ABS Module	0.01		0.1					B	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	93	1		
PDB 93	5	R/S	PDB	mini	Aux Blower Relay Coil Heated Backlite/Mirror Relay								B B	0.00	0.00	0.00	0.00	0.00 0.00	0.00	0.00 0.00	0.00	25	1		
PDB 94	30	R/S	PDB	mini	SPDJB R/S								C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1130	1		
PDB POWER (R/A)																									
PDB (From PCM Relay)																									
PDB 67	10	VPWR	PDB	mini	VPWR2	0.05	0.12	0.3					C	0.12	0.30	0.00	0.00	0.00	0.00	0.00	0.00	93	1		
PDB 68	15	VPWR	PDB	mini	VPWR4 (IGN COILS)	7	8	14					C	8.00	14.00	0.00	0.00	0.00	0.00	0.00	0.00	270	1		
PDB 69	15	VPWR	PDB	mini	VPWR1								C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270	1		
PDB 70	5	VPWR	PDB	mini	VPWR3 (A/C Relay Coil)								B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25	1		
PDB 71		VPWR	PDB	mini	SPARE								C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A	1	#N/A	
PREFUSE BOX																									
PFB A	450	B+	HCFB	Mega	Alternator/Starter		152.3	163.5					C	152.30	163.50	0.00	0.00	0.00	0.00	0.00	0.00	0			
PFB B	100	B+	HCFB	MIDI	SPDJB			110					C	0.00	110.00	0.00	0.00	0.00	0.00	0.00	0.00	0			
PFB C		B+	HCFB		SPARE								C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A			
PFB D		B+	HCFB		SPARE								C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	#N/A			
PFB E	100	B+	HCFB	MIDI	EPAS module			14					C	0.00	14.00	0.00	0.00	0.00	0.00	0.00	0.00	0			
PFB F	60	B+	HCFB	MIDI	Cooling Fan	20	32	28					A	32.00	28.00	0.00	0.00	0.00	0.00	0.00	0.00	19500			

16- Figure 4.3.3Vehicle Fusing Assessment Matrix[28]

Also, using more fuses improves electrical diagnostics. With fewer loads per fuse, locating and correcting a shorted circuit is easier. Another benefit of minimizing the number of loads per fuse is losing fewer electrical functions if a fuse blows. This improves customer satisfaction. When assigning fuse sizes to loads, inrush and stall currents must be carefully considered. JCase or Maxi fuses are more forgiving in temporary overloads than are Mini or ATO fuses, and are better at withstanding temporary inrush loads. Stall currents may force even fewer loads per fuse, or the use of circuit breakers. When choosing fuse sizes, the EDS engineer must bare in mind to maintain the total current load substantially less than the actual fuse size. Typical industry standards recommend loading a fuse to no more than 60-80% of the fuse rating.

4.3.3 Distribution Box Requirements

As explained previously, distribution boxes locate all fuses, relays, diodes, etc. in a central area. By minimizing the use of individual relay or fuse holders, packaging complexity is reduced and electrical problem can be better diagnosed. These distribution boxes provide mainly power to wiring harnesses, but also convey signals, like in the case of the SJB. They can contain electronics, or be linked to electronic modules via data bus.

When designing a distribution box, the EDS team must specify what its electrical functionality will be. The number and types of fuses is available from the power distribution analysis and is essential to this analysis. To minimize splicing, if a given circuit goes to several harnesses, that circuit can be bussed inside the ECU to the output terminals for those harnesses. If the selected ECU mates to more than one harness, the inputs and outputs to each harness are then identified. If multiple distribution boxes are being used, each load should be evaluated to determine the optimal location of this box that minimizes wiring content. Electrical centers can be power only, or can contain electronics. One advantage of combining electronics into distribution boxes is that it reduces the number of circuits from the distribution box to the separate ECUs.

4.3.5 Connector Requirements

There are both electrical and physical considerations when selecting connectors. The electrical, or functional, requirements include:

- ***Number of individual circuits that must pass through the connector.*** This determines the number of cavities, or circuit locations, the connection must have. Examples include: 2-way, 4-way, 12-way, 17-way and 59-way connectors, among several others.
- ***Current requirements for each circuit.*** This will determine the type of terminal to be used. In general, as the current increases, the terminal physical size also increases. For example, a 2.8 mm wide terminal will successfully conduct higher currents than a 1.5 mm terminal. But terminal size is not the only factor affecting current capability. The terminal design is a

factor as well, given the fact that higher normal force between the male and female terminals increases current capacity (and connector engaging force). Also, the conductivity of the alloy chosen affects terminal performance.

- ***Circuit protection device.*** The connection should not be the weak link in the circuit protection scheme. A better design practice is to select a connection whose terminals will accept maximum current allowed by the applicable circuit protection device for that circuit. This prevents permanent terminal or connector damage. Cables act as *heat sinks* that conduct heat away from the terminal interface. The use of larger cables allows a terminal to carry more current than with a smaller cable.
- ***Cable sizes of the individual circuits.*** This can also affect the terminal type to be selected. Larger cable sizes, in general, require a larger terminal. All terminal types have maximum cable sizes that can be used, and smaller terminals are obviously limited to smaller cable sizes. The connector must have cavities that accommodate the required cable sizes.

The physical considerations in connector selection include:

- **Packaging requirements.** Depending on the actual vehicle there will be size restrictions in the available space. For instance, in many occasions the connector must pass through a routing hole when assembled in the vehicle. An extremely important wiring design consideration is the connection packaging location in the vehicle. Connections must be located in accessible areas where the assembly operator, or service technician, can easily mate, or un-mate, the connection. If a connector is packaged in a place that is difficult to access, it will represent a problem for the assembly operator or service technician when plugging the connector to the mating device or connector. This will result in partial connections and either immediate or eventual disconnection. Virtual tools are used to simulate the assembly of these components with real-sized 3D human models, which aid to foresee any potential assembly issues.
- ***Ergonomic requirements.*** As a rule, the connection mating force should not exceed 75 Newtons for a hand plugged connection. If the engagement force is higher, using more, smaller connectors should be considered when possible. Another option is to select a connection with an assembly assist, such as a lever lock, or bolt together connection. The lever lock is preferred, since no assembly tools are required. Other ergonomic consideration is to avoid connections with sharp angles in the push surface area of the connector. Smooth

surfaces create less discomfort for the operator during the connector mating process. As previously mentioned, the vehicle packaging of the electrical devices and connections plays a large role in ergonomics. Connections that are inaccessible or obstructed by other parts will result in a poor connection and potential warranty claims.

4.3.6 Serial Data Links

The use of serial data links can reduce the number of wires in harnesses. Rather than using conventional wires to hardwire a signal to the receiving electronic module, the signal can be wired to the nearest module that has a data link, and sent to the receiving module. However, there are some conditions that should be met before considering the application of a serial data link:

a) Electronic modules with serial data links must already exist in the design;

b) The software for these modules can be modified;

c) The circuit to be put on the data link is a signal circuit and exists in two or more harnesses that have electronic modules with data links (ECUs work as 'end-nodes' for the serial data link network, so this strategy would not make sense in a design scenario with less than two modules or with modules that cannot use a data link).

If these conditions are met, then a circuit in harness A can be hardwired to the nearest module. The signal is then communicated over the data link to a module in another harness, say B, where the signal input is required. This compares to sending the signal circuit from harness A to harness B through an inline connection.

4.3.7 Ground Design

The most common grounding strategy is zone grounding, which consists in dividing up the vehicle into areas or zones. The devices are then grounded in the nearest zone: left side engine compartment, right side engine compartment, B-pillar, battery cable, left front fender, etc.

There are two types of grounds: *noisy* and *clean*. Noisy grounds are relatively high current grounds, such as motor or lighting grounds. Clean grounds are low current electronic grounds such as for sensors and electronic modules. These grounds should not be mixed within the same ground splice.[29] This is because the high current from the ground splice to the ground point (ring terminal) will result in a significant voltage drop. The ground splice where the clean ground attaches is not then actually at ground potential, but above ground potential by the amount of the previously mentioned voltage drop. This is called a ground offset, since the clean ground is not really at zero potential. Also, a loose or unattached ground terminal could cause a failure mode associated with this phenomenon. For example, if an HVAC blower motor and HVAC control module grounded to the same ring terminal, the motor could try to ground back through the HVAC module, damaging the module.

Besides ground type, there are a few other considerations that the EDS engineer takes into account when conceiving a ground strategy. Things like keeping grounding surfaces free of paint or coatings, or adding weld studs or nuts for grounds to thin sheet metal, as well as anti-rotation features when possible, are well-known to the seasoned FSS and OEM EDS engineers.

4.3.8 Cable Sizing

Cable sizing guidelines and requirements vary somewhat by OEM and vehicle type, but there are some general design rules that are common across the board.

In the case of *power circuits*, for instance, cables should be able to take worst case current allowed by the circuit protection device. Thus, the minimum cable size for a power circuit is based on the corresponding circuit protection device size. Most North American automotive OEMs accept the premise that the worst case current is caused by a resistive short circuit. This limits the current to a level that may require considerable time before the device opens. A resistive short is defined as one that allows a current flow of up to 135% of the rated circuit protection device value. At this current level, Mini and either JCase or Maxi fuses have maximum opening times of ten and thirty minutes, respectively. Minimum cable sizes for each corresponding fuse size can be established using this resistive short rule. The cable must be able to carry 135% of the protecting fuse size for thirty minutes without permanent cable damage. This design rule assures that in a resistive short circuit situation, the cable will not be the weak link in the system. Resistive short circuits, although not common, do occur. For example, a motor with a portion of the windings shorted, or an exterior lamp lens that has cracked or broken, allowing salt spray to enter and form a resistive salt path from the power terminal to the ground terminal. Some circuits are not fed directly from a fuse or relay, but rather are controlled by solid state devices. In these cases, the cable must be sized to accept the maximum current allowed by the solid state device in a short circuit situation. Designing to a resistive short protects the wiring, yet still allows for aggressive cable downsizing by minimizing the average fuse size.

After determining the circuit minimum size based on the circuit protection device, voltage drop needs to be considered. Some devices require cable upsizing to meet the device's power requirements, or to maximize voltage at the device. Examples of this are headlights and fuel pump motor feeds. Properly sizing circuits to a device requires knowing the device's power requirements.

Different rules apply when designing for *ground circuits*. For devices that can fail closed (i.e., a shorted motor), the ground side should be sized the same as the feed side. In this situation the ground side becomes an extension of the feed circuit, and must take the worst case current allowed by the circuit protection device. For devices that fail open, such as bulb filaments or relay coils, the ground circuit can be downsized from the feed side, since the bulb filament or coil wire will fail open before the ground cable can be damaged. The cable can only be downsized if the additional voltage drop is acceptable. As with power circuits, the ground side must be large enough to allow for any specified device minimum power requirements to be met. Those requirements are not often available, so the experience of the EDS team is crucial for identifying typical circuits that need upsizing, such as the headlamp and fuel pump circuits referenced in power circuit sizing.

4.3.9 Wire Harness Weight

Weight reduction technologies for wire harnesses have appeared during the last decade, mainly due to the expansion of the EES, which entails a proportional growth of the EDS. This has resulted in difficulties in bending and assembling them in a vehicle body and a burden on the assembly workers, since the weight of the harnesses also increases. Another consequence is the increase of the total vehicle weight, which directly impacts fuel economy.

As part of JSAE study for lightweight vehicles, Watamabe and Kosuda[30] state that there are two approaches for reducing the weight of the EDS. The first is to decrease the size of the wire harness components, and the second is to decrease the number and the size of the wires in terms of the system.

Component Size Reduction. In order to decrease the *cross section of wire*, a thinner covering can be used, or the wire core can be made smaller. A thinner covering can be achieved by increasing the roundness of the wire by increasing the twist pitch of the stranded core, changing the composition of vinyl chloride and the covering material, while their tensile strength and smoke characteristics are maintained equivalent to those of conventional wires. With these provisions, it has been possible to realize smaller wires the diameter and cross section of which are reduced, respectively, to 80% and 60% on conventional cables. Aluminum conductors for the core section of the wire have been developed, which are lighter than the corresponding copper conductors.

As control designs are being streamlined, components now require less current to operate, decreasing the diameter of power supply wires, resulting in the utilization of *smaller connectors*. These new connectors can hold the same number power supply wires, but are able to be routed through areas that were almost impossible for older high current connectors.

Bundling materials are also being re-designed and optimized. A typical bundling material for wire harnesses is tape, and tape thickness has also been decreased in recent years. Currently, tape thickness is only 0.09 mm, while progress is being made in the development of environmentally friendly, de-chlorinated tape materials. Even the materials that protect the harness insulation, like tubes or corrugations, are becoming thinner and smaller in size. Conventional tubes having a thickness of 0.5 mm are being replaced by those having a thickness of 0.25mm, and corrugation having a diameter of 5 mm has been added to the current minimum corrugation diameter of 7 mm to achieve weight reduction while maintaining the same performance.

Systematization. As explained in section 3.4.5, the function of an *SJB* is to split a wire harness so that it is easier to assemble in vehicles, to simplify power distribution, and to arrange the wiring in an orderly manner. In addition to these functions, SJBs can reduce the number of wires through sharing power and signal circuits.

Generally, in a conventional EES system, one ECU controls one system. By *integrating multiple control units*, it is possible to decrease the number of wires by eliminating duplicate power lines and signal lines. This strategy, combined with *multiplexed communication* permits the transmission of a lot of data by a fewer number of wires.

In the next-generation vehicles, it is believed that integration of parts in all systems will be advanced, leading to an expansion of area-by-area *modularization*. New lightweight wiring materials inside a module consist of Flexible Flat Cable (FFC), the cross section of which is made rectangular so that the wire can adhere flat to the film, and Flexible Printed Circuit (FPC) in which the circuit patterns are printed over a film. Compared to the conventional round cables, flat cables contribute greatly to space saving, and are easy to be assembled into modular structures since they are flat and flexible. With the advances in area-by-area modularization of instrument panels, duplicated circuits for lighting and grounding can be eliminated, resulting in weight reduction.

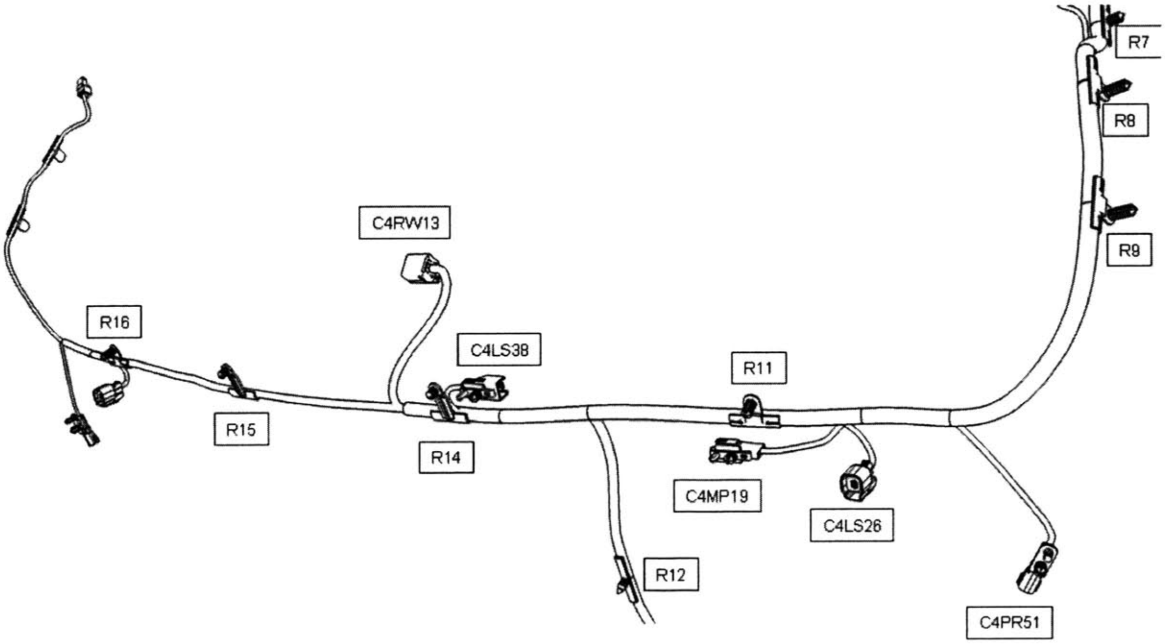
Wire sizes are dependent on fuse capacity, which also depends on the relationship between the fusing characteristics of the fuse and the smoking characteristics of the cable. When wire sizes are selected to match the fusing characteristics of the fuses, the wire class can be elevated by one or more grade from the conventional gauge number, for which the current carrying capacity is rated. By replacing conventional control systems with a *semiconductor relay-based control system*, which has a higher current detection accuracy, it is possible to use a wire size that matches the rated load current of the electric equipment. Since semiconductor relays have a switching function (silent), are maintenance-free, and have a free-layout capability, they permit optimization of the parts' layout.

Although *wireless design* is still a futuristic vehicle technology, further reduction in the number of wires is anticipated by controlling the load of the multiplexed communication lines or other signal lines by infrared beams or millimeter waves. Connectors can also be eliminated if the connections among the parts in the power lines or load drive lines can be achieved by non-contact point connections through the use of electromagnetic induction waves.

Physical Design Considerations

The design goal for the physical portion of wiring design is to design 'in' the wiring, rather than allocate the leftover space to wiring at the end of vehicle design. In other words, the wiring should be designed concurrently with the rest of the vehicle. The EDS design engineers are well aware of guidelines such as selecting safe routing paths in areas not prone to environmental damage, away from high heat areas and moving parts. These routing paths should be free of sharp edges and weld splatter. When designing new plastic or metal structures, it is a normal practice to design in depressions or channels to assist with harness routing. When routing from a stationary to a moving part is necessary, a 'loop' is designed in the wire routing to dissipate the flex movement. Attaching the harness to both the moving and stationary parts also helps to provide wiring strain relief.

Harness attachments, such as clips and clamps, are always part of the wiring assembly, not supplied as loose piece parts to the vehicle assembly plant, as this induces variability in the placement of those attachments. In general, attachment points are provided every 300 to 400 mm along the harness, closer when routing near moving parts or where the wiring path sharply changes direction. The harness attachment locations should be specific to wiring, not shared with other parts. Where possible, the wiring attachment locations are made visually distinguishable from other vehicle part attachments. One example would be attachment holes in sheet metal. With multiple attachment holes in the same area, it is difficult for the assembly operator to locate the proper hole for wiring attachment. This leads to selection of the wrong attachment location, and subsequent misrouting of the wiring. One method to reduce this problem is to use hex shaped holes, rather than round holes, for wiring attachment. This provides a visual aid to the assembly operator, and greatly reduces misrouting of the wiring.



17- Figure 4.3.83D View of Harness, Connectors and Attachment Points (Vehicle Position)[31]

The coverings selected for wiring should have a degree of robustness that will survive and protect the wiring in the specific environment that section of the harness encounters. For example, tape is normally acceptable in many interior applications, but exterior wiring requires tubing or conduit that has superior abrasion and pinch properties, compared to tape. However, even robust coverings may not survive in a poorly routed application. The best protection for wiring is a well-engineered, safe routing path. If, for example, the harness contacts a sharp metal edge, abrasion resistant tape or conduit will delay a chafing failure mode, but may not prevent an ultimate failure.

4.4 Manufacturing Considerations

The methods and controls used in the manufacturing of wiring assemblies can impact the quality, and ultimately, the long term reliability of the wiring. There are two main elements in harness manufacture: a) cutting and terminating of the individual wires; and b) harness assembly of the terminated wires, connectors, attachments, coverings, and other components.

4.4.1 Wire Cutting and Terminating

Cutting and terminating individual wires is the start of the manufacturing process. Actual individual wire lengths should not be approximated from harness drawings. Rather, they should be derived from building a harness to nominal print dimensions, and measuring the individual lead lengths. Proper lead lengths depend on the harness build sequence, i.e. the order in which the leads are assembled to the harness build fixture. A specified build sequence is a requirement for determining the correct, tailored wire lengths, which is devised based on the harness topology. This method will facilitate building repeatable, dimensionally correct wiring assemblies.

Terminal crimping is critical to the long term electrical integrity of vehicle wiring. Standards typically specify both core crimp and insulation crimp heights for each terminal-cable combination. The preferred method for crimping terminals to cable is with an automated crimp force monitoring system. This method monitors the actual force curve (force over time) of each crimp operation, and compares that to a force curve standard.

When validating terminals, the voltage of the circuit should also be taken into consideration. Most circuits are at 12 Volts, but many sensor circuits are module controlled at 5 Volts. These low energy circuits have more stringent validation standards. This is because at 5 Volts potential, any thin film or oxide can become an electrical barrier. Gold or other precious metal plating is often used to help prevent these barriers from forming.

4.4.2 Harness Assembly

The harness assembly of the various component parts is obviously a critical operation that can impact the wiring's overall performance. Normally, this is in charge of one or various FSS. The harness quality depends on the build tooling, build method, and visual aids employed in this operation.

Tooling. The tooling should be a build fixture specific to a certain harness, or family of harnesses. This build fixture must be designed to provide a dimensionally accurate harness. One method to achieve this is to have a build board, where the board and individual wire lengths are modified until the harness dimensions are ± 2 mm of nominal dimensions. The build board can then be released and accurate individual wire lengths measured and documented for lead prep manufacturing.

The harness must also be electrically checked to assure that circuit indexing and continuity are correct. In many occasions, the suppliers also perform a *presence check* on other components, such as attachment clips, to verify they have been assembled to the harness in the correct locations.

Method. The build method also has a significant impact on harness quality and consistency of build. The harness manufacturer should create a documented assembly sequence that provides repeatability from harness to harness. As detailed earlier, actual wire lengths for each circuit should be measured only after the build sequence is determined, and a harness has been built to nominal dimensions. The build sequence for how wires are assembled into the harness is important. The individual lead lengths vary depending on whether they are in the middle or outside of the harness bundle. This, in turn, depends on the sequence of wires plugging to connectors.

Visual Aids. Visual aids provide assistance to the build operators, especially for lower volume vehicles where one operator may build multiple harnesses. One example of a visual aid is having color coded circuit labels on the connector holding fixtures. These labels show the proper wire colors that should be plugged into each connector cavity. Another example is to display the build method in the operator's work station. This build method is a combination of words and visual guides to display the sequence of tasks involved in building the wiring harness. Sometimes a stick drawing with symbols for the types of coverings used on the various harness branches is displayed. Other visuals may be used; the idea is to provide visual guidance to help the operator make a quality product.

4.5 Harness Installation Considerations

Harness installation is the final step in the EDS process. Installation is affected by the previous design and manufacture stages. A well-engineered wiring assembly, which electrically and physically adheres to the design guidelines, has a large impact on how well the wiring gets installed into the vehicle. Harness manufacture highly influences a successful installation process too, as the manufacture operation must accurately reflect the design intent, and parts must be manufactured to print specifications. The installation process itself can be divided into four major factors: a) method; b) training; c) visual aids; and c) material handling.

4.5.1 Method

The installation method should be designed and properly validated, not just left to be evolved in the vehicle assembly operation. This means, the OEM manufacturing engineers should determine the sequence that provides the best opportunity for the wiring to be routed and located in its intended vehicle location. Wiring must be installed in the sequence that minimizes installation interference with any part. For example, if the wiring is intended to be routed underneath an electronic module that is held by a bracket, the wiring may need to be installed before the bracket, so the bracket does not block access during wiring installation.

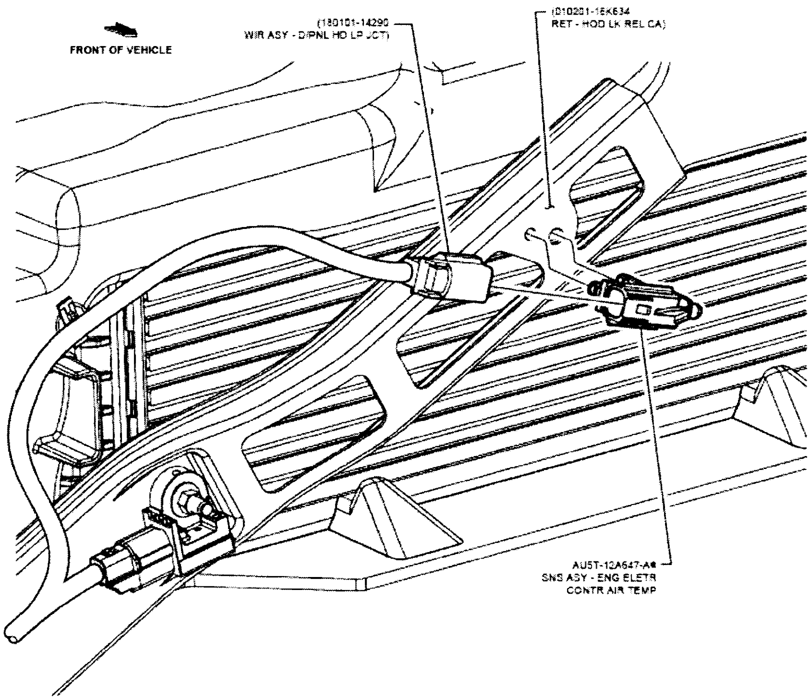
In general, the installation sequence should maximize the accessibility to the electrical components to which the wiring connects or attaches. Connections and attachments should be easily accessible in order to maximize the probability for the operation to be successfully carried out. Whenever any component is blocking the path of the connection or attachment, there is an opportunity for missed connections and attachments. OEMs make use of process planning for tools to analyze these kinds of potential ergonomic concerns. These manufacturing tools are global repositories for standardized engineering processes and data for assembling vehicles, including pars, tools and standard labor time.

4.5.2 Training

Training operators in the proper method is critical to repeatable, reliable wiring installation. If the method reflects the best, most efficient way of assembling the wiring to the vehicle, operators will use that method. In general, assembly personnel will help determine the easiest method of assembly. It needs to be confirmed that the trouble-free assembly does not create a subsequent wiring problem. This is why improvements to the build method should be used only after the change has been approved and the official method revised.

4.5.3 Visual Aids

Visual aids are an efficient way to provide guidance and assistance to the installation operator. This is especially true when a significant vehicle design change occurs, and the operators have to learn a new installation method. An example of an applicable visual aid would be displaying three-dimensional views of the harness routing, with pertinent surrounding devices that are required to show the correct routing. For example, if the wiring is intended to route under a bracket, that bracket should be included in the displayed view.



18- Figure 4.5.3Visual Aid Example: Harness Routing Installation Process Drawing

4.5.4 Material Handling

Material handling is as important as the previous factors. Proper wiring removal from the shipping containers is one example. Many times, operators randomly grab the harness and aggressively pull it from the container. This can result in damaged wires, or wires being pulled out of connectors. Instead, assembly line supervisors should instruct the operators to pick the harness from the container by grasping it with both hands and carefully removing it, while making sure care that no connectors or wires snag on another wiring harness. Common examples of material mishandling that can cause damage to wires or wiring components are:

- For a long, coiled section of harness, uncoiling the harness, holding one end, and throwing the other end of the harness in the direction it routes; or
- Allowing partially installed harness branches to hang down and touch the floor.

Regarding harness storage in the assembly area, a good practice is to select the wiring directly from the shipping container. Experience has shown that hanging wiring on racks or pre-staging the wiring for the installation operators can result in harness damage, and adds unnecessary rework. Any mechanical drivers used to assemble threaded fasteners should be calibrated to allow proper torque of the fasteners.

Correct material handling is also the responsibility of the FSS. Properly packaging the harnesses, such as coiling or folding the harness and securing it with tape or ties, is one way to minimize potential wiring damage. Putting cardboard separators between layers of harnesses is another method to prevent tangling upon removal from the shipping container.

4.6 Electrical Design Process

All the considerations identified previously have the greatest impact on the development process and ultimately on the performance of the wire harnesses. For the present work, however, the emphasis is on the design process solely, so a further definition and analysis of this process is required in order to understand its impact on the EES architecture, present and future challenges, as well as opportunities for the growing EDS.

Each automotive company has a different wire harness design process. However, most of these OEMs have common wire harness full service suppliers, so at a deeper level, there is a common underlying process that each of the companies follow based on the best practices learned from their suppliers. Figure 4.6.1 represents the overall EDS process flow, with inputs from other systems, the vehicle architecture constraints, and design considerations –in the form of system design requirements.

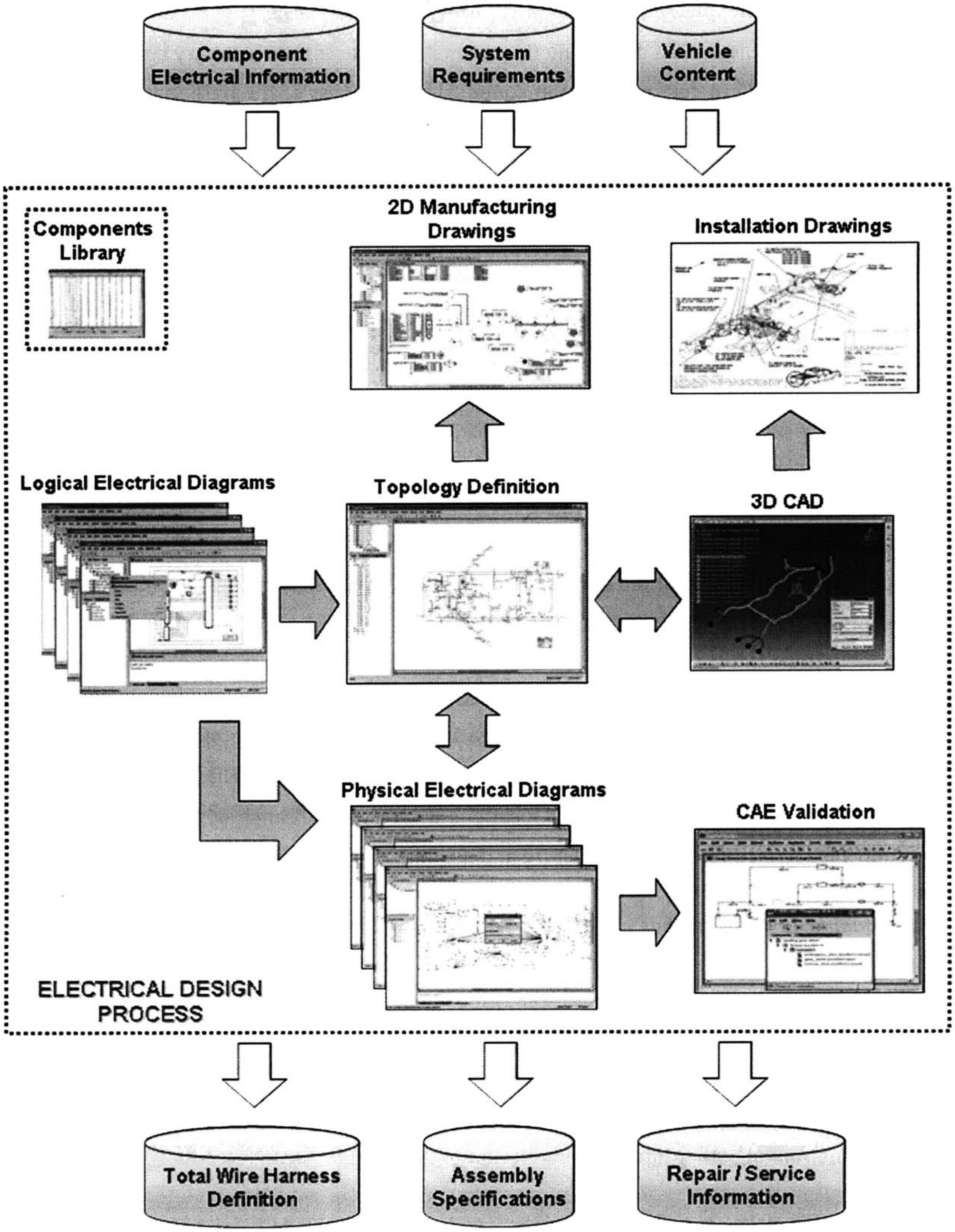
4.6.1 Logical Electrical Diagrams

This is the initial deliverable of the EDS process, where engineers decide how the individual electrical functions will be achieved, based on input such as the electrical information for each electrical and electronic component in the vehicle, and the EES architecture and requirements for the specific vehicle model. During this functional definition step, decisions are made about power and ground distribution, fusing, switching, and logical function that in conjunction determine the 'shape' of the electrical system at a generic level.

During this process, functional partitioning of the different subsystems takes place. Engineers decide how to distribute and aggregate the individual functional entities into electrical power distribution boxes, SJBs, relays, switches, etc. It is at this stage that the number of distribution boxes and SJB will be defined. In general, this definition of functional partitioning will be designed to stay constant across the vehicle program with very little modification even as the customer option content changes.

4.6.2 Topology Definition

In the topology definition stage, engineers decide where to locate the individual components and electrical distribution boxes within the vehicle space. Electrical componentry, in general, is fairly flexible with respect to how or where it can be located. One of the main concerns during this process is to guarantee accessibility for assembly and serviceability. From an electrical design standpoint the exact location of components could be critical. It depends on the preferred location requested by the component owner based on his/her component requirements, but it also depends on the harness partitioning.



19 -Figure 4.6.1Electrical Distribution System Design Process Flow Diagram

In the harness partitioning process, engineers will decide how the harnessing of the entire vehicle program can best be achieved. To determine the optimal partitioning, the primary consideration is to balance the variability in customer option content with the cost of the harnesses. The second consideration is the vehicle 3D CAD data available at that moment, which may or may not be sufficient to have a representative 3D harness path definition – this will depend on the stage of the design process when this takes place and the uniqueness of the vehicle body (modified from an existing model vs. brand new).

This harness partitioning process is a crossover effect of customer optional content, take rates and data availability, that represents a challenge for the EDS engineer, who needs to manage these three considerations appropriately for determining an optimized wire harness topology.

4.6.3 3D CAD Wire Harness Design

During this process, engineers define the wire pathways through the vehicle. Decisions will also be made about ease of installation of the harness in the vehicle, which may require the insertion of in-line connectors to break the wire paths at key points.

At this point, and based on the wire harness topology, elements like splices and breakouts can be defined. The electrical cost of the system can often be reduced by the use of spliced wires. The requirement for each splice will be influenced by the physical size of the vehicle, cost, safety, and reliability considerations. The breakouts, or locations where wires branch out from the harness, must be controlled to facilitate the manufacture and installation of the harness.

4.6.4 2D Manufacturing Drawings

Manufacturing drawings are the primary piece of information – together with the 3D CAD drawings – that is transferred to the harness manufacturer, either directly from the OEM or the FSS. It contains the electrical circuit definition at the greatest detail for each of the harnesses: circuit colors, names, connector part numbers, terminal plating, harness-dressing, splices, in-lines and attachment points, among other information relevant to the manufacturing process.

4.6.5 Harness Installation Drawings

The creation of harness installation diagrams for the assembly plants is another output of the EDS design process. All assembly plants require a representation of electrical harnesses within the same

3D space used to describe the mechanical assembly of the product. Installation drawings show the harness location relative to the vehicle and the rest of the electrical components to which it connects. They show how to route all harnesses within the vehicle, how to fix them to the vehicle's frame or body and which tools are needed by the operator, in case any aid is required to perform the correct installation.

4.6.6 Physical Electrical Diagrams

Physical electrical diagrams capture the electrical system wiring, component and connector definition as defined in the generation of the vehicle wiring harnesses. These are similar to the logical electrical diagrams, with a few additional requirements: inclusion of connector characteristics (terminal plating, cavity definition, connector faceviews), splices, harness characteristics (part number, in-lines, wire gauge and length), and ground characteristics (location, type and name). These physical electrical diagrams are used for the CAE validation process, since they include all the electrical characteristics required to model each component and simulate at a subsystem level.

4.6.7 CAE Validation

CAE validation is an important step in the EDS design process, given that the correct and reliable implementation of the wire harness represents one of the most expensive and technically challenging aspects of vehicle EES design. The idea behind CAE is to analyze electrical systems before manufacturing to avoid system failure in production.

Electrical CAE has been used for a few decades in the auto industry, and nowadays it is considered an essential tool to verify that the harness meets the required specifications. CAE validation helps to ensure the creation of correct-by-design wire harnesses. For example, DC-analysis to show the voltage levels at the terminals, while transient simulation helps to determine the correct fuses, optimal dimensions of the fuses, cross-sectional areas of all wires, existence of sneak paths, etc. CAE engineers employ simulation tools to perform analysis in order to determine the electrical functionality and quality of the design.[32] Physical electrical diagrams and the component electrical information are used for creating the virtual models to perform the simulations, since these contain all relevant information.

4.6.8 EDS Design Process CPM Analysis

Although the process described thus far in section 4.6 follows the general flow outlined in Figure 4.6.1, the steps are by no means sequential, with significant overlap between and across steps. A particular problem with electrical design is that these steps are performed by different groups. There are a lot of different influences from three major design groups at work on electrical harness design systems: Electrical, Packaging and Manufacturing. Given the complexity of such project, the identification of those activities/tasks that are critical to the timely completion of the EDS deliverables is not straightforward.

One of the quantitative tools that has been added to the growing business decision making toolkit is the Critical Path Method (CPM) – a powerful tool but basically simple technique for analyzing, planning, and scheduling large, complex projects.[33] Using CPM, it is possible to identify the path with the longest duration to completion, determine which activities have no slack (or too much slack), and also the earliest date for when the project may be completed.

Throughout the EDS design process there are hundreds of individual tasks that many different people from each of the aforementioned teams have to perform. In order to manage this complexity, and with the idea of analyzing the design process as a whole, it is required to decompose the project in clusters of tasks, or meta-tasks.

Appendix A shows the detail of all these tasks for a particular vehicle program organized following the Work Breakdown Structure (WBS) guidelines. For the purpose of the CPM analysis, we are only going to consider 98 meta-tasks that represent the generic steps that most OEMs and FSS follow in a typical vehicle harness design process.

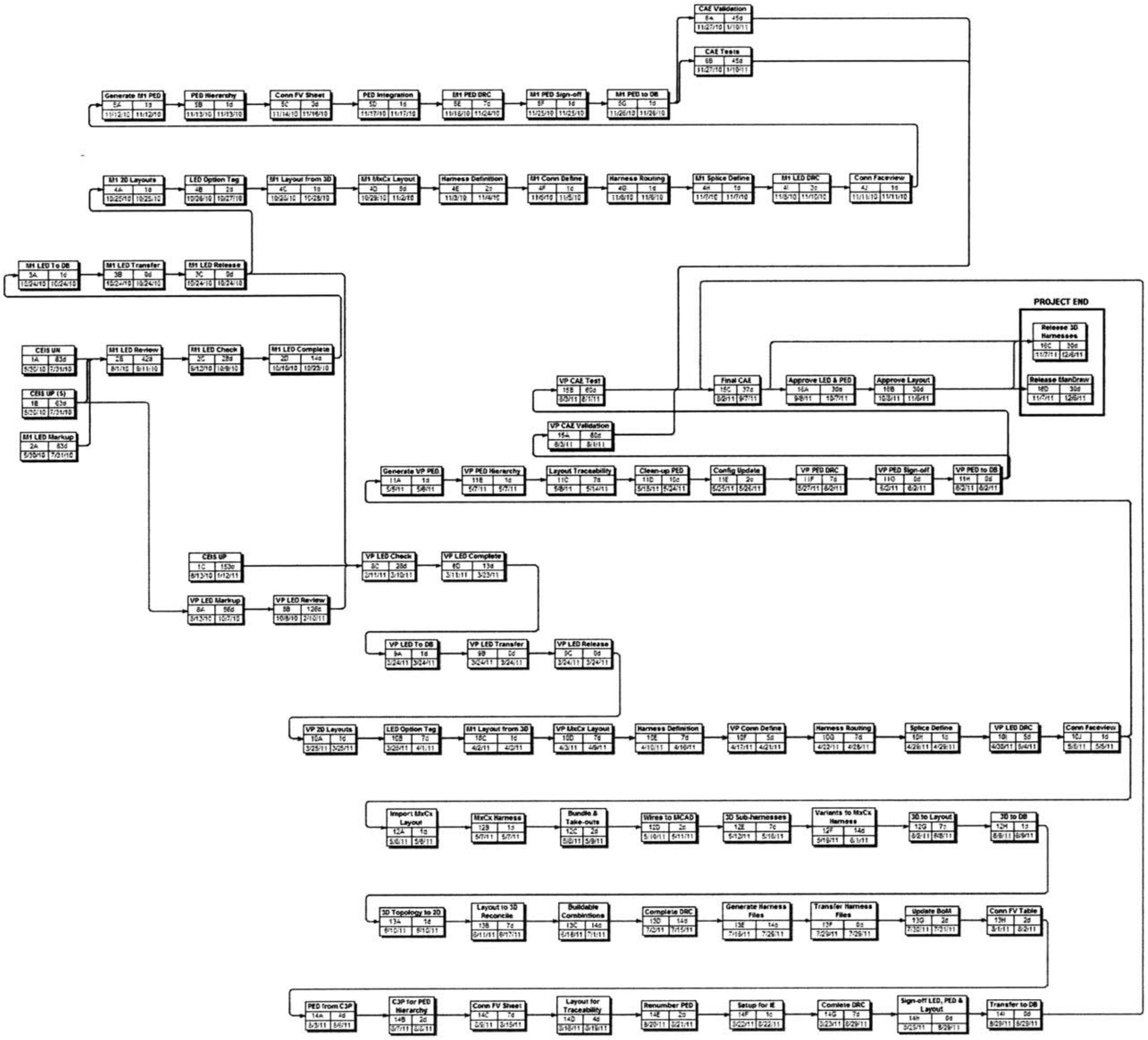
The first column contains the task number and the second column contains a brief description of the task. It only shows two levels of decomposition, and the tasks are of similar complexity, to keep it controllable. Even though many of these tasks may start and stop independently of each other, it has been attempted to sort them in the most sequential manner trying to follow a technological order. The sequence relationship among tasks is contained under the 'Immediate Predecessor(s)' column. 'Duration', 'Start' and 'Finish' dates for each task were estimated based on data from real projects.

Using the *PERT Chart Expert* software, all the information from the WBS was translated into the charts shown on Appendices B, C and D. Each job is drawn on a graph as a box. All relevant information is shown in these boxes: task number, task name, task duration (in days), early finish and early start dates. Jobs are connected with immediate predecessors using unidirectional arrows.

From the analysis of the design process described in the present chapter, the project starts when the information regarding expected electrical functionality and the electrical characteristics of the different electrical and electronic devices is made available to the EDS team - tasks *1a, 1b* and *1c.* Using the program EES assumptions, the EDS team can create the diagrams and drawings required for each of the program milestones: Logical electrical diagrams, physical electrical diagrams, topology diagrams, MCAD drawings, etc. Depending on the OEM, there can be anything from four to ten revisions of these documents to support different prototype phases. However, the main milestone is vehicle production start, and that milestone is what has been defined as the final step for the EDP CPM analysis.

Figure 4.6.8 shows the result of the CPM analysis performed using the *PERT Chart Expert software.* One critical path was identified and highlighted in red. The total project duration is 556 days, starting on 5/30/2010 and ending on 12/6/2011.

After a closer look to the critical path, it is evident that the activities and tasks involved in the 'Verification Prototype' (VP) -lower half of the graph - design phase take longer and are more constrained in slack time between one block of activities and the next one. This is mainly because the 'Mechanical Prototype' (M1) design phase -upper half of the graph- starts many months earlier than the VP phase, and there are only couple of tasks from the M1 phase that are predecessors to a VP phase activity, which in have a lot of slack. For instance, task *3c* ends on 10/23/2010, while task *8c* does not need to start until 2/11/2011. However, this does not mean that *3c,* and all its immediate predecessors, could start 111 days after their pre-established start date. The reason behind is that even when these two processes run somewhat in parallel, the completion of M1-related deliverables in the time that has been allocated is fundamental for supporting M1 prototype vehicle build events.



20- Figure 4.6.8EDP Critical Path

On the other hand, could *8c* start before 2/11/2011 and consequently reduce the overall project duration? That could be accomplished if the 13-day slack on path *1b-8a-8b* is reduced or eliminated. No other task beyond this point seems to allow for further time compression, which means that the process has been already highly optimized in terms of slack.

When looking for opportunities to reduce the time some other ways, it is inevitable to look at those tasks that take the longest time. In this case, the first three tasks on the critical path add up to 245 (44% of the total project), while the last four tasks represent 23% of the total project time (127 days). Collection of electrical interface sheets (*1b*) is the first task in the process, which depends on different parties external to EDS to provide this essential part of information. It happens relatively often that these electrical interface sheets are submitted with inconsistencies or missing information, which is blamed to the fact that the design has not yet been finalized at the moment these are requested. Thus the average time to get the information has been established as 63 days, to allow for corrections and surrogate data creation – in case no formal design exists.

During the next two phases, *8a* and *8b*, the logical electrical diagrams mark-up and review take 182 days to be completed. These two tasks may involve two to five iterations depending on the quality of the information received in the preceding task (*1b*). EDS teams have developed processes that aim to facilitate the flow of information, reduce errors, and consequently rework. However, there are many elements that can be improved for reducing the task duration. In consequence, the impact on the overall project duration could be substantial.

As for the last four tasks in the critical path, *15c-16a-16b-16c/16d*, they represent the last step in the verification though CAE of the M1 and VP design information, and the compilation of all previous EDS documentation in the right format prior to release to the different information and database systems. Further detail may be required to understand what sub-tasks exist under each of these meta-tasks that could be expedited, either trough allocating more resources, or improving the current processes, therefore eliminating unnecessary rework.

4.6.9 Electrical Design Process Integration Challenges

In the 1980's, the output from the electrical wiring process was a physical diagram and many modern tools continue to focus on the diagram as the output without recognition that upstream and downstream attribute relationships and dependencies should be maintained. The expectation with these tools is that, once the drawing is completed, it can be passed over to the next design team in the process.

Many software tools have been designed to improve a specific step of the traditional electrical design process. However, the creation of specialized tools to support individual steps has not always been matched with a corresponding capability for the tool to work with other tools in the process.

The tools used at each step of the design process refer to the same part number but will have differing relevant characteristics of the part. For instance, a connector in a 3D CAD model is unlikely to contain cost information, just as a connector in a costing system is unlikely to have links to a corresponding CAD model. As a consequence, it is not uncommon to find each tool in the design flow defining and maintaining its own relevant characteristics of a particular part independent of any other tools. Each engineer believes he/she is working at optimum efficiency, because irrelevant data relating to other steps in the process does not need to be captured or defined. However, at the organizational level there are huge inefficiencies because many of the tools share overlapping information about the same components and the same data is being defined in several places. Worse still, individual designers may erroneously enter critical data causing further problems during transfer of data from one tool to the next. Engineering design changes originate further problems as a change must be implemented at each step. In a better integrated process, the change could be entered just once in the common parts library and it would automatically propagate to each of the design steps.

Tool incompatibility can exist both within the OEM and between the OEM and its FSS. Incompatibility within the OEM usually takes place when design processes are implemented as a sequence of discrete steps, each with its specialized design tool, with inputs from the previous team and outputs for the next team in the design process. Frequently these steps are highly optimized and appear perfect when viewed from within the individual groups –nonetheless the outcome may not be what the next team expected. In some occasions, the teams cannot use the information. Inefficiencies and costs can be hidden by rigid organizational boundaries resulting in an incomplete appreciation of the degree of duplication occurring at each step. All these result from the lack of a systems approach when selecting the tools for performing the different tasks during the EDS development process. In the next section of this chapter, recommendations on how to implement a streamlined process to solve this and other problems are presented.

Tool incompatibility between OEMs and FSS is even more common, yet for many companies, the duplication of effort is seen as something to be expected, and is perceived as having little impact on cost or timing. It is not uncommon for suppliers to receive a customer drawing and redraw it in their own system because the scope and content of the customer drawing is incompatible, incomplete, or incorrect. Whenever this occurs, the efforts of the OEM and FSS electrical design teams are now directed to figuring out a way to make all the existing tools work and translate information from one to the other. The reason behind this is the variety of MCAD and electrical CAE tools available to carry out EDS development, which are not fully compatible because they have been customized to the needs of the OEM or FSS.

4.6.10 Recommendations

In the previous section, the main challenges for process and data integration for both manufacturers and their suppliers have been presented. A key element to address these issues is the creation of a *streamlined process*[vii] amongst the different groups involved in the EDS design process, rather than the disconnected approach frequently found with the process formerly described. Streamlined design processes address several key issues in the traditional electrical design process:

- Transparency of data flows between wiring and harness processes, i.e. poor interface between the electrical and the mechanical CAD tools.
- The lack of a shared part library, which forces the existence of multiple part libraries: one for the 3D CAD systems and other one for the harness design tools.
- Consistency of 3D CAD data. In many occasions, this does not reflect what is being manufactured, because updates can be made in the harness design tool without being reflected in the 3D CAD tool.
- Accuracy of the downstream design information to ensure manufacturability before it is released to the FSS.

With the streamlined process, part definitions and design artifacts, such as drawings, are managed at each stage in the project to include both their basic engineering attributes such as part number, cost and weight, and other attributes relating to their role in the design process, such as release level, revision and version. These attributes are propagated across tools to ensure that changes are implemented efficiently and correctly, without requiring individual designers to make the same change in several tools.

Streamlined processes also make use of common part definitions and data structures within the software tools. The common definitions can contain information about the relationships between parts and their individual roles at each step in the design process. For example, a harness connector is a complex assembly of terminals, seals, and other related parts, and each of these sub-parts has a complex relationship with the wires that terminate inside each of the connector's cavities. A simple change to a wire can initiate a cascade of changes to other parts within a connector, potentially

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[vii] Streamlined (adj.): made efficient by stripping the nonessentials; being effective without wasting time or effort or expense.

changing the specification and part number of the connector itself. With the streamlined data-flow approach, these relationships are modeled almost unseen by the designer, ensuring that the connector definition is correct and also that it will be accurately cascaded at all steps in the process. This would represent a significant improvement compared with the current disconnected tool method, where the dependencies and relationships between parts may only be recognized at a late stage in the prototype manufacturing stage, prompting costly reworks.[34]

Data integration between OEMs and suppliers can provide large savings in design-cycle time and cost. For those OEMs whose electrical design process is entirely managed in-house, the design task ends with the completion of the electrical wiring design, which can then be sent to the harness manufacturer for quotation and/or build. The quality of this data can be highly variable, and for many harness manufacturers it is necessary to redraw much of the data to ensure correct, quality engineering. This is a necessary item of rework, but it is paid for by the OEM customer in both cost and time.

Close coupling can ensure that the electrical design data can be reused in the harness engineering stage without rework. Basic coupling can be achieved by adoption of common data exchange standards between OEM and FSS. However, an important additional element in close coupling is ensuring the quality and completeness of the data being exchanged from the electrical design tool to the harness maker. This can be achieved by providing electrical designers with access to electrical and harness engineering validation capabilities. By granting them access to validation software tools, electrical wiring designers can validate their designs for manufacturability. This can help the wiring designer refine the specification of connectors, splicing, and other parts to minimize cost. A further major benefit is that the design data communicated to the supplier responsible for manufacturing the harness is of sufficient quality to quote and build.

In the case of the FSS that deals with different OEMs, the selection of a data exchange standard represents huge savings, since they don't have to acquire one tool for each OEM. Instead, they can have one tool, as long as it complies with the necessary standards set between the OEMs and the FSS for information handling and transfer. Of course, this goes beyond the FSS's domain. It also involves the electrical and mechanical design tools' suppliers, who need to adhere to these standards. Some tools have promised to be compatible with multiple existing systems, but the lack of a common standard has hindered a successful implementation.

The *integration of 3D CAD* data with electrical design data is required at two major points in the electrical design flow: for electrical wiring diagrams and for harness engineering. Physical packaging of the EES in 3D CAD is meant to define the locations of parts and the routing of cabling between parts. In contrast, the electrical wiring diagrams define the connection of wires between parts. Simulation and analysis of the electrical behavior is primarily dependent on information contained within the electrical diagram (logical), but also requires wire length information that can only be obtained from the 3D CAD system, so an interface is required between the electrical and mechanical systems. Compatibility between the 3D CAD tools and the harness engineering tools is fundamental to ensure that the harness lengths and locations of connectors, clips and grommets are correctly defined in each tool.

The interface between electrical and mechanical systems depends on both the ability to exchange data –a purely technical issue– and the creation and coordination of common design information and attributes –an organizational and technical issue. It is usually the latter requirement which causes the greatest difficulties during the EDS design process. An elemental requirement is that parts, such as connectors, should be named identically in both 3D CAD and the electrical design tools. This simplifies the data exchange and ensures that a component in 3D can be correctly identified and matched with its counterpart in the electrical diagram. In practice, this is difficult to achieve during the first trial, so the data exchange interface needs to be capable enough to help the user identify and rectify problems. At the simplest level this could mean to display a simple error message, but more sophisticated interfaces can provide a number of key improvements that simplify the task by:

- Providing feedback and auto-matching based on inference and comparison of the data from each system;
- Cross-probing of the data on each system allowing the user to select components in one system and easily identify it in the other system; and
- The ability to save and recall relationships so that the system can automatically update itself as new revisions of 3D CAD data or electrical diagrams are issued.

Another important consideration on the topic of ensuring data correctness is an adequate *change management* strategy. Many of the simpler 3D CAD and electrical design changes are done by overwriting the older information. While this is suitable for initial synchronization between the tools it is not always a good solution for handling the continuous stream of changes that can occur on large projects. The 'overwrite' method works well for smaller EDS teams, but for larger design teams with many engineers working concurrently it creates major problems, like rework, because some data can be authored simultaneously in either or both tools, posing a risk on the design compatibility not only of the one vehicle program that is being revised, but for any other program that shares the same component/design solution.

A traditional 'overwrite' mechanism cannot support optimal data integration. Every time a user imports changes from one system to the other, he/she faces the risks of losing any changes he/she had made locally. This lack of configuration control has created a major bottleneck in the design process that hinders concurrent design work in the mechanical and electrical design tools, as each tiny design change must be carefully communicated and transcribed from one system to the other, rather than exchanged electronically. Consistency and reliability of the design get 'lost in translation', from one design release to the next one, and from a particular vehicle application to the other, resulting in major revisions, that are time-consuming and pose a risk to the design quality.

Recent advances in data exchange management have directly addressed this issue. Tools that simplify the interfaces are now being used, but require a significant level of task granularity. This is achieved by the system using a series of fine-detailed, user-defined 'masks' that define which tool is the 'master' and every attribute of each type of entity -wires, terminals, connectors, splices, clips, grommets, and so on. Additional user-defined validation modules then provide a second tier of data validation to be applied to resolve any conflicts. This allows data-exchange to be automated, with formal and repeatable behavior, eliminating the slow and error-prone task of interactively synchronizing design changes.

In addition to the technical implications described, there are organizational implications and competency issues that have to be addressed in order to make the necessary improvements to the process. Roles and responsibilities should be revisited and agreed upon the teams involved in the design process, both internal and external to EDS, at the OEM and FSS. Also, migrating to a new set of development tools, or modifying the existing ones to make them compatible to the extent here described, has an economical component: the investment in software tools and training the engineers to utilize these tools. All these issues have to be evaluated by the OEM management, and its FSS management, based on the long-term EDS strategy.

5 EDS Validation Methods

> *"The logic of validation allows us to move between the two limits of dogmatism and skepticism."*
>
> *Paul Ricoeur*

Almost every active safety system that exists in an automobile relies on the EDS to provide the expected functionality: airbags, ABS, TPMS, Blind Spot Monitor (BSM), Heads-Up Display (HUD), among others. Most of the emphasis has been on the development of new deterministic and robust validation methods to prevent and identify failures of these safety components, but the physical aspects of the EDS, which provides the data communication medium and the power distribution network, should also be taken into consideration when defining the appropriate testing strategy for the EES as a whole.

All the major automotive OEMs have created extensive and well-documented EDS verification and validation processes, which keep evolving as new features are added to the EES and the interactions among components become more complicated and difficult to test. This chapter contains a brief explanation of the current validation methods and processes, as well as a glimpse into others that are yet to be incorporated as part of the suite of compulsory tests that OEMs perform through their EDS development teams.

5.1 EDS Validation and Verification

The engineering V was explained previously in section 2.2. It is commonly used in the development of automotive systems, particularly when applied to the validation of electronic hardware and its associated software. Depending on the OEM's specific EDS design process strategy, the responsibility to carry out the validation and verification (right side of the V) may be split between the automotive manufacturer and the FSS.

Regardless of the strategy, the commitment to provide high vehicle quality while still reducing vehicle development times and costs is a common factor in the industry. Therefore, OEMs have been using various methods to guarantee the successful fulfillment of all requirements by validating the design at different stages throughout the EDS development process.

5.1.1 Failure Mode Effect Analysis

The EDS is designed taking into account the OEM's target vehicle life, typically 10 years or 150,000 miles. Within the design process, random and systematic failures are anticipated. The former includes the failures due to ageing and wear out mechanisms, like the breakdown of cable insulation, corrosion of connectors or the effects of thermal stress on fuses. Systematic failures are the consequence of an imperfect design process such as the selection of an inappropriate terminal material.

Both these elements are considered when calculating EDS reliability performance. For economic reasons, the probability of failure and confidence levels are assigned to meet the normal vehicle life performance targets which imply that, statistically, some vehicles will experience EDS failure within their operating design life. For some safety related systems, however, the failure probability is reduced to a minimum.

OEMs have created fairly detailed FMEAs that are constantly reviewed by multifunctional teams to ensure robustness of the design. Unfortunately, it is often the case that a linked process falls into the 'too difficult' category such that the FMEAs are only performed at each discrete level (system, subsystem, component), within a boundary diagram. These partitioned FMEAs simplify the application of the process, but they fail to differentiate between the potential impacts to the interconnected systems.

To address these issues, the EDS team could identify circuits with potential criticality during the Design Failure Mode Effect Analysis (DFMEA) process by adding a column to the usual spreadsheet. These FMEAs consider effects and relationships beyond the EDS boundary diagram through the use of "criticality", which is conventionally defined mathematically as:

Frequency of Failure x Consequence of Failure

However, an EDS DFMEA review team would be unable to quantify criticality based upon such a definition. The EDS 'criticality' column should have two valid states: 'N' for normal and 'C' for critical. At the beginning of the process all lines are defaulted to C and the effect would be to force the risk priority number (RPN) to the highest value.[35]

An example on the complexity of assigning the criticality of a particular failure mode is discussed next. Let's consider the case of the exterior lighting, which is protected with duplicate fuses to comply with legislative requirements. However, the lighting control module is supplied by a single fuse, the failure of which can extinguish all external lighting. Such risky situations are not as unusual as they might appear because in any vehicle there are many opportunities for a single point failure to extinguish the external lighting. What is being considered here is the avoidance of any additional risks from single point failures beyond the current custom and practice. This is an example of how an otherwise minor electrical failure can have a disproportionate impact on a critical vehicle system.

Another example of criticality level assignment, but now related to data communication: for EDS manufacturing purposes and vehicle assembly requirements, both network cables share the same connectors. If those connectors are not correctly mated and subsequently separated, or if they suffer water intrusion and corrosion, both data lines are at risk of an open circuit.

5.1.2 Failure Mode Electrical Test

Failure Mode Electrical Test (FMET) is one of the final validation tests during the vehicle development process for EDS. It is a method to assess the calculated and modeled results by setting up on a vehicle the operating and fault conditions which had been anticipated, and correlating the predicted and measured results. It is the equivalent to crash testing a real vehicle following extensive computer based simulation. FMET is beneficial in two regards: a) discrepancies between modeled and measured results can flag up errors in the original design assumptions, and b) lessons can be learned for current and future programs. It also can identify where the manufactured EDS is not to design intent and it allows corrections to take place before volume manufacture starts, because it is usually carried out on early series build vehicles prior to production.

5.2 Breadboard Testing

5.2.1 EDS Validation

Breadboards are an indispensable validation method used in the development of automotive electrical systems. A breadboard consists of a 2D or 3D spatial representation of the vehicle onto which all the major items of electrical hardware are mounted, located approximately where they would be fitted in the eventual vehicle, and interconnected with early versions of the EDS design, derived from a fusion of 3D packaging and circuit information.

Instrumentation required on the breadboards may include real time simulators to produce the major dynamic electrical signals which are necessary to test functionality, e.g. vehicle speed, crankshaft speed, engine coolant temperature and ambient temperature. Breadboards allow basic system connectivity and functionality to be tested, but they are also very useful during software development; since they make it possible to quickly evaluate the impact of changes without the need to use a development vehicle.

It is expected that in the future, breadboards will be used to test individual components together with many other representative system elements and parts, and this might still happen a long time before physical vehicles become available. Hence, breadboard capabilities should be exploited further than at present time, not only by the EDS team, but also by other electrical and electronic components' developers.[36]

The breadboard is the first opportunity to validate the EES as an integrated system with real hardware. Therefore, more detailed analyses should be preformed in order to get the maximum benefit from the breadboard. Voltage drops, fuse blow times, power and data distribution strategies will be evaluated under representative vehicle conditions by introducing the faults that have been found when creating the EES DFMEA. The effects of ground disconnections or blown fuses and their associated sneak paths may also be identified. All these tests would confirm the basic integrity of the EES design. Other tests, like replicating the expected sheet metal ground impedances, may be performed to assess the effects of ground voltage offsets between ECUs and their impact on the network systems. The introduction of faults on the network systems allows the containment strategies and diagnostic capabilities to be assessed.

5.2.2 Radio Frequency Interference

Without the vehicle sheet metal present, it is difficult to estimate the radio frequency (RF) susceptibility of the vehicle EDS. The metal structure in most cases provides screening to attenuate RF transmitted noise, although panel gap resonances can increase propagation through slot antenna effects. However, RF susceptibility can be assessed using the bulk current injection process to determine the system immunity. It involves placing a current transformer around the EDS harnesses and using it to inject interference signals onto the power and data communication cables.

Bulk current injection (BCI) is recommended over the frequency range 1MHz – 400 MHz which includes the range of frequencies at which wiring harnesses are resonant. As standard, a harness length of 3 feet is used, but by utilizing the actual vehicle design intent harness on the breadboard, a much more realistic assessment of system performance in the final vehicle situation can be obtained. With the standard 3 feet test harness, an injection current of 60mA has been established as the baseline interference level. It may be necessary to perform tests to evaluate whether this level is independent of harness length, or whether a length / current profile must be established.[37]

Currently, correlation between BCI and other test methods such as transverse electromagnetic wave (TEM) cells and strip lines is not linear, and it may be necessary to adopt the double bulk current injection technique to achieve the desired confidence levels of RFI immunity at the breadboard stage of development.[38]

5.2.3 Hardware in the Loop

Hardware in the Loop (HIL) is the current trend in ECU validation methods and in particular the software contained within these modules. The typical HIL set up consists of the ECU under test, relevant hardware associated to it, a simulator of input/output signals, and a breakout box to allow instrumentation to be used to analyze external signals, all interconnected with a wiring harness, which is usually provided only to effect the required electrical connectivity, but is not representative of the EDS that will be used on the vehicle.

The next step for HIL test is to move into the breadboard setting, where the verification takes place in a more representative environment of the production vehicle. Real hardware is present, and the effects of the harness impedances on data transmission can be accounted for. An electronic component or module that undergoes HIL testing in the breadboard is a very good approximation of the vehicle application and thus confidence in the complete system performance can be increased. A further opportunity to evaluate system function at its margins of operation is to replace the battery with a power supply capable of external voltage modulation. Furthermore, the integration of Software in the Loop (SIL) along with HIL testing can reduce the number of expensive prototypes needed for production level testing by creating a virtual representation the rest of the systems. However, we should not forget that the simulation is good only in so far as the model represents the actual vehicle conditions – which can be biased in many occasions –, so a full vehicle validation cannot be completely eliminated from the validation process.

5.3 Other Validation Methods

5.3.1 CAE Testing

As mentioned previously in section 4.6.7, CAE testing is nowadays being widely used to validate the performance of vehicle systems, including electronic hardware and the EDS. Parametric models are used to validate ECUs and other system components, while static, state-based models have suffice to evaluate the EDS parameters, such as circuit integrity, voltage drop and short circuit. However, these models do not account for the effects of circuit reactance, mutual couplings and common noise under dynamic or transient conditions. Therefore, the effects of signal transient and signal to noise ratio are not quantified.

Simulating this kind of electrical phenomena is very challenging from the software perspective. It will be necessary to develop a better integrated suite of modeling tools to enable complete system dynamic evaluations, including EDS. This is a challenge for the industry and its CAE tools suppliers. This special set of conditions is extremely hard to simulate only by the use of CAE tools, thus the relevance of a 'closer-to-reality' model, such as that offered by HIL. This would increase the level of confidence in the intended new designs in advance of vehicle testing.

5.3.2 Vehicle Functional Test

The first functional test on a representative production intent vehicle takes place normally at a very late stage in the vehicle development process, at which all parts come together on a drivable, testable car. At this point, no major problems are expected if the previous validation steps were followed and problems addressed.

During early development stages, these vehicles will not necessarily be to a production intent condition, but they still provide a good insight on how the different systems work together and serve to detect major potential failures early on in the design process.

6 Conclusions

6.1 Summary

Developing a common EES architecture for future automobiles is a very challenging task. The constant introduction of innovations due to customer needs and regulations has led to an increasing amount of functions that depend on the EES to operate. Consequently, both hardware and software aspects of the EES have been impacted.

Common architectures are by no means unchangeable; on the contrary, the integration of new functions into the common architecture during its life cycle forces them to evolve constantly. In order to integrate these new technologies with the existing ones, and to preserve the harmony of systems, various factors have to be considered. One of them is the early selection of an open, flexible architecture, which allows adding new features without altering the rest of the systems and the architecture itself. Several others, such as the OEM's brand strategy, industry standards, vehicle homologation requirements, and functional classification, are fundamental considerations that need to be taken into account when developing a common EES architecture.

Various design factors influence a successful integration, from the cost efficiency and manufacturability points of view. Several requirements and limits have to be evaluated and fulfilled when integrating all electrical and electronic components into the common architecture. Major requirements and limits are packaging limits and space, wiring harness routing, bundle sizes, weight, processing power, data storage capacity, networking load, networking transmission timing. As we can see, many of these design aspects are directly related to the EDS architecture. Any changes or adaptations to the EDS, especially if the target vehicle is based on a common global platform represent an enormous challenge.

All elements need to be covered, from fusing, wiring harness, and option level definition, to have a successful integration of these EDS factors into the EES architecture. As discussed in Chapter 4, a change in the fusing strategy is necessary to supply the additional functions. In the same way, by integrating new functions into the vehicle architecture, the wiring harness is immediately affected, and the complexity of the design changes is directly correlated to the partitioning of the wiring harnesses. However, there are different options to realize the communication for new functions. Besides a hardwired connection where each signal requires a wire connection, a multiplexing via network systems is possible. Which network is to use depends on the requirements of the function (e.g. communication speed, volume of data). Major advantage of using network systems is the reduction of wires and the capability of diagnostics.

In addition to the abovementioned factors, efforts to communize and reuse electrical systems, components, and designs, have to be synchronized with the common architecture definition. OEMs have proven for many years the benefits of communization and reusability by taking advantage of economies of scale, increased quality and reduction of engineering and manufacturing cost. Thus, the continuing application of these principles into the EDS development processes is irrefutable.

6.2 Reflections

When developing a common EES architecture, several factors must be addressed, not only the traditional electrical and electronic cost and time metrics. Everything, from issues associated with vehicle manufacturing or with component installation and ergonomics requirements, to inefficiencies in the development process, are to be considered. In reference to the EDS in particular, alternatives to harness routing and module placement, for example, can greatly impact the overall efficiency of the EES architecture. These alternatives should be examined by the OEM prior to fixing the overall vehicle manufacturing sequence. Cost savings can be achieved by reducing the number of wire leads, optimizing fuse size and wire gauge, if sufficient EES architecture design flexibility is allowed.

Several other important factors that play an integral role in the EES architecture also influence the EDS architectural design. Weight reduction, which has a direct impact on fuel economy, is most important than ever before given the economical and environmental pressures on automotive OEMs to offer more fuel efficient vehicles and reduce carbon dioxide emissions. Wire harness weight reduction can be achieved either through improvement of wire and bundle design, or through a systematic optimization of the entire EES. This systematic optimization encompasses functions modularization and decomposition, software and networking capabilities enhancement, and alignment of packaging requirements with vehicle limitations, routing constraints and power distribution strategies.

From the strategy perspective, the variables that have been identified as being the most relevant when developing a common architecture for any system within the EES are those related to the engineering development lead time and the vehicle life cycle, development and vehicle quality, development and platform cost, market wants and the specific OEM brand strategy. Imbedded within these variables are the technological tendencies in the industry, as well as technical capabilities, production capacity, and the OEM's supplier base.

6.3 Future EDS Development

From the design and development perspectives, there are also opportunities of improvement for the EDS. As explained in Chapter 4, the electrical design process is a multi-stage process involving a number of different design groups working in several organizations. For many organizations, significant inefficiencies continue to exist in the process, particularly regarding exchange of data from one step in the process to the next, and in the implementation of design changes. These inefficiencies negatively impact quality, the overall design cycle time and the manpower required to complete each design. The use of streamlined electrical design processes can provide major improvements to both quality and the design cycle time, particularly when using common data exchange formats. This is particularly important for exchange of data between the OEM and its EDS FSS.

An additional inefficiency, that is only beginning to be recognized, occurs when information about the downstream cost impact of design choices is unknown. As a consequence, designers may make sub-optimal or even incorrect design choices that will demand later rework. EDS cost efficiency can be improved by using streamlined electrical design tools that integrate both schematic design and harness engineering by sharing common parts and cost libraries and providing automated part selection capabilities at all steps in the design process. Since this process is intended to facilitate access to absolute cost information to the design team for a better decision-making process, the data that is embedded in the EDS tools should be commensurate to the design data, which does not only refers to part cost, but every other possible aspect of the design: from packaging and transportation fees, to engineering and service expenditures. A suite of tools with these capabilities will ensure that EDS designers define and specify the electrical design to comply with the engineering requirements of the product and making use of lower-cost system solutions, while conforming to the constraints of the manufacturing process, resulting in less rework and reduced design cycle-time.

As the vehicle functions enabled by the EDS become more safety related, and vehicle development programs are forced into the virtual world, the need to make the EDS validation and verification process more robust has also gained importance. One way to do this is though alignment of the EDS development process with the engineering V model, which is used for other vehicle systems.

Thanks to the implementation of the Six Sigma methodology across the automotive industry, tools like FMET and FMEA are nowadays well known and widely used within the EDS design verification and validation process. Also, opportunities to add value to the test results currently delivered from the vehicle breadboard should be explored, such as integration with HIL, and expansion of testing capabilities beyond basic EDS and component functional testing.

6.4 Further Research

Understanding all the EDS architectural elements and how these affect the EES common electrical architecture is an enormous task. The vast majority of these elements are many times interrelated, which poses an extra challenge when trying to analyze them individually. The present work has outlined most of these elements, identified their relationships and implications to the overall EES architecture. However, there are some topics that were not covered in the present work or were not studied in depth, but well deserve further study given their implications for the EES and EDS architectures:

- The impact of electronic module integration, especially as it is related to optional content.
- Generate metrics of the EDS architecture for a comprehensible view of all relevant characteristics.
- The effects of future copper escalation costs and how that would impact the EES/EDS architecture cost when viewed from a complete vehicle life cycle.
- The usage of recyclable and environmental-friendly materials in harnesses and related components.
- A supply chain strategy to reduce the rising harness manufacturing and shipping costs.
- A survey of the technological trends from different OEMs and dissimilar industries to create a framework of the attributes that can be adapted for the EDS.
- An adequate design cost modeling system to identify the impact of all relevant elements to the EDS.

7 Appendices

Appendix A EDS Design Process Work Breakdown Structure

Task #	Task Name	Immediate Predecessor(s)	Duration (days)	Start Date	Finish Date	Responsibility
	EDS Electrical Design Process					
1	**Component Electrical Information Sheet <V0 UN/UP>**					
1a	Collect UN Component Electrical Information Sheet <UNV0 Start> - <UNV0 End - 6Weeks>	none	63.0	05/30/05	08/01/05	OEM EE Systems Engineer
1b	Collect UP Surrogates Component Electrical Information Sheet <UNV0 Start> - <UNV0 End - 6Weeks>	none	63.0	05/30/05	08/01/05	OEM EE Systems Engineer
1c	Collect UP Component Electrical Information Sheet <UPV0 Start> - <UPV0 End - 6Weeks>	none	153.0	08/13/05	01/13/06	
2	**UN Logical Electrical Diagrams <UNV0 Start> - <UNV1 Start + 6 weeks>**		**147.0**	**05/30/05**	**10/24/05**	
2a	"Common Subsystem Electrical Diagrams" Markups <UNV0 Start> - <UNV0 End - 6Weeks>	none	63.0	05/30/05	08/01/05	OEM CAD Designer, OEM EE Systems Engr
2b	Complete Electrical Diagrams / System Compatibility Reviews <UNV0 End - 6Weeks> - <UNV0 End>	2a, 1a, 1b	42.0	08/01/05	09/12/05	
2c	Develop Logical Electrical Diagrams <UNV1 Start> - <UNV1 Start + 4 Weeks>	2b	28.0	09/12/05	10/10/05	OEM EE Systems & CAE Apps Engrs and CAD Designer
2d	Design Checks Completed w/Importable Netlist <UNV0 End + 4 Weeks> - <UNV0 End + 6 Weeks>	2c	14.0	10/10/05	10/24/05	OEM CAD Designer
3	**Transfer of UN Logical Electrical Diagrams to Wiring Supplier <UNV1 Start + 6 Weeks>**		**0.0**	**10/24/05**	**10/24/05**	
3a	Check In Logical Electrical Diagrams to Diagram Database as Design Intent <UNV1 Start + 6 Weeks>	2d	0.0	10/24/05	10/24/05	OEM CAD Designer
3b	Transfer Logical Electrical Diagrams & POL to Supplier Per Sign-off Procedure <UNV1 Start + 6 Weeks>	3a	0.0	10/24/05	10/24/05	OEM CAE App Eng,PMT,OEM/FSS
3c	Release CS Level Electrical Diagram / Electrical Diagram Change Control /LCM Approval <UNV1 Start + 6 Weeks>	3c	0.0	10/24/05	10/24/05	OEM EE Systems Eng, OEM CAE Apps
	M1 / Under Body (UN) Support					
4	**2D Layout(s) <UNV1 Start + 6 Weeks> - <UNV1 End>**		**18.0**	**10/24/05**	**11/11/05**	
4a	Review/Update Logical Electrical Diagrams/Import Netlist	3c	1.0	10/24/05	10/25/05	OEM/FSS CAE Designer
4b	Option Tag Logicals Electrical Diagrams	4a	2.0	10/25/05	10/27/05	OEM/FSS CAE Designer
4c	Review 3D Harness Model Root Config to determine Layout Configuration	4b	1.0	10/27/05	10/28/05	
4d	Create Max Complexity Harness Topology and Place Components	4c	5.0	10/28/05	11/02/05	OEM/FSS CAE Designer

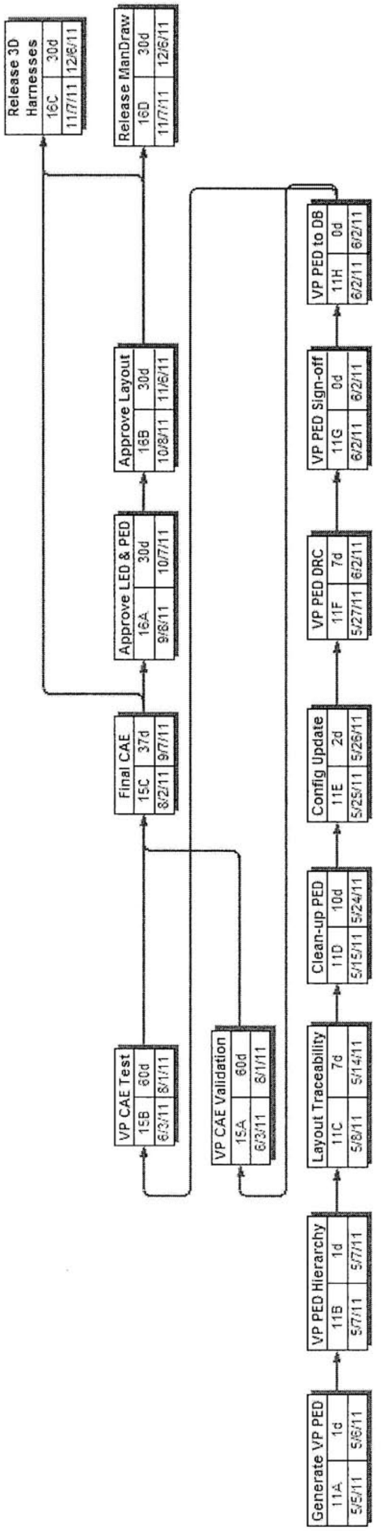
4e	Define Wires, Inlines, Harness ID's & length estimates	4d	2.0	11/02/05	11/04/05	OEM/FSS CAE Designer, OEM/FSS Harness Eng
4f	Verify/Define Part#'s for Connectors, Terminals & Assoc Parts	4e	1.0	11/04/05	11/05/05	OEM/FSS Harness Designer, OEM/FSS CAE Designer
4g	Verify/Re-route Wires, Splices & Multi-terminations	4f	1.0	11/05/05	11/06/05	OEM/FSS CAE Designer, OEM/FSS Harness Eng
4h	Verify/Optimize Splice Locations	4g	1.0	11/05/05	11/06/05	OEM/FSS CAE Designer, OEM/FSS Harness Eng
4i	Design Rule Checks (DRCs) Completed & Design Updated Accordingly	4h	4.0	11/06/05	11/10/05	
4j	Create Connector Table for Faceview Generation	4i	1.0	11/10/05	11/11/05	OEM/FSS CAE Designer
5	**Generate Physical Electrical Diagrams <UNV1 End> - <UNV2 Start + 4 Weeks>**		**28.0**	**11/11/05**	**12/09/05**	
5a	Generate Physical Electrical Diagrams	4j	1.0	11/11/05	11/12/05	OEM/FSS CAE Designer
5b	Create Top Level Physical Electrical Diagrams	5a	1.0	11/12/05	11/13/05	OEM/FSS CAE Designer
5c	Generate Connector Faceview Electrical Diagram Sheets	5b	3.0	11/13/05	11/16/05	OEM/FSS CAE Designer
	Manually Insert Parent Layout Number for Traceability		1.0	11/16/05	11/17/05	OEM/FSS CAE Designer
5d	Setup for Integrated Electrical	5c	1.0	11/17/05	11/18/05	OEM CAE, OEM EE Systems Engr
5e	Design Rule Checks (DRCs) Completed & Design Updated Accordingly	5d	7.0	11/18/05	11/25/05	
5f	Sign-off Procedure to Transfer Logicals and Physicals to Ford	5e	1.0	11/25/05	11/26/05	
5g	Check In Logicals and Physical Electrical Diagrams to Diagram Database	5f	1.0	11/25/05	11/26/05	OEM/FSS CAE Designer
6	**Perform CAE Analyses for Design Verification <UNV2 Start + 4 weeks> - <UNV2 End>**		**32.0**	**12/09/05**	**01/10/06**	
6a	Perform CAE for SDS Requirements Verification	5g	32.0	12/09/05	01/10/06	OEM CAE Apps Engr, OEM/FSS CAE Engr
6b	Perform Standard Analyses Set Per CAE Plan	6a	32.0	12/09/05	01/10/06	OEM CAE Apps Engr, OEM/FSS CAE Engr
7	**C3P Harness Release Process <UNV2 End> <M1DJ>**		**49.0**	**01/10/06**	**02/28/06**	**OEM/FSS CAE Designer**
7a	Release of CS Level Electrical Diagram in WERS/LCM Approval <UNV2 End> <M1DJ>	6b	49.0	01/10/06	02/28/06	OEM EE Systems Eng, OEM CAE Apps
	Release of Agreed Upon Buildable Layouts <PTC>		49.0	01/10/06	02/28/06	
7b	Release of all 3-D Wire Harness Packages <UNV2 End> <M1DJ>	7a	49.0	01/10/06	02/28/06	
7c	Release of all Harness Manufacturing Drawings <UNV2 End> <M1DJ>	7b	49.0	01/10/06	02/28/06	
	VP / Upper Body (UP) Support					
8	**UP Logical Electrical Diagrams <UPV0 Start> - <UPV1 Start + 4 Weeks>**		**223.0**	**08/13/05**	**03/24/06**	
8a	"Common Subsystem Electrical Diagrams" Markups <UPV0 Start> - <UPV0 Start + 8 Weeks>	1b	56.0	08/13/05	10/08/05	OEM / FSS EE Systems Engr

8b	Complete Electrical Diagrams / System Compatibility Reviews <UPV0 End - 10Weeks> - <UPV0 End - 2 Weeks>	8a	56.0	12/16/05	02/10/06	
8c	Develop Logical Electrical Diagrams (Update / Replace UP Surrogates) <UPV0 End - 2 Weeks> - <UPV0 End>	8b, 1c, 3c	28.0	02/10/06	03/10/06	OEM / /FSS EE Systems & CAE Apps Engrs and CAD Designer
8d	Design Checks Completed w/Importable Netlist <UPV1 Start + 2 Weeks> - <UPV1 Start + 4 Weeks>	8c	14.0	03/10/06	03/24/06	OEM CAD Designer
9	**Transfer of UP Logical Electrical Diagrams to Wiring Supplier <UPV1 Start + 4 Weeks>**		**0.0**	**03/24/06**	**03/24/06**	
9a	Check In Logical Electrical Diagrams to Diagram Database as Design Intent <UPV1 Start + 4 Weeks>	8d	0.0	03/24/06	03/24/06	OEM CAD Designer
9b	Transfer Logical Electrical Diagrams & POL to Supplier Per Sign-off Procedure <UPV1 Start + 4 Weeks>	9a	0.0	03/24/06	03/24/06	OEM CAE App Eng, PMT, OEM/FSS
9c	Release CS Level Electrical Diagram / Electrical Diagram Change Control /LCM Approval <UPV1 Start + 4 Weeks>	9b	0.0	03/24/06	03/24/06	OEM EE Systems Eng, OEM CAE Apps
10	**2D Layout(s) <UPV1 Start + 4 Weeks> - <UPV1 Start + 10 Weeks>**		**42.0**	**03/24/06**	**05/05/06**	
10a	Review/Update Logical Electrical Diagrams/Import Netlist	9c	1.0	03/24/06	03/25/06	OEM/FSS CAE Designer
10b	Option Tag Logicals Electrical Diagrams	10a	7.0	03/25/06	04/01/06	OEM/FSS CAE Designer
10c	Review 3D Harness Model Root Config to determine Layout Configuration	10b	1.0	04/01/06	04/02/06	
10d	Create Max Complexity Harness Topology and Place Components	10c	7.0	04/02/06	04/09/06	OEM/FSS CAE Designer
10e	Define Wires, Inlines, Harness ID's & length estimates	10d	7.0	04/09/06	04/16/06	OEM/FSS CAE Designer, OEM/FSS Harness Eng
10f	Verify/Define Part#'s for Connectors, Terminals & Assoc Parts	10e	5.0	04/16/06	04/21/06	OEM/FSS Harness Designer, OEM/FSS CAE Designer
10g	Verify/Re-route Wires, Splices & Multi-terminations	10f	7.0	04/21/06	04/28/06	OEM/FSS CAE Designer, OEM/FSS Harness Eng
10h	Verify/Optimize Splice Locations	10g	2.0	04/28/06	04/30/06	OEM/FSS CAE Designer, OEM/FSS Harness Eng
10i	Design Rule Checks (DRCs) Completed & Design Updated Accordingly	10h	5.0	04/30/06	05/05/06	
11	**Initial Sets of Physical Electrical Diagrams <UPV1 Start + 10 Weeks> - <UPV1 End>**		**35.0**	**05/05/06**	**06/09/06**	
11a	Generate Physical Electrical Diagrams Using Current C3P Tools	10j	1.0	05/05/06	05/06/06	OEM/FSS CAE Designer
11b	Create Top Level Physical Electrical Diagram Sets Using Current C3P Tools	11a	1.0	05/06/06	05/07/06	OEM/FSS CAE Designer
11c	Manually Insert Parent Layout Number for Traceability	11b	7.0	05/07/06	05/14/06	OEM/FSS CAE Designer
11d	Cleanup Initial Physical Electrical Diagram Set	11c	10.0	05/14/06	05/24/06	OEM/FSS CAE Designer
11e	Update Configuration Electrical Diagram with Physical Set	11d	2.0	05/24/06	05/26/06	OEM/FSS CAE Designer
11f	Design Rule Checks (DRCs) Completed & Design Updated Accordingly	11e	7.0	05/26/06	06/02/06	

11g	Sign-off Procedure to Transfer Logicals, Physicals and Buildable Layouts to Ford	11f	0.0	06/02/06	06/02/06	
11h	Check In Logicals, Layout(s) and Physical Electrical Diagrams to Diagram Database	11g	0.0	06/02/06	06/02/06	OEM/FSS CAE Designer
12	**ECAD/MCAD Topology Integration <UPV1 Start + 10 Weeks> - <UPV1 End>**		**35.0**	**05/05/06**	**06/09/06**	
12a	Import of Max Complexity Wirelist/Topology Files (MCAD)	10j	1.0	05/05/06	05/06/06	MCAD Support, OEM/FSS Harness Eng
12b	Designate Max Complexity(s) Buildable Harnesses Components (MCAD)	12a	1.0	05/06/06	05/07/06	MCAD Support, OEM/FSS Harness Eng
12c	Map Bundle & Take Out Topology	12b	2.0	05/07/06	05/09/06	MCAD Support, OEM/FSS Harness Eng
12d	Assign Wires to MCAD Bundles	12c	2.0	05/09/06	05/11/06	MCAD Support, OEM/FSS Harness Eng
12e	Design Subharnesses in 3-D	12d	7.0	05/11/06	05/18/06	MCAD Support, OEM/FSS Harness Eng
12f	Apply OVM to Max Complexity Harness (MCAD)	12e	14.0	05/18/06	06/01/06	MCAD Support, OEM/FSS Harness Eng
12g	Generate Wirelist/Export Harness Topology Files Individually 3-D -> Tlayout	12f	7.0	06/01/06	06/08/06	MCAD Support, OEM/FSS Harness Eng
12h	Check In 3-D Harness Models to Diagram Database	12g	1.0	06/08/06	06/09/06	MCAD Support, OEM/FSS Harness Eng
13	**2D Layout Reconciliation <UPV2 Start> - <UPV2 Start + 8 Weeks>**		**56.0**	**06/09/06**	**08/04/06**	
13a	Import Wirelist/Topology Files from 3-D	12h	1.0	06/09/06	06/10/06	OEM/FSS CAE Designer
13b	Reconcile Max Complexity Layouts using 3-D Topology Files	13a	7.0	06/10/06	06/17/06	OEM/FSS CAE Designer, Harness Eng, MCAD Support
13c	Generate Buildable Combinations	13b	14.0	06/17/06	07/01/06	OEM/FSS CAE Designer, Harness Eng,MCAD Support
13d	Design Rule Checks (DRCs) Completed & Design Updated Accordingly	13c	14.0	07/01/06	07/15/06	
13f	Generate .hdf Files in Tlayout for all Harnesses	13d	14.0	07/15/06	07/29/06	OEM/FSS CAE Designer
13g	Transfer .hdf Files to Ford	13f	0.0	07/29/06	07/29/06	OEM/FSS CAE Designer
13h	UBOM Update	13g	2.0	07/29/06	07/31/06	OEM/FSS Harness Designer
13i	Create Connector Table for Faceview Generation		2.0	07/31/06	08/02/06	OEM/FSS CAE Designer
14	**Physical Electrical Diagram Generation <UPV2 Start + 8 Weeks> - <UPV2 Start + 12 Weeks>**		**28.0**	**08/04/06**	**09/01/06**	
14a	Generate Physical Electrical Diagrams Using Current C3P Tools	13i	2.0	08/04/06	08/06/06	OEM/FSS CAE Designer

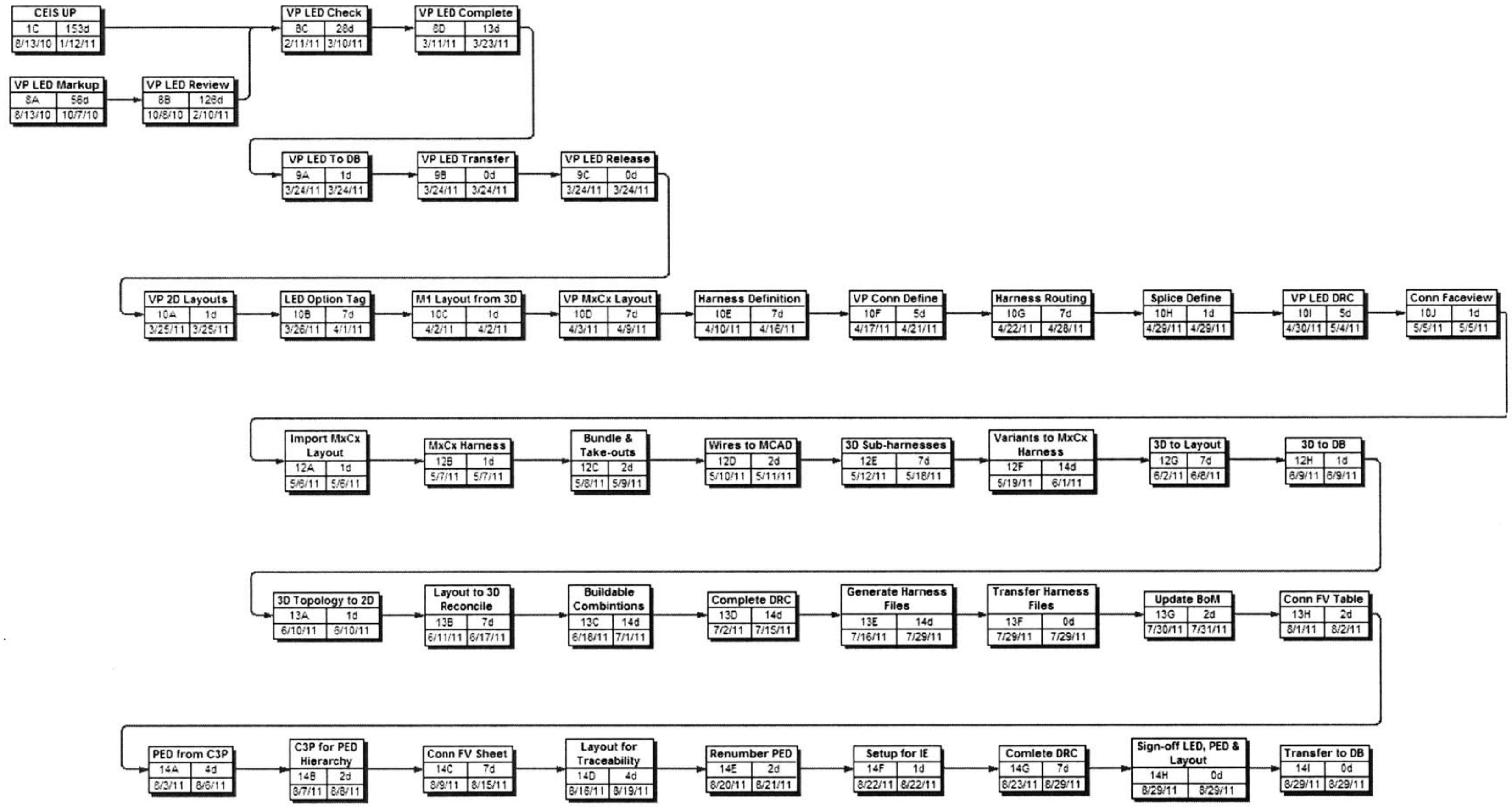
14b	Create Top Level Physical Electrical Diagrams Sets Using Current C3P Tools	14a	2.0	08/06/06	08/08/06	OEM/FSS CAE Designer
14c	Generate Connector Faceview Electrical Diagram Sheets	14b	7.0	08/08/06	08/15/06	OEM/FSS CAE Designer
14d	Manually Insert Parent Layout Number for Traceability	14c	4.0	08/15/06	08/19/06	OEM/FSS CAE Designer
14e	Renumber Physical Electrical Diagrams	14d	2.0	08/19/06	08/21/06	OEM/FSS CAE Designer
14f	Setup for Integrated Electrical	14e	1.0	08/21/06	08/22/06	OEM CAE, OEM EE Systems Engr
14g	Design Rule Checks (DRCs) Completed & Design Updated Accordingly	14f	7.0	08/22/06	08/29/06	
14h	Sign-off Procedure to Transfer Logicals, Physicals and Buildable Layouts to Ford	14g	0.0	08/29/06	08/29/06	
14i	Check In Logicals, Layout(s) & Physical Electrical Diagrams to Diagram Database	14h	0.0	08/29/06	08/29/06	OEM/FSS CAE Designer
15	**Perform CAE Analyses for Design Verification <UPV1 End> - <UPV2 End>**		**90.0**	**06/09/06**	**09/07/06**	
15a	Perform CAE for SDS Requirements Verification Using Initial Physical Electrical Diagrams	11h	90.0	06/09/06	09/07/06	OEM CAE Apps Engr, OEM/FSS CAE Engr
15b	Perform Standard Analyses Set Per CAE Plan Using Initial Physical Electrical Diagrams	15a	90.0	06/09/06	09/07/06	OEM CAE Apps Engr, OEM/FSS CAE Engr
15c	Perform / Update CAE Analyses Using the Final Physical Electrical Diagrams Set <UPV2 End>	15a, 15b, 14i, 6a, 6b	90.0	06/09/06	09/07/06	OEM CAE Apps Engr, OEM/FSS CAE Engr
16	**C3P Harness Release Process <UPV2 End> - <FDJ>**		**90.0**	**09/07/06**	**12/06/06**	**OEM/FSS CAE Designer**
16a	Release of CS Level Electrical Diagram in WERS/LCM Approval	15c	60.0	09/07/06	11/06/06	OEM EE Systems Eng, OEM CAE Apps
16b	Release of Agreed Upon Buildable Layouts	16a	60.0	09/07/06	11/06/06	
16c	Release of all 3-D Wire Harness Packages	16b	30.0	11/06/06	12/06/06	
16d	Release of all Harness Manufacturing Drawings	16c	30.0	11/06/06	12/06/06	
16e	Repeat any & all steps necessary to capture latest design for EC, LS & J1	16d	0.0	12/06/06	12/06/06	

Appendix B PERT Charts for CMP Analysis – Chart 1

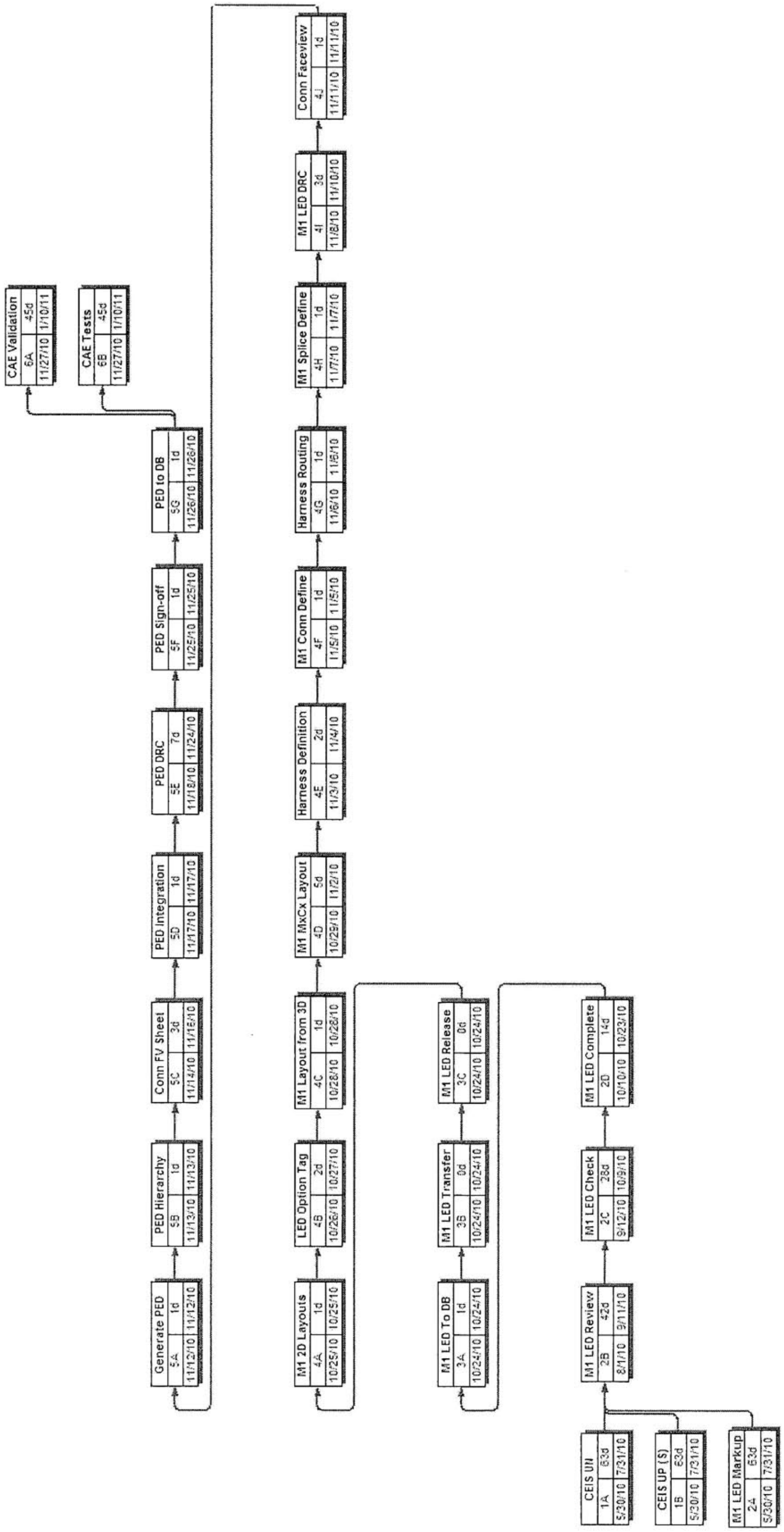


Appendix C

PERT Charts for CMP Analysis – Chart 2



Appendix D PERT Charts for CMP Analysis – Chart 3



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