Systematic Approach for Safety Development Process

by

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

1. Abstract

Thesis work provides a systematic approach for structuring safety development process with respect to vehicle program timing and objectives.

The primary objective of the thesis work is to develop an adaptive crash safety development procedure, which can be customized for a specific vehicle program application. The goal of the developed process is to allow safety teams to effectively deliver vehicle program design targets. The thesis work will primarily focus on the truck safety development work.

In this work, author addressed two key factors of the safety development process: timing and complexity. In conjunction with the main focus, the third aspect of the work describes how to align the vehicle program deliverables with the use of Design Structure Matrix (DSM). The fourth and last portion of procedure, talks about establishing the development gateways and directions for selecting appropriate tools to accomplish the deliverables. A special attention was given to understanding the complexity, during the process of the thesis, a tool: Safety Toolkit was developed. Safety Toolkit helps determine the complexity level of the design in relations to number of parts and requirements. The developed Safety Toolkit can help design engineers to determine design at component level, whereas management can utilize it to estimate the magnitude of their decision with respect to design change.

The new safety design approach will assist vehicle program safety team in accurately defining development effort and assessing the progress of the work. In addition, it will assist new team members in learning the safety development process. Management can utilize the developed tools as an additional indicator to estimate development status, and assess complexity due to unplanned changes in the vehicle program.

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2. Acknowledgement

I would like to convey my sincere appreciation to Dr. Dan Whitney, for all his support, guidance and teaching. The relationship with Dr. Whitney through the course of the thesis work remained very open and honest, which was critical to the planning and completion of this work. During my entire tenure at MIT, Dr. Whitney was very accommodating in listening to my comments, and then provided me with the valuable feedbacks. Initially, in the thesis work I was open to explore my interest in a loosely defined space, however, continuous dialogue with Dr. Whitney helped me focus on a specific area of product development. The weekly follow-ups directed me toward different aspects of the issue, which broadened my thought process, and refined the thesis objectives. Since, I completed this work away from the MIT Campus, it took an extensive effort in coordinating and conducting the meetings. However, I'm thankful to Dr. Whitney, who's patience and experience helped me overcome the difficulties introduce by distance.

Dr. Priya Prasad's support and vision was essential in the selection of the thesis topic. Dr. Prasad's involvement enabled me to utilize his leadership qualities and expertise in designing the thesis work, which maximized the benefit to Ford Motor Company. I thank Dr. Prasad for finding a time to consult me on the thesis work, and defining a concise direction for thesis.

Dr. James Cheng's eagerness to make difference at every level of the organization, and his desire to find innovative solutions to the issues of product development provided me with lots of incentive to work on this topic. Dr. Cheng recognized the need for a structured solution for safety development, which provided me a lot of encouragement for this work. I would like to thank Dr. Cheng for all this support and trust.

This acknowledgement would be incomplete without mentioning the support of my colleagues: Jeff Laya, Jeff Vinton and Kris Warman. And, special thanks to Dr. Phil Przybylo for his coaching and proofreading the thesis.

Contribution of my family during the entire process is immeasurable. Their support and desire to see me excel, provided me with the much-needed adrenalin to take upon this challenge, and accomplish it.

Thank you all

3. Introduction

This work takes a systems approach to the solution of a complex system problem through a holistic view of the safety development process in the Ford Motor Co. The thesis work is framed primarily around the principles and knowledge acquired in Product Development, Systems Engineering and Systems Architecture courses. Beside the mentioned disciplines, completion of this work required extensive knowledge in working principles of the various safety systems, and their influence on the various mechanical and electrical systems of the vehicle. The objectives of this thesis are defined in support of the corporate leadership strategy of the Ford Motor Company.

Designing a safety system for a vehicle involves engineering a highly complex and technical safety system. An automotive safety system is represented by several mechanical, chemical and electrical sub-systems. Mutual interaction of components and sub-systems of the safety system results in generating positive work to protect vehicle's occupant during a crash event. The goal of a vehicle safety system is to meet various competing and non-competing requirements. A generic safety system consists of various dedicated components and common components. The dedicated components are designed to meet objectives of a specific requirement. And, common components are designed for meeting multiple requirements. A well-balanced safety system can effectively protect occupants in a wide array of impact modes. The program safety team is assigned to deliver a safety system, which meets the vehicle program objectives. Due to the numerous design constraints, safety teams are constantly challenged to obtain the desirable performance in a stringent design environment.

Developing a generic process for designing of a complex system results in a vaguely and/or complicated procedure. Often such process are not implemented or completely followed in designing the complex system. In to order to develop a procedure for designing a complex system, in this case safety system, author designed an interactive procedure. An interactive procedure constantly requires action from the user, which in turn customizes the procedure for a specific application, and eliminates the unnecessary steps. Author used his past experience in automotive technology and knowledge of worldwide safety regulations, in conjunction with the newly acquired skills in system engineering and product development to develop the new interactive procedure. The resolutions of issues of designing a complex system are performed through unique tools, which are developed based on the following popular engineering tools: DSM, QFD and Design Verification.

The goals of this procedure are to identify all the design interactions, optimize design effort and reduce resources waste. The proposed approach forces safety engineers to think and design on a system level. This procedure helps safety team generates vehicle program objectives based on the system level requirements. The procedure at first step provides the sense of program timing and deliverables. The second step guides to establishing component level targets based on the system level objectives. The third step optimizes the deliverables for an efficient execution of the vehicle program. The fourth and final steps, provides direction to establish safety gateways, to protect vehicle program for high-risk decisions. Also, in this step, supportive tools are defined, which can help accomplish the individual deliverables. The new design approach should help safety teams in clearly defining program objectives, estimate development effort and follow product development milestones. All these factors have strong implications to a successful execution of product launch.

This work can potentially help management in resource allocation, budget planning and estimation of potential risk associated with the safety deliverables for a specific vehicle program.

4. Historical Background

As the public becomes increasingly aware towards the need of a safer vehicle, automobile manufacturers are driven to stringent requirements to deliver safe products; so as to limit injuries to people. Therefore, a product's quality is now no longer measured solely in terms of aesthetic, comfort, and durability but increasingly in terms of its mitigating features. The safety of the vehicle has become the major factor for driving the design of new vehicles. Innovative safety concepts are continuously sought after and evolved by safety engineers to forestall crash (crash avoidance design concepts), reduce injury when crash does occur (vehicle crashworthiness), and to protect occupants and pedestrians from flames and other hazards after crash (post crash protection design concepts). The later paragraphs provide a brief overview of safety evolution in automobile and predict the future trends in automotive safety.

4.1. Evolution of Safety Regulation

French Punhard Company first introduced a distinctly motorized vehicle, referred to in U.S. as the "automobile", in 1894. However, these vehicles were used to demonstrate the token of wealth and privileges, rather than need. In the early twentieth century Henry Ford's mass production revolution transformed the early image into an affordable venture. The "automobile" enthusiastically embraced by masses, since it fitted very well into the highly mobile American culture. Explosive adoption of the automobile, gave little time for supportive infrastructure considerations. The automobiles shared the street with carriages, however over-crowdedness of the street and beleaguered users of the roads, pushed the need for the traffic management. Initially, no consideration was given to safety of the road system.

In the years leading up to 1920s, auto safety advocates were mostly concerned with road construction and maintenance. The automotive industry together with other safety advocates urged the Federal Government to take over from the states, the construction, maintenance, and regulation of the road system.

There was an increased concern for auto safety after 1920, because of the increasing number of auto related fatal accidents. New trend in fatality lead to organization of the first National Conference on Street and Highway Safety. The conference resulted in initiating the groundwork for the uniform motor vehicle laws. However, the pervading thinking then was that a car under normal usage does not cause an accident but the bad driving or a careless driver does. This belief guided to a campaign for increased driver education.

A concentrated safety advocacy group, mostly among the medical profession, related occupant's injury patterns to a specific vehicle designs. This probably was the beginning of recognition that automobiles may not be inherently safe products after all, but by design, may have some attributes of being injurious to users. Eventually in 50's, the new understandings of the mechanics of injury causation in the automotive accidents initiated the hearings and introduce auto safety legislation in the Congress.

Automotive design philosophy has progressed from the initial total belief that automobiles are inherently safe products and therefore, cannot by themselves cause injury, through a token recognition of their culpability in injury causation to a formal acceptance that safety designs are important attributes to auto product quality through injury mitigation. In 1967, after years of legislative hearings and publications, the Department of Transportation enacted the Highway Safety Act and the National Traffic and Motor Vehicle Safety Act (MVSS). This legislation included regulations for accident prevention, injury protection, post accident protection, consumer information, and others intended to protect people and improve vehicle safety.

Today, safety regulations are the initial means for developing a safe vehicle. The codes of the safety regulations are expanded to address the requirement of a component to full-system. In the US, safety regulations are defined and enforced by the National Highway and Transportation Safety Agency (NHTSA). All the vehicle sold in the US, which has a capacity to carry passenger and within a certain weight limit, are required to meet all the applicable safety regulations codes. These codes are listed under the Federal Motor Vehicle Safety Standards (FMVSS). Similar to FMVSS, the European countries have vehicle safety standards, which are called ECE Standards. Automotive manufacturers are subject to meeting the ECE Standards for sale of their product. Other major automotive markets: Japan, Australia and South America adapted the US or European safety standards. Demonstration of compliance to safety standards is performed by satisfying the requirements of a rigidly defined testing procedure.

The system level safety regulation testing procedures were developed after years of research. Scientist used the field data of automotive accidents, driver behavior and available safety technology to design the regulatory testing procedures. These testing procedures derived the need for the instrumentation, data acquisition and data processing procedures to evaluate the injury mechanism. In order to assess the occupant injury severity, crash dummies were developed. Crash dummies has the capacity to collect occupant injury related responses, through the integrated instrumentation systems. Development of the crash dummies involved in simulating a human-like features and properties. It took years of human and cadaver testing to accumulate the critical properties to devise a biofidelic dummy. Crash dummies have evolved in time, and recent dummies are classified in size, weight and application. Also, there are several types of dummies for the similar purpose. For example, US regulation for side impact uses SID dummy for injury measurements, whereas European regulation requires use of EuroSID-1. There are other dummies for the side impact application, which are used for the research purposes.

4.2. Safer Design

The history of the early automotive design was based initially on a philosophy that emphasized styling rather than safety function. At that early period, vehicle power, speed, size, and even psychological factors came to serve as symbols of qualities of the vehicle. The introduction of the safety regulation and consumer awareness, motivated the automotive manufacturer to continuously implement safety innovations in the vehicle design. Several innovative safety features were evolved in times from different industries or inventions, and find it ways into the vehicle design. For example: airbag, seat belt, energy absorbing materials, safety cage, etc. Influenced by its environment, vehicle quality has become intertwined with synonymous to vehicle safety, style, durability, and comfort. Today's auto companies advertise safety gadgets and features in new vehicles more readily than bodily appearances.

Current practices of designing passenger cars and trucks are similar to early days, where vehicle development started in the design (essentially, styling) department. However, safety has become the major factor driving the design of new vehicles. Unfortunately, there are conflicting constraints satisfactions in trying to meet both quality requirements. Designers and Safety Engineers are each continually contesting for priority of each role. However, as the public becomes increasingly aware of the huge cost of auto-related injury, greater demands and emphasis are now being placed on vehicle safety. Indeed, there is now a paradigm shift from a pure aesthetic vehicle design to a safe design. Yet, styling, safety and other factors need to blend together to produce a total quality vehicle.

4.3. Current & Future Safety Trends

In the last twenty years, automobile redefined the means of the vehicle in our lifestyle. It plays a unique role in an individual's life, based on the person's needs. With this need, consumers expect their vehicles to not only satisfy their needs, but also do it in a safe manner. In the early 90's consumer demand for assessing the safety of a vehicle, which lead to development of the several public domain testing procedures. Based on the testing procedure, a rating system was defined, to help consumer interpret the complex performance metrics of the test. Today, the widely known public domain safety ratings are:

- NCAP and LINCAP, front and side testing procedure, develop by NHTSA. The performance is rating is based on the number of stars, highest rating: five-star.
- IIHS, front offset procedure, developed by the Insurance Institute for Highway Safety (IIHS).
- Euro-NCAP, front and side procedure by the European Authority. The performance is based on the point system.

Safety regulations and counter measure designs will continue to evolve as the Government tries to cut down on the huge costs of auto related accidents and auto companies feel the pinch of product liability. One does not need to be clairvoyant with respect to future safety demands in the auto industry. Clues as to the safety trends of the future may be found in the research programs. For example: NHTSA's latest short-term research mission is stated as follows: "in the next five-year period NHTSA will continue research to increase the understanding of system performance levels for collision avoidance (CA) products and systems". Despite this short-term goal statement, it is conceivable to forecast that research activities will be spread out in the areas of: Environment, Crash Avoidance, Crashworthiness, Biomechanics and Trauma.

The future trends in the safety technology can be divided into three categories: crash avoiding, crash enablers, and post crash technology. Below is the glimpse of the future safety technologies, which will be soon (if not already) implemented in the vehicle:

Crash Avoiding Technologies

- Navigation Systems
- Drowsy Driver Warning Systems
- Crash Avoidance Systems
- Intelligent Cruise Control
- Blind Spot Detection System
- Collision Avoidance Breaking
- Lane Guidance
- Intelligent Warning System

Crash Enablers

- Vehicle Compatibility
- Dynamic Restraints System
- Occupant Identification System
- Adaptive Materials

Post- Crash Technologies

- Advance Emergency Request System
- Crash Notification System

Implementation of these technologies will revolutionize the safety perception of a vehicle. It is forecasted to significantly reduce, both the traumatic and minor injuries due to automotive crashes.

In conclusion, safety design consideration in the automotive industry has evolved from a miniature status in vehicle quality definition to a major factor that shapes the design of new vehicles. Innovative safety concepts are not only as of necessity, evolved to meet safety regulations, but also to fit into the new increasing consumer definition of total vehicle quality. For any automotive product to survive, and indeed thrive in the fierce competitive market environment, style and safety design attributes must be blended to produce a total vehicle quality.

5. Safety Development Process

Designing a safe car for its customer has always been the primary objective of every vehicle program at the Ford Motor Company. In order to insure that safety is considered at every design level of vehicle, several measures are placed at the various stages of the design process. Every component to system engineer, supplier, and vehicle program management is responsible for delivering the well-defined safety targets.

However, before discussing about the safety at Ford Motor Company, a brief look at the fundamentals of the product development and Ford's product development process (FPDS). The remaining chapters relate to the safety development, and describe current practices, motivation for change and propose changes to safety development process.

5.1. Generic Product Development Process

A successful product development and implementation depends on the effective execution of the product development process. Product development process establishes discipline in development work. A well-defined product development process provides step-by-step coordinated process for program management, engineers, and suppliers. In a mass production set-up, a disciplined development process allows organizations to control quality, timing and cost.

Current market environment and economical benefits compel product development process to be a *Front-End* process. In a front-end process, high-level product related decisions are skewed towards the initial stage of the development process. Product concept is established early in the design process and design iterations are streamlined for lesser changes in the late stages of development. In general, a front-end development process is distributed into five distinct stages, as shown in Figure 5.2. The five stages of development process are: concept, system design, detail design, verification and production.

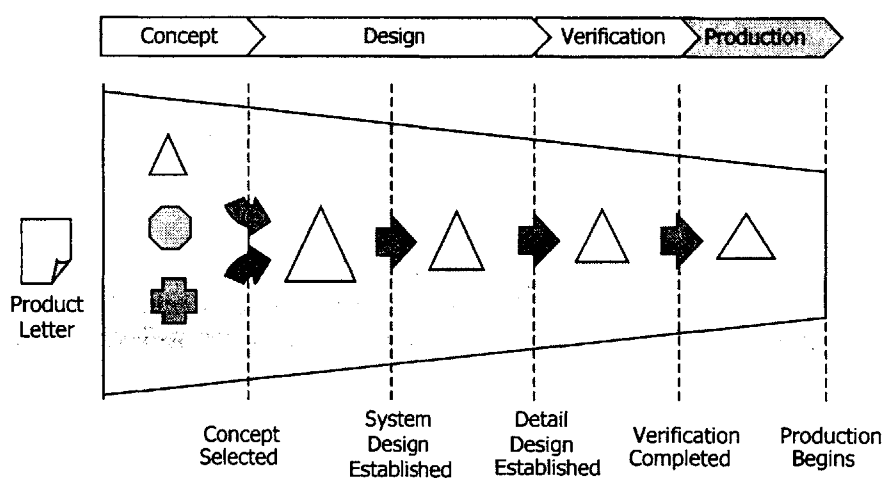


Figure 5.2

Leading to the concept stage, product development team receives product letter, which is prepared by the marketing, planning and strategy groups. The product letter specifies details of the product goals, budget and timing.

In the concept stage product team establishes the conceptual design based on the product goals. The concept stage involves in transforming customer needs into product objectives, competitive benchmarking, resource estimation, concept design selection and design target specifications. The concept design is determined through a series of iterative process of design selection. The selection procedure is based on the feasibility of technology, manufacturability and business case.

Design evolves from the concept stage into a product sections in the system-level design stage. In system-level design stage product design strategy and targets are defined. The established system target specifications are cascaded to component level. The component target specifications are specified during the detailed design stage. Design verification stage is followed by the design stages. Component to system level design is verified through analytical tools and/or testing procedures. At the end of the verification stage minor tunings to product design are completed, and product design is ready for pilot manufacturing.

During the production stage intended product design is tried-out for the production system. Production tooling, fixtures and strategy are verified and minor manufacturing issues are resolved. At the end of the production stage, final product design is launched and production volume is ready for ramp up to intended production level.

5.2. FPDS

In mid 90's Ford Motor Company implemented new product development process, called Ford Product Development System (FPDS). The need for the new development process was driven by the competitiveness in market and rising product development cost. The FPDS was developed based on the front-end product development process. The new product development strategy allowed the vehicle program with major changes to reduce its development effort by ~30%. The objectives of the FPDS are to enable product organization to achieve their goals, work as a team, and reduce waste during the product developments process.

The product development stages of the FPDS are distributed into program milestones. A vehicle program going through a development process is required to accomplish deliverables assigned to specific milestone. Major FPDS deliverables with respect to the program milestones are shown in figure 5.3.

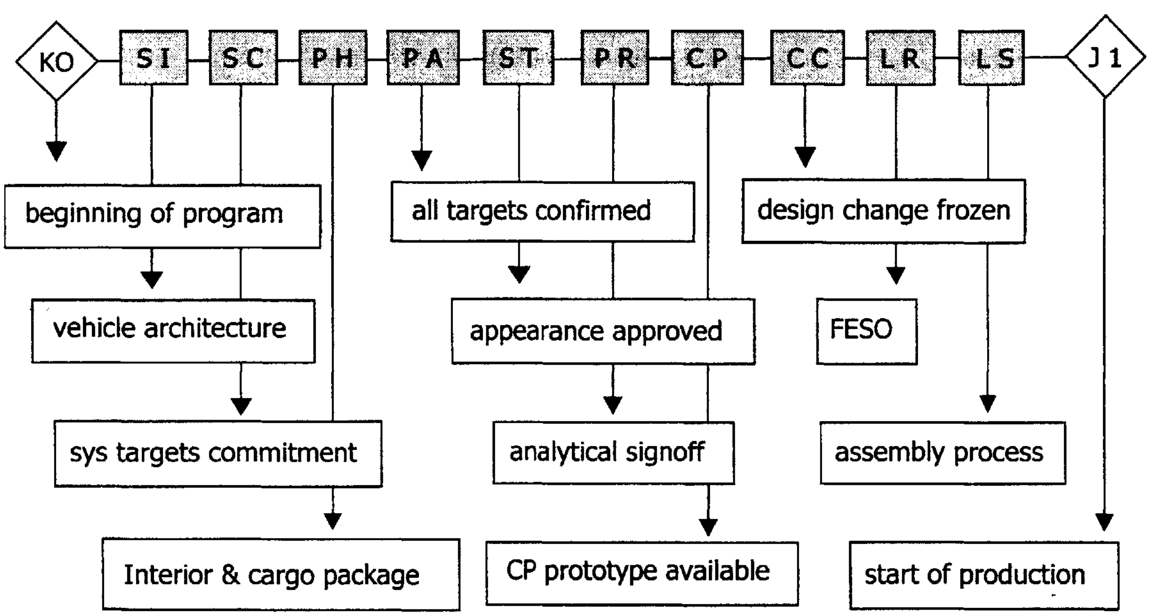


Figure 5.3

The time durations between the milestones are determined by the vehicle program complexity level. Vehicle program complexity is based on its level of design changes, and classified between several levels. These levels are called scalability level of the vehicle program. A higher scalability level of the vehicle program indicates drastic design changes, and redesigning of the major systems. A vehicle program with lower scalability level has minor design changes, for example: change in trim color or addition of minor convenience features. Scalability level of a vehicle program is established based on the company's product strategy.

Implementation of the FPDS played a key role in support of the enterprise's corporate strategy. The FPDS goals were defined based on the correlation with the corporate strategy. These goals has direct implications on:

- Quality
- Cost
- Speed
- Employee Pride

5.3. Current Practices in Safety

The current Ford Motor Company organizational structure shows several safety organizations. Product design associated safety organizations are responsible for delivering safety targets for vehicle program, developing advance safety technologies and supporting non-safety product teams. Safety research groups are involved in identifying future trends in the safety technologies, developing solution to future consumer needs related to safety. In addition to the two safety engineering organization, Ford has an administrative branch of safety. The role of the safety administrative organization is to support product teams in interpreting and forecasting safety regulations, advocate for safety design, and a formal node of communication about the safety of product with the external sources.

The current generic safety process for vehicle crash development is designed to achieve new vehicle program design targets. The vehicle program specific crash development team customizes the development process based on the number of tasks and their relationships, which are necessary to achieve the design objectives. The current crash development process serves as an effective tool to provide directions to crash development team in accomplishing tasks. The new upcoming federal regulation and public domain testing procedures continually push technology to its limits, and increase the level of complexity in the crash development process. In light of mentioned trends in the automotive industry, the crash safety teams will benefit from a procedure/tool, which will enable them to clearly determine the design direction, and reduce development effort.

The roles of the current crash development team is to achieve safety design targets utilizing CAE tools and testing, provide support to various functional teams in understanding crash safety needs, provide design directions to component engineers with respect to crash performance of the components, and maintain interface with the suppliers.

5.4. Motivation for Change

Ford is considered to be a leader in the vehicle safety. Vehicles manufactured by the Ford Motor Company go through a risk-averse design and validation process to meet stringent internal safety metrics.

Recently announced new federal safety regulation in US, has drastically expanded the list of requirements. The new regulation will take in effect from the September 2006 for the entire fleet. As anticipated and forecasted by the automotive manufacturer's, the new rule includes expanded list of procedures for the frontal impact requirements, and defines future revisions. The future revisions to regulation will include further revisions to frontal, side and rear impact modes. Automakers were aware of the level of complexity associated with the new regulations, and invested in the several technologies to meet the requirements.

Beside the new regulation in US, public domain safety evaluations performed by the affiliated agencies are becoming an additional source of information for the consumer. Increasing number of consumer consider safety as their major factor in the purchase of a vehicle. Consumer uses results of the public domain testing procedures to compare the performance of their choices. As the popularity of the public domain evaluations are gaining among the consumer, the associated agencies look for expanding their methods of evaluation.

As mentioned earlier, consumer's need for safety demands a safer vehicle for its occupants, irrespective of their age, size, weight or demographics. Generally, in the past innovative and costly new technologies were introduced in the luxury vehicles. And later, found its widespread use in the other vehicle segments. Growing number of safety conscious buyers lead to definition of safety as a part of product strategy. The new direction attracted the safety conscious buyer, and motivated automakers to implement innovative engineering solutions into every vehicle.

Today's advanced safety technology includes safety system, which can tailor its performance based on its occupant, intelligent warning system and change vehicle behavior based on the driver's input. Although, these new technologies will definitely contribute towards a safer driving environment, it carries a high implementation cost. And today's consumers are not always willing to pay for these added benefits.

In the fiercely competitive market automakers are challenged with designing a vehicle, which satisfies requirement of the new regulation, expanded public domain evaluations and consumer need for safety. These tasks are further complicated with the consideration of raising variable cost, high fixed cost and uncertain market. For example, every 10 new models introduce in the market, only one succeed to be a "hit". Other models are discontinued after a short period, either go through a costly makeover or break-even with the help of rebates.

Survivability in the market is not a strategy for sustainability, hence automakers must generate "hit" products to stay competitive. The product success can be attributed to the three major factors: style, features and price. Price and features are the competing elements of the design. Vehicle program management and engineering team struggle with providing an attractive set of features at a desirable cost. However, this delicate balance of feature-vs-cost requires an efficient product development effort, with the flawless execution in manufacturing.

5.5. Proposed Safety Development Process

The new federal regulation, public domain testing procedures and consumer safety awareness continually pushes current technology to its limits, and increase the level of complexity in the crash development process. The increasing number of tasks and shrinking design solution space requires the crash safety development teams to be effective and efficient. During the safety development process teams are faced with the conflicting design requirements, change in design targets or other related issues. Consequently, teams are required to perform late design changes and/or potentially missing vehicle program development milestones. These situations cost abundance of resources and effort, which has adverse effects on the morale of people, the financial performance of the company and constrains relationships with the suppliers.

In order to produce an efficient engineering solution with the consideration of the new constraints, safety team should adapt a safety system design process, which is:

- aligned with the corporate strategy
- correlates with vehicle program timings and milestones
- empowers safety team to lead the design
- clearly communicates complexity and needs to the management
- forces discipline and stretches to innovate

Although, the mentioned requirements for a safety development process appear logical, the numerous external factors act as emergent properties to distract the team from the desired path.

Some of the external factors are predictable and common between the vehicle programs. For example, changing of the vehicle program goals. It is pre-mature to assume that a vehicle program during the course of its development, will not revise the deliverables. The need for revising the deliverables is driven by the market, corporate strategy and/or product objectives. Timing and magnitude of the change are most critical elements to the safety system development. As the mid-course changes are introduced in the system, safety team re-establishes the design and plans to meet the new challenges. In such circumstances there is a potential to underestimate the effect of changes due to the program timing constraints. The gaps at the design stage surface during the elaborate verification process, forcing the vehicle program to resort for the costly late changes and/or delaying vehicle production timing.

This thesis-work as shown in the framework (figure 5.6) is divided into four different modules of the product development process: timing, relationship between design & requirements, deliverables and integration of first 3 modules in a coherent system. The objective of the timing module is to stress the importance of the timing in the product development process. Product development process of the Ford Motor Company (FPDS), defines the process milestones, and deliverables for each vehicle program. The timing module interprets the vehicle program FPDS deliverables, and defines the safety development deliverables with respect to it. The relationship module establishes the number of interaction required for delivering the vehicle program safety requirements. An interactive relationship tool: *Safety Toolkit* is developed to show the relationships between effected components and design requirements. The deliverable module gives a high-level sense for the flow of work in the development process. This module utilizes DSM to helps optimizes the deliverables for an effective safety development effort. The final module integrates all the modules and provides a complete overview of development effort for a vehicle program.

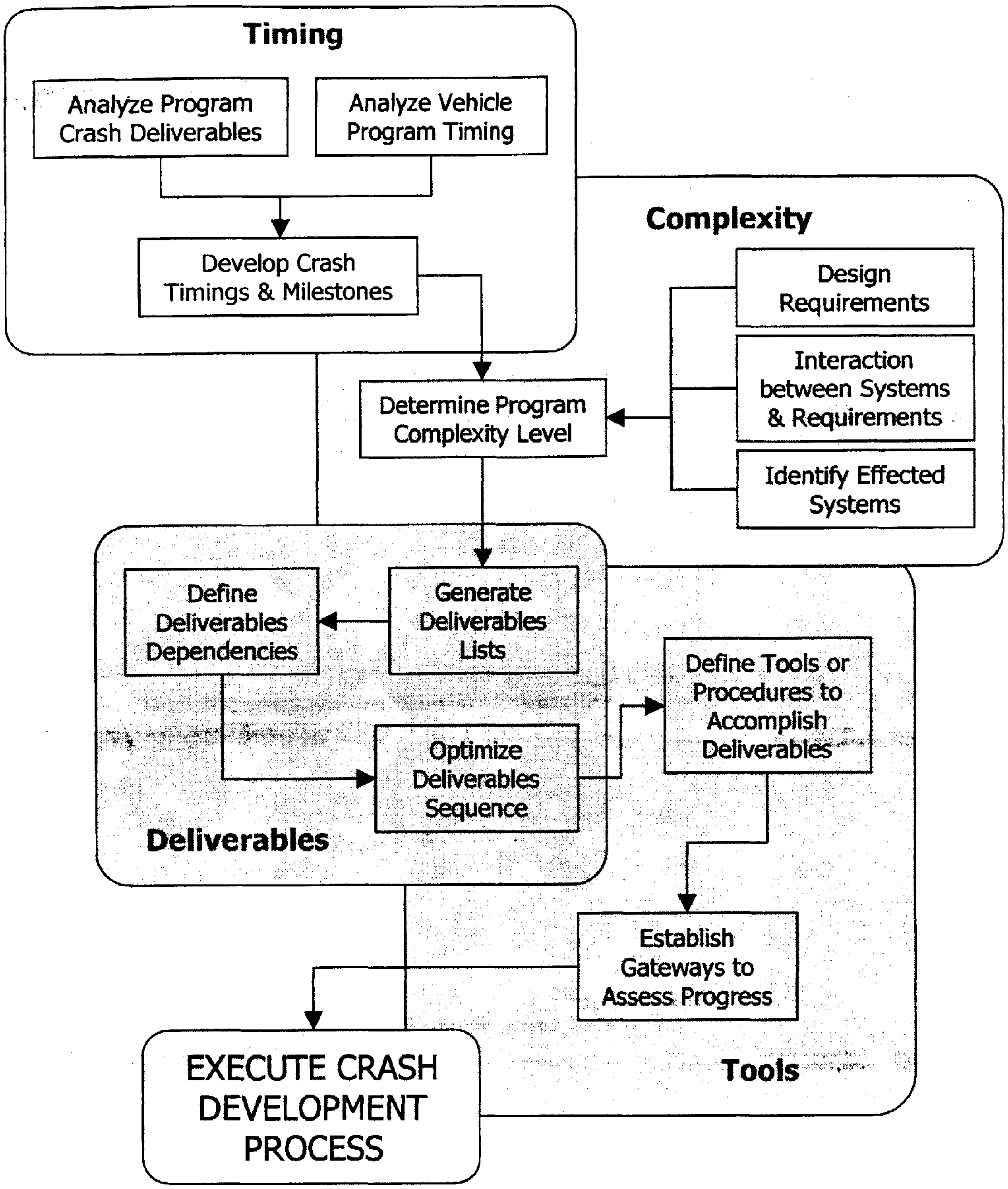


Figure 5.6

The following sub-headings provide a detailed description of each module, and examples of its application in a vehicle program.

5.5.1. Safety Deliverables

As mentioned earlier, every vehicle program development process is derived from the FPDS process. Project management members of the development team are responsible for customizing the development process for the specific program. The customization of the product development process is based on the vehicle program complexity (scalability) level, program timing and product objectives. These factors lead to definition of the deliverables with respect to each program milestones. Once the vehicle program development process is established, the program attribute teams define attribute specific development process.

Safety, being one of the attributes of the vehicle program, drive safety development process from the vehicle FPDS process. The safety deliverables are aligned with the vehicle program milestones, deliverables and safety objectives. The figure 5.5.1.1 shows a generic safety development process with respect to vehicle program milestones.

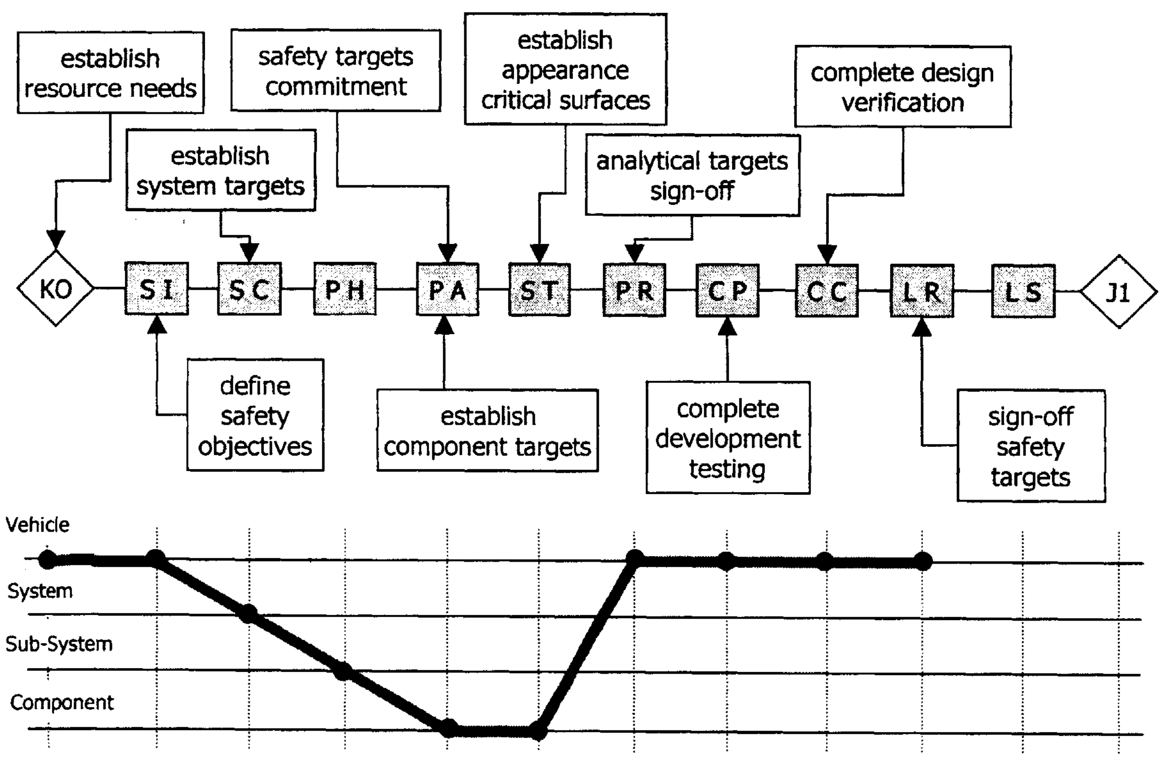


Figure 5.5.1.1.

The generic safety development process illustrated in figure e5.5.1.1 shows that, safety development work starts from the initial stage of the vehicle program, <KO> Kick-off and continues until the <LR> Launch Readiness milestone. The safety development work ramps up after the <SI> Strategic Initiative milestone, where vehicle level targets are specified and vehicle architecture is defined. Also, vehicle program prototype requirements, new technology commitments and high-level design trade-offs are established at this milestone. At the <SC> Strategic Confirmation milestone, system level targets are specified, initial verification plans are developed, supplier selection is finalized and safety team verifies vehicle level safety objectives. After the <SC> safety teams are responsible for leading safety specific design. The Sub-system level targets are specified at the <PH> Proportions and Hardpoints milestone, which are derived from the design iteration studies. <PA> Program Approval milestone serves as a critical junction in the safety development process, safety team commits to all the design targets, which in turn become the final safety objectives of the vehicle program. At <PA> safety team resolves all the major design issues, establishes the safety design specification and establishes the verification plan. The design stage of the safety system is concluded at the <PA> milestone, and product design transitions to the verification stage.

The verification stage begins with the confirmation of the component level targets. Since, most of the components in the safety system are out-sourced to tier 1 supplier, they are generally, responsible for verifying the component level targets. Component level verification and surface critical design are established at the <ST> Surface Transfer milestone. The design verification process continues to <PR> Product Readiness milestone. The intended product design from the component to the vehicle level should be verified, and safety team is responsible for analytically sign-off the vehicle program safety objectives.

In order to better understand the safety system at the various design level, figure 5.5.1.2 shows the decomposition of system.

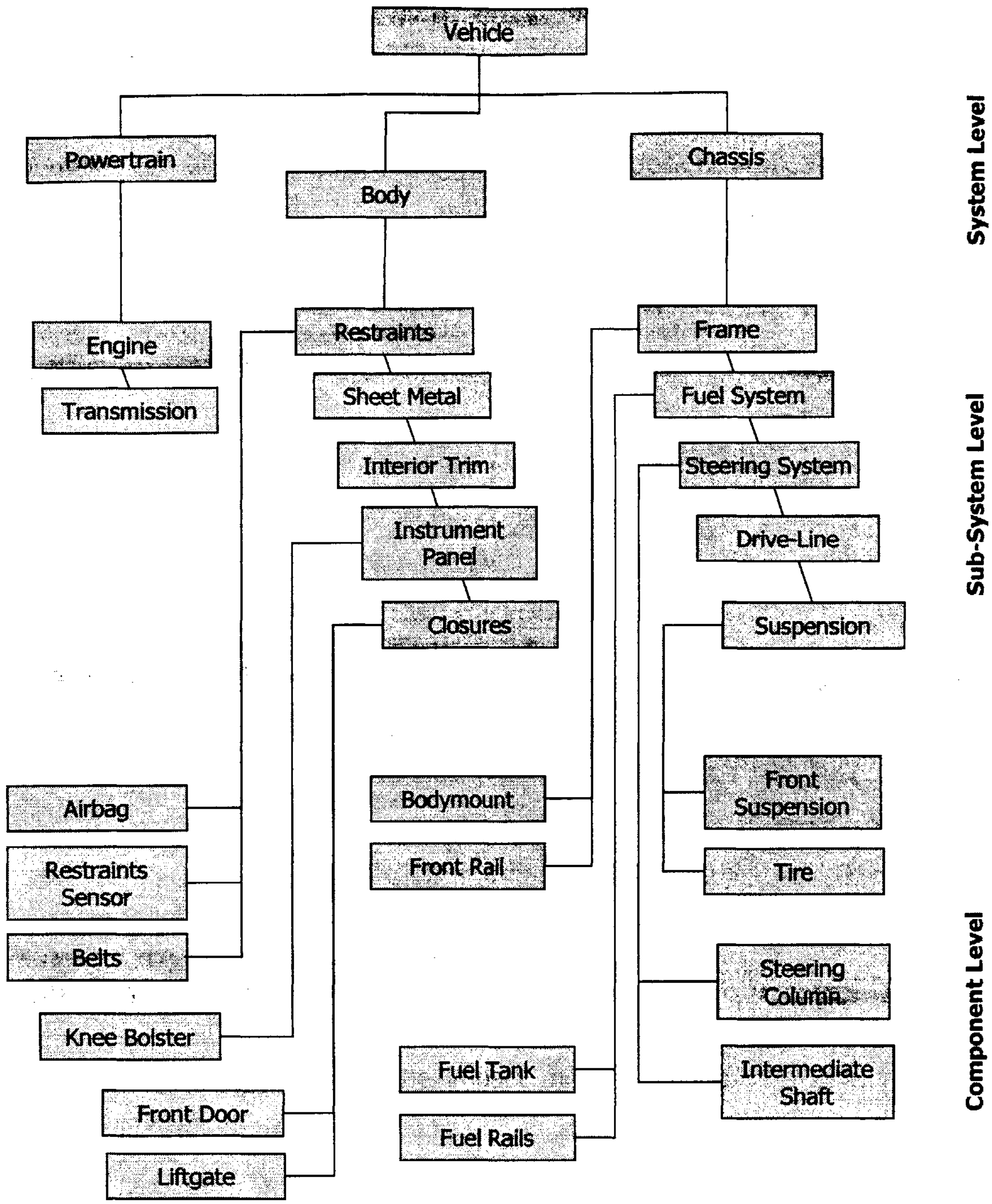


Figure 5.5.1.2

The figure 5.5.1.2 helps understand the design evolution of the safety system from the vehicle to the component level.

Between the <PR> and Confirmation Prototype millstones, safety team performs development testing and begin taking delivery of the confirmation prototypes. The confirmation stage of the safety development process follows by the <CP> milestone. During the confirmation stage, safety team performs vehicle level testing to confirm the product performance objectives. Safety team meets the <CC> Change Cut-off milestone deliverables by completing the confirmation testing, and resolves all the open design issues.

The team sign-off the vehicle program safety objectives at the <LR> Launch Readiness milestone. The completion of the sign-off process is performed by submitting the vehicle program compliance and objective documents to the management. The safety system is ready to be implemented in production. The safety development work begins to ramp-down after the <LR> milestone. Generally, critical members of the team remain part of the vehicle program team to support the pilot production issues.

In the timing module of the proposed thesis, safety development process deliverables for a vehicle program are derived from FPDS process deliverables. The number of safety deliverables for a vehicle program is determined by the complexity level and safety objective of the program. Since, complexity level and safety objectives are unique to each vehicle program, a generic set of safety deliverables were assigned to each FPDS milestone. Some vehicle program might require additional deliverables at a specific milestone. The exceptional deliverables are determined from the level of the development work required to accomplish the objectives.

Overview of common safety deliverables with respect to the FPDS milestones is provided in the table 5.5.2.1.

Milestone		Safety Deliverables
<KO>	Kick-Off	Establish resource need Establish safety program team Assess vehicle program safety goals
<SI>	Strategic Initiative	Develop safety workplan Interpret market safety needs Establish occupant concept design Complete architectures assessment Identify new safety technology Complete competitive benchmark study Establish program safety targets
<SC>	Strategic Confirmation	Complete prototype requirement Establish system level targets Complete design package study Commit to implementation ready new technology
<PH>	Proportions and Hardpoints	Establish critical design hardpoints Establish sub-system level targets
<PA>	Program Approval	Complete performance trade-off study Establish component level targets Commit to safety targets Resolve major design issues
<ST>	Surface Transfer	Complete surface critical design Verify component level targets
<PR>	Product Readiness	Analytically sign-off safety objectives Complete sub-system, system and vehicle level design verification process
<CP>	Conformation Prototype	Complete development vehicle level testing Develop confirmation testing schedule Major/Minor risk assessment
<CC>	Change Control	Complete confirmation testing Resolve minor design issues
<LR>	Launch Readiness	Sign-off safety objectives Complete compliance documentation
<LS>	Launch Sign-off	Support production
<J1>	Job 1	Support in-house compliance testing Document lesson learned
	Post Job 1	Support compliance and public domain tests

Table 5.5.2.1

Definition of the correct safety deliverables with respect to the safety objectives is critical to the vehicle program development. Delay in addressing the key deliverables has potential for adverse effects to program timing and objectives. Safety teams should invest sufficient resources to safety deliverables and progress of its completion through out the vehicle program development process.

5.5.2. System Complexity

5.5.2.1. Assessment of Design Level Complexity

The second area of interest in the safety design process is to assess complexity level of the design. The complexity level of the design in a safety system can be evaluated based on the following factors:

- Number of critical components
- Number of relationships between the critical components
- Number of the interactions between various design teams
- Number of interfaces between attributes
- Number of system objectives/targets
- Cost and Timing

All of these factors play different role in the design process, based on the initial conditions. A deeper understanding of each factor helps in the assessment of a system complexity level. In order to get a better perspective of each factor, these factors are briefly described in the later paragraphs.

In the early design process it is practically impossible to predict the number of the critical components required to achieve the design objectives. There are several factors that can influence the change in the number of critical components. The most common factors are cost objectives, stringent deliverables and change in the design requirements during the design process. Usually, design requirements become more stringent, which leads to increase inter-dependencies between components.

In a design process, some component interactions have minor influence on performance. This balance changes in the case of a design alteration. As the number of components increases, the number of relationships between the critical components grows exponentially. Usually, late changes in the design process immediately identify the number of effected components, but the degree of their dependency is often underestimated. The consequences of such underestimation can lead to costly fixes, and increase product-to-market time. Relationship between the critical components should be established affectively at any stage of the design process. And, every change should be addressed with a well-thought out design process.

In order to meet the vehicle design objectives, multiple safety teams work simultaneously on different modes of impact. It is critical to have well-defined communication channels between teams for continuous exchange of information. Since, number of critical components for various modes of impact are similar, safety teams rely on the common components to achieve the performance objectives. A continuous feedback between these teams should be clearly defined, in order to reach mutual beneficial solutions, in case of performance trade-off.

Not only the safety teams share common components, other vehicle attributes teams (NVH, Durability, Vehicle Dynamics, ...) are faced with the similar challenges. For example, part of safety design strategy is to introduce weak points in structural members to initiate the buckling modes for energy absorption. However, such design strategy is directionally undesirable for the durability. Similar interaction exists between other attributes and safety. The complexity level of these relationships can be further increased due to organizational structure and/or geographical location of teams. In addition, vehicle teams need to consider cost objectives, manufacturing feasibility and program timing. Considering all these challenges at the various levels of development process, it is essential to clearly define vehicle program objectives. These objectives can be represented with a weighted ranking based on the described factors. Such strategy helps design team during the performance trade-off decisions. In case of a design change, it is vehicle program management responsibility to re-establish all the deliverables and timings.

Vehicle program deliverables are defined based on the market needs, regulation and corporate strategy. Vehicle program deliverables should be clearly defined in the early stages of the development process. Over constraining the design due to increase in number of vaguely defined design objectives, stringent requirements and continuously changing deliverables has major influence on the design. These consequences can lead to huge cost and timing penalties. In some cases, the redefinition of the deliverables requires use of advanced technology to accomplish the requirements, which depends on the timing of the new technology readiness. In case of the delay in the new technology implementation, a vehicle program can suffer huge economical setback.

Cost and timing should be re-evaluated at every stage of the product development process. These two factors are critical to vehicle program complexity level. A increase in complexity level is generally proportional to cost and timing.

5.5.2.2. Safety System Performance Targets

During the initial stages of the safety development process, vehicle program management establishes the safety goals. In the design process safety goals are decompose into lower level goals, which are called safety targets. Once the safety targets are established at every level of design, the vehicle program safety team is responsible for delivering those safety targets. In order to achieve a high degree of confidence in meeting the safety targets requires following actions from the safety team:

- Identifying the critical components to safety performance.
- Manage the relationships between the components
- Make performance trade-off decisions between system targets
- Establish component design objectives to meet system performance

In order to effectively deal with the mentioned tasks, a new approach is proposed in the design process. The recommended procedure defines a structured approach for identifying the critical components with respect to each design requirements, components inter-relationships, and area of trade-offs in design.

All of the safety targets can be distributed between the following five modules: frontal impact modes, side impact modes, rear impact modes, head interior impact modes, and roof crush modes. Designing for the impact modes defined in a module are heavily dependent on each other, and often share similar critical components. Considering such relationship, it is to a team's advantage to design for all of the modes in a module simultaneously. However, if several modules dependent on a critical component, then all modules should be considered in establishing component's target. In addition, within a module, a critical component can be required to different sets of conflicting performances. In such conditions, the procedure helps to identify the secondary components. The secondary components help leverage the performance, in case of a conflicting design requirement. In order to better execute the procedure for achieving safety targets, *safety toolkit* has been developed. Safety Toolkit assists in identifying the critical components, secondary components, component inter-relationships, and conflicting requirements.

The need for a *safety toolkit* is warranted due to the interaction at the different levels of design. Performance of dedicated safety components, and other critical components are influenced by the sub-systems. Managing of the relationships at the several design level can be complicated. In order to understand the level of interaction between different design level, figure 5.5.2.1 shows the example of design interactions in the frontal offset test mode. Various sub-systems are interfacing with the components, which results in providing a desirable solution. However, an interaction has equal potential to produce adverse result, if it was not considered in the design process. The *safety toolkit* is designed to account for 3 type of design level interactions: components-to-components, sub-system-to-sub-system and component –to-sub-system.

In addition, the pictures of the several test modes are shown in the appendix. These pictures provide a perceptive of number of design elements contribute to achieve the desirable safety performance.

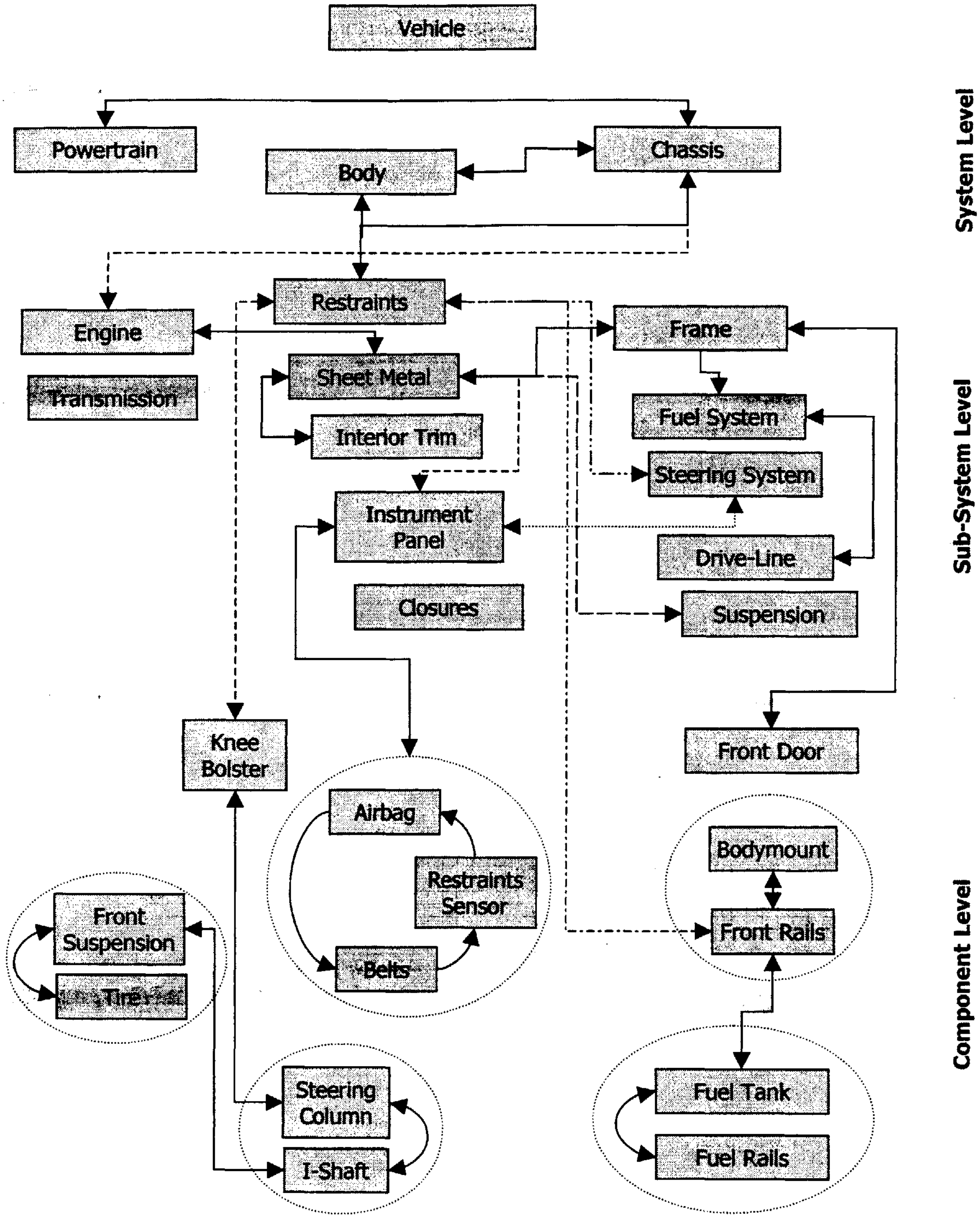

Vehicle
Powertrain
Body
Chassis
Engine
Transmission
Restraints
Sheet Metal
Interior Trim
Frame
Fuel System
Steering System
Instrument Panel
Drive-Line
Closures
Suspension
Knee Bolster
Front Door
Airbag
Restraints Sensor
Belts
Bodymount
Front Rails
Front Suspension
Tire
Steering Column
I-Shaft
Fuel Tank
Fuel Rails
System Level
Sub-System Level
Component Level

Figure 5.5.2.1

5.5.2.3. Safety Toolkit

Safety toolkit is designed to provide design aid to safety team to define the complexity level of the vehicle program. The tool helps determine the number of critical components with respect to each impact modes, components interface with each other, impact modes interaction with respect to a component. The figure 5.5.2.2 shows safety toolkit, and identifies the critical elements of the tool. In order to simplify the delivery of information, all the components and sub-assemblies in the safety toolkit are referred as component.

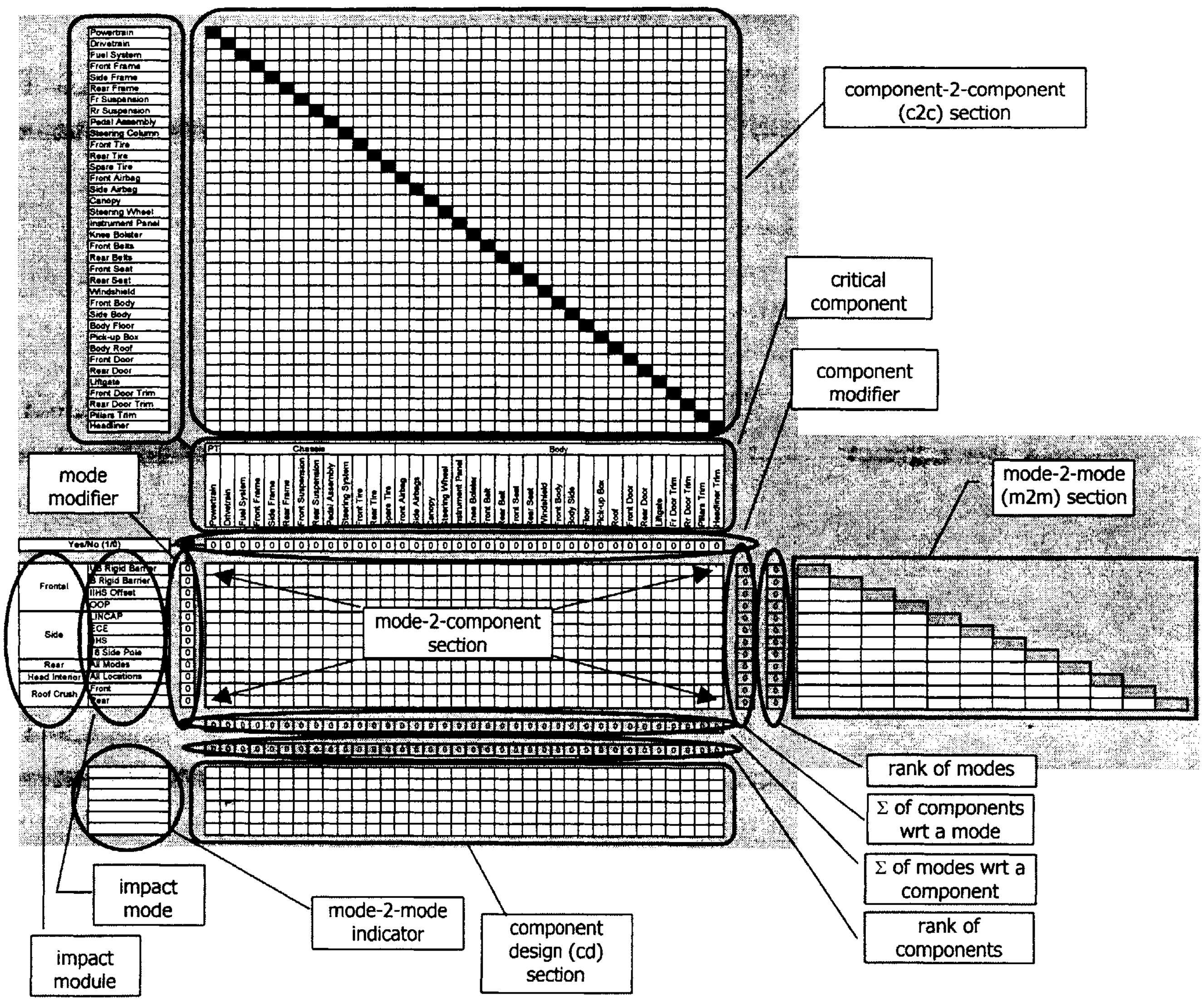


Figure 5.5.2.2

The working logic of the safety toolkit is defined in the figure 5.5.2.3. The yellow color items defined the actions, where user interface is required inform of physical input or thought process. The green color items are performed automatically by safety toolkit. These actins are in results of the user interface in the preceding items

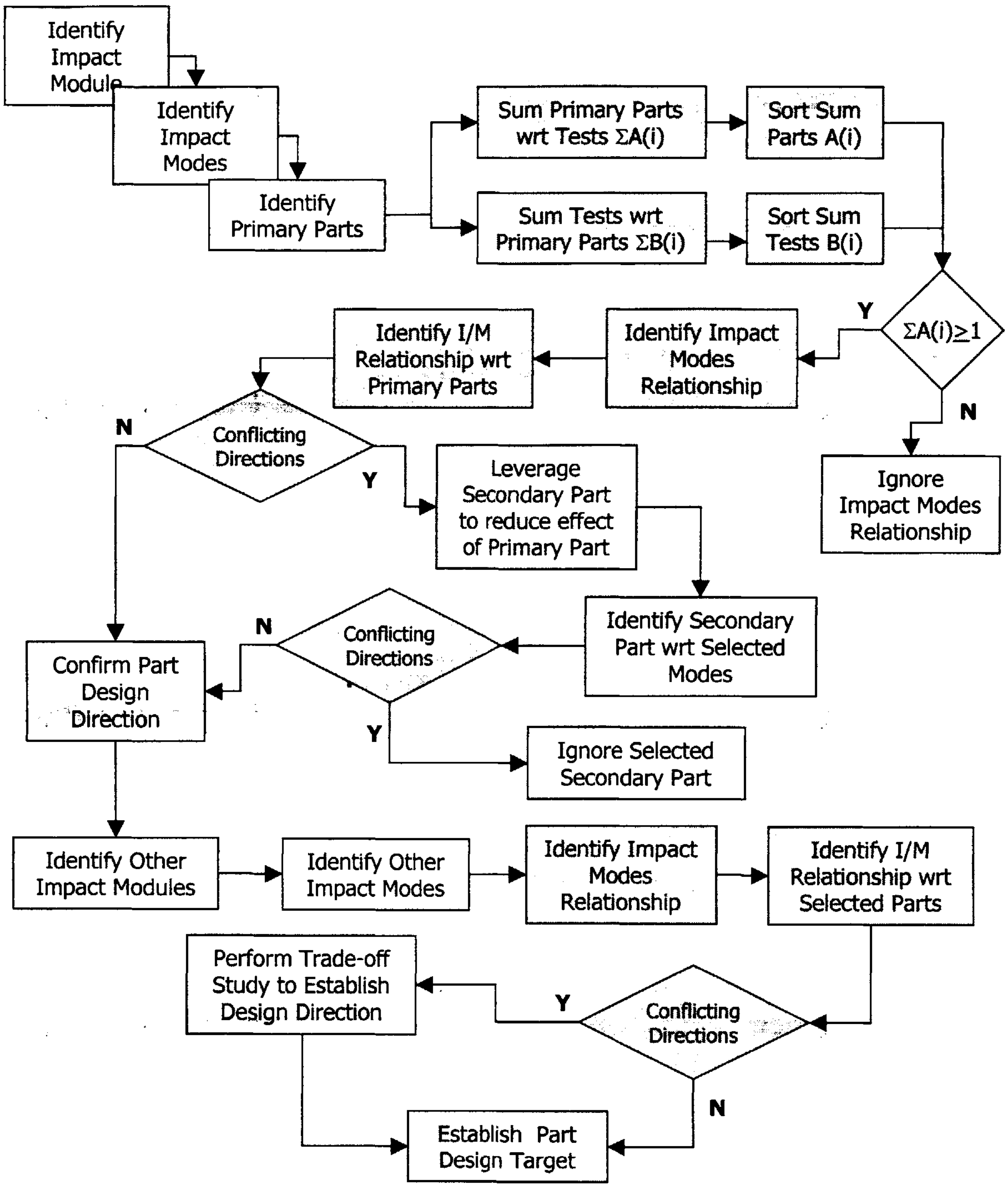


Figure 5.5.2.3

5.5.2.4. Analysis I – Side Impact Analysis

In order to validate effectiveness of the Safety toolkit in the safety design process, the side impact design targets analysis is performed through a step-by-step procedure.

<u>Step 1: Impact Module</u>

The selection of the module is based on the design targets, established for the vehicle program. The design targets are usually relate to the metrics associated with the impact modes. It is recommended to work-on each module individually, selection of a single module is required at this step. The non-gray area of the Safety Toolkit (figure e1.1) shows, where impact module can identified. The figure e1.1 below shows the selection of impact module is highlighted in yellow, it is suggested to shade the area of interest.

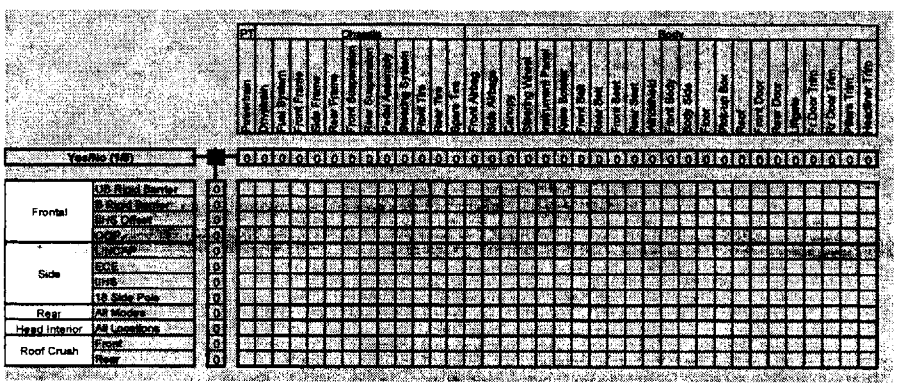


Figure e1.1

In this case, side impact module is selected.

<u>Step 2: Impact Modes</u>

The selections of the impact modes within the previously selected impact module are based on the safety targets. The non-gray area of the Safety Toolkit in figure e1.2 shows the previously selected impact module and associated impact modes of interest. As suggested earlier, highlight the interested impact modes by shading the cells, as shown in figure e1.2.

After impact modes are identified, activate the selected impact modes by changing the mode modifier. Mode modifier *User* should enter "1" in the cells related to impact mode. The modifier cells associated to impact mode are aligned in a column right of the impact mode description.

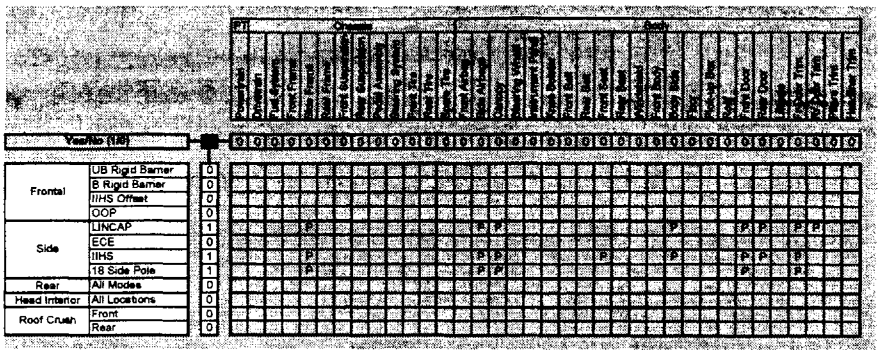


Figure e1.2

In the figure above, team has selected LINCAP, IIHS and 18 Side Pole impact modes in the side module. The ECE impact mode is not the objective of the design, and it not selected. The 3 selected impact modes are activated through *USER* interference by entering modifier "1" in the respective cells as shown in figure e1.2.

Step 3: Parts Relationship

Posting of the impact mode modifier "1" in previous step leads to activation of the primary components for each selected impact modes. The process of determining the primary components is performed by the *Safety Toolkit*, upon the placement of mode modifier its automatically displays the relationships. The primary components of a impact mode are determined by the displaying of letter "P" in the cell. The cell with "P" establishes the relation of component with the impact mode. The Figure e1.3 shows the described relationship. The highlighted rows in the *Safety Toolkit* (figure e1.3) shows the interested cells, and are recommend to be shade the area of interest.

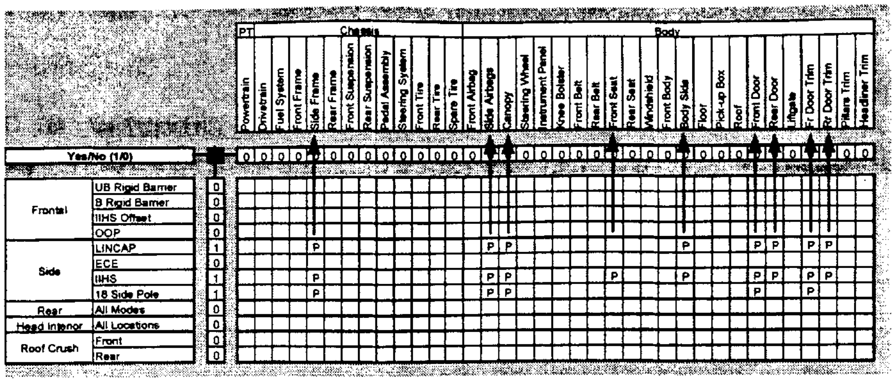


Figure e1.3

In the example above, activation of three impact modes leads to displaying of the primary components for each mode. It can be notice that, all three impact modes are dependent on the similar primary components: Side Frame, Side Airbag, Canopy, Front and Rear Doors. Bodyside, Front and Rear Door Trims, are dependent on the two modes, and Front Seat on the IIHS impact mode.

Step 4: Number of Dependencies

After the determination of primary components relationship with the impact modes, this step identifies the number of primary parts influencing on an impact mode, and impact modes dependency on a primary component. The *Safety Toolkit* calculates the sum of primary components in relation to an impact mode and automatically displays the results in the pink color column (look right), as shown in figure e1.4. Similarly, The summation result of the impact modes with respect to a primary component is automatically displayed in the pink row, below (figure e1.4).

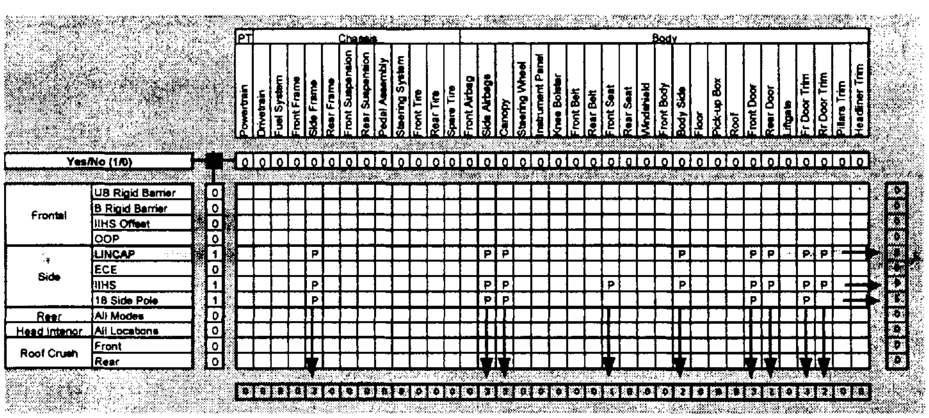


Figure e1.4

In above case, Front Seat has dependency on only one impact mode: IIHS. The Rear Door and Trim are dependent on the LINCAP and IIHS impact modes, the remaining primary components influences all three impact modes.

Respectively, the pink column shows that Side Pole mode is dependent on the five primary components, LINCAP on 8 and IIHS mode on 9 primary components.

<u>Step 5: Sorting of Dependencies</u>

In this step *Safety Toolkit* performs the sorting operation based on the summation of the primary components and impact modes. The results of sorting are automatically displayed in the turquoise color row (figure e1.5) for the primary components, and column automatically displays the results for impact modes. The sorting logic assigns the lowest ranks to the primary components with least number of dependencies to an impact mode. Similar logic is used for sorting the impact modes. The results of components and impact modes sorting will be used in the future steps.

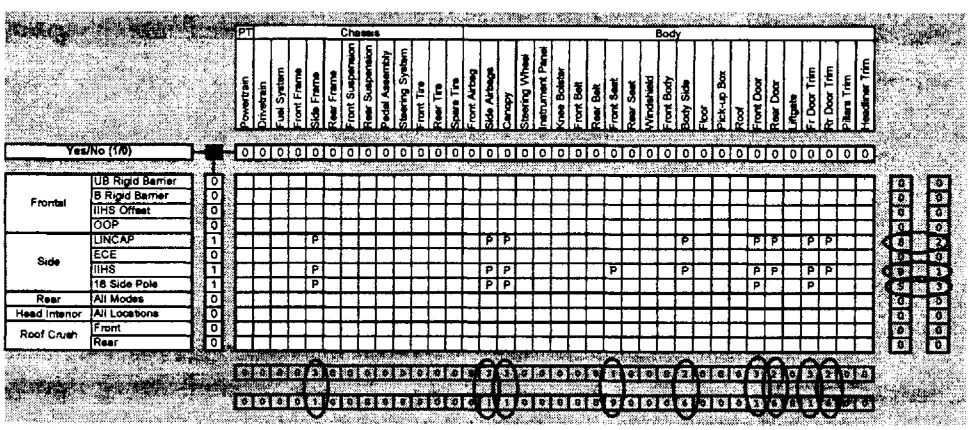


Figure e1.5

Example above shows impact mode IIHS has the most dependencies on primary components and ranks one. And Side Pole rank lowest, due to least number of dependencies. Respectively, Front Seat has the lowest primary component ranking, and then followed by the Rear Door and Trim. The remaining primary components share the same rank, since they have equal number of dependencies.

Step 6: Impact Modes Interaction

The preceding five steps help identify the initial number of the primary components in relation to impact modes. It is imperative to learn about the impact mode relationship with each other. The inter-relationships of impact modes are derived from the impact mode dependency on the primary components. The mode-2-mode section of the *Safety Toolkit* as shown in the figure e1.6, automatically displays the active impact mode relationships by turning-on the cell in orange color. The activated cell reflects the existence of a relationship between two impact modes. Displayed relationship between the impact modes is identified with the designated name (figure e1.6).

In the design process, a primary component has dependencies on the several impact modes. The relationship between the impact modes enables to determine if a design objective of the interested primary component will be sufficient to satisfy the impact mode design requirement. For this reason, significance of relationship is very critical in the design process.

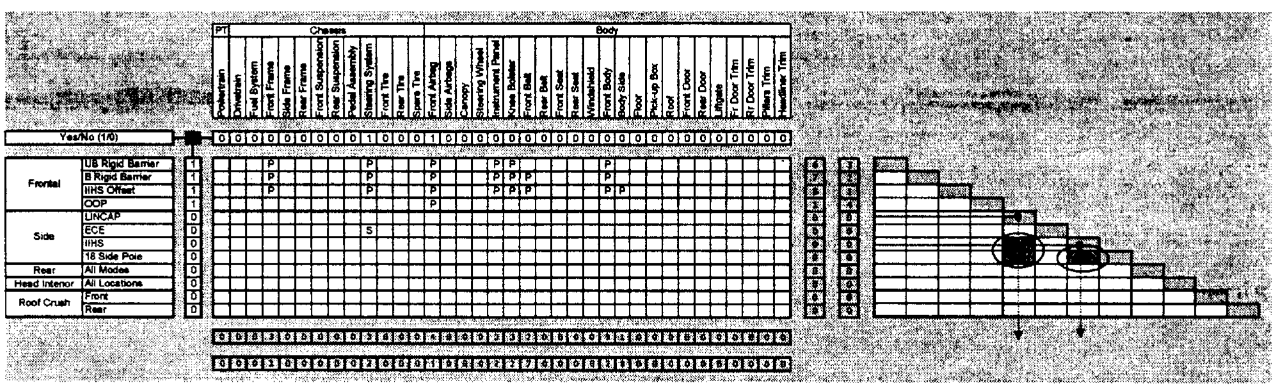


Figure e1.6

In the above case, LINCAP mode has relationship with the IIHS and Side Pole (shown above), and relationships are identified by SS21 and SS31, respectively. The relationship between IIHS and Side Pole modes is displayed as SS33.

Step 7: Primary Component Design Relationships

In this step *Safety Toolkit* automatically displays the primary component design relationships with respect to each impact mode interaction in design component section. The impact mode interactions identified in the previous step are used to display the design relationship for the effected primary components due to this relationship. Since, a primary component performance is critical to the impact mode relationship, it's mutually beneficial to learn about the component relationship to mode interaction. If relationship is displayed by the letter "O", it establishes that primary component design direction is beneficial to both impact modes. However, if a primary component relationship is displayed by the letter "N", it establishes that component has conflicting design direction.

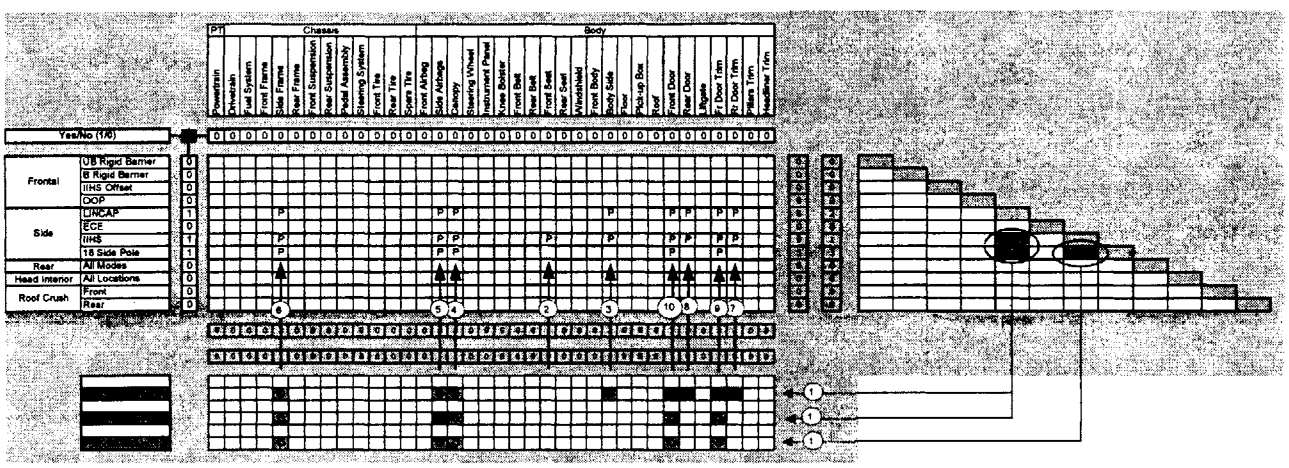


Figure e1.7

In the above example (figure e1.7), we can observe that most of the primary components in the relationship between LINCAP and IIHS (SS21) are positive in design direction. The positive direction is displayed by the letter "O" in the blue cells. This tells us that, design target for the component can be established based on the most critical need between the two modes. And the second mode requirement will be meet, since it is least stringent. The empty cells show that no relationship exists for these components. Also, it is evident from the cased above, that Doors and Door Trims has conflicting design requirements and to be considered for further attention.

The numbers in the blue arrow specify the sequence of design action for primary components. This sequence is derived from the primary component sorting described in the step 5 for all the components with "0" relationship. All the parts with the conflicting relationship are considered in the end.

Step 8: Parts with Conflicting Design Direction

The identified primary components with conflicting relationship might require further attention to balance the performance need. The involvement of the additional components in design can help leverage the performance, these components can be considered as secondary components. Primary component performance can be influenced by several secondary components. Also, the relationship between the primary and secondary parts is unique to each impact mode.

In this step, the identified conflicting primary components are activated. Figure e1.8 shows identification of the conflicting components in the component section of the *Safety Toolkit*, and then activation of the identified components through *USER* interface by change of the component modifier from "0" to "1" in the respective cells.

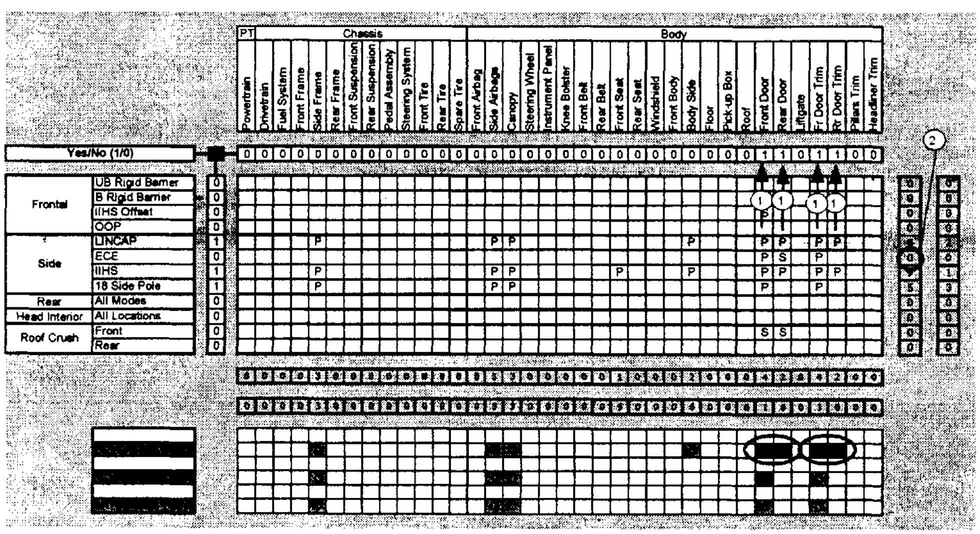


Figure e1.8

In the above case, primary components with conflicting design direction are Doors and Door Trims. Its considered that further attention is required to identify the secondary components for achieving the performance targets. USER enters modifier "1" in the cells related to the above mentioned four primary components.

Step 9: Search for Secondary Parts

As discussed in the earlier steps, secondary components act as supportive agent to achieve the desired performance. The following process helps identify the secondary component related to a primary component. Application of the modifier (described in previous step) automatically displays relationships of secondary components with a primary component in the component-2-component section. The letter "X" in a cell identifies the existence of a relationship between two components. The figure e1.9 shows, how secondary components are identified for a primary component. It is recommended to highlight the identified secondary components by shading the cells with yellow color (figure e1.9).

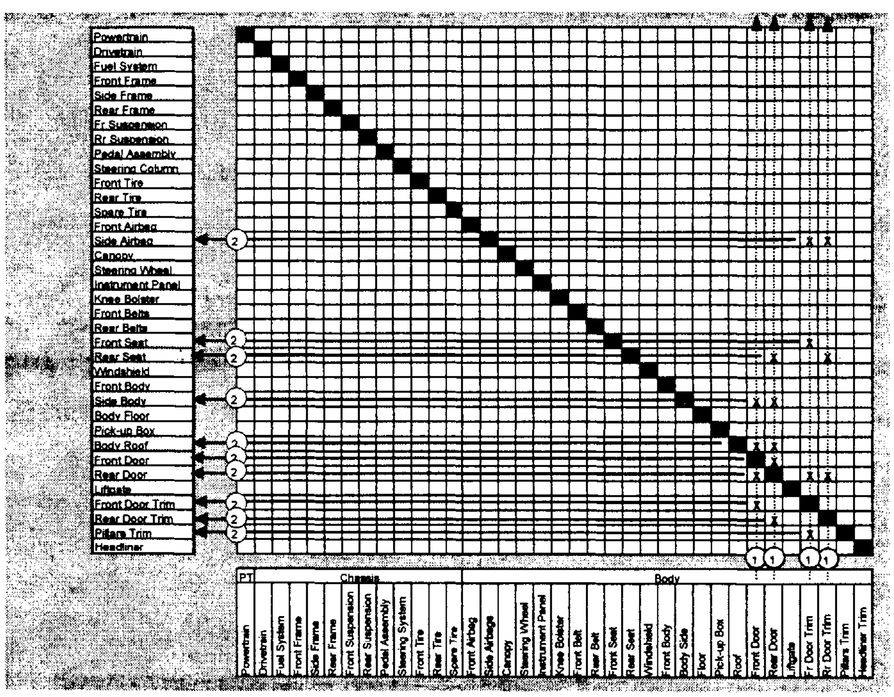


Figure e1.9

However, in some conditions some of the primary components can also act as the secondary to a different primary component. It is suggested to select all the components, which can help in achieving desired design goals.

The figure e1.9 shows identification of the secondary components to Door and Door Trims. For the ease, identified secondary components are highlighted in the vertical columns of component description. Also, it can be noted that most of the identified secondary parts already has been considered as the primary to the selected impact modes, with a exception of few. The following steps looks into this process.

<u>Step 10: Secondary Parts Selection</u>

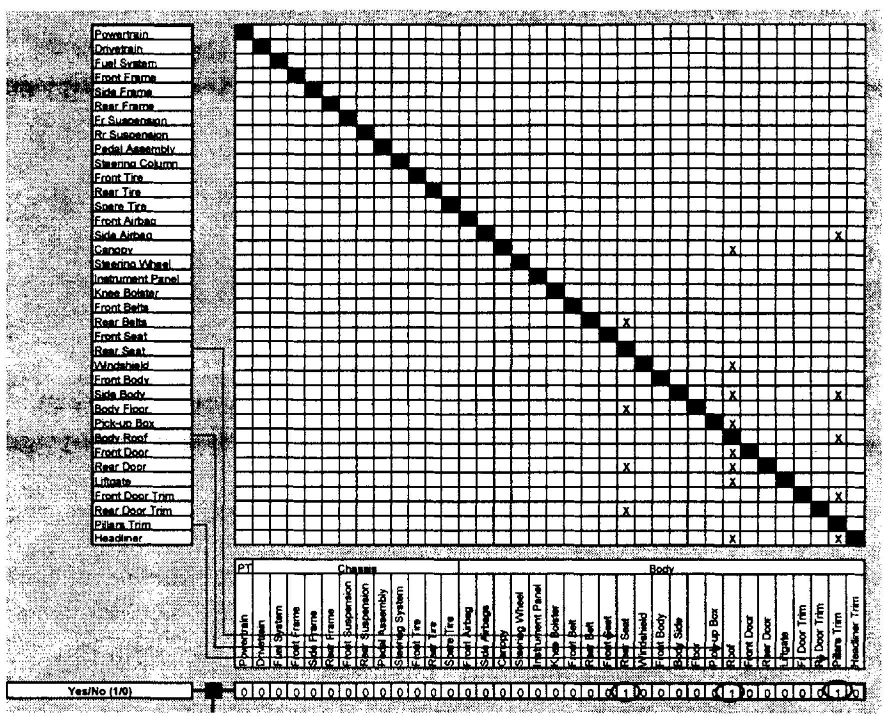


Figure e1.10

Once all the secondary components are identified for the interested primary components, the redundant components get eliminated from the analysis. Redundant components are those secondary components, which are already been considered as the primary in the previous steps. Only the new components, which were not considered in the design process earlier, are selected. As shown in figure e1.10, the selected secondary components are activated by *USER* through entering "1" in respective cells of component modifier. Its recommended that selected secondary components cells is to be shaded for ease of identification. Cells in figure e1.10 were shaded in color yellow to highlight the interested components.

In this case, Roof, Pillars Trim and Rear Seat are identified as secondary components. These components were not considered in the design process. The modifier for these components are changed by *USER* to "1", in order to activate the selection. The placement of the component modifier displays the secondary component relationship with the impact modes. This relationship is discussed in the next step.

<u>Step 11: Secondary Parts Relationship</u>

Application of component modifiers for the secondary component in the previous step, automatically displays interested component relationship to the impact modes. This relationship is established, if the selected secondary component has letter "S" in the cell associated to the impact modes, as shown in figure e1.11. In that case we can consider secondary component performance to balance the conflicting requirements of the primary component.

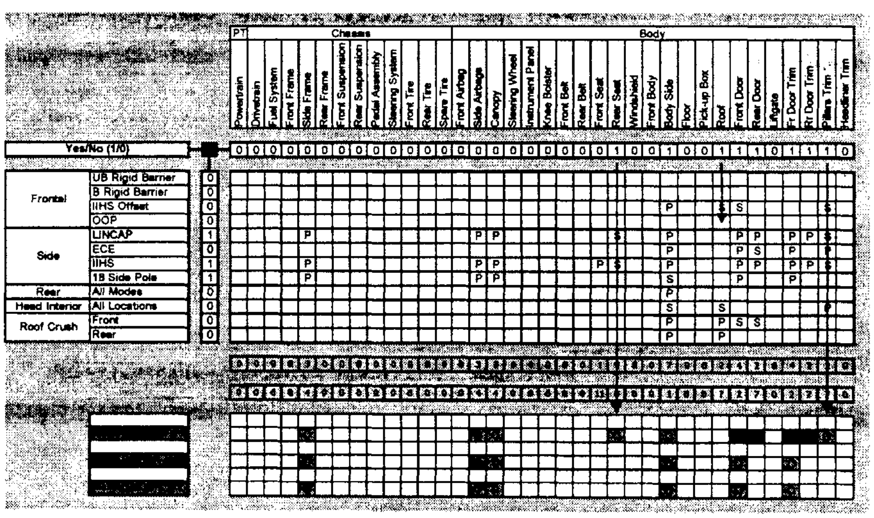


Figure e1.11

Similar to the primary components, it's critical to identify the secondary components relationship to the impact modes. Activation of the secondary component through component modifier, automatically displays relationship in the component design section. If the relationship in the component design is identified with the letter "O", it reflects that secondary component can leverage the performance. In case of the letter "N", it is recommended to eliminate the selected secondary components from the design consideration. The figure e1.11 shows the impact modes dependency on the selected secondary components, and parts relationship in case of modes interaction.

In the example above, secondary component: Roof has no dependency on any of the interested impact modes. The Roof was eliminated from further design consideration. Both Rear Seat and Pillar Trims are dependent on the LINCAP and IIHS modes. Next, validity of the Rear Seat and Pillar Trims are established, since in the component design section these components are directionally positive in case of LINCAP-IIHS interaction (SS21). These two secondary parts can be used to further assist in achieving the design targets.

Step 12: Input into DSM

Once the above-mentioned steps are completed, it is efficient to start building the DSM model for the specified tasks. The sequence of inputting the components in the DSM can be performed by the order defined in the step7. At first we'll input the components with the least number of dependencies to impact modes and positive in design directions. Later, we'll input all the primary parts with the conflicting design directions, and at the end, selected secondary components are incorporated into the DSM.

The dependencies between the components are defined based on the component relationship learned in the earlier steps. Since, performance of the primary components with positive design directions are independent from the other components, no dependencies are defined between them. However, the primary components with conflicting relationships could be dependent on each other, selected secondary components and other primary components. In this case, dependencies are to be defined between these components.

The figure e1.12 shows the DSM input, and dependencies between the components. Since, some of the primary components with conflicting relationship are dependent on each other, the recursive dependency are defined between these components.

Task Name		1	2	3	4	5	6	7	8	9	10	11
Front Seat	1											
Body Side	2											
Canopy	3											
Side Airbags	4											
Side Frame	5											
Rear Door Trim	6				1			1				1
Rear Door	7		1		1		1			1		1
Front Door Trim	8	1			1					1	1	
Front Door	9	1	1		1			1	1			
Pillar Trim	10	1	1	1	1							
Rear Seat	11											

Figure e1.12

Step 13: Influence on Other Impact Modes

After completing the design process for an impact module, which consisted of: impact modes selection, determination of the primary and secondary components, and generation of the DSM. The next stages of the process address the relationship between the designed module and other impact module. The new modules satisfy vehicle design targets associated with these modules. However, there are some primary and secondary components, which have critical influence on the metrics of the several modules.

In order to learn the influence of the components on other modes, all the modifier for the selected components should be replace by *USER* with "1" in the respective cells, as shown in the figure e1.13. This operation automatically displays the relationship of active components with the other impact modes. It's critical to identify the primary components of other modes. The displaying of letter "P" establishes the primary component relationship with the respective mode. Once the primary components are identified for the impact modes, it's critical to learn primary component design direction in case of impact modes interaction. The newly displayed primary components point to additional; impact modes interaction in the mode-2mode section, as shown in the figure e1.13. The blue arrows in figure e1.13 help identify the newly displayed components, and additional impact modes interactions due to activation of the modifiers.

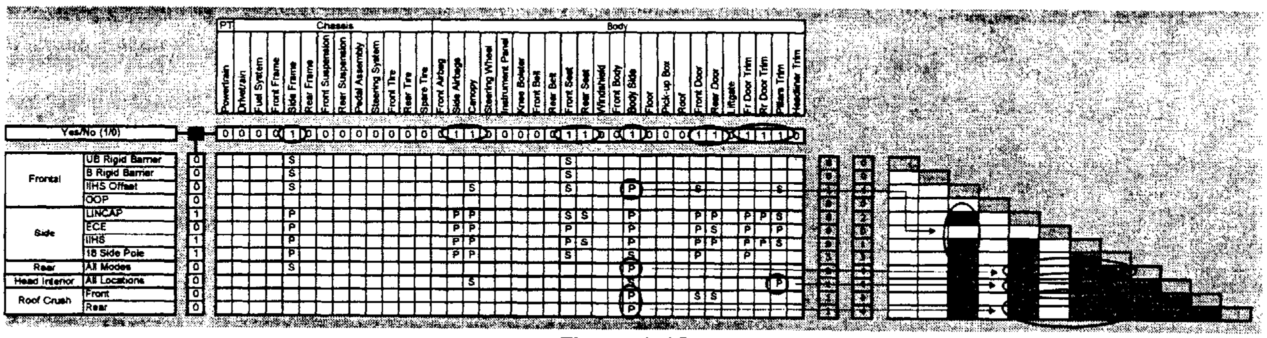


Figure 1.13

Example above shows that, after turning on the components through modifier, it shows that Bodyside is primary to impact modes of the Frontal, Rear, and Roof Crush modules. Also, Pillars Trim is primary to Head Interior impact modes. These new findings, lead to displaying of the impact modes indicator in the mode-2-mode section of the Safety Toolkit. The next step is to find out the relationship between impact modes for the Bodyside and Pillar Trim.

Step 14: Other Modes Relationships to Critical Components

The identification of the new relationships can be critical to the design process. An accurate assessment of theses dependencies will create need for the interaction between the different design teams. At this moment, teams needs to establish the level of dependencies to achieve the desired performance. The assessment of dependency level is unique to each design cannot be factor in the design process. However, we can establish the design direction relationship of component, similar to operation in previous steps. It will provide us a glimpse of the complexity involve in the interaction between impact modules, and defined the need for interaction between teams.

As learned earlier, components relationships to the impact modes automatically displayed in the component design section. If the relationship in the component design is identified with the letter "O", it reflects that component design direction is mutually beneficial. In case of the letter "N", the relationship is conflicting and it will require trade-off decision between the teams.

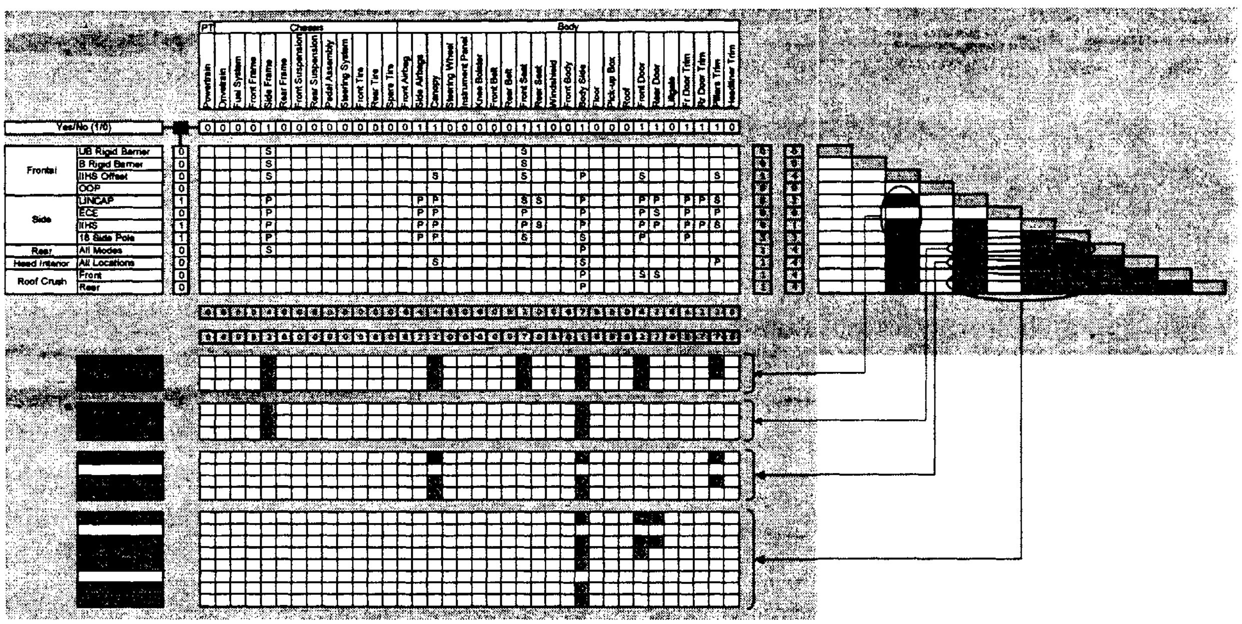


Figure e1.14

In the example (figure e1.14), Bodyside is primary to several impact models in three other modules. Based on the mode-2-mode relationships, Bodyside design direction is positive for all the mode-mode interaction. However, teams need to communicate with each other to establish the design parameters for the Bodyside. Similar is true for the Pillar Trim, its relationship is also positive, but design parameter should be establish based on all the effected modes of impact.

Step 15: Final DSM Input

After identifying all the relationship within an impact module, and with other modules, the input to DSM should be completed. The dependencies between the modules should be defined based on recursive flow of design parameters. The figure e1.15 shows the feedback loop between impact modes.

Task Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Front Seat	1															
Body Side	2												1	1		1
Canopy	3															
Side Airbags	4															
Side Frame	5															
Rear Door Trim	6				1			1				1				
Rear Door	7		1		1		1			1		1				
Front Door Trim	8	1			1					1	1					
Front Door	9	1	1		1			1	1							
Pillar Trim	10	1	1	1	1										1	
Rear Seat	11															
Front Impact Modes	12		1													
Rear Impact Modes	13		1													
Head Interior Modes	14										1					
Roof Crush Modes	15		1													

Figure e1.15

The above case shows that, Bodyside has feedback dependencies between Frontal, Rear and Roof Crush modules. And, Pillar Trims has feedback dependencies with the Head Interior module. This establishes the communication links between safety teams based on the interested components.

Step 16: DSM Analysis

Once the DSM is build for the side impact module, the analysis is performed to optimize the design dependencies. The results of the DSM analysis provide, an initial direction for leading the design, manage of cross-team interactions and identify the critical junctions in the design process. Figure e1.16 shows the results of the DSM analysis. The results of the analysis suggest that all the interaction between the modules needs to resolve in parallel with the components with no preceding dependencies. At the end, critical components should be designed. In addition to that, analysis results clearly show the dependencies between the elements (components & modules) of the design.

Task Name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
Body Side		1		1	1	1			Block1									1
Front Impact Modes		2	1		[illegible]	[illegible]												2
Rear Impact Modes		3	1	[illegible]		[illegible]												3
Roof Crush Modes		4	1	[illegible]	[illegible]													4
Front Seat		5																5
Canopy		6																6
Side Airbags		7																7
Side Frame		8																8
Rear Seat		9																9
Pillar Trim	2	10	1				1	1	1				1			Block2		10
Head Interior Modes	2	11										1						11
Rear Door Trim		12							1		1							12
Rear Door		13	1						1		1							13
Front Door Trim		14					1		1			1						14
Front Door		15	1				1		1									15
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	

Figure e1.16

In the design process of the side impact module, as shown in figure e1.16, Bodyside interactions with the Front, Rear and Roof Crush modules should be address simultaneously with the components with no dependencies: Front Seat, Canopy, Side Airbag, Front Frame and Rear Seats. Since, Pillar Trims performance is dependent on the several components, it is address at the next level. In addition to that, Pillar Trim interaction with the Head Interior module is defined at the same level. At the end, critical components: Front and Read Door and their Trims are considered. Since, the Door and Trim performance is dependent on each other, the feedback loop is defined at this stage of the design process.

The analysis result shown in figure e1.16 provides a clear level of dependencies between the components. In designing of a component, team can utilize the results of the analysis to identify the critical dependencies. This approach helps team concentrate on the most effected components, leading to maximize the value of effort and reducing waste.

Step 17: Complexity Performance

At the conclusion of the design analysis, team should evaluate complexity level of the designed impact module. Complexity level of an impact module can be established based on the following metrics:

- Number of Primary Components
- Number of Secondary Components
- Number of Dependencies
- Number of Interaction between Modules
- Number of Feedback Dependencies

These metrics provides an idea about the level of complexity for the associated design. The lesser are the value of each metric, the less complexity is involved in the design. Design should strive for the lesser number of primary components with the conflicting requirements, and number of interaction between the impact modules. These factors significantly contribute to the level of complexity for a design.
Combination of metrics mentioned earlier defines the essentials complexity level for the design. During the development process, design complexity level can changed due to numerous factors, which are external to vehicle safety. In this case, the design complexity should be evaluated, and if number is higher than essential complexity, team should consider complexity reduction.

Side impact module design example, gave an overview of the challenges and decisions required in the design process stages. The example shows that Front and Rear Doors and their Trims are the critical components in meeting the design objective. In addition to that Bodyside designing is a complex process, due to repeated interaction between several design teams. This indicates that teams should share responsibility of establishing the design target for the Bodyside. If several teams are depending on the performance from a component, it can further complicate the design process. Although, in this case design directions between the modules are positive, and interactions does not involve the performance trade-off decisions.

It is to be noted that, if desired performance is not achievable due to conflicting relationship of a component. And, involvement of secondary components is insufficient to fill the performance gap. In this case, teams should consider invoking new technologies in design. One should be careful in relaying on the new technology to deliver the desirable performance. In case of new technology implementation readiness timing slips, this can lead missing the program deliverables at critical milestones. Such drawbacks can be very costly for the vehicle program, and require the interference of program management to redefine the vehicle targets. Another approach in resolution this issue, is to involve third level components in design. The drawbacks of this option: introduces additional components, and further increases number interactions. The component interaction at third level has potential for failure in the assessment of relationships. In case of poor assessment in design process, can introduce emergent properties at later stages of the vehicle program and require fixes. The late changes are deterrent to quality and cost.

5.5.2.5. Analysis II – Frontal Impact Analysis

The second validation of the Safety Toolkit is related to frontal impact targets analysis.

Step 1: Select Impact Module

In this case, side impact module is selected. The figure e2.1 shows the selection of impact module is highlighted in yellow.

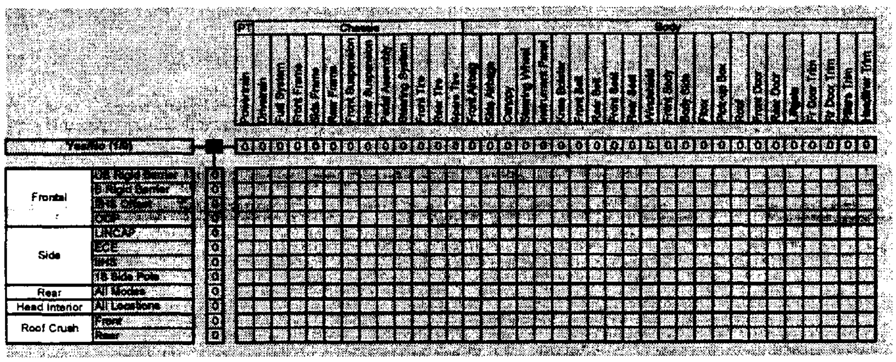


Figure e2.1

Step 2: Select Impact Modes

The selection of the impact modes within the selected impact module is performed. In the figure e2.2 team has selected all impact modes in the frontal module: UB Rigid Barrier, B Rigid Barrier, IIHS and OOP. These modes are selected based on the vehicle program objectives.

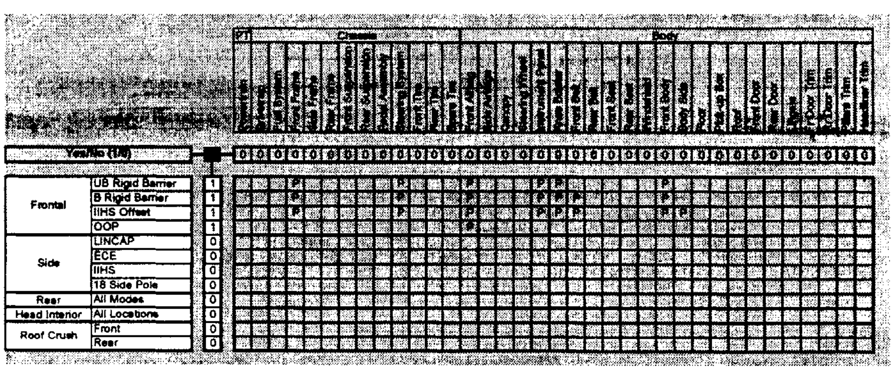


Figure e2.2

After impact modes are identified, they are activated by *USER* applying modifier "1" in the respective mode modifier cell. Figure e2.2, shows the previously selected impact module, impact models associated with it, and application of the mode modifier. The areas of interest are highlighted with yellow in figure e2.2.

Step 3: Identify Parts Relationship

Posting of the impact mode modifier "1" in previous step leads to activation of the primary components for the selected frontal impact modes. As shown in the figure e2.3, primary components to each mode are automatically displayed in the mode-2-component section. It can be notice that, all modes are dependent on the similar components, except for OOP mode. OOP mode is only dependent on the Frontal Airbag. The highlighted areas in yellow show the areas of interest.

			PT	Chassis										
			Powertrain	Drivetrain	Fuel System	Front Frame	Side Frame	Rear Frame	Front Suspension	Rear Suspension	Pedal Assembly	Steering System	Front Tire	Rear Tire
Yes/No (1/0)			0	0	0	0	0	0	0	0	0	0	0	0
Frontal	UB Rigid Barrier	1				P						P		
	B Rigid Barrier	1				P						P		
	IIHS Offset	1				P						P		
	OOP	1												
Side	LINCAP	0												
	ECE	0												
	IIHS	0												
	18 Side Pole	0												
Rear	All Modes	0												
Head Interior	All Locations	0												
Roof Crush	Front	0												
	Rear	0												

			Chassis	Body										
			Spare Tire	Front Airbag	Side Airbags	Canopy	Steering Wheel	Instrument Panel	Knee Bolster	Front Belt	Rear Belt	Front Seat	Rear Seat	Windshield
Yes/No (1/0)			0	0	0	0	0	0	0	0	0	0	0	0
Frontal	UB Rigid Barrier	1		P				P	P					
	B Rigid Barrier	1		P				P	P	P				
	IIHS Offset	1		P				P	P	P				
	OOP	1		P										
Side	LINCAP	0												
	ECE	0												
	IIHS	0												
	18 Side Pole	0												
Rear	All Modes	0												
Head Interior	All Locations	0												
Roof Crush	Front	0												
	Rear	0												

			Body											
			Front Body	Body Side	Floor	Pick-up Box	Roof	Front Door	Rear Door	Liftgate	Fr Door Trim	Rr Door Trim	Pillars Trim	Headliner Trim
Yes/No (1/0)			0	0	0	0	0	0	0	0	0	0	0	0
Frontal	UB Rigid Barrier	1	P											
	B Rigid Barrier	1	P											
	IIHS Offset	1	P	P										
	OOP	1												
Side	LINCAP	0												
	ECE	0												
	IIHS	0												
	18 Side Pole	0												
Rear	All Modes	0												
Head Interior	All Locations	0												
Roof Crush	Front	0												
	Rear	0												

Figure e2.3

Step 4: Identifying Number of Dependencies

After identifying the primary components, the most critical component is Frontal Airbag. All frontal impact modes are dependent on the Front Airbags. The least critical component is Bodyside, and then Front Belts. Beside these components, the remaining primary components have same number of dependencies. The summation result of primary component, critical to impact mode is automatically displayed in pink color row (figure e2.4).

The figure e2.4 shows OOP has only one dependency, and UB Rigid Barrier, Rigid Barrier, and IIHS has 6,7,8 (respectively) dependencies to primary components. The summation results are automatically displayed in the pink column in figure below.

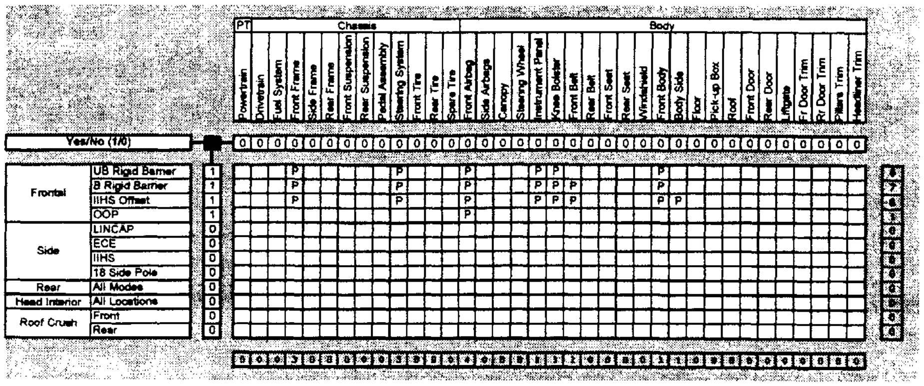


Figure e2.4

Step 5: Sorting of Dependencies

After the numbers of component and impact mode dependencies are sorted, their ranking can be established. Figure e2.5 shows that OOP mode is rank the lowest, and IIHS mode is rank highest in the number of component dependencies. The results of impact mode sorting are displayed in the turquoise color column. The Front Airbag is rank the most critical component due to most dependencies to impact modes, and Bodyside has the least. Most of the primary components share the same rank. The results of component sorting are displayed in the turquoise color row.

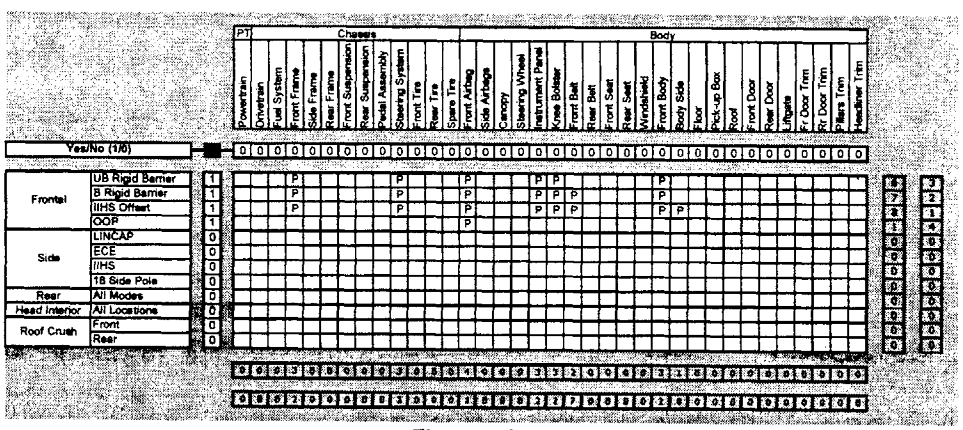


Figure e2.5

Step 6: Impact Modes Interaction

After the initial analysis of the primary components relations to impact modes, impact mode relationship are established. The inter-relationships of impact modes are shown in the mode-2-mode section in figure e2.6. The interactions are defined by automatically displaying the relationship indicator: FF11, FF21, F22, ..., F33. The relationship indicator FF1 defines the existence of relationship between UB Rigid Barrier and B Rigid Barrier modes. Similarly, other indicators define relationship between two specific impact modes.

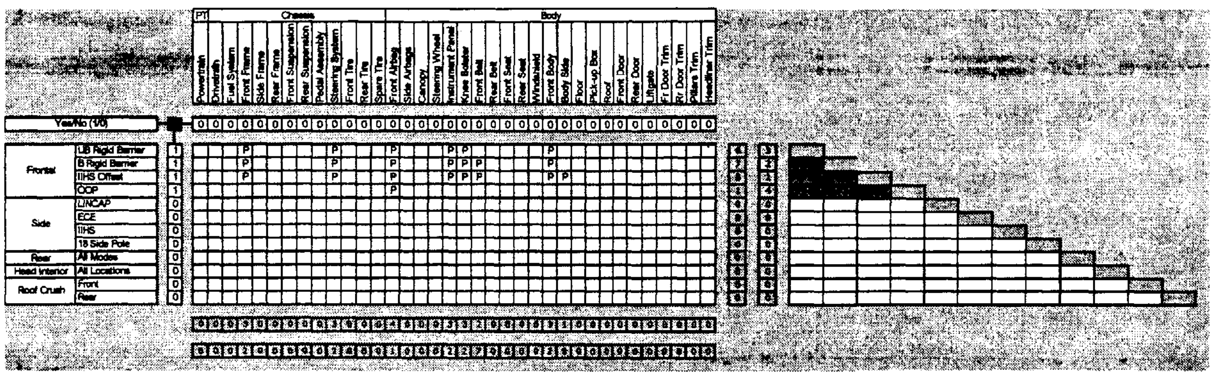


Figure e2.6

Step 7: Primary Component Design Relationships

Activation of the impact mode interactions described in the previous step display the design relationship for the effected primary components with respect to the selected impact modes. It can be observe from the figure e2.7 that most of the primary components in the relationship between UB Rigid Barrier, B Rigid Barrie and IIHS are positive in design direction. The positive direction is displayed by the letter "O" in the blue cells. This shows that, design target for the component can be established based on the most critical need between the two modes. And the second mode requirement will be meet, since it is least stringent. The empty cells show that, no relationship exists for these components.

Figure e2.7 show that Front Airbag has most number of conflicts between the impact modes. Also, Steering Column design direction is positive for the FF22 interaction but conflicting for F11 and F21. These findings lead to further attention to these components in the design process.

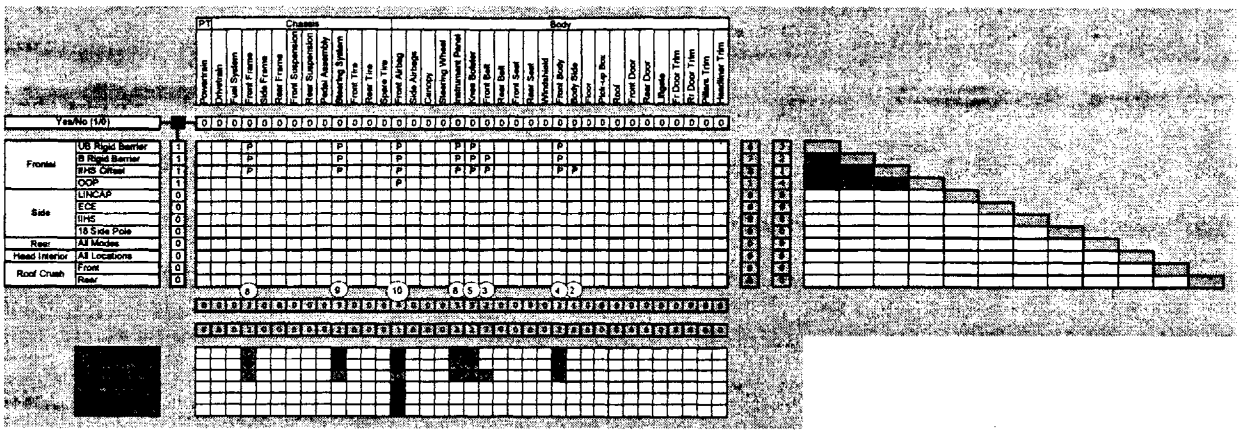


Figure e2.7

The numbers in the blue circle specify the sequence of design action for primary components. This sequence is derived from the primary component sorting described in the step 5 for all the components with "O" relationship. All the parts with the conflicting relationship are considered in the end.

Step 8: Identifying Parts with Conflicting Design Direction

The identified primary components with the conflicting primary components might require further attention to balance the performance need. The need for the additional components in design leads to identification of the secondary components. First step of identifying the secondary components is to activate the component modifier of Front Airbag and Steering Column. The modifier for interested components are replaced with "1" in the designated cells (figure e2.8). The placement of modifier activates the relationship with the secondary parts. This relationship is discussed in the next step.

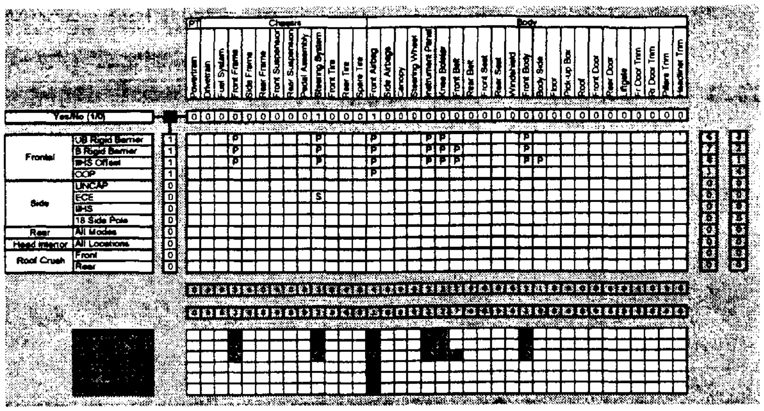


Figure e2.8

Step 9: Search for Secondary Parts

Application of the modifier (described in previous step) shows relationships of secondary parts with a primary part in the component-2-component section. The letter "X" in related cell for the effected components displays this relationship. Figure e2.9 shows Front Airbags and Steering Column are in relations with several components. Beside the primary component, Steering Wheel, Windshield and Front Seats are the new components in the design process. The interested areas are highlighted with color yellow in figure e2.9

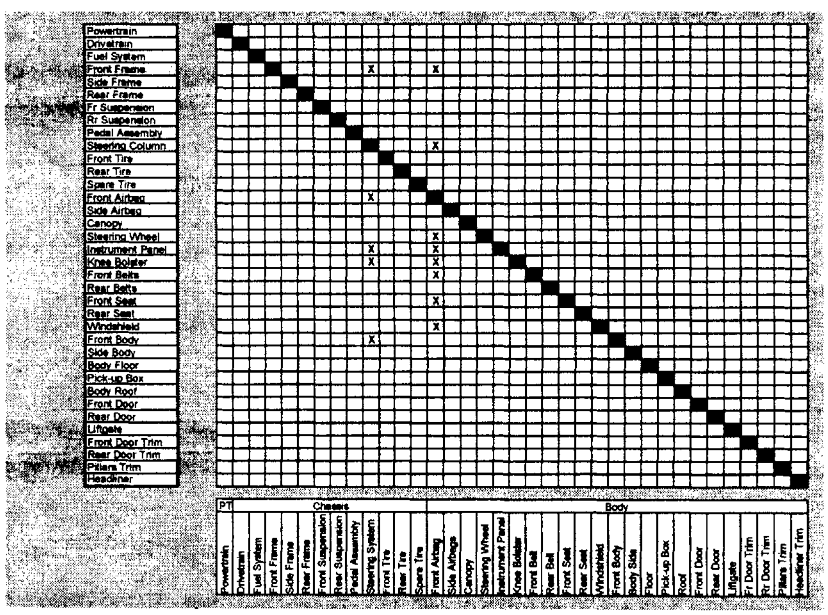


Figure e2.9

Step 10: Secondary Parts Selection

After identifying the secondary components, redundant components are eliminated from the analysis. As shown in figure e2.9, the selected secondary components: Windshield, Steering Wheel & Front Seat are activated by placing the modifier "1" in respective cells of component modifier. These components were not considered in the design process. Its recommended that selected secondary parts cells is to be shaded for ease of identification. Cells in figure e2.10 were shaded with color yellow to highlight the interested components.

Once user enters the component modifier "1" in the respected cells, *Safety Toolkit* automatically displays the secondary component relationship with the impact modes. This relationship is discussed in the next step.

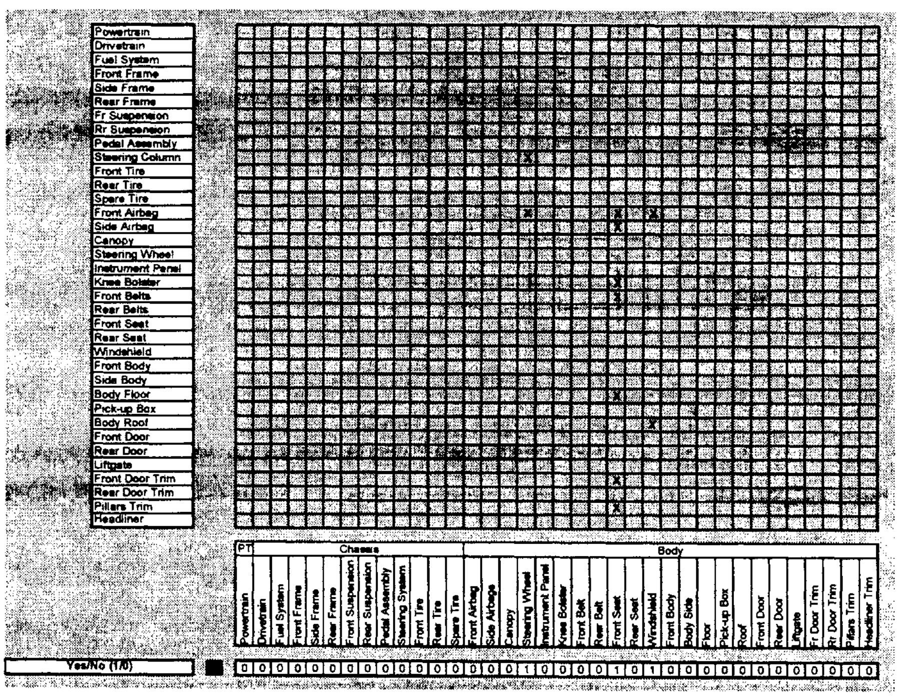


Figure e2.10

Step 11: Secondary Parts Relationship

Application of component modifiers for the secondary component in the previous step, *ST* automatically displays interested component relationship to the impact modes. This relationship is displayed in the component-2-mode section of the *Safety Toolkit*. This relationship is true, if the selected secondary component has letter "S" in the cell associated to the impact modes. As shown in figure e2.11, Windshield, Steering Wheel can be considered secondary components for all four frontal impact modes. However, Front Seat is secondary component for UB Rigid Barrier, B Rigid Barrier and IIHS modes. So far, we can use these components as secondary to balance the conflicting requirements of the primary components.

Similar to the primary components, it's critical to identify the secondary components relationship to the impact modes. Activation of the secondary component through component modifier in the previous step, *ST* automatically displays the relationship in the component design section. Figure e2.11 shows that Windshield, Steering Column and Front Seat have positive relationship with the active modes FF11, FF21 & FF22. These relationships are verified with the letter "O" in the respective cells in the component design section. These relationship show that secondary component can leverage the performance for conflicting primary components.

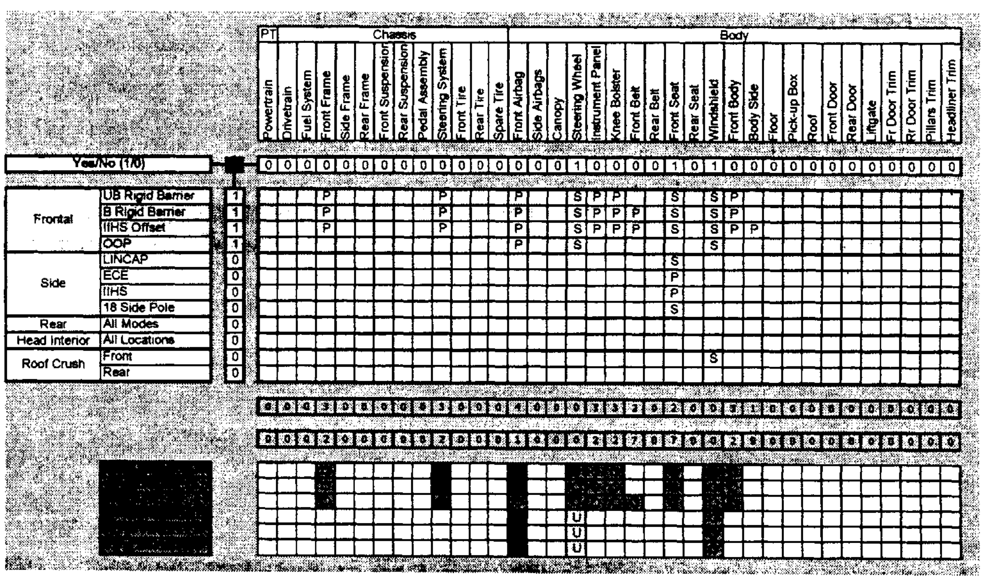


Figure e2.11

In addition, to above describe positive relationships, Windshield can be used as secondary component for FF31, FF32 & FF33 impact modes interactions. Since Windshield relationship with the above mentioned impact interactions is defined with the letter "O", meaning mutual beneficial performance. The displayed letter "U" for the mentioned impact modes relationships with the Steering Wheel indicates that, it's an "unknown" condition. In case of an unknown relationship, team must further learn about the relationship between impact modes and components. For example, we are only requested to change the passenger airbag, in that case there is no need to consider steering wheel as a secondary component. Since Steering wheel interaction is limited to driver airbag, and it cannot be utilize to help in performance improvement of the passenger airbag. For sake of learn, for the above example, Front Airbags are represented by the both, driver and passenger airbags. In this case, Steering Wheel is viable component for performance improvement.

In case of the letter "N" between the impact modes relationship with the interested components, it is recommended to eliminate the selected secondary components from the design consideration. But, in above example no secondary components have conflicting relationship.

In result of the above analysis Front Seat, Steering Wheel and Windshield can use as secondary components to help improve the performance of the conflicting relationship of Front Airbag and Steering Column.

Step 12: Input into DSM

After identifying the primary and secondary components, it is logical to proceed with building the DSM mode. The sequence of entering components in the DSM is performed by the order defined in the step7. First input the parts with the least number of dependencies to impact modes and positive in design directions. As shown in figure e2.12, Bodyside is the first component to meet this criterion. Followed by the primary components: Front Belts, Front Body, Kneebolster, Instrument Panel and Front Frame. Next primary components with the conflicting design directions are entered, and at the end, selected secondary components are entered into the DSM.

After completing the components entry, dependencies between these components are defined. The dependencies are based on the components relationship established in the earlier steps. Since, performance of the primary components with positive design directions are independent from the other parts, no dependencies are defined between them. However, the primary parts with conflicting relationships can dependent on each other, selected secondary parts and other primary components. In this case, dependencies are to be defined between these components.

Task Name		1	2	3	4	5	6	7	8	9	10	11
Body Side	1											
Front Belts	2											
Front Body	3											
Knee Bolster	4											
Instrument Panel	5											
Front Frame	6											
Steering System	7		1		1	1	1		1			1
Front Airbag	8		1	1	1	1	1	1		1	1	1
Front Seat	9		1		1							
Windshield	10											
Steering Wheel	11											

Figure e2.12

The figure e2.12 shows the DSM input, and dependencies between the components. Since, some of the primary components with conflicting relationship are dependent on each other, the recursive dependency are defined between these components

Step 13: Influence on Other Impact Modes

The steps between 1 to 12 addresses the design actions related to an impact module. The next few steps of the design process involve in learning the relationship between the interested design impact module and remaining impact modules. The need for learning about these relationships is dictated by the fact that, there are some primary and secondary components, which have critical influence on the metrics of the several modules. In the above example, team is assigned to deliver vehicle program objectives based on several impact modules, in this case it is essential to learn about the all the possible interactions between the impact modules.

In order to learn the influence of the components on the other modes, *USER* should enter component modifier "1" for the selected components. As shown in figure e2.13, Front Frame & Body, Steering Column & Wheel, Instrument Panel, Knee Bolster, Windshield, Front Airbag, Seat and Belts are activated by the entering of the component modifier "1" in the respective cells. This operation automatically displays the relationship of active components with the other impact modes. Any relationship by the letter "P" establishes the primary component relationship with the respective mode. Figure e2.13 shows that Bodyside is primary to number of impact modes of Side, Rear, and Roof Crush impact modules. Whereas, Front Seat is primary to ECE and IIHS impact modes.

New relationships of primary components suggest that there must be a relationship between the impact modes and components. Additional impact modes interactions are automatically displayed in the mode-2-mode section. These interactions are defined by the specific description between two impact modes. For example, indicator FS11 shown in the figure e2.13 establishes interaction between UB Rigid Barrier and LINCAP. Similarly, a specific indicator describes for every interaction.

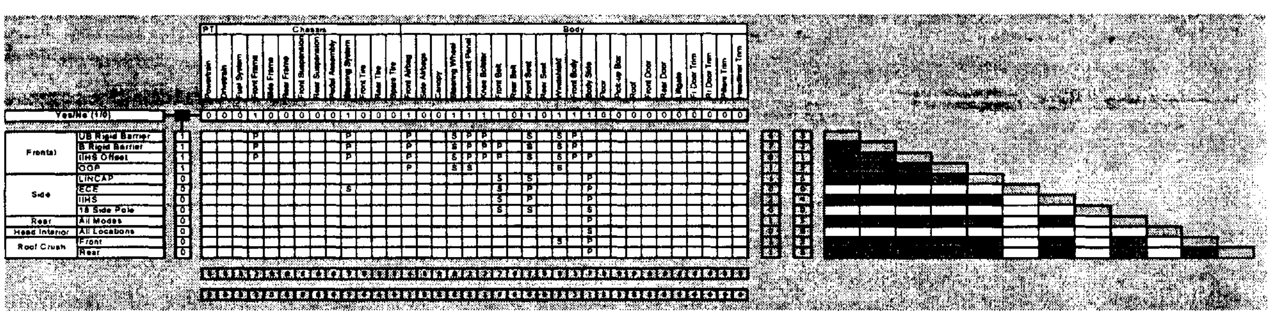


Figure e2.13

The next step is to find out the relationship between impact modes for the Bodyside and Front Seat.

Step 14: Other Modes Relationships to Critical Components

The identification of the new relationships can be critical to the design process, it defines the level of interaction between design teams. At this stage, teams should work together to achieve mutually beneficial solution with respect to the interested components. Similar to earlier steps, design direction relationships of components are used to help teams identify the need for interaction.

As learned earlier, components relationships to the impact modes are automatically displayed in the component design section, upon the entering of component modifier "1" in the previous step. If the relationship in the component design is identified with the letter "O", it reflects that component design direction is mutually beneficial. In case of the letter "N", the relationship is conflicting and it will require trade-off decision between the teams.

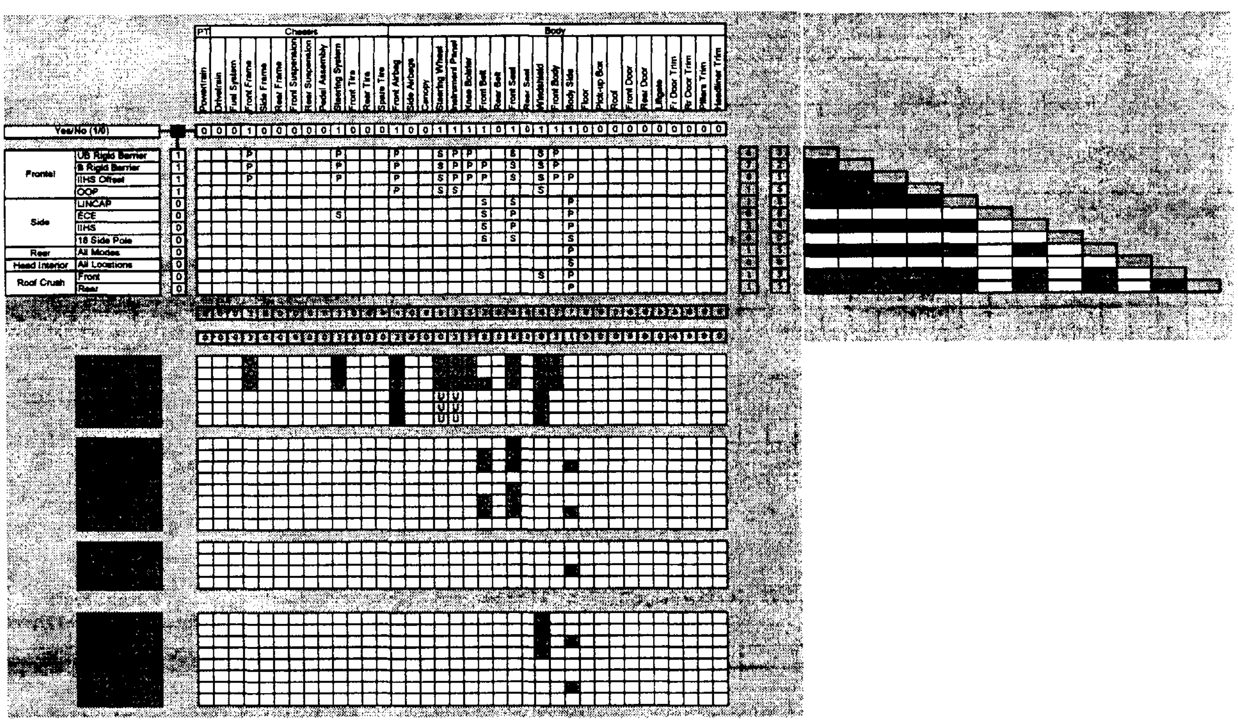


Figure e2.14

Bodyside is a primary component to several impact models in three other modules, as shown in figure e2.14. Based on the mode-2-mode relationships, Bodyside design direction is positive for all the mode-mode interaction. However, teams need to communicate with each other to establish the design parameters for the Bodyside. Similar level of interaction will be required in the designing of the Front Seat. The secondary components relationships are analyzed, if the other modules teams are utilizing these components to gain performance. In such condition similar process of evaluation is followed.

Step 15: Final DSM Input

After identifying all the relationship within an impact module, and with other modules, the information should be transferred to DSM. The DSM input is complete at this stage. The dependencies between the modules should be defined based on recursive flow of design parameters. The figure e2.15 shows the feedback loop between impact modes.

Task Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Body Side	1												1	1	1	
Front Belts	2															
Front Body	3															
Knee Bolster	4															
Instrument Panel	5															
Front Frame	6															
Steering System	7		1		1	1	1		1			1				
Front Airbag	8		1	1	1	1	1	1		1	1	1				
Front Seat	9		1		1								1			
Windshield	10															
Steering Wheel	11															
Side Impact Modes	12	1								1						
Rear Impact Modes	13	1														
Roof Crush Modes	14	1														
	15															

Figure e2.15

The above case shows that, Bodyside has feedback dependencies between Frontal, Rear and Roof Crush modules. And, Front Seat has dependencies with the Side Impact module. This establishes the communication links between safety teams based on the interested components

Step 16: DSM Analysis

The result of the DSM analysis provides, an initial design direction to team with respect to the dependencies. In addition to that, team should use results for managing cross-module teams interaction and identify the critical junctions in the design process. The results of analysis, as shown Figure e2.16, suggest that component with no design dependency should be address first. Front Belts, Front Body, Knee Bolster, Instrument Panel, Front Frame, Windshield and Steering Wheel are designed first. Next, interaction between the modules needs to resolve in parallel with Bodyside and Front Seat. Since these two components are dependent on the other component and other impact modules, they are designed at the second level. At the end, critical components: Front Airbag and Steering Column design are defined. The Front Airbag and Steering Column performance is dependent on each other, which results in feedback loop between the two components.

Task Name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Front Belts		1															1
Front Body		2															2
Knee Bolster		3															3
Instrument Panel		4															4
Front Frame		5															5
Windshield		6															6
Steering Wheel		7															7
Body Side	2	8										1	1	1			Block1
Front Seat	2	9	1		1							1					9
Side Impact Modes	2	10								1	1						10
Rear Impact Modes	2	11								1							11
Roof Crush Modes	2	12								1							12
Steering System		13	1		1	1	1		1							1	13
Front Airbag		14	1	1	1	1	1	1	1		1				1		14
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	

Figure 2.16

Step 17: Complexity Performance

At the conclusion of the design analysis, design complexity level of the designed impact module is evaluated. Based on complexity metrics, the following number define the frontal impact module complexity level:

- Number of Primary Components
- Number of Secondary Components
- Number of Dependencies
- Number of Interaction between Modules
- Number of Feedback Dependencies

The lesser are the value of each metric, the less complexity is involved in the design. Performance goals should be achieved with the lesser number of primary components with conflicting requirements, and number of interaction between the impact modules. In this case, such components are limited to two, and module interaction to 3. These factors significantly contribute to the level of complexity for a design. Team should periodically evaluate the complexity level of design with the number of essential complexity. In case there is a margin for reduction in complexity or waste.

Front impact module study show Front Airbags and Steering Column are the critical components in meeting the design objective. In addition to that Bodyside and Front Seat design introduces complexity of repeated interaction between several design teams. This indicates that teams should share responsibility of designing the Bodyside and Front Seat. Since, design directions of Bodyside and Front Seat relationships between the modules interaction are positive, the design doe not require performance trade-off decisions.

Performance deficiency can be addressed through the invoking of the new technology in design. One should be careful in relaying on the new technology to deliver the desirable performance. In case new technology implementation readiness timing slips, it can lead to costly late changes, quality issues and/or delaying program. For example, there several conceptual designs exist for the adaptive steering column. The adaptive steering column tailors the energy absorbing capacity base on the conditions. Such technologies will be mutually beneficial for any conflicting requirements. However, implementation and robustness of new technology needs to verify. If a team solely relies on the use of new technology to achieve performance, it can be subjecting the vehicle program to higher risks.

5.5.3. Process Optimization

The goal of the third module of the proposed safety development process is to define an efficient path to accomplish safety deliverables. The desirable paths is achieved by listing the safety program deliverables, defining dependencies between the deliverables and utilize Design Structure Matrix to optimize for an efficient result.

The list of safety deliverables of the vehicle program with respect to FPDS milestone is acquired from the results of the timing module. As mentioned in the earlier module, each vehicle program has its unique list safety deliverables. The vehicle program safety deliverables are consists of the generic and distinctive deliverables. However, some vehicle program base on their design objectives, are not subject to every generic deliverable.

In order to convey the dynamics of the safety development process, generic safety deliverables are used to show the objective of this module. At first, list of generic safety deliverables are established from the module 1. The specified deliverables are organized by the milestone and inputted into the DSM. Once all the deliverables are specified in the DSM, the next involves defining the deliverable dependencies. The deliverable dependency characterizes the flow of information between the deliverables. The dependencies to a deliverable are assigned if a proceeding deliverable(s) is(are) required to be completed, in order to accomplish the interested deliverable. In some case, there is a need for the feedback information to previous deliverables; in that case a feedback dependency is assigned between the two deliverables.

During assigning the deliverable dependency, safety team should consider the design interactions establish in the complexity module. If a deliverable is required to consider the specific design level action, the interactions defined in the safety toolkit should be assigned with a dependency in the DSM.

An example of DSM input is shown in figure 5.5.3.1. The DSM inputs are based on the generic safety deliverables. The safety deliverables are arranged in the column with a designated task number. For example, define resource need deliverable has task #1, and same task number is listed in the top row.

The deliverable dependency are represented by the number "1". All the proceeding dependencies are defined in bottom of the diagonal, and feedback dependencies are defined above the diagonal. For example: task #13 (establish system level targets) is dependent on the completion of tasks #10 & #12. The task #13 cannot be completed until tasks #10 & #12 are finished. Also, after the completion of task #13, there is feedback loop to task # 10. Such dynamics of interaction defines the need for a potential rework.

Deliverables		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
<KO> assess program safety goals	1																																		
<KO> desfine resource needs	2	1																																	
<KO> establish program team	3		1																																
<SI> define safety workplan	4	1	1																																
<SI> interpret market safety needs	5	1			1																														
<SI> complete architecture assessment	6	1				1			1																										
<SI> identify new technologies	7					1	1																												
<SI> complete occupant concept design	8	1					1	1																											
<SI> complete benchmark study	9					1			1																										
<SI> establish vehicle level targets	10	1				1				1				1																					
<SC> commitment to new technology	11								1		1																								
<SC> complete design package study	12						1		1			1																							
<SC> establish system level targets	13										1		1				1																		
<SC> complete prototype requirement	14				1									1																					
<PH> establish critical hardpoints	15													1																					
<PH> establish sub-system level targets	16													1		1				1															
<PA> resolve major design issues	17																1																		
<PA> complete performance trade-off study	18															1		1																	
<PA> establish component level targets	19																		1																
<PA> commitment to safety targets	20																			1															
<PA> establish system design	21																				1								1						
<ST> complete surface critical design	22																			1		1													
<ST> verification at component level	23																			1			1												
<PR> complete design verification	24																				1			1		1									
<PR> analytical sign-off of safety targets	25										1			1			1			1	1				1										
<CP> complete development testing	26														1							1			1	1									
<CP> develop confirmation testing schedule	27														1										1	1									
<CP> major/minor risk assessment	28																									1	1								
<CC> complete confirmation testing	29														1						1	1					1	1	1						
<CC> resolve minor design issues	30																												1	1					
<LR> complete compliance documentation	31																														1				
<LR> sign-off safety targets	32																													1	1	1			
<LS> support production issues	33																																1		
<J1> document lesson learned	34										1			1			1			1		1				1			1		1			1	

Figure 5.5.3.1

The last step of the operation, perform optimization of the safety deliverables using DSM. After all the deliverables are inputted to the DSM, it re-sequences the order of the safety deliverables, in manner that defines the most efficient path to accomplish the deliverables. The results of the optimization are shown in figure 5.5.3.2.

Deliverables	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	
<KO> assess program safety goals		1																																			1
<KO> desfine resource needs	2	2	1																																		2
<KO> establish program team		3		1																																	3
<SI> define safety workplan		4	1	1																																	4
<SI> interpret market safety needs	4	5	1			1																															5
<SI> complete architecture assessment		6	1				1			1			Block1																								6
<SI> identify new technologies		7					1	1																													7
<SI> complete occupant concept design		8	1					1	1																												8
<SI> complete benchmark study	6	9					1			1																											9
<SI> establish vehicle level targets		10	1				1				1				1								Block2														10
<SC> commitment to new technology		11								1		1																									11
<SC> complete design package study		12						1		1			1																								12
<SC> establish system level targets		13										1		1			1																				13
<PH> establish critical hardpoints		14													1																						14
<PH> establish sub-system level targets		15													1	1				1																	15
<PA> resolve major design issues		16															1																				16
<PA> complete performance trade-off study		17														1		1																			17
<PA> establish component level targets		18																	1																		18
<SC> complete prototype requirement	8	19				1									1																						19
<PA> commitment to safety targets	8	20																		1																	20
<PA> establish system design		21																				1							1			Block3					21
<ST> complete surface critical design		22																		1			1														22
<ST> verification at component level		23																		1				1													23
<PR> complete design verification		24																				1			1		1										24
<PR> analytical sign-off of safety targets		25										1			1		1			1		1				1											25
<CP> complete development testing		26																			1		1			1	1										26
<CP> major/minor risk assessment		27																									1	1									27
<CP> develop confirmation testing schedule	10	28																			1					1	1										28
<CC> complete confirmation testing		29																			1	1	1					1	1	1							29
<CC> resolve minor design issues	12	30																											1		1						30
<LR> complete compliance documentation		31																														1					31
<LR> sign-off safety targets	14	32																													1	1	1				32
<LS> support production issues		33																																1			33
<J1> document lesson learned	16	34										1			1		1			1			1				1		1			1			1		34
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	

Figure 5.5.3.2

The results of the optimization show that practically, the order of deliverables remained unchanged. Only Compete prototype requirement deliverable can be slipped until <PA>. However, other program groups might dictate the completion of this deliverables at <SC>. Beside the order of deliverables, safety team can learn more about the rework during the development. The optimization results show that, there are three feedback loops in this process. Each feedback loop requires flow of information transition back to the defined task for the rework. In the first feedback loop, relationship between task #6 and #8 are critical for the rework. Similarly other feedback loops can be analyzed.

5.5.4. Process Supportive Elements

5.5.4.1 Design Tools

Safety design tools play an important part in delivering the safety design objectives. The widespread usage of the tools during the development process allows safety team to achieve higher product quality, reduce cost, adaptability to design changes and perform numerous iterations for the most optimized solution. The safety tools can be classified between the predictive and supportive tools.

Different predictive tools are used throughout the concept and design process. The accuracy of prediction is the most important characteristic of the predictive tools. The higher level of accuracy of prediction is associated with the higher cost in form of substantial computing resources, longer time and increased user effort in application. The advantages of the lesser accurate tools are, quick turnaround, lesser resource requirement and low degree of design details. Analyzing the results of predictive tools demands careful interpretation from the user, irrespective of the level of accuracy. Generally, user's experience is the key factor in accurately interpreting the results, and drawing conclusion based on it. The lesser accurate predict tools might require additional sources for design direction.

The finite element approximation codes, lumped mass models, and statistical applications represent the predictive tools in the safety development. The statistical and lumped mass models are considered to have lesser degree of accuracy in prediction. These tools are primarily used in the early design process to evaluate the conceptual designs or established high-level goals. The finite element applications are utilized for establishing sub-system and component level targets, design optimization and verifying design change performance. These tools are used during the verification process, late stages of the design process, and achieving the critical design targets.

The supportive tools encompass a wide variety of applications. These tools can be used to better interpret the results of design iteration through the graphical illustrations, procedures to maintain standardization in application, quality procedures, plotting packages with built-in macros for test data analysis, solution cookbooks for common design issues, CAE applications for analyzing the design assemblies, test films and digital still analysis guidelines.

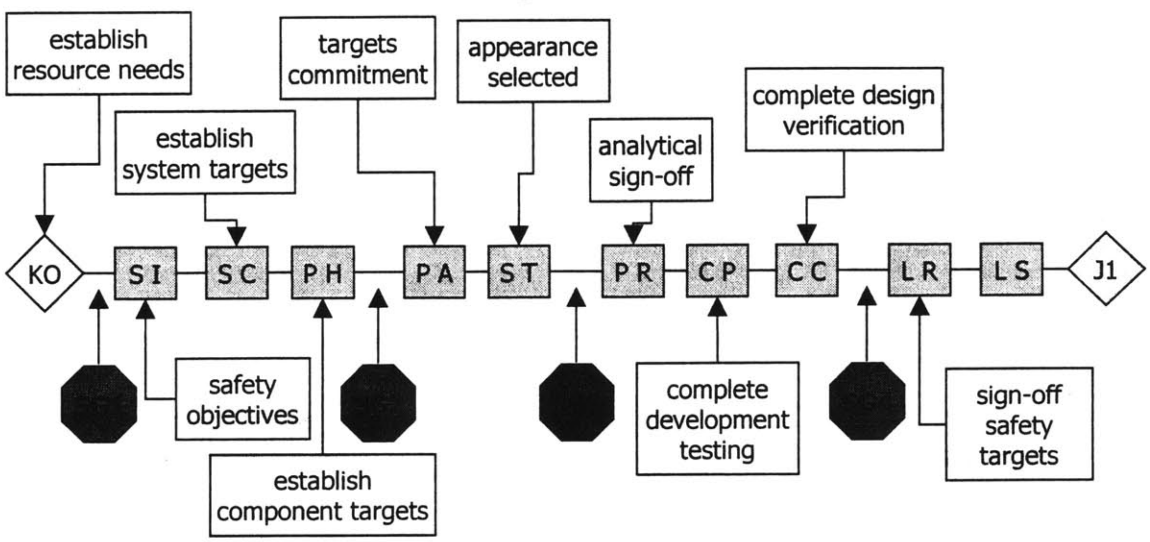
These supportive tools might seem minuscule in their level of contribution to design, but capabilities of these tools allows safety team to save tremendous amount of effort in their daily routine work.

5.5.4.2. Safety Gateways

The implementation of the safety gateways can be crucial to success of any vehicle program. Definition of the safety gateways in the development process can benefit safety team meeting program objectives and vehicle management estimating the potential risks associated with the safety requirements.

A vehicle program should establish its safety gateways based on the level of changes, program safety objectives and market conditions. It's recommended to have at least 4 safety gateways for a new vehicle program or with major changes. A vehicle program Safety Gateways should defined before the <SI> milestone. The gateways should be established before the completion of the vehicle level targets, definition of safety objectives and vehicle level sign-offs. Figure 5.5.4.2 show the development process of vehicle program and recommended safety gateways before the major milestones.

Figure 5.5.4.2



A panel of safety experts should assess a vehicle program at each safety gateway, and assess safety objectives alignment with the corporate strategy, and major/minor risk to meeting those objectives. The safety gateways will act as early warning system and allow safety team and vehicle management to take necessary steps.

6. Conclusion

The objective of this thesis is to provide a system level solution to the vehicle safety development. The intention was not to revolutionize the safety development process at the Ford Motor Company, but rather introduce an initial concept to resolve traditional product development issues from a systems approach.

The thesis framework was designed to address three crucial elements of the product development: timing, design and process. Design for cost is not a philosophy for designing the safety system, and it was not the focal point of this work. The four modules of the thesis framework provided a holistic view of the safety system development. The thesis work describes the deliverable, process optimization and tool modules in detail. Since, safety deliverables are relatively unique to each vehicle program a generic set of deliverables were used in this work. These deliverables reflected on the steps performed in the optimization and tool modules. The content of these modules are sufficient to guide safety team in utilizing the methodology. Also, the information addressed in these modules is information, which limited the scope of the work.

The complexity module was intended to be the focal point of the thesis work, and added attention was given in this work. The initial direction of the thesis did not contain development of the Safety Toolkit. However, during the research process, the need for a user-friendly tool to determine design complexity warranted the inclusion of the Safety Toolkit. The Safety Toolkit delivers the complex makeup of the safety system to user in a simplified form. The logic of the Safety Toolkit function was developed based on the principles of the safety system designing. Implementation of the Safety Toolkit in designing for the side and frontal impact modes validated the tool for the safety applications. The concept of using the Safety Toolkit can provide an effective assessment of the design content, estimate the magnitude of the design change and reduce the probability of rework at the later stages of the vehicle program.

A safety team can utilize the proposed methodology to achieve desirable goals in an effective manner. This work can help manage resource requirements through the development process, and estimate the magnitude of the design change. These two factors are critical defining a nimble and efficient development process.

The deliverables and tools in the proposed methodology can be further modified for a specific design application. The safety team can customize the procedure by including the unique deliverables, components and relationships. Specifically, the Safety Toolkit can be re-designed to further include the details of the design and requirements. This enables safety team to extensively learn about the details of the design. Although, the current version of the Safety Toolkit is developed for body on frame vehicle, It can be easily modified for unitized body architecture.

In addition to that, the developed Safety Toolkit concept can be applied to represent other design or organizational problems.

7. Appendix

A-1. Frontal Rigid Barrier Impact Mode

The subject vehicle is impacted straight on (90 degree) into a rigid wall at 35mph. The vehicle is equipped with the two belted frontal impact dummies seated in the front seats. The objective of this test is to establish frontal occupant injury performance in a high-speed frontal impact. The vehicle crashworthiness star ratings are established from based on the occupant injury performance.

Figure a1.1

Figure a1.2

The figures a1.1 and a1.2 show vehicle after the crash tests. These pictures provide an overview of the critical design elements to the performance of the vehicle design. The critical design elements for this mode are: frame, body, front airbags, steering column, front belts and knee bolster. Safety team is challenged to meet performance through balancing the structural energy absorption capacity and restraints system energy management.

A-2. Frontal Offset Impact

Front of the vehicle is impacted into an offset deformable barrier at 40 mph. The overlap of the barrier face and vehicle is set at 40% of the vehicle width. Vehicle is equipped with a frontal impact dummy seated at the driver seating position. The objective of this test is to establish rating of the occupant injury performance and structural integrity due to the impact. This test is classified among the most destructive tests for the vehicle structure. The design of the vehicle is challenged to show crashworthiness performance from a one side of the vehicle. The occupant injury performances in this test are governed by instruction of design elements into the occupant compartment.

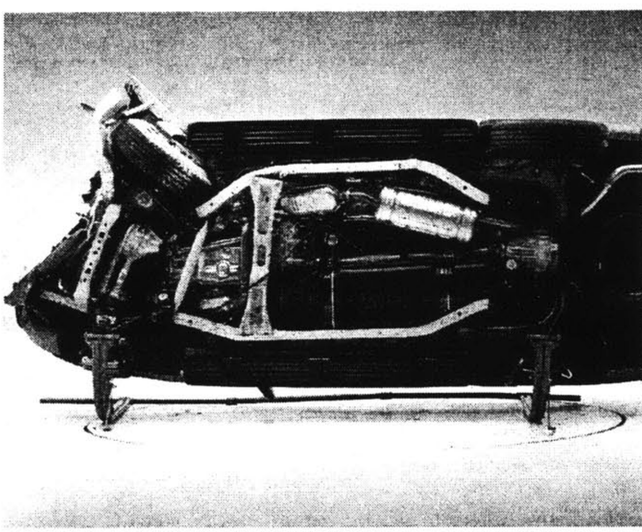


Figure a2.1

Figure a2.2

Figure a2.1 and a2.2 show the structural deformation after the impact. The crashworthiness performance is achieved through following critical components: frame, body, tire, door, bodyside, driver airbag, steering column, driver belts, and interior trims.

A-3. Side Barrier Impact

The objective of the tests is to show that vehicle provides minimal risk to severe injuries in case of a side impact crash. The concept behind all the side impact procedures is a moving deformable barrier impacting into a stationary subject vehicle. The US and European regulations specify different testing procedures, number of occupants, impacting barriers and injury metrics. The US requirements are based on the injuries induced by deceleration, and the European are based on the deformation of cabin, this drives different crash dummies. The unique testing procedures introduce additional complexity to the overall vehicle design. The safety teams overcome the design challenges with the inclusion of the latest safety technologies: airbag, energy absorbing foams and advanced trim materials.

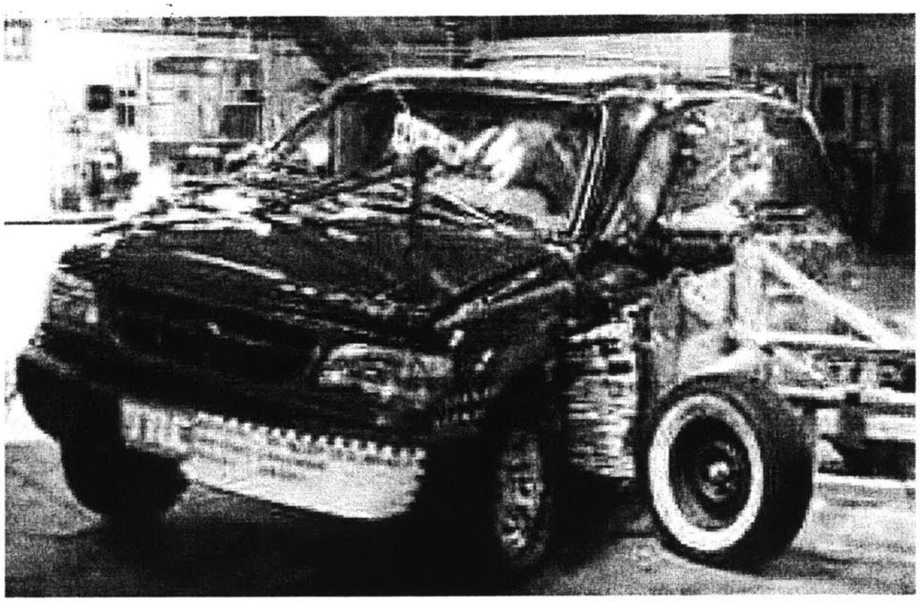


Figure a3.1

Figure a3.1 shows the US side impact procedure, where deformable barrier impacts at 33.5mph into the side of the subject vehicle. The critical components to meet the side impact requirements are: side/curtain airbag, seats, trim panels, doors, body structure, frame and suspensions.

A-4. Side Pole Impact

The side pole requirement is one of the most recent US regulations. The vehicle side is impacted into a 10" rigid pole at 18 mph. The rigid pole is aligned with the front occupant's head C.G. The objective of the test is to measure head injury performance of the front occupant. During the crash event, vehicle structure is subjected to an extreme localized loading condition. In result of such loading condition, vehicle structure exhibits higher deformation mode. Combination of various advance technologies and innovative design solutions are utilized to meet the test requirements.

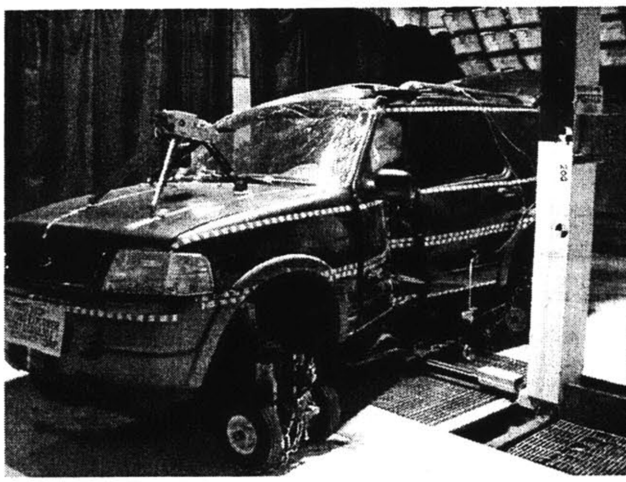


Figure a4.1

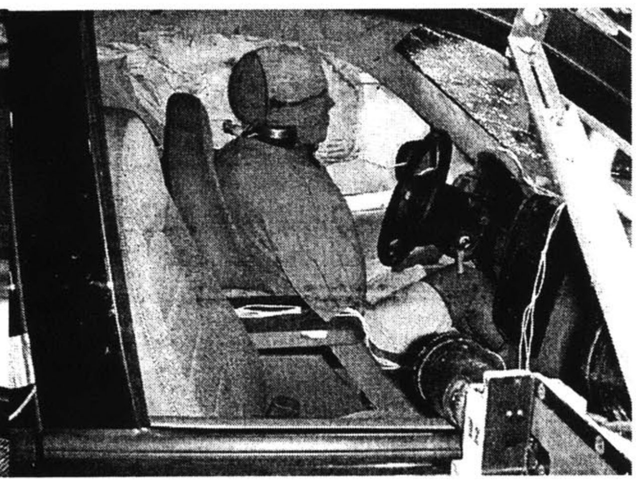


Figure a4.2

Figure a4.1 shows the deformation pattern of the vehicle after the impact, and figure a4.2 shows post crash occupant compartment with the deployed curtain airbag and crash dummy position. The critical components are similar to the side impact procedure, however, design strategy and solutions are different.

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