Demand Driven Side Impact Restraint System Development Method

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Abstract

This paper describes a demand driven product development method that applies a synergetic combination of numerical simulation and physical test techniques to guide the development of side impact restraint systems and associated simulation procedures and physical test devices.

Introduction

The motivation to improve product development methods that are used to develop and integrate restraint systems into vehicles originates from increasingly complex vehicle crashworthiness requirements (1) and market forces that relentlessly demand shorter development times and lower costs(2).

The consequential sharing of vehicle platforms and outsourcing and commoditisation of business processes (3) is highlighting the need to develop and then harmonise best practice product development methods. Indeed the harmonisation of development methods and the “thinking behind” product design are often cited as having a greater priority than harmonising the physical hardware itself(4).

The need to not only improve restraint system product development tools but how they are applied is recognised by both vehicle manufacturers(5) and restraint system suppliers alike(6).

Method Description

Method Overview

Advances in the capabilities of numerical simulation and physical testing have created new opportunities to improve the structure of product development activities. Rather than automate the traditional product development method by replacing physical tests with equivalent numerical simulations (7), the proposed method applies a combination of numerical simulation and physical tests that overcomes many of the traditional side impact restraint system design challenges that are experienced early in the product development cycle:

- Perform feasibility studies rapidly.
- Set functional vehicle and restraint system performance targets.
- Define component test specifications that can be used by vehicle manufacturers to out-source restraint systems yet leave the freedom to fulfil the desired design function in alternative ways.
- Define physical component tests that can be used to tune the restraint system towards vehicle system performance targets.

The method can also be used to create a product development project plan or to identify where to direct improvements to simulation procedures and test devices and provide a framework within which to harmonise them.

A virtue of the method is that although it is numerically intensive, it is not heavily dependent upon the physical equivalence of the restraint system numerical model and is therefore suited to applications where design specifics of the restraint system are difficult to simulate. The method is however heavily dependent upon the accuracy and physical equivalence of the occupant and vehicle crash environment numerical models and the formulation of valid physical component test specifications.

The overall philosophy of the method is demand driven both in terms of product design and product development and as such is not constrained by existing restraint system design types, simulation procedures or physical test devices. The method is applicable to current and future side impact loadcases and dummies and encompasses the entire product development cycle; from feasibility studies and target setting to physical full scale validation tests.

Benefits sought by the method are to:

- Invent and develop new and better side impact restraint systems faster, at lower cost and technical risk.
- Identify where to direct improvements to numerical simulation procedures and physical test devices.

Method Flowchart

The method consists of ten activities which are depicted by the flowchart in Figure 1. Feedback loops are omitted for simplicity.

Note that although the description of the method refers to side airbags, standard barrier loadcases and dummies by way of example, the method is applicable to other restraint system types, loadcases and dummies.

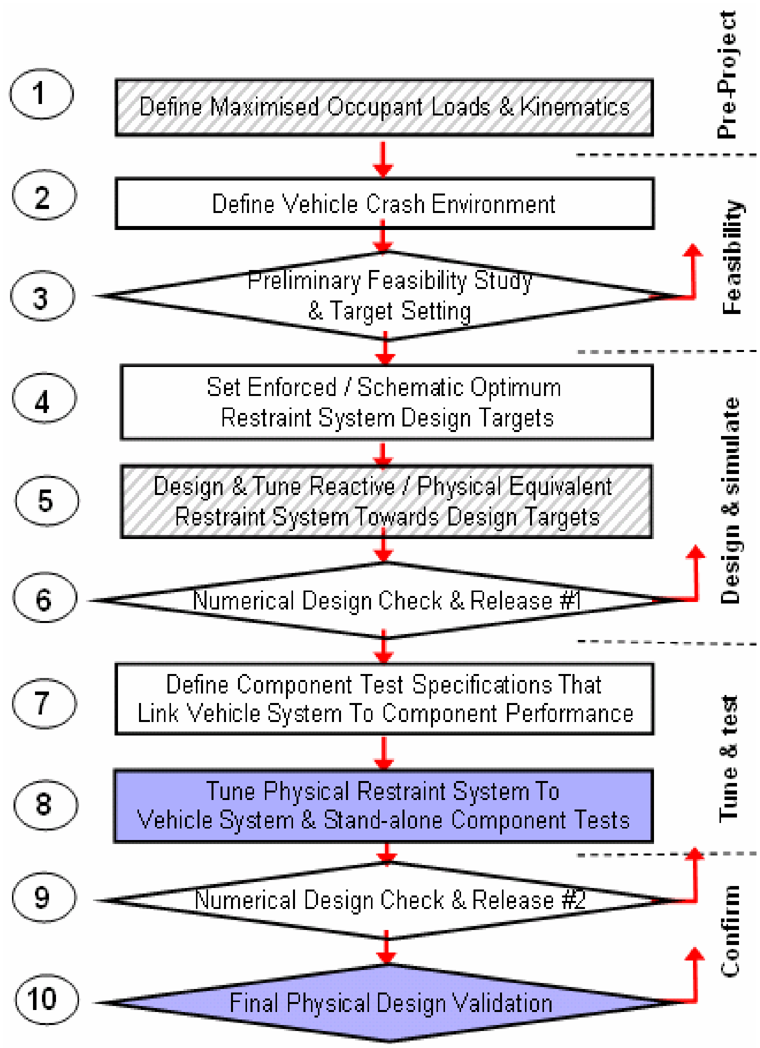

Figure 1: Method flowchart

Flowchart Definitions:

- Cross hatched boxes represent a mixture of simulation and physical test activities.
- Clear boxes represent numerical simulation activities.
- Solid boxes represent physical test activities.
- Diamond shaped boxes denote key milestones and where feedback loops originate.

Method Activity Summary

1 Identify the best ways to push occupants sideways without injuring them.

2 Define how the interior of the vehicle deforms during the side impact crash.

3 Check that it is theoretically possible to achieve the dummy injury targets by overlaying results from Activity 1 and 2 and estimate the required restraint system and vehicle performance targets.

4 Identify the restraint systems performance targets for each individual load case. *(e.g.: What behavior of the restraint system is required to achieve the dummy injury targets? What airbag pressure time history is required for each load case?)*

5 Design and tune the restraint system towards the performance targets across multiple load cases. *(e.g.: What does the detailed design of the restraint system look like that achieves the dummy injury targets? What airbag inflator and vent size gives good results across all load cases?)*

6 Check the design of the restraint system and if OK, release it for physical component testing. If the design is not OK then re-iterate Activity 5.

7 Define component tests that are linked to vehicle system performance. *(e.g.: Free fall, sled and enforced motion tests.)*

8 Using physical component tests that have the same boundary conditions as Activity 7, physically tune the design of the restraint system towards the responses obtained in Activity 7.

9 Correlate the restraint system model to the best physical restraint system design that was achieved in Activity 8 and then evaluate the performance of the restraint system model in complete vehicle crash simulations. If the results are OK, release the restraint system design for complete vehicle physical testing. If the design is not OK, re-iterate Activity 7 and/or 8.

10 Evaluate the physical restraint system in complete vehicle physical crash tests. If the restraint system design is OK, release it for detailed validation testing and series production. If the design is not OK, evaluate why and re-iterate activities as required. *(e.g.: Does the numerical simulation of the vehicle deform in the same way as the physical vehicle? If not then the restraint system needs to be re-tuned to the actual vehicle crash environment.)*

Method Detail

ACTIVITY 1: Define Maximized Occupant Loads & Kinematics

Purpose: Determine the applied loads and occupant kinematics associated with the fastest way to push occupants away from the intruding structure without exceeding a given set of injury criteria; *the best way to load the occupant.*

Scope: This activity encompasses combining numerical simulation and physical test dummy data with real life experience and practical design considerations to create a series of maximized occupant loads and kinematics(8). Both applied force and resulting displacement time histories, F(t) and x(t), are recorded at each dummy region of interest. Figures 2, 3 and 4.

During this activity a thorough understanding of side impact injury mechanisms is acquired that is useful throughout the entire development cycle, however the scope of this activity should keep the direct application of its quantitative results in Activity 3 and their redundancy thereafter in perspective; the quantitative results should not be over-worked.

Note that applying the maximum load to each individual body region does not necessarily result in maximized global translation of the exterior surface of the occupant therefore loads must be balanced over the occupant. E.g.: High loading of the pelvis can rotate the occupant about its fore/aft axis resulting in the shoulder rotating towards the door more than if a lower load were applied to the pelvis.

Limitations: The applied loads and kinematics are independent of the vehicle and side impact load case however are dependent upon occupant injury targets, occupant kinematic strategies and applied loading assumptions; in particular the assumed occupant loading contact areas.

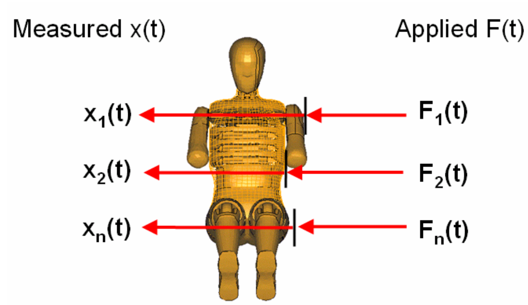

Figure 2: Determine $F_n(t)$ that maximizes $x_n(t)$ without exceeding injury targets

	Force [kN]	Crush Strength [KPa]
Shoulder	3.5	186
Thorax	3.0	131 - 137
Abdomen	3.0	96 - 117
Pelvis	8.0	241 - 448

Figure 3: Proposed forces and padding crush strengths for 50%ile cadaver (9)

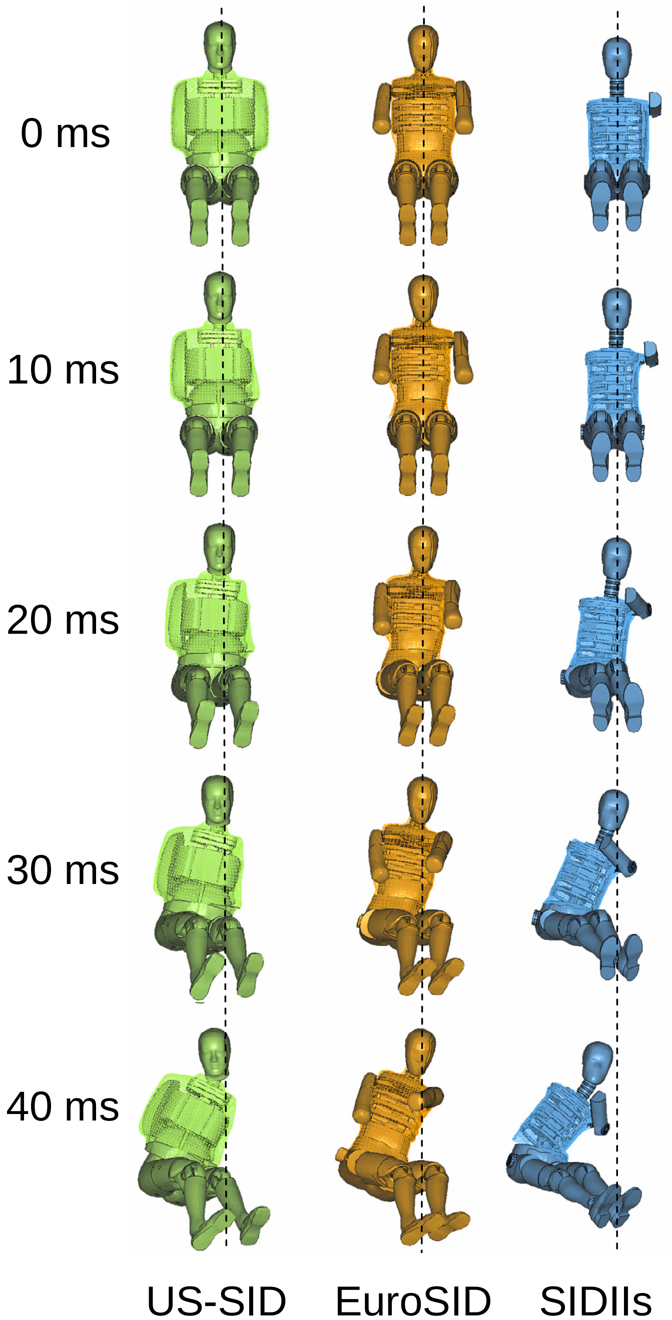

Figure 4: Maximized load dummy kinematics

ACTIVITY 2: Define Vehicle Crash Environment

Purpose: Define the geometry and dynamic intrusion of the vehicle near the occupant for each load case; *the vehicle crash environment.*

Scope: This information can be obtained from numerical simulation or physical test data. Alternatively vehicle crash environment dynamic intrusion targets can be derived from the dummy kinematics obtained in Activity 1; idealized intrusion targets being x(t) at each applied load dummy region multiplied by a softening function to allow for restraint system activation and utilization of the initial gap distance between the occupant and door-trim. A more detailed description on how to use the x(t) and F(t) together with partially known vehicle intrusion velocities to set vehicle and restraint system targets is described in Activity 3.

A lateral section through a typical vehicle crash environment is shown in Figures 5 and 6.

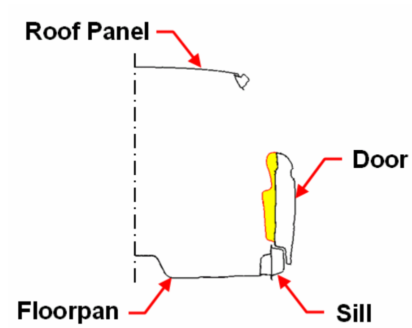

Figure 5: Lateral section through typical vehicle crash environment

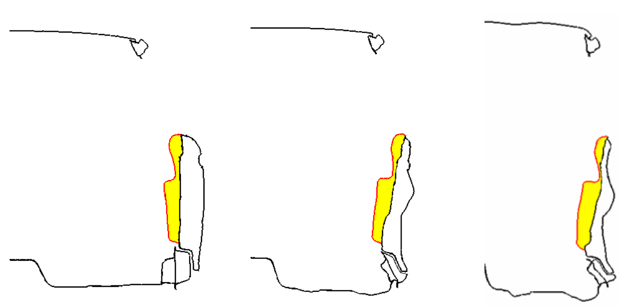

Figure 6: Vehicle crash environment: 3 time intervals

A number of vehicle crash environments exist *for each load case* due to variations in the vehicle crash environment that are caused by load case boundary conditions and vehicle design tolerances aa shown in Figure 7.

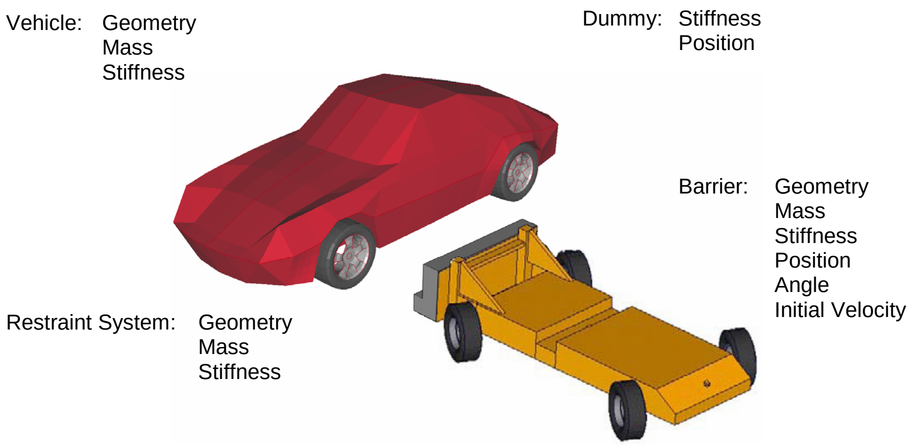

Figure 7: Typical sources of variations in the vehicle crash environment

The type and magnitude of variations are load case and vehicle dependent however side impact barrier location and initial velocity are highlighted as significant sources of variability in dynamic intrusions(10). Whilst considering these variations, the chaotic or stochastic nature of the vehicle crash environment and also the dummy and restraint system should be kept in mind. The Monte Carlo method is well suited to address this phenomena(11).

If the vehicle crash environment is obtained from numerical simulation data, a sub-structure model can be used to reduce the computing resources required to perform downstream activities and therefore make it possible to study a larger number of crash scenarios than would otherwise be the case. This involves running the complete vehicle model and recording the motion at the boundaries of the region of interest. The sub-structure model is then created by cutting the region of interest from the complete model and using the recorded motions to drive its boundaries.

The vehicle crash environment can embody geometry and intrusions for a single vehicle or for a number of vehicles. This is relevant if, for example, the design objective is to use one airbag across multiple vehicle platforms.

Limitations: It is crucial to obtain good vehicle crash environment data and understand its behavior (12) since it describes the environment in which the restraint system must operate and is tuned towards.

The influence that the dummy and restraint system has upon the behavior of the vehicle crash environment is not precisely quantified until the design of the restraint system and vehicle is finalized. The embodiment of these occupant / structure coupling effects must therefore be progressively updated and refined throughout application of the method.

ACTIVITY 3: Preliminary Feasibility Study & Target Setting

Purpose: Indicate if it is theoretically possible to achieve the dummy injury targets for each load case and estimate the required restraint system performance and associated vehicle crash environment targets; *restraint system and vehicle target sanity check.*

Scope: Overlay the dummy kinematics, Activity 1, with the vehicle crash environment, Activity 2, see Figure 8. If the intruding vehicle crash environment does not contact the dummy then it is possible to implement a restraint system that will enable the injury criteria to be achieved and vice versa. This process indicates the location and magnitude of limiting dummy and vehicle crash environment regions, enables rapid "what-if" studies for restraint system activation timing, see Figure 9, and by visual inspection and gap closure analysis provides a basis upon which a restraint system concept can be proposed.

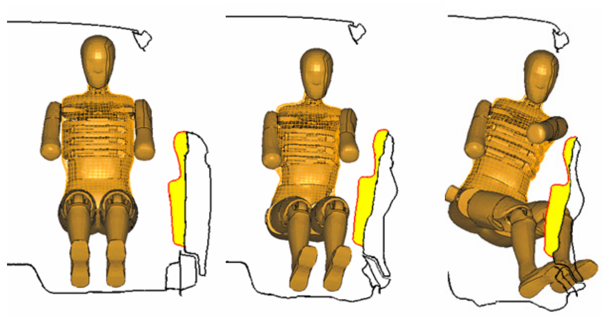

Figure 8: Maximized load dummy kinematics overlaid with vehicle crash environment

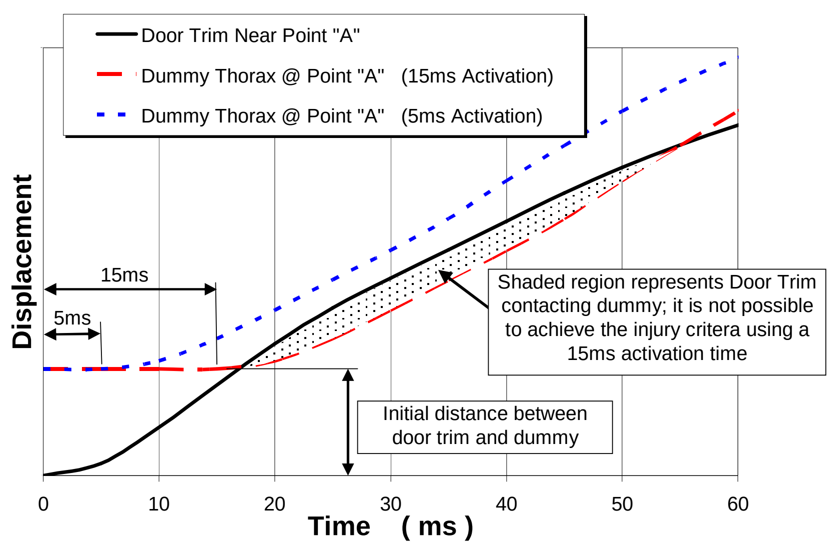

Figure 9: Maximized dummy and door trim displacement versus time for two restraint system activation times

Furthermore a preliminary estimate of required restraint system performance can be made by using F(t) and x(t) from Activity 1 and 2 to calculate, for example, an average restraint system stiffness for an average occupant to door trim closing rate. If rate effects are neglected then the required restraint system performance can be expressed as a force versus displacement function, the area under which describes the energy absorption of the restraint system. This energy is equivalent to the *change* in pressure versus volume that a side airbag must experience.

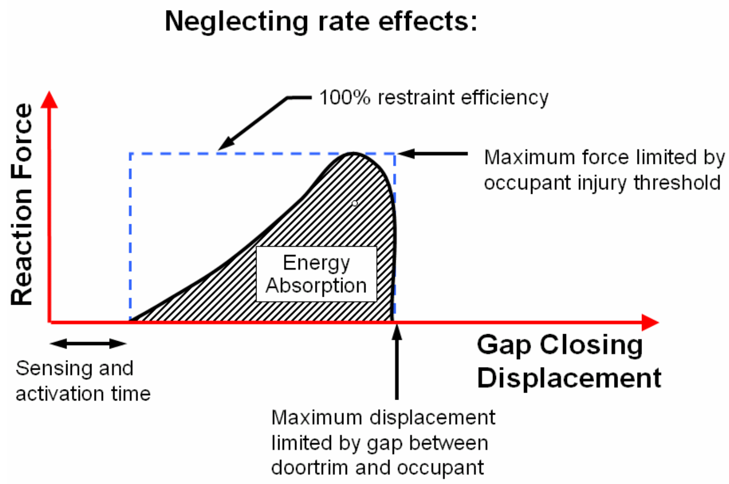

Figure 10: Restraint system reaction force versus gap closing displacement

It is also possible to use this information to express the required restraint system performance for each region of the dummy and each load case in terms of damping functions as shown in Figures 11, 12, 13, and 14.

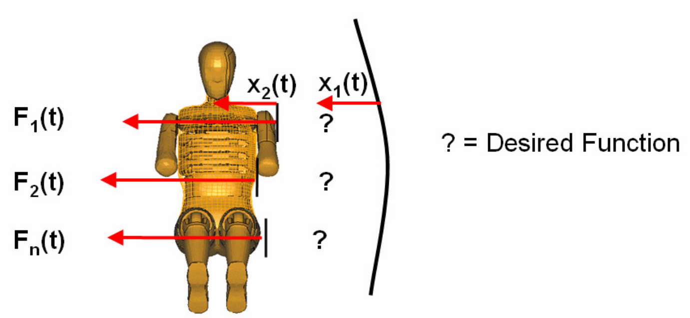

Figure 11: Known force and displacement time histories F(t) and x(t)

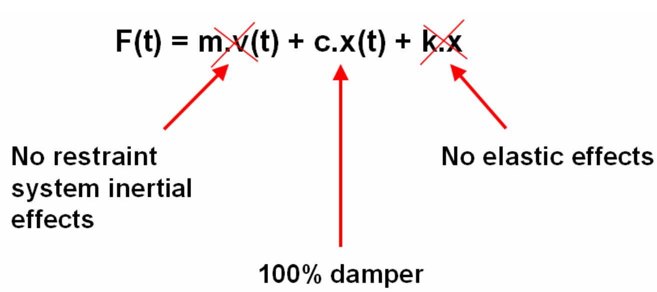

Figure 12: Equation of motion from which damping function is derived

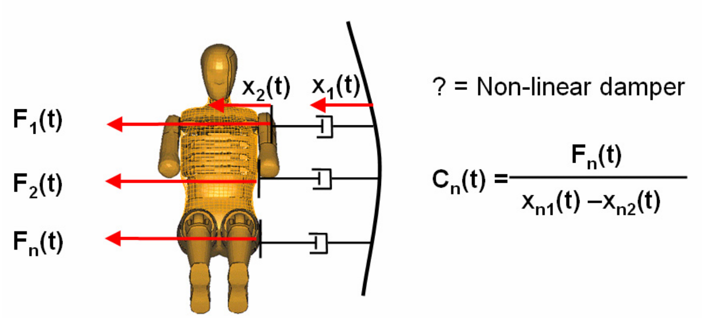

Figure 13: Desired restraint system performance expressed as a non-linear damper

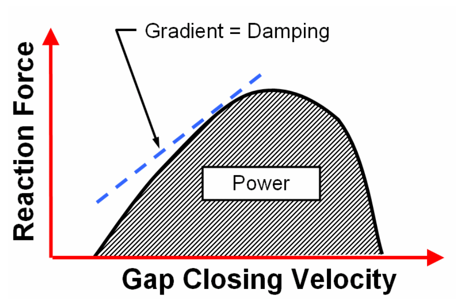

Figure 14: Restraint system damping function

The damping functions can be used to set preliminary vehicle intrusion targets. E.g.: Determine the intrusion $x_1(t)$ required at region "A" given that the same restraint system has been prescribed at region "B".

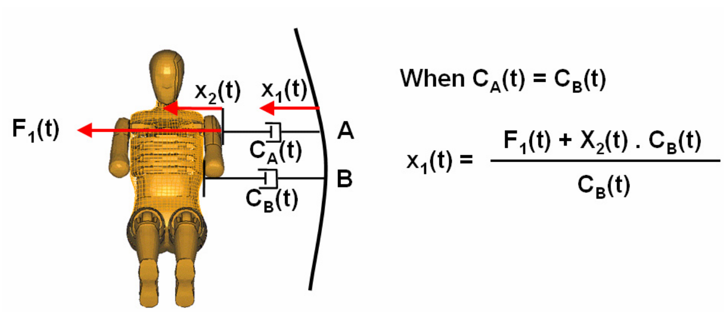

Figure 15: Determine the target intrusion velocity at region "A" given the same restraint system exists at region "B"

Similarly, for a prescribed restraint system in load case "X" determine the structural intrusion targets required to fulfill load case "Y" shown in Figure 16. Preliminary damping functions can be created and used to set vehicle intrusion targets that maximize the possibility that one restraint system can be implemented that satisfies multiple load cases.

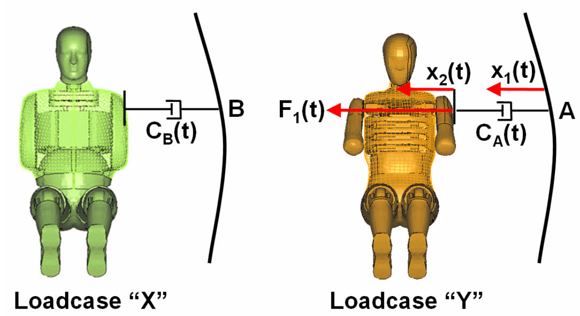

Figure 16: Determine the target intrusion velocity at region "A" in load case "Y" given the same restraint system is prescribed at region "B" in load case "X"

Limitations: It is highlighted that although overlaying the dummy kinematics with the vehicle crash environment is a sound and rapid process, it is subject to many assumptions, particularly those carried over from Activities 1 and 2, with the consequence that such a study can at best indicate tendencies rather than provide definitive results. Furthermore, the study only indicates if the injury targets that were used in Activity 1 can be fulfilled; not the best injury criteria that can be achieved for a particular vehicle crash environment.

Although preliminary estimates of restraint system performance and vehicle targets can be made, practical application of restraint system stiffness and damping functions to set detailed vehicle targets and guide the detailed design of the restraint system is problematic since such simple and abstract representations do not account for the complex interactions that occur during the crash event.

It is useful however to formulate the restraint system design objective as these types of simple mathematical expressions in order to create "ballpark" estimates of performance targets and maintain a demand driven line of thought while generating possible design solutions. Eg: "Aim to achieve the same occupant load, F(t), for a range of dynamic intrusions, x(t)" leads to the notion of a rate independent load transmitting device which could be embodied as, for example, an airbag with internal pressure dependent venting.

ACTIVITY 4: Set Enforced / Schematic Optimum Restraint System Design Targets

Purpose: Define enforced optimum in-vehicle design targets for each of the restraint systems design properties for each individual load case; *set ideal performance targets.*

Scope: Enforcing the design properties to behave in a prescribed manner regardless of their interaction with the vehicle crash environment enables optimum responses to be quickly obtained for each individual load case.

The enforced characteristics can be constrained within current performance envelops or left unconstrained to identify functional targets that can be used to guide the invention of future restraint system devices. Figure 17.

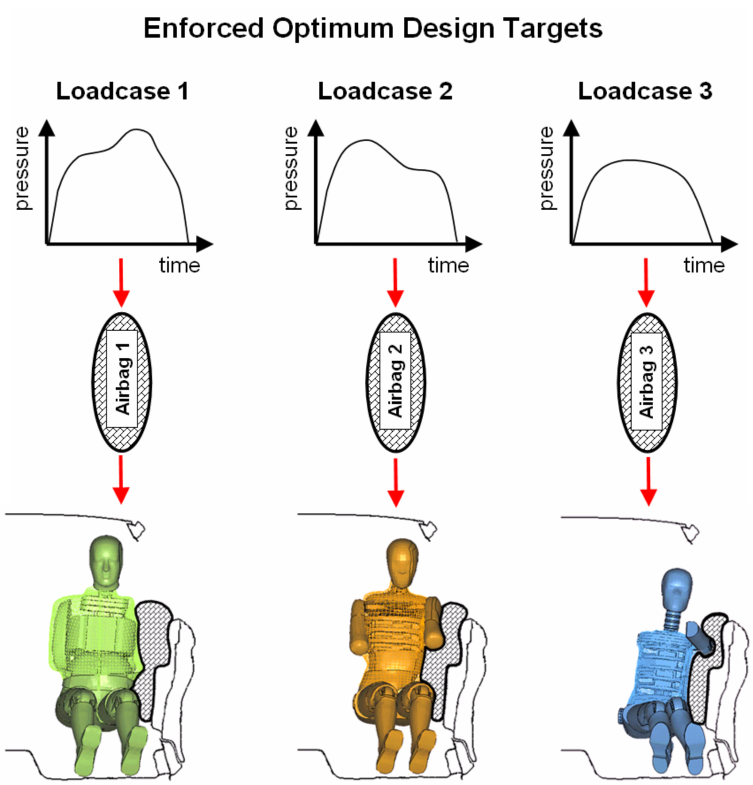

Figure 17: Enforced optimum internal airbag pressure for each individual load case

Since *unenforced* design properties are typically not used as tuning parameters and are unlikely to change from one project to the next, obtaining their accurate and physical equivalent values has a lasting effect on improving the numerical model and reducing overall technical risk. Airbag fabric stiffness is a good such example since it is not typically used as a tuning parameter yet significantly influences the response of the airbag both in terms of initial pressure and deflation rate.

Limitations: This activity relies heavily upon the accuracy and physical equivalence of the vehicle and dummy numerical models and is particularly sensitive to those entities that interact directly with the restraint system. Although the accuracy of the enforced restraint numerical model is implicit, it's conversion to a reactive numerical model in Activity 5 is simplified if its unenforced design properties are accurate and physically equivalent.

ACTIVITY 5: Design & Tune Reactive / Physically Equivalent Restraint System Towards Design Targets

Purpose: Define reactive design properties that aim to fulfill the optimum vehicle performance targets across multiple load cases; *tune the restraint system towards the ideal performance targets.*

Scope: Allowing the design properties to react in a realistic manner with the vehicle crash environment enables one restraint system design to be tuned across multiple load cases, see Figure 18.

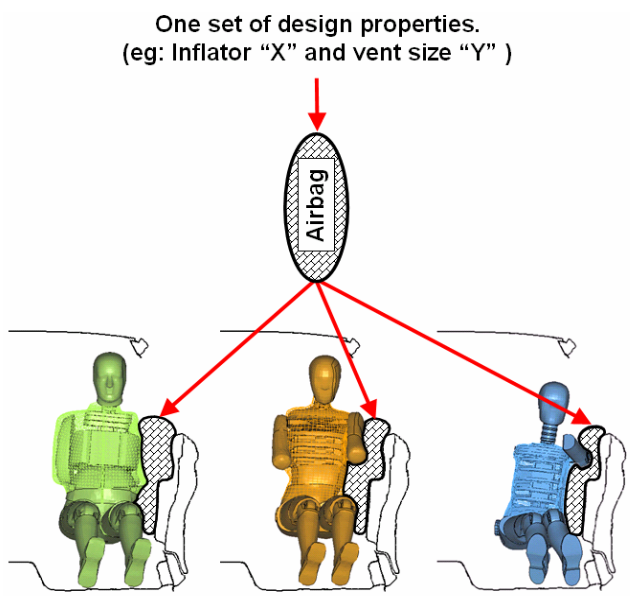

Figure 18: One airbag design that fulfill targets across multiple load cases

If during this activity one restraint system design that satisfies all load cases cannot be found, the dimensioning load cases, associated vehicle crash environment behavior and required type of adaptive restraint system design properties are able to be identified.

The process of finding one restraint system that satisfies all load cases can be automated by using the optimal design targets for each of the restraint systems design properties that were derived in Activity 4 as objective functions in a numerical optimization scheme. E.g.: Tune airbag venting towards airbag internal pressure. This is less complex than the traditional procedure of tuning individual design properties such as airbag venting across multiple dummy injury criteria.

The scope of this activity encompasses the simulation and cross checking of restraint system performance across both vehicle system load cases and stand-alone component load cases such as OOP, overload, etc.

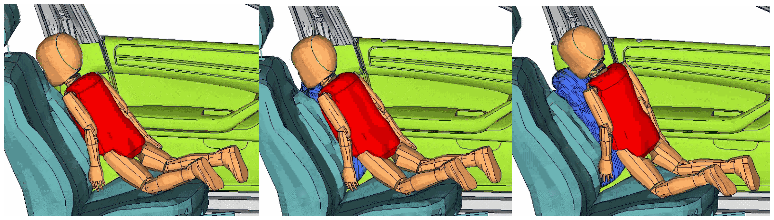

Figure 19: Typical simulated standalone component load case; OOP; 3 time intervals

Limitations: Physical tests of individual design properties may be required to ensure that their simulated responses are realistic. Although the simulated design properties must respond in a realistic manner they do not need to be physically equivalent since as it will be shown in Activity 7, it is the overall functional response of the restraint system that is important. However the more physically equivalent the design properties are, the lower the risk is of creating an invalid component test specification in Activity 7 and the closer the first version of the physical prototype will be to satisfying the component test performance targets in Activity 8.

ACTIVITY 6: Numerical Design Check & Release #1

Purpose: Numerically check that the restraint system satisfies all performance requirements and release its first detailed design specification; *check the restraint system before manufacturing physical prototypes.*

Scope: For practical reasons a number of design, model and load case simplifications may have been made during previous activities that at this point should be redressed.

For example:
- Replace enforced sub-structure boundary conditions with reactive boundary conditions.
- Update the design status of the vehicle crash environment if it was “frozen” during preceding activities.
- Consider a broader range of vehicle system and standalone load cases and associated tolerances.

This activity represents a significant milestone since at this point the best design of the restraint system based primarily upon numerical simulation is achieved and physical prototypes can be ordered for component testing.

Limitations: The restraint system design specification is yet to be confirmed via physical component and vehicle physical testing.

ACTIVITY 7: Define Component Test Specifications That Link Vehicle System to Component Performance

Purpose: Define physical component test specifications that will be used to physically tune the design properties of the physical prototype towards the vehicle system performance targets; *define "vehicle system linked" component tests.*

Scope: The component test specifications are created by extracting the reactive restraint system model from the vehicle system model and subjecting it to a *series* of carefully derived component tests. The boundary conditions and measured responses constitute the physical component test boundary conditions and performance targets respectively. This activity therefore creates the link between the numerical model and physical component and also the vehicle system and component tests, see Figure 20.

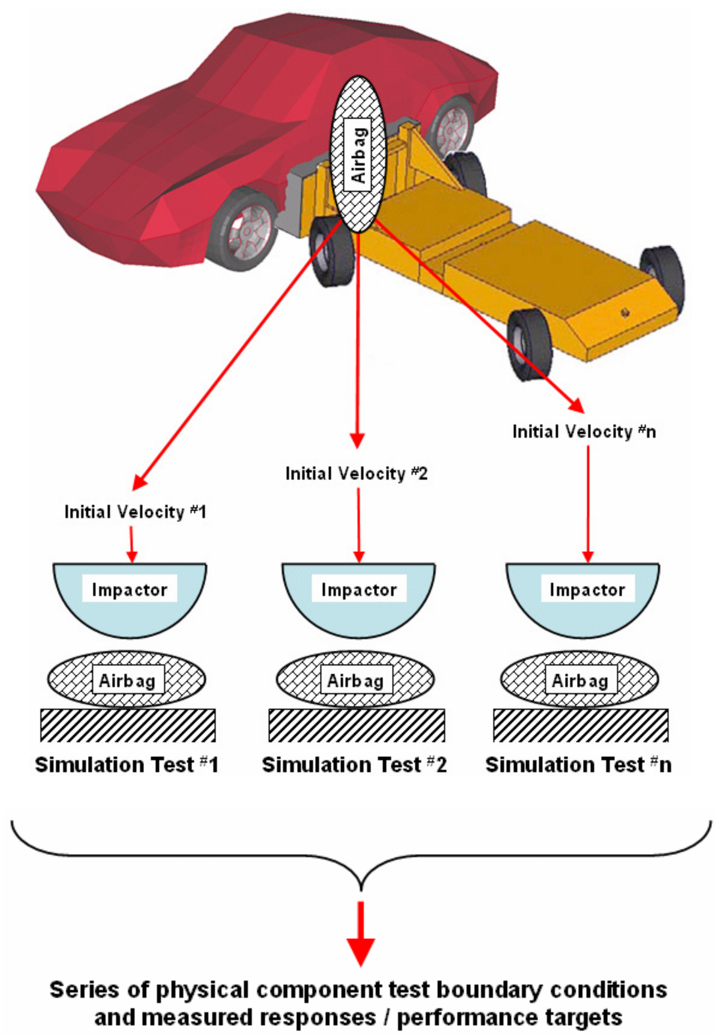

Figure 20: Restraint system model extracted from vehicle system model and subjected to a series of component tests

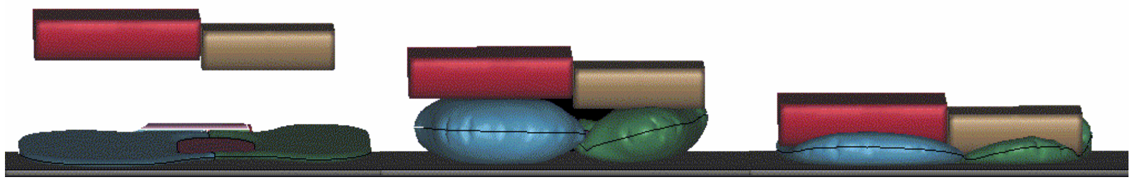

Figure 21: Typical simulated component test; 3 time intervals

Only the component test boundary conditions and performance targets are carried into the physical tuning phase; the design and numerical model of the restraint system is effectively discarded after it has been used to set the component test specifications. This trait implies that up to this point the numerical model of the restraint system does not have to be physically equivalent and underscores the importance of the component test specification.

The component tests must embody the type and range of typical vehicle system interactions between the restraint system and its surroundings and activate each design feature. More specifically for side airbags, aim to reproduce the same deformation rates, (e.g.: gap closing velocities), and reaction force time histories over discrete regions of the restraint systems surroundings. Rather than overwork the pursuit of one all-encompassing component test, a number of component tests involving variations such as impactor speed, shape, location and direction are required.

Some examples of side airbag component tests are shown below in Figures 22, 23 and 24 and discussed in more detail in Appendix I.

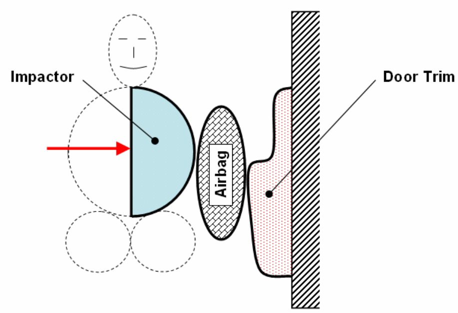

Figure 22: Typical Free Fall Test

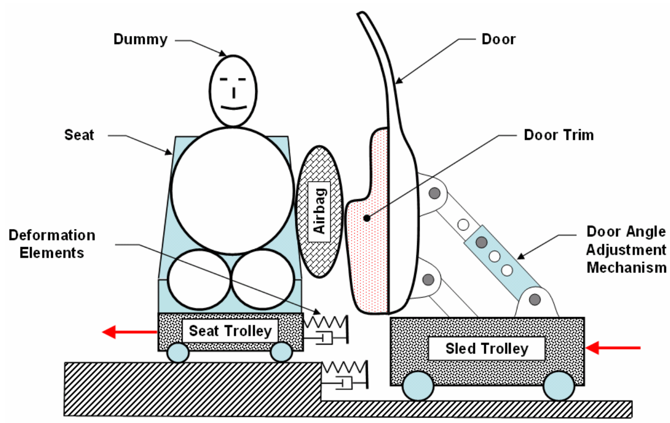

Figure 23: Typical Sled Test

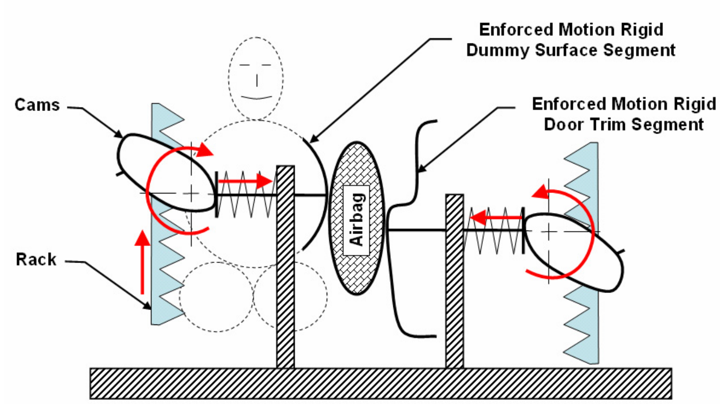

Figure 24: Enforced Motion Test; OWEN Rig(13)

The closer the component test boundary conditions emulate the vehicle system, (component test system fidelity), the less risk there is of neglecting important phenomena and creating an invalid component test. However increased component test system fidelity usually equates to increased component test complexity that must be balanced against the need for fully dimensioned, (able to be simulated precisely), repeatable and cost effective physical tests.

The component test measured responses, which in turn become the component performance targets, should primarily be attributes that are directly related to the overall functional response of the restraint system; what the restraint system feels over discrete regions of its surface as it interacts with its surroundings rather than responses of the restraint systems internal design properties. In particular, performance targets should not set on internal design properties that for the same value can have different overall functional responses. E.g.: Airbag internal pressure is not a good performance target since airbag's with the same internal pressure and occupant contact areas do not necessarily impart the same reaction forces to the occupant. (If the airbag extends beyond the occupant contact area membrane effects increase the force that is transmitted.) Similarly whilst airbag mass outflow implies correct volume change and deflation rate the volume *shape change* may be different and impart different reaction forces. Likewise, impactor acceleration implies correct overall reaction forces however does not discriminate between different reaction force distributions.

Airbag internal pressure, airbag mass outflow and impactor acceleration are therefore all at best secondary responses that should be monitored and used to guide the tuning of individual design properties towards the overall functional performance targets. They should not be used as performance targets since they do not necessarily relate to how the reaction forces are applied to the occupant. It is imperative to focus upon what the restraint system feels as it interacts with its surroundings both when setting the component test specifications and when correlating the numerical model towards the physical tests in Activity 9.

The component test specifications can be used by vehicle manufacturers to out-source the development of restraint systems. Since the specification is based upon a functional response, (eg: provide a device that transmits forces in a certain way when subjected to certain boundary conditions), it provides clear performance goals yet leaves the freedom to fulfill the required function in alternative ways; it does not matter what the restraint system is, as long as it transmits the forces in the desired way.

<u>Limitations</u>: This is the highest risk activity in the entire method; both in terms of having the highest probability of error and severity of outcome. It is crucial to define valid component test specifications since they are absolutely relied upon to physically tune the restraint system in Activity 8. In light of this requirement, the significance of the enforced motion rig is highlighted.

A *series* of component tests must be carefully formulated for each restraint system and vehicle project to ensure that the type and range of typical vehicle system interactions are captured. Although many component test boundary conditions can be standardized the component test performance targets will always be vehicle dependent.

The component test specifications require a high level of knowledge and experience to formulate and their validity cannot be *numerically* confirmed until after they have been used to physically tune the physical prototype. Furthermore they are not *physically* confirmed until the complete vehicle physical crash tests are performed during the final stages of development.

ACTIVITY 8: Tune the Physical Restraint System to Vehicle System & Stand-Alone Component Tests

<u>Purpose</u>: Tune design properties of the physical restraint system towards vehicle system performance targets using the component tests derived in Activity 7 and cross check that stand-alone performance targets are met; *physically tune the restraint system using physical component tests.*

<u>Scope</u>: The physical prototypes of the restraint system are subjected to the vehicle system component test boundary conditions derived in Activity 7 and their design properties are tuned towards the component test performance targets, see Figure 25.

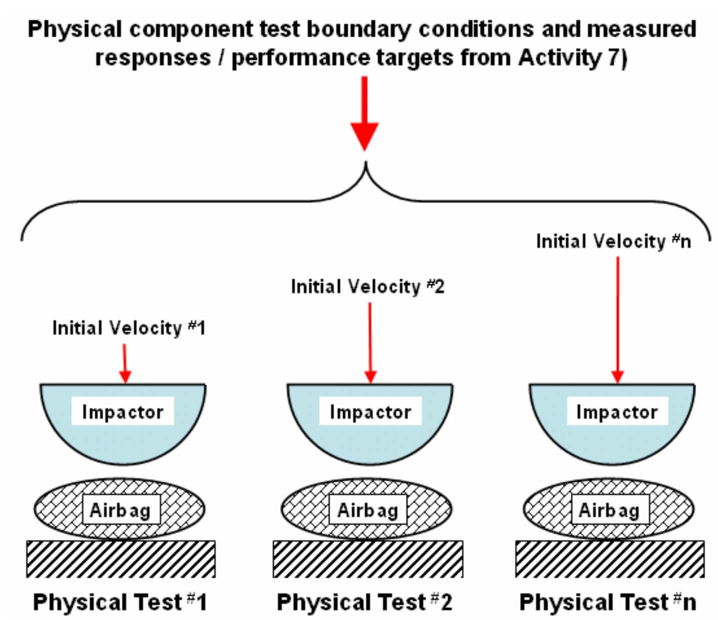

Figure 25: Series of physical component tests with identical boundary conditions to those simulated in Activity 7

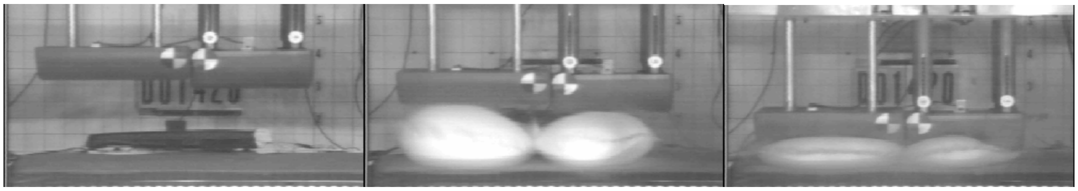

Figure 26: Typical physical component test; 3 time intervals

The design of the restraint system does not have to be the same as the numerical model however it must respond in the same way. Recall that the component test specifications provide clear performance goals yet leave the freedom to fulfill the required function in alternative ways; it does not matter what the restraint system is, as long as it transmits forces in the desired way. Alternative restraint system designs that achieve the component test performance targets can be evaluated and invented by means of physical testing during this activity.

The scope of this activity encompasses the testing and cross checking of restraint system performance across both vehicle system load cases and standalone component load cases such as OOP, overload, etc.

Figure 27: Typical physical standalone component load case: OOP; 3 time intervals

Limitations: This activity is heavily dependent upon the validity of the component test specifications.

If the physical component performance targets are not precisely met, it is not known what level of vehicle system performance has been achieved by the restraint system. These two limitations are addressed using numerical simulation in Activity 9.

ACTIVITY 9: Numerical Design Check and Release #2

Purpose: Numerically check that the restraint system satisfies all vehicle system performance targets and release its second detailed design specification; *update and correlate the restraint system model to the physical component tests and check its performance in complete vehicle simulations.*

Scope: Update, refine and correlate the numerical model of the restraint system to the best physical restraint system design that was achieved in Activity 8. The correlation should ensure that the applied boundary conditions are identical in both the numerical simulations and physical tests and then focus upon tuning the numerical models to the overall functional response targets, (e.g.: airbag gap closure rates and/or reaction force time histories), whilst monitoring secondary responses, (airbag internal pressure, mass flow and impactor acceleration).

Since the main purpose of this activity is to evaluate the response of the physical restraint system in numerically simulated vehicle tests, the numerical model does not have to be physically equivalent. However given the ready availability of physical test data from Activity 8, and that the more physical equivalent the numerical model is the lower the subsequent technical risk, it is during this activity that the most effort should be expended in making the numerical model of the restraint system physically equivalent.

The functional accuracy of the numerical model should be based upon how well it reproduces the overall functional response targets. Tuning response targets independently of one another is intuitive, (e.g.: reaction force versus time and gap closing velocity versus time), however cross plotting them enables the models accuracy to be expressed as a single function, (e.g.: reaction force versus gap closing velocity).

Furthermore if the boundary conditions and primary performance targets are accurately reproduced, Figure 28, a measure of the physical equivalence of the numerical model, (or a measure of all the other errors in the model combined, such as leakage, fabric stiffness, thermal effects, etc.), can be expressed in terms of any of the restraint systems internal secondary responses that are able to be physically measured, see Figure 29.

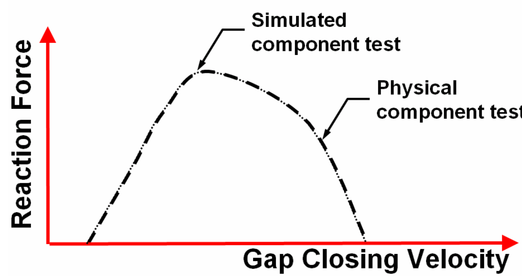

Figure 28: Functional accuracy expressed as reaction force versus gap closing velocity for numerical and physical restraint system

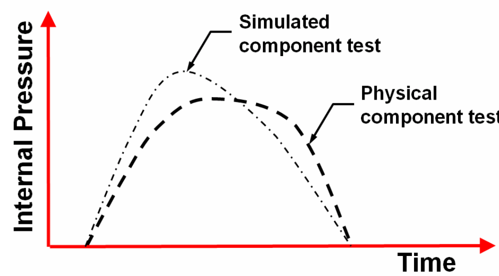

Figure 29: Physical equivalence between numerical and physical restraint system expressed as internal airbag pressure versus time

Confidence in the numerical model can therefore be expressed in two ways:

Functional Accuracy: How well it reproduces the overall response of the physical restraint system.

Physical Equivalence: How well it reproduces the restraint system's internal secondary responses.

After the numerical model of the restraint system is correlated to the physical tests, it is implemented into the vehicle system model and evaluated against all vehicle system performance requirements, see Figure 30.

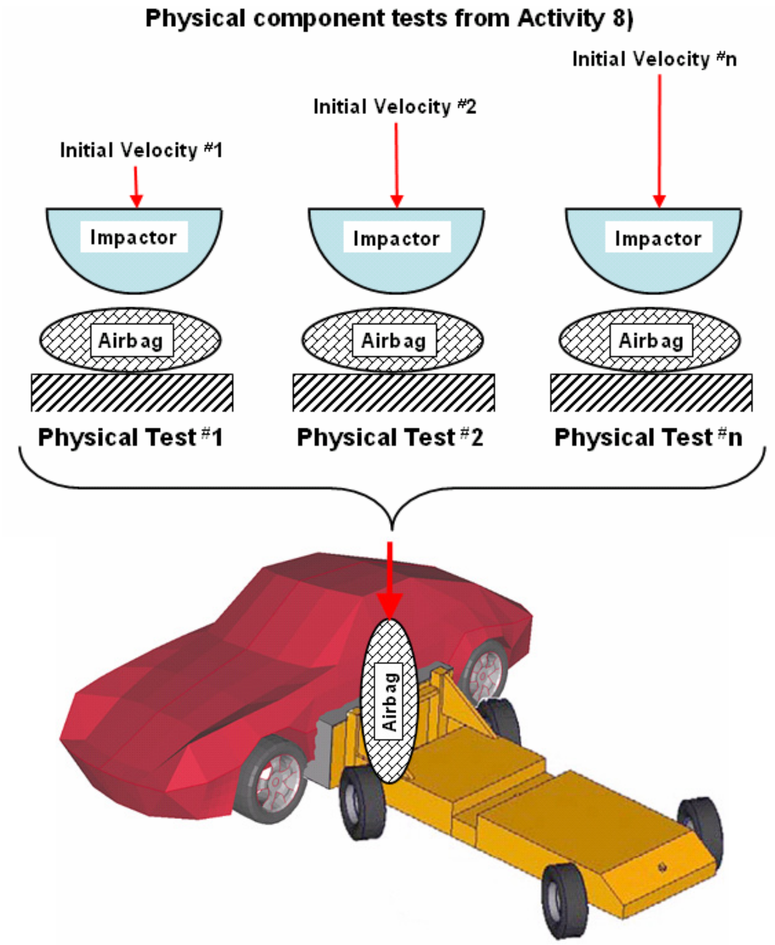

Figure 30: Airbag model correlated to physical component tests and then evaluated in vehicle system models

During this activity the dimensioning load cases that define the performance extremes of both the occupant and restraint system are able to be identified.

It is not necessary to numerically simulate the stand-alone component load cases since the restraint system was physically ratified against them in Activity 8.

This activity represents a significant milestone since the best design of the restraint system based upon both numerical simulation and physical component testing is achieved and physical prototypes can be ordered for final vehicle system validation testing.

Limitations: Although at this point the restraint system has passed all physical component tests, (both vehicle system linked and stand-alone), its ability to fulfill vehicle system requirements is completely based upon numerical simulation data.

ACTIVITY 10: Final Physical Design Validation

Purpose: Physically check that the restraint system satisfies all vehicle system requirements and release its final detailed design specification; *physical full scale vehicle crash tests.*

Scope: Install the physical restraint system into the physical vehicle and perform all vehicle system crash tests. It is not necessary to perform the standalone component tests since this was done with the same version of the restraint system design in Activity 8.

The dimensioning load cases identified in Activity 9 can be used to reduce the number of vehicle system physical tests.

Results from all simulations and equivalent physical tests should be compared and if required, used to refine the design of the restraint system. The same information can be used to improve numerical simulation and physical test methods for future projects.

This activity represents a significant milestone since the restraint system design specification can subsequently be released for extensive pre-production testing.

Limitations: This activity occurs late in the development process, is expensive and time consuming and typically only considers the nominal design and boundary conditions.

Figure 31: Typical physical vehicle system test; 3 time intervals

Conclusion

This paper has described a demand driven product development method that guides the development of side impact restraint systems early in the development cycle and identifies where to direct improvements to associated simulation procedures and physical test devices.

Key features of the method:

- Provide the logic for restraint system product development project plans.
- Provide a framework in which to harmonise simulation procedures and test devices.
- Perform preliminary feasibility studies rapidly.
- Define vehicle crash environment targets based upon maximised occupant loads and kinematics.
- Define optimum restraint system performance targets that can be used to guide the development of commercial restraint systems or invent future restraint systems.
- Define component test specifications that can be used by vehicle manufacturers to out-source restraint systems yet leave the freedom to fulfil the desired design function in alternative ways.

- Define component test specifications and associated test devices that enable design properties of the restraint system to be physically tuned towards vehicle system performance targets using physical component tests.
- It is not heavily dependent upon the physical equivalence of the restraint system numerical model and is therefore suited to applications where the design of the restraint system is difficult to simulate.

Critical requirements of the method:
- Accurate and physically equivalent vehicle crash environment and dummy models.
- Physical component test specifications that embody the type and range of typical vehicle system interactions between the restraint system and its surroundings and measure the functional response of the restraint system.

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Definitions, Acronyms, Abbreviations

Occupant: Human.

Dummy: Anthropomorphic device.

Simulation: Numerical calculation.

Test: Physical test.

OOP: Out of position.

Enforced Model: Design properties are forced to behave in a prescribed manner regardless of their interaction with their surroundings. e.g. Airbag internal pressure is forced to follow a prescribed pressure time history regardless of its interaction with its environment.

Reactive Model: Design properties are free to react in a physical manner with their surroundings. e.g:. Airbag internal pressure is influenced by the airbags interaction with its environment.

Physically Equivalent Model: Design properties of the numerical model are directly comparable to those of the physical component. e.g.: Airbag leakage is defined by a similar size vent hole in the numerical model and physical component.

Physically In-equivalent Model: Design properties in the numerical model are not directly comparable to those of the physical component. e.g.: An airbag vent hole does not exist in the numerical model; leakage is defined by some other method.

Vehicle Crash Environment: Initial geometry and motion of all components that the restraint system and occupant interact with during the crash event.

Functional Target: Not concerned with how design features perform their tasks. E.g.: Not what they look like, but what they do.

Detailed Design Specification: Explicit definition how design features perform their tasks. E.g.: What they look like.

Dimensioning Load Cases: Load cases that define performance extremes. E.g.: Worst case, governing, dominant or critical load cases.

Vehicle System Load cases: Full scale barrier side impact tests.

Vehicle System Component Tests: Component tests that are linked to the vehicle system and therefore enable design properties of the restraint system to be physically tuned towards vehicle system performance targets.

Stand-alone Component Load cases: Component load cases that provide design ratification in their own right. E.g.: OOP, overload, etc.

Occupant Kinematic Strategy: The interpretation of occupant injury criteria and overall desired motion of the occupant. E.g.:

> *Legal:* Fulfill legal injury criteria.
> *Ideal:* Fulfill legal injury criteria and "real life" considerations. E.g.: Maintain spine vertically aligned in saggittal plane to reduce lumbar spine loads.
> *Unconventional:* Fulfill legal injury criteria however exploit crash test dummies lack of biofidelity. E.g.: Transmit loads through non-instrumented regions.

Appendix I: General Dynamic Component Test Specification Guidelines

Free Fall Tests

Free fall tests encompass those tests where an impactor is given an initial velocity, released and other than some form of directional guiding mechanism, is not restrained by the test rig. E.g.: Drop, pendulum and linear impact tests.

Unless the vehicle crash environment of the restraint system is indeed the same as a "free fall" dynamic impact test, then the free fall test requires gap closure rates and/or reaction force time histories to be compromised: they are not the same as the vehicle crash environment.

Figures 32 and 33 depict a traditional and improved "free fall" dynamic impact test respectively. The distinguishing feature of the improved test is that reaction forces and closing velocities are measured over discrete regions.

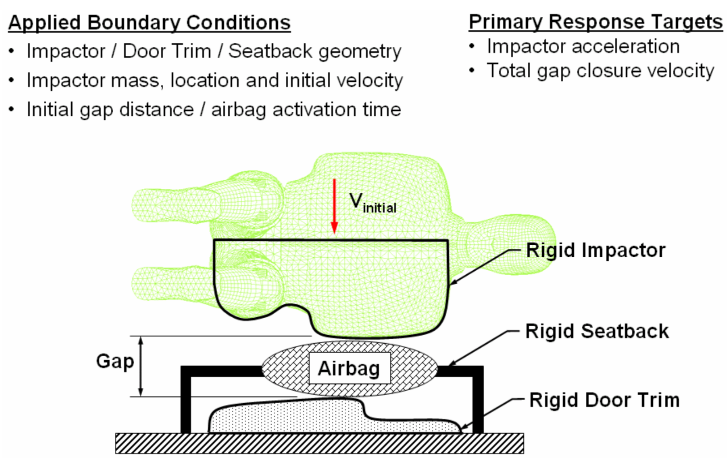

Figure 32: Traditional "free fall" dynamic impact test

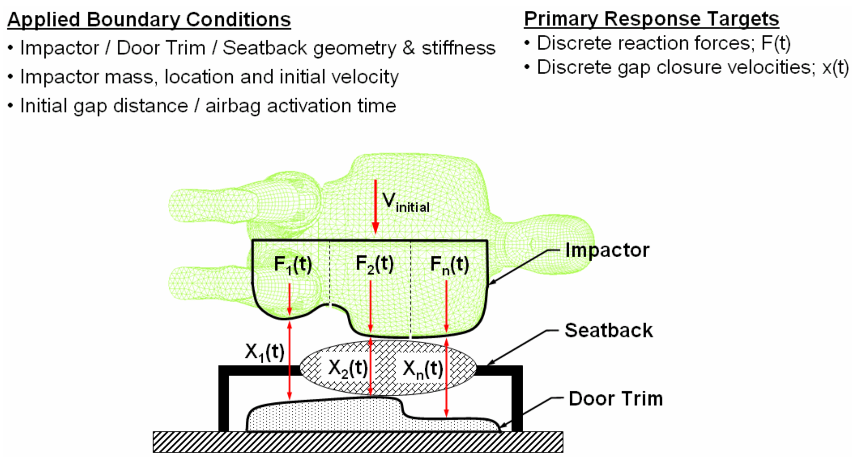

Figure 33: Improved "free fall" dynamic impact test

How well the component test boundary conditions emulate the vehicle system, component test system fidelity, can be quantified by comparing reaction force time histories versus gap closure rates for both the component test and vehicle system, see Figure 34.

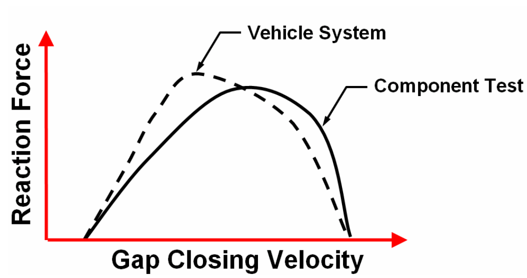

Figure 34: Reaction force versus closing rate for airbag in vehicle and airbag in component test.

Recall that rather than pursue one all-encompassing component test, it is better to define a number of component tests to ensure that the range of boundary conditions and responses are captured.

In the case of a "free fall" dynamic impact test, two classes of boundary conditions can be created. One set aspiring to reproduce the same gap closure rates that the airbag experiences in the vehicle and the other set aspiring to reproduce the same reaction forces. A trial and error approach is required to set these boundary conditions however initial values for the impactors mass and initial velocity can be derived from contact force time histories applied to the airbag in the vehicle system.

From Newton's 2nd Law, equation (1), it can be seen that the impulse of force is equal to change in momentum.

$$F = ma = m\frac{dv}{dt} \qquad eq\ (1)$$

$$I = Fdt = mdv$$

So for an impactor striking an airbag, the product of the impactors mass and initial velocity equates to the reaction force on the impactor integrated as a function of time.

$$I = mv_{contact} = Fdt$$

The same total impulse can therefore be applied by an infinite combination of impactor mass and initial velocities, or, for a given impactor mass there is only one initial velocity that will apply the same total impulse in the component test as that applied to the airbag in the vehicle.

Sled Tests

Sled tests have the potential to reproduce the vehicle crash environment more accurately than free fall component tests however still approximate the vehicle crash environment and therefore have similar trade-offs between gap closure rates and reaction forces. (Tuning the restraint system to work in a sled does not lead to a restraint system that will work in the vehicle unless the sled truly reproduces the vehicle crash environment.)

Even if the sled tests cannot reproduce the vehicle crash environment accurately they still are useful in the context of this method provided that they are fully dimensioned, (able to be simulated precisely), and repeatable. However if they are not fully dimensioned and repeatable, then using them to tune the restraint system is risky since not only is the vehicle crash environment approximated, the response measurements are confounded; it is not known which design feature contributed to the overall response nor how. In this situation the free fall test or ideally an enforced motion test should be used.

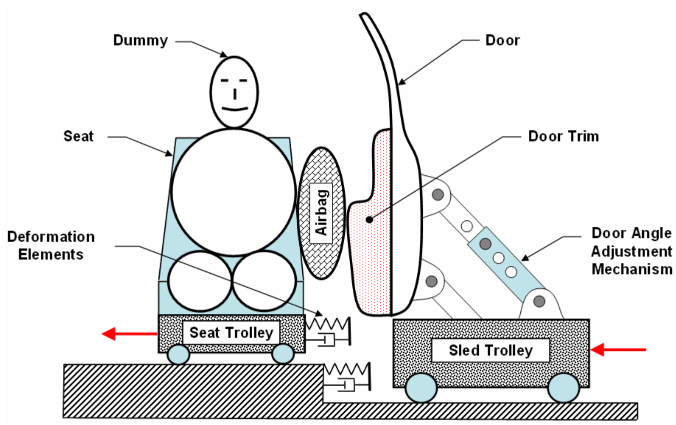

Figure 35: Typical side impact sled test

Enforced Motion Tests

An alternative and new form of physical component testing that eliminates the need to compromise the reproduction of vehicle crash environment gap closure rates and/or reaction force time histories is an enforced motion test. Ref. OWEN rig; (13)

The enforced motion test enforces the surroundings of the restraint system to move in the same way as during the crash event. The enforced motion is applied through discrete rigid regions that through their motion embody the deformation of the vehicle crash environment, see Figures 36, 37, 38.

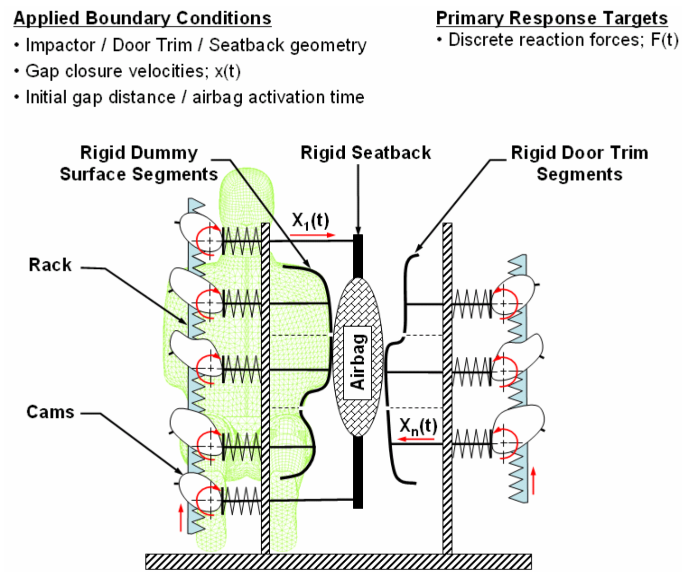

Figure 36: Enforced motion OWEN rig: Front View

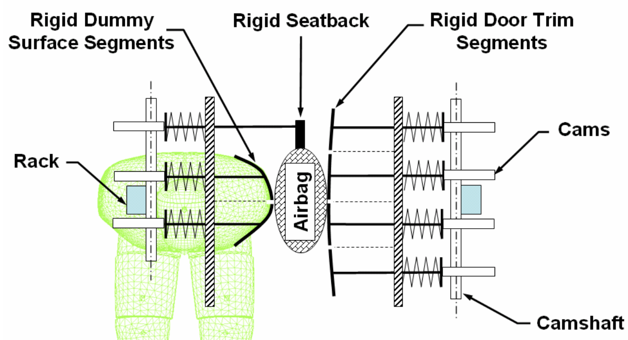

Figure 37: Enforced motion OWEN rig: Top View

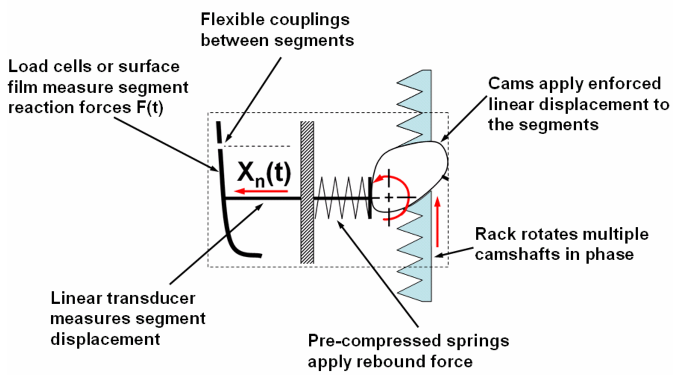

Figure 38: Enforced motion OWEN rig: Mechanism

Since the motion of the restraint systems surroundings is reproduced accurately, the restraint system is able to be tuned towards only one performance target; reaction force time histories. (Free fall and sled performance targets are typically both deformation rates and acceleration or reaction force time histories.)

The discrete rigid regions can represent the external surfaces of the dummy, seat and door-trim thereby isolating the response of the airbag and enabling it alone to be tuned towards the desired reaction forces. Alternatively the discrete rigid regions can be more remote, such as the door inner panel, and enable the tuning of multiple restraint system components located in series or parallel towards the overall desired reaction forces, see Figure 39.

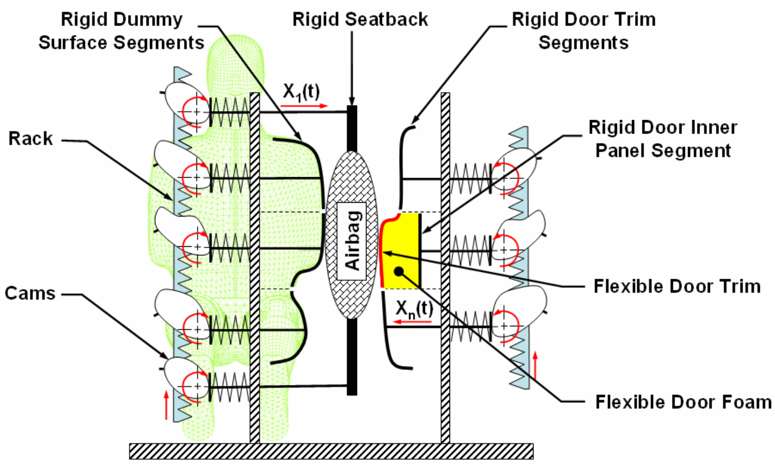

Figure 39: Airbag, door-trim and door foam tuned towards desired overall response; regional force time histories

Enforced motion tests have a number of advantages compared to traditional free fall tests and sled tests:

- Complex, 3D motion of the vehicle crash environment can be accurately reproduced including rapid increases and decreases in velocity. (This is a key enabler to develop restraint systems using component tests that are linked to vehicle system behavior and in turn to facilitate the out-sourcing and commoditization of restraint systems.)
- The test setup and test execution is rapid since the enforced motion "pulse" can be set precisely without trial and error and the instrumentation that measures the performance targets is built into the rig, not the restraint system that is being tested.
- The restraint system *tuning* process is faster since the number of performance targets are reduced to one; reaction force time histories.
- Capital investment costs are low since the rig does not require a large laboratory and can be used for all vehicle system load cases such as barrier, pole, etc and also stand-alone load cases such as restraint system positioning, overload, etc.
- The rig can be used to develop all side impact restraint system components including airbag, foam padding, door trim panels, etc.
- The test is non-destructive with the exception of the restraint system components being tested.
- Numerical simulation and physical test activities can be harmonized across multiple vehicle manufacturers and restraint system suppliers since the rig is vehicle, load case and restraint system independent.