DRIVER OUT-OF-POSITION INJURIES MITIGATION AND ADVANCED RESTRAINT FEATURES DEVELOPMENT

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ABSTRACT

Airbag related out-of-position (OOP) injuries in automotive crash accident have drawn great attention by public in recent years. In the interim-final rule of Federal Motor Vehicle Safety Standards that NHTSA issued in May 2000, OOP static test becomes a mandatory requirements of new regulation and will be phase in starting from year 2003. Due to the complexities and constraints of vehicle design, such as extreme vehicle styling and packaging as well as multiple safety requirements, it is a great challenge for both restraint safety suppliers and automobile manufacturers work together to come up proper designs to meet requirements of new regulation and provide additional protection for both in-position and OOP occupant at various vehicle crash scenarios.

In this paper, the technique of developing advanced restraint system and mitigating the OOP injuries is described. With the aid of computer simulation using coupled structural/computational fluid dynamics scheme in conjunction with laboratory test, various OOP countermeasures are illustrated. The design guidelines are outlined. The reduction of OOP injury is demonstrated with proposed design concepts. A useful and unique tool for advanced restraint system and OOP protection is developed that yields promising results.

INTRODUCTION

There are several challenges associated with advanced restraint system development. First of all, the system must satisfy all occupant protection requirements in different vehicle crash scenarios; sometimes those requirements are confront with each other. For example, during a severe vehicle crash accident or high speed barrier test, airbag needs to be deployed as quick as possible with sufficient power to protect in position occupant and achieve better rating in consumer advocate test. In another hand, airbag needs to be deployed as slow and gentle as it could when occupants sit close to the steering wheel/instrument panel during a minor crash accident to avoid potential harm and injury to occupant. Those design dilemmas have to be resolved for a reliable and robust restraint system development.

Besides, due to airbag deployment is a very complex process and occurs in an extreme short duration that adds more difficult for design engineer to fully understand how system works, the effects and contributors of individual design parameters on the system performance. Hence, developing a good methodology that leads to gain valuable information and potential design guidance is critical. Laboratory testing is a very good tool to validate the system performance. Computer simulation, in another hand, can be extensively used to systematically evaluate design proposals that leads to an in-depth understanding the relationship and the effects of individual design parameter on system performance and an optimized design solution.

Simulating the interaction of airbag with OOP occupant and achieving reliable results that are capable of assisting restraint system development is still a difficult task. Unlike simulating fully or almost fully deployed airbag that interacts with in-position occupant, uniform pressure method is accurate enough and is widely accepted by safety community as a standard CAE practice. Airbag interacting with OOP occupant often occurs at very early stage of the airbag deployment. Under such circumstance, large pressure gradient still exists inside of airbag. Therefore, simulating partially deploying airbag with uniform pressure approximation is not a desire and accurate approach. It is not surprise to find large discrepancy between the simulation results using uniform pressure method and the laboratory test data. In order to improve the accuracy of OOP computer modeling, some of the software vendors have implement the analytical jet model feature in the computer code; but only slight improvements are discovered by this attempt. This improvement is not good enough to correlate well with experimental results. Mu et al applied structural/fluid coupling method to simulate the OOP occupant thorax interaction with partially deploying airbag in 1999, the simulation results agrees well with the experimental data so this method will be applied in present study.

The difficulties of simulating OOP occupant interacting with airbag are not only existed at how to proper modeling gas dynamics of deploying airbag and complex airbag folding, but also can be found from many other respects, such as the accuracy of mathematical dummies modeling in OOP condition. Mathematical dummies that widely used in CAE simulation in safety community needs to be carefully examined and validated for OOP study because no significant mathematical dummies calibration data are available. It is worth while to simulate the laboratory dummy thoracic and neck pendulum calibration procedure and validate the mathematical dummy critical characteristics with the test data of physical dummy to ensure good correlation exist so the good quality of simulation results can be achieved.

OVERVIEW OF DRIVER OOP DEVELOPMENT

The interim-final rule of Federal Motor Vehicle Safety Standards that NHTSA issued in May 2000 requires that future airbag must be designed to create less risk of serious airbag induced injuries than current airbag, particularly for small women and young children. One of the regulations in NHTSA proposed final rule requiring that automotive manufactures demonstrate that their vehicles and restraint systems are capable of passing specified worst case static OOP test. There are two static driver OOP test positions with 5^{th} percentile female dummy, referred as NHTSA #1 "chin on wheel", and NHTSA #2 "chest on module", are specified in OOP test. Figure 1 and 2 illustrate the laboratory static OOP test set up. There are nine injury criteria, such as HIC; Chest G's, Chest Deflection, four Nij, Neck Tension and Neck Compression as well as related injuries limit are described in regulation.

According to the findings of biomechanics research, field automotive accident and laboratory test, chest and neck are the most vulnerable objects subjecting injuries during airbag interacting with OOP occupant. So they are the focus of static OOP test. It has been found that chest injury often associates with airbag "punch out" force and occurs at very early stage of the airbag deployment, but neck injury is more likely induced by the "membrane" loading at relative late deployment time.

Investigations were carried out in the past to systematically evaluate the effectiveness of airbag design parameters on OOP injury by combined laboratory testing and computational simulation approach. Inflator technology and output, inflator nozzle location, size and orientation, airbag module cover and housing, module cover tear seams, module mounting technique, airbag folding pattern, size, shape, venting hole size and location, tether length, shape, location, conventional tether vs. woven tether, etc are all studied. In addition, steering wheel and column are also investigated for the effects and potential improvements on OOP protection since those components are closely related with driver airbag performance.

It has been identified that effectively utilizing advantage of distance between OOP occupant and airbag as well as airbag deploying direction are the critical paths to improve the OOP protection. Utilizing either single design or combined multiple design features to achieve overall OOP injury mitigation are the primary focused at present study so the alternative countermeasures can be discovered for various system design requirements. Besides, all the proposed OOP countermeasures must also satisfy the in-position occupant protection requirements at dynamic crash. In addition, since the causes of chest and neck injuries may be different, so the design countermeasure that demonstrates benefit of one performance may not be necessary to satisfy another performance requirement then additional efforts are needed to achieve total system performance requirements.

Below are the summaries of the design guidelines that were established from our previous investigation of identifying the effects of airbag design parameters on OOP performance. There are as follows:

(1) Developing restraint system with multiple functional capability, such as multi-stage airbag, dual stage tear seams and multiple airbag that allow restraint system flexible enough to response according to different crash scenario.

(2) Design restraint system with an appropriate inflator nozzle location and gas flow direction, inverse airbag module door opening, optimizing airbag folding pattern with compatible air bag module cover tear seam design to promote desired airbag deploying direction.

(3) Enforcing the offset between occupant and airbag module, such as the design with recess airbag module, flexible airbag module mounting and pyrotechnic-assist collapsible steering column.

COMPUTER MODELING AND VALIDATION TEST

Effectively utilizing both computer simulations and laboratory tests are the best approaches of advanced restraint system development. Computer simulation is a very useful and cost effective tool in the early stage of development that allows engineer to quick evaluate wide range of design proposals and establish optimized design solution. But computer simulation results must be carefully verified with the laboratory test data to ensure the accuracy of the modeling and high confidence of utilizing CAE tool for system development.

At present investigation, coupled structural/CFD technique in conjunction with rigid body dynamics scheme is employed in mathematical modeling to simulate the airbag and OOP occupant interaction using MSC/DYTRAN and TNO/MADYMO. MSC/DYTRAN is an explicit finite element program with unique feature of structural and CFD coupling technique that is ideal for OOP simulation to calculate accurately the airbag deploying force. TNO/MADYMO is a rigid body dynamics code, which is widely used at CAE simulation by occupant safety community. The mathematical OOP model is comprised of finite element airbag module housing, cover, tear seam and folded airbag, FE deformable and rigid body steering wheel, rigid body MADYMO hybrid III dummy, rigid body seat, steering column, vehicle structure and CFD mesh. One of the close views of computer simulation of OOP static test is illustrated in Figure 3. Detailed mathematical model was described and illustrated in our previous publications.

The base line computer model, which comprises of a single stage pyrotechnic inflator, a single module cover made of TPO material, a hybrid accordion-fold airbag made of nylon 420 (airbag is coated at front but uncoated at back panel) with 673mm diameter (26.5 inch) and two 30-mm diameter vents.

The simulation results are validated with the experimental data for both NHTSA-1 and NHTSA-2 OOP static test position. In order to achieve decent correlation between computation simulation and test, computer model needs to be very carefully developed. Steps by step approach to achieve correct components and sub-system modeling is critical for successful OOP CAE model development. For example, mathematical model with appropriate CFD mesh size, representing airbag module tear seam, module housing and inflator nozzle are essential to yield good simulation results. The correlation between component level of modeling and test may be necessary for developing the system model.

In addition, care also needs to be given in computer modeling to ensure the fidelity of mathematical dummy model used in computer simulation. OOP simulation is a new field for CAE community and no significant validation data are available when mathematical dummy was developed. So the calibration of mathematical dummy before performing OOP simulation is one of the critical steps to ensure the success of computer modeling. In this study, basic computer simulations using laboratory pendulum chest and neck calibration procedures are carried out to ensure the mathematical dummy having similar characteristics of physical dummy. Mathematical dummy properties are modified to achieve better correlation with physical dummy if discrepancies are observed in above calibration.

Finally, proper position dummy into steering wheel and airbag in the simulation model according to the laboratory NHTSA #1 and NHTSA #2 OOP test setup procedures is another critical step to ensure the successful of the computer modeling.

There are three initial steps of validating the mathematical model are performed before it is used for routine advanced restraint system development. First, a series of tests are conducted to verify the importance of airbag module housing and tear seams on the magnitude of airbag deployment force. Airbag deploying force that calculates from mathematical model is compared with test data using drop tower test. The schematic of test setup is illustrated in Figure 4. The time history plots of airbag deploying force is compared between test and simulation with and without airbag module and illustrates in figure 5 that demonstrates a reasonable correlation between test and simulation is established.

Further validations of thoracic characteristics of mathematical dummy are performed through simulating the standard dummy calibration procedure with laboratory pendulum test. Similarly, the neck characteristics, such as flexion and extension responses using head-neck assembly are also calibrated according to laboratory standard procedure.

The validations of OOP system models are carried out after above components level correlation are finalized. Both OOP simulations at NHTSA # 1 and NHTSA # 2 test position are validated with test data. Kinematics of the airbag cover tear seams breaking and airbag cover opening, airbag deployment shape as well as associated timing, are compared between CAE results and laboratory test data. The injury values, such as head acceleration, chest acceleration, chest deflection, neck tension and compression, flexion and extension are all compared. Various simulation results of airbag systems with different design parameters are validated with test to ensure the accuracy of the modeling. Some of the comparison of the OOP injury curve between modeling and test are showed in Figure 6, 7, 8, 9, 10 and 11. It demonstrates the good correlation of experimental and analysis results.

DEVELOPMENT OF ADVANCED RESTRAINT FEATURES FOR OOP COUNTERMEASURE

The effective countermeasures of OOP thoracic injury, which closely associates with the mitigation of airbag "punch out" force, are identified from our previous investigation. Those countermeasures include multiple stage inflator, dual tear seams, recess airbag module cover, flexible module mount, pyro-technique assist steering column and airbag with hood/band tether. Computer simulation is first carried out to evaluate the effectiveness of above proposed design countermeasures on neck injury mitigation. Then further study of discovering additional countermeasures will take place to identify other design alternatives that have significant effects on neck injury countermeasure. The ideal design proposals are those which can effectively reduce both chest and neck injuries. It is necessary to avoid the designs that are only capable of mitigating part of OOP injuries but they degrade the performance for other OOP injury mitigation. Design with multiple countermeasure features may be necessary to achieve desired over all OOP protection.

The primary focuses of present study are discovering the effective countermeasures of neck injury since thoracic injury mitigation were thoroughly studied in the past. There are two folds of tasks are performed at current investigation. First, verify the design features that were demonstrate good thoracic injury mitigation from previous study and determine weather they are capable of mitigating neck injury. Secondly, identify additional countermeasures and possibility of combining them with previous countermeasure, if necessary, to achieve total system design target. Computer simulation of OOP static test at both NHTSA # 1 and NHTSA #2 position are conducted to verify the design proposals. Detailed analysis is described below.

As indicated early in this paper, the principle of design guideline to mitigate OOP injuries are enforcing distance between airbag and occupant, deploying airbag in the favorable directions to avoid hard contact of deploying airbag to the critical areas of occupant body and utilizing less powerful airbag when OOP scenario is identified. But due to the complicated impact scenario and many restrictions of vehicle design, it is still a great challenging to apply above principles into working proposals for restraint system development.

Following are the examples of some good practices of airbag design that demonstrate the superior OOP countermeasure and they will not compromise the high-speed crash performance.

Reversible multi-stage and variable output inflator – Inflator slope and peak pressures are the two critical characteristics to determine the inflator output aggressiveness. Studies have indicated that inflator slope has significant effect on both OOP thoracic and neck injuries. But inflator peak pressure only has very little effect on OOP neck injury and it does not affect the OOP thorax injury at all. It is always a good strategy for OOP occupant protection that design inflator with the lowest possible pressure slope. However, the lower boundary of inflator output and associated pressure slope are constrained by various impact requirements. For example, regulatory and consumer rating tests using rigid barrier test typical requires more powerful airbags than it actually need in real world accident to achieve better rating. In addition, rigid barrier test with small occupants who sit close to steering wheel also requires airbag deploying considerable quick than the requirement of real world accident so the airbag can be in position on time to avoid either occupant contacting with the steering wheel or before occupant ride on steering wheel while airbag is deploying. Above requirements need somewhat higher initial pressure slope of inflator output that restricts the lower boundary of primary stage of inflator output for a conventional multi-stage inflator.

The challenge of the inflator design also can be identified by how to optimize the inflator pressure slope corresponding to critical timing. For example, inflators with "S" shape tank pressure curve show promising results of reducing the "punch out" force owing to its very low initial pressure slope. However, in order to maintain the adequate timing of airbag fully deployment, the rapid pressure-rising rate will not be avoidable after initial low-pressure slope that introduces high membrane force and neck injury risk. Developing a cost-effective modeling tool to evaluate optimized inflator output as one of the primary OOP occupant injuries countermeasure and leads to proper design solution is a critical task.

Studies are also taking place by evaluating emerging multi-stage inflator technologies and their effects on OOP countermeasure at present study. There are two type of inflator design, refers as a reversible multi-stage inflator and a variable output inflator, will be focused in this study. Utilizing independent dual chamber of pyrotechnic inflator technology, reversible multiple stage inflator is capable of firing either squib based on crash condition. Under the OOP scenario, the squib associates with small amount of propellant mass of combustion chamber should be ignited as the primary stage, which provides much soft deployment than conventional dual stage inflatior that ignites the combustion chamber with large quantity of propellant as primary stage due to non reversible firing constraint and inflator full output requirements. This technology supplies more tailorable inflator output than conventional multi-stage inflator through the combination of alternating inflator firing sequence in conjunction with variable firing time between squibs.

Comparing with reversible dual stage inflator, variable output inflator has clear technical advantage and additional flexibility. By utilizing liquid propellant and capable of controlling propellant injection and combustion rate with magnetic alloy fluid via electronic control module, variable output inflator is not only able to generate wide range of inflator outputs but also enable to temporary or completely shut down the burning of propellant then re-establish the combustion if it is necessary in a very rapid pace. This inflator technology provides great opportunity and flexibility to meet OOP and in position occupant protection requirements in various high or low speed crash accident. It facilities the advanced airbag system design. Figure 12, 13 and14 shows the simulation results of maximum injury value of occupant head, chest and neck injury values with standard dual stage inflator, reversible multi-stage inflator and variable output inflator with respect to the injury limit that specified by final rule as 100% value.

Pyrotechnic-assist collapsible steering column – One of the straight forward design principles to countermeasure the OOP injury is making every effort to enforce the distance between the airbag and occupant and forces occupant away from the proximity of steering wheel and airbag when airbag is deploying. This includes preventing the occupant from injury even they are in OOP position before airbag is inflated. The intention of pyrotechnic-assist collapsible steering column design is to generate steering column motion away from occupant and synchronize it with airbag deployment. In this design, when airbag is deployed and gas is emitted, deploying airbag will release the steering column pin which used to lock the upper and lower column in normal driving condition and force the upper and lower steering column telescoping together and moved away from occupant. The entire steering column motion will be stopped when it contacts the stopper. The offset between the occupant and airbag due to steering column collapsing can drastically reduce the OOP injury. The longer the collapsing distance of the telescopic column, the greater the reduction of the OOP injury can be observed. It has been demonstrated that 50 to 75 mm collapsing distance of steering column can significant reduce OOP injury. In addition to achieve better OOP performance, this design also enhances the protection of in-position occupant because it increases the potential occupant ride down distance. The maximum head, chest and neck injury number from 75mm collapsing distance of steering column is plotted in Figure 15 with respect to injury limits as 100% value.

Recess air bag module cover with "I" tear seams – Some of the OOP injury mitigation need to take multiple countermeasure features into design consideration to achieve successful system performance. This is due to the nature of certain design and limitation of the design window. Like recess module design, the potential recess distance of airbag module is very limited. Although the small offset between occupant and airbag demonstrate significant reduction of OOP thoracic injury, it also indicates that recess cover itself will not be good enough to overcome the OOP neck injury. Discovering additional OOP countermeasures are necessary. According to the design guideline, airbag deployment direction is a critical factor to mitigate the OOP injury. Combining recess module design with the design to achieve desired airbag deploying direction is the potential solution of improving overall OOP injury protection. For example, airbag with about 25-mm recess cover design in conjunction with "I" tear seams pattern with compatible airbag folding successfully promotes the lateral or radial airbag deployment and avoiding early deploying airbag strikes the neck or stake underneath the chin to generate excessive force and moment on occupant. Our study has demonstrated a "I", or "S" types of tear seams pattern with 25-mm recess cover can successful pass 5^{th} female OOP injury static test requirements. Above system with optimized airbag folding will further reduce injury number. The simulation results of maximum OOP injury number plotted in Figure 16 as a percentage-based value with respect to the injury limit as 100% specified by NHTSA to illustrate the effectiveness of OOP performance with such countermeasure.

Flexible airbag mounting with petal cover seams - Relying on similar OOP countermeasure principle that describes above, this design induces offset between OOP occupant and airbag with flexible airbag module mounting feature that allows the module stroking backward while airbag is deploying. The offset between the occupant and module cover, which creates by the reaction force of airbag deployment, helps to reduce the OOP injury through distance effect. In addition, the stroking of the airbag module absorbs part of the airbag deploying energy that can further reducing power of airbag for potential harm on OOP occupant. Different types of module mounting springs, which are attached either between an air bag module and a mounting bracket, or between an inflator and a mounting bracket, are evaluated and compared with computer simulation. Simulations are also carried out to determine the appropriate load/displacement characteristics of mounting springs for the optimization of restraint system performance and effective OOP injury countermeasure. It demonstrates the significant reduction of OOP occupant thoracic injury with this design. Flexible module mounting feature needs to be combined with proper cover tear seams pattern to achieve neck injury mitigation and meet total system design requirement for OOP countermeasure. Besides "I" tear seams pattern, the "X" type of petal tear seams also demonstrates as a very good countermeasure to meet both OOP chest and neck injury mitigation requirements. Figure 17 shows the percentage of the maximum head, chest and neck injury values with flexible module mounting feature and "X" petal tear seams design with respect to injury limit as a 100% threshold.

Air bag with hood/band and dual tear seams – It has been identified that one of the effective way to mitigate the OOP neck injury, which involves in more design challenging than chest injury mitigation according to injury criteria and the values specified by NHTSA at OOP static test, is to design airbag with desired deployment direction so the early deploying airbag will contact the area of neck and underneath the chin with excessive force. The design countermeasure describes here that utilizes a piece of fabric tether to wrap the front center of folded airbag to force airbag first deploying downward. The shape, size and stiffness of the fabric can be altered as a design parameter to achieve ideal OOP countermeasure requirements. Computer simulation results reveal this design will not have significant effects on OOP thoracic injury mitigation due to the primary contribution of chest injury generated by "punch out" force, but it demonstrates this design has significant effects on OOP neck injury countermeasure that induced by "membrane force". The drawback of this design is that will require additional force to break module tear seams and tether that wrapped the airbag before module door open. This can cause the risk of OOP thoracic injury. Additional OOP countermeasure must be in place to address this issue.

There are various design countermeasures can be applied to mitigate the thoracic injury. One of the examples is dual tear seams feature. In this design, there are primary and secondary tear seams with different stiffness. Various thickness and strength of primary and secondary module tear seams are analyzed to ensure the secondary weak tear seams breakaway early at side or corner of the module cover, then the primary tear seams opening up at the center, which creates desired air bag escaping path to avoids severe impact on the OOP thorax and achieve good countermeasure. Computer simulation indicates as long as the module cover slightly opening up at sides, the pressure inside the center module and airbag can be drastically reduced. Hence, the OOP thoracic injury risk can be significantly improved. The stiffness of the tear seam needs to be carefully determined to satisfy the requirements of OOP, high-speed crash, product reliability and manufacturability. Multiple dual tear seams patterns are analyzed with computer model. Figure 18 illustrates the percentage of the maximum neck and thoracic injury value from this design with respect to the maximum allowable value as 100%.

Additional computer simulation to further exposure other OOP countermeasures of mitigating the neck and thoracic injury are also performed. Those design features that includes multiple airbag to allow smaller bag inflating first then deploying the regular airbag; the integrated steering wheel/airbag with deep dish design to enforce the offset between occupant and airbag; airbag with various folding pattern, such as "star" fold and airbag with unturned fabric, airbag with loop diffuser, etc to mitigate both neck and thoracic injury will not be described in great detail in this paper.

CONCLUSIONS AND RECOMMENDATIONS

This paper presents a methodology to assist OOP countermeasure development. By applying computational simulation with coupled structural/CFD and rigid body dynamics modeling scheme in conjunction with laboratory test, the primary paths of OOP injury mitigation are identified and the multiple promising solutions for driver OOP injury reduction are demonstrated.

It is also illustrates in the paper that good computer simulation of static OOP test relies on not only the accurate gas dynamic scheme, representable airbag system modeling, but also depends on correct behave, well validated mathematical dummy model and the precise modeling the position of airbag and dummy according to the OOP test setup procedure. Missing any of the above elements can cause inaccurate and unacceptable simulation results.

Computer simulation is the primary development tool applied in present OOP study. Laboratory tests were conducted to verify part of the design proposals. Because some generic data, such as reversible and variable output inflator output, etc are utilized in the computer simulations further verification with experimental test in the laboratory environment are highly recommended.

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Figure 1 Driver OOP NHTSA #1 Test Setup

Figure 2 Driver OOP NHTSA #2 Test Setup

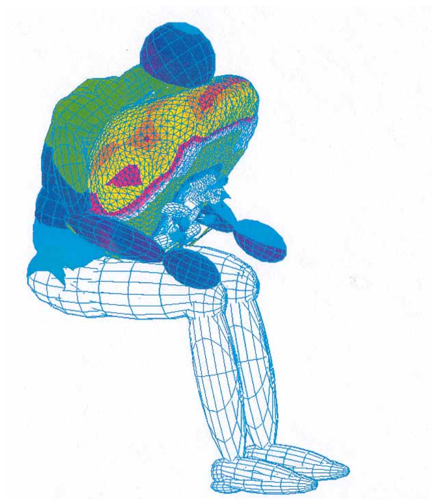

Figure 3 FEM OOP Simulation

Figure 4 Airbag Drop tower Test Setup

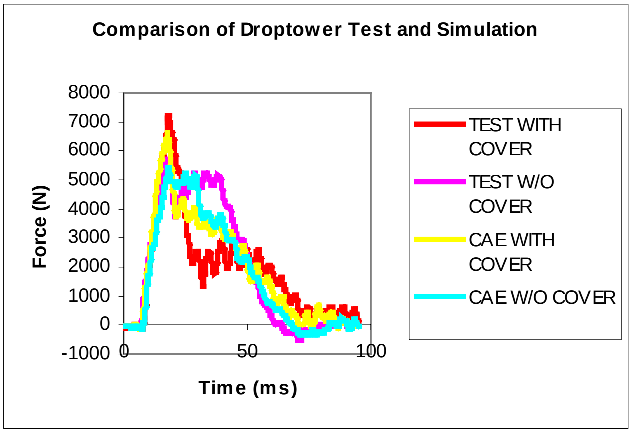

Figure 5 Simulation and Test Comparison of Airbag Deployment Force with and without Airbag Cover

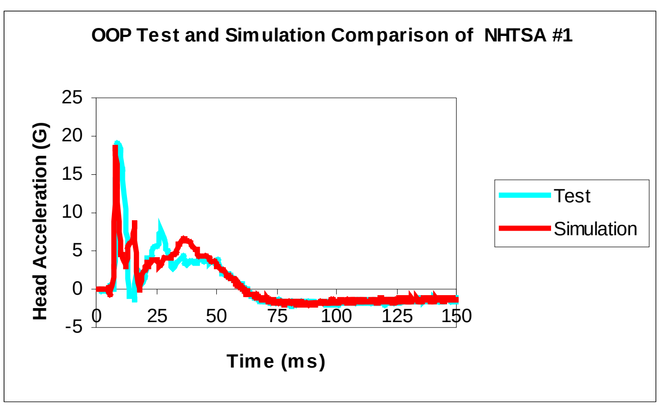

Figure 6 OOP Head Acceleration Comparison of Test and Simulation

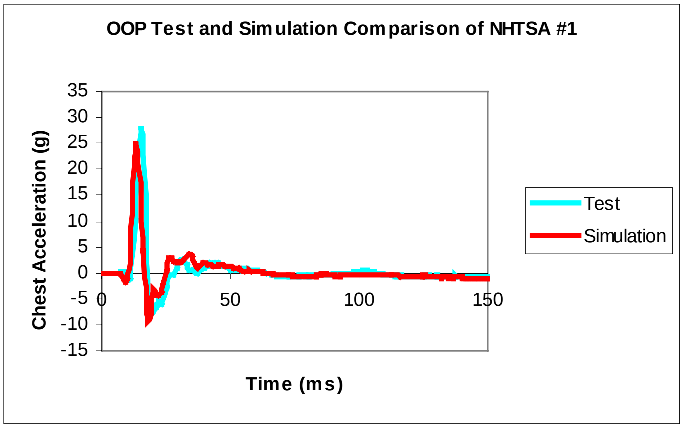

Figure 7 OOP Chest Acceleration Comparison of Test and Simulation

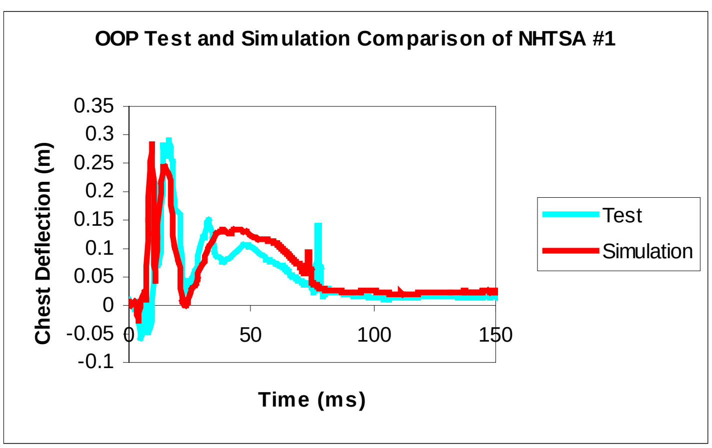

Figure 8 OOP Chest Deflection Comparison of Test and Simulation

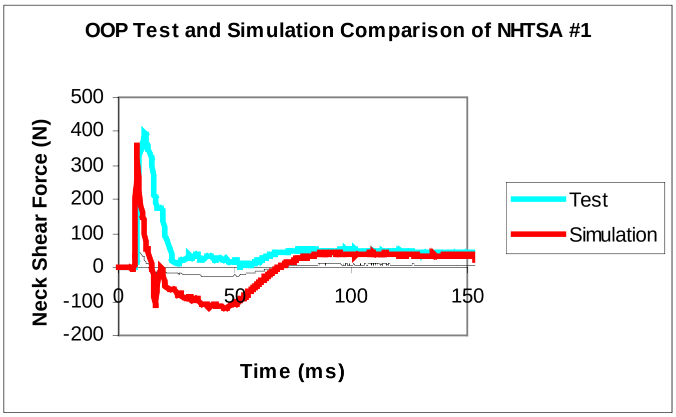

Figure 9 OOP Neck Shear Force Comparison of Test and Simulation

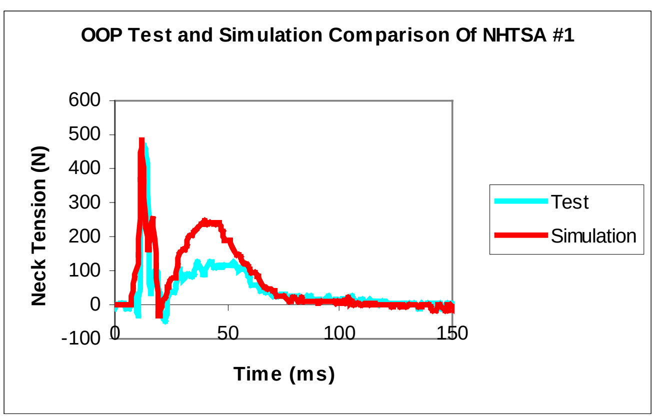

Figure 10 OOP Neck Tension/Compression Force Comparison of Test and Simulation

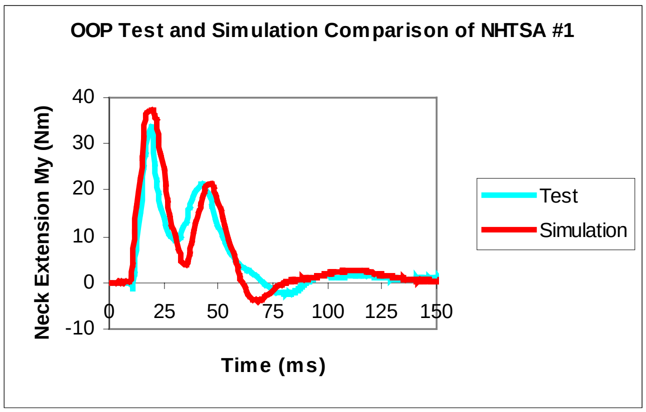

Figure 11 OOP Neck Extension/Flexion Moment Comparison of Test and Simulation

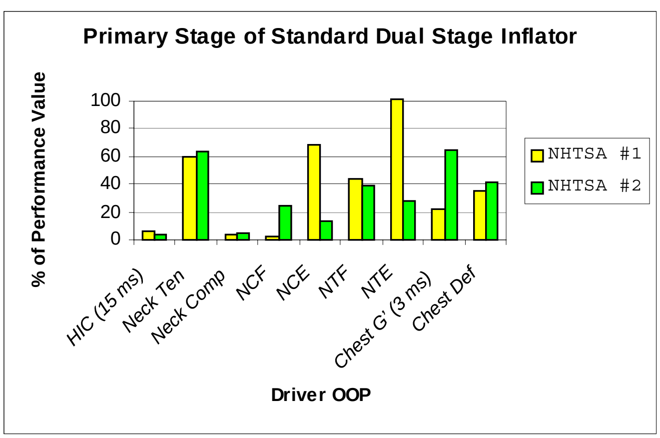

Figure 12 Simulation Results of OOP Performance with Primary Stage Regular Dual Stage Inflator

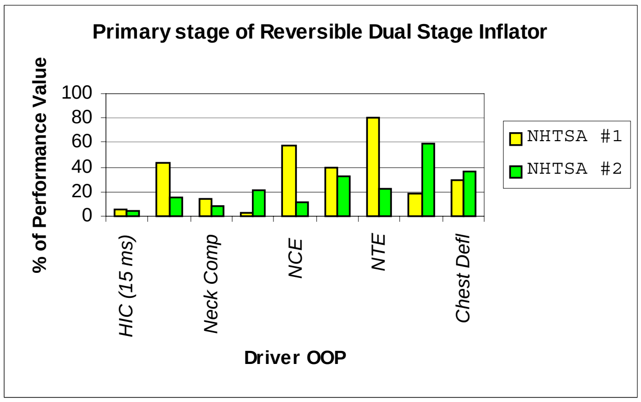

Figure 13 Simulation Results of OOP Performance with Primary Stage of Reversible Dual Stage Inflator

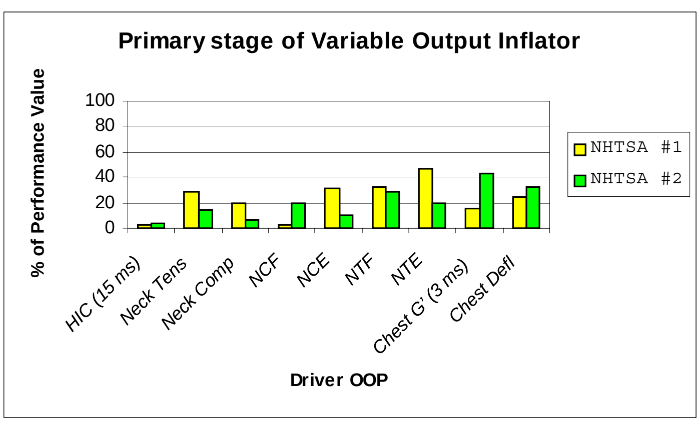

Figure 14 Simulation Results of OOP Performance with Variable Output Inflator

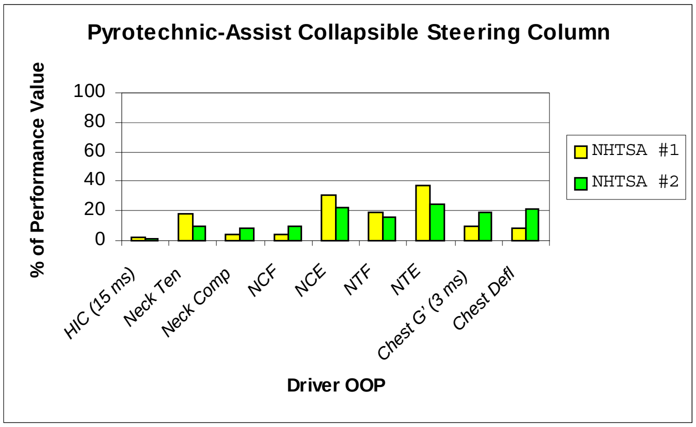

Figure 15 Simulation Results of OOP Performance with Pyro-technique Assist collapsible Steering Column

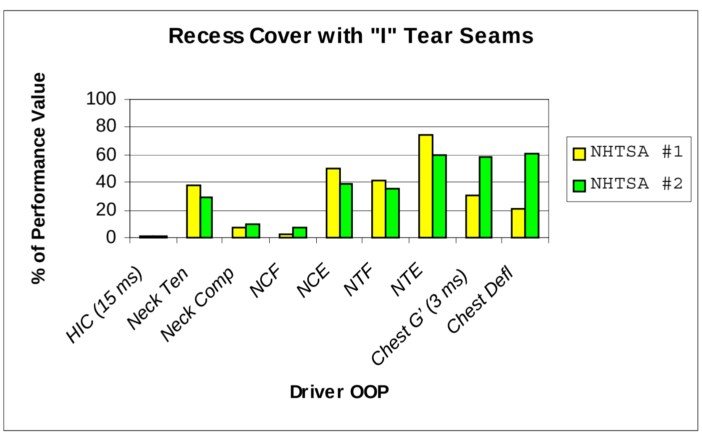

Figure 16 Simulation Results of OOP Performance with Recess Airbag Cover and 'I" Tear Seam

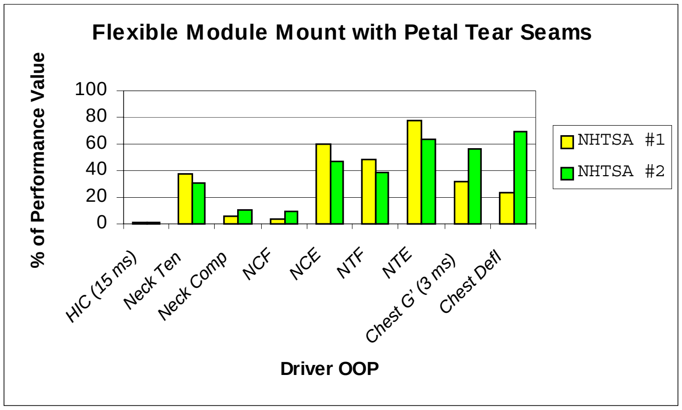

Figure 17 Simulation Results of OOP Performance with Flexible Module Mount and Petal Tear Seams

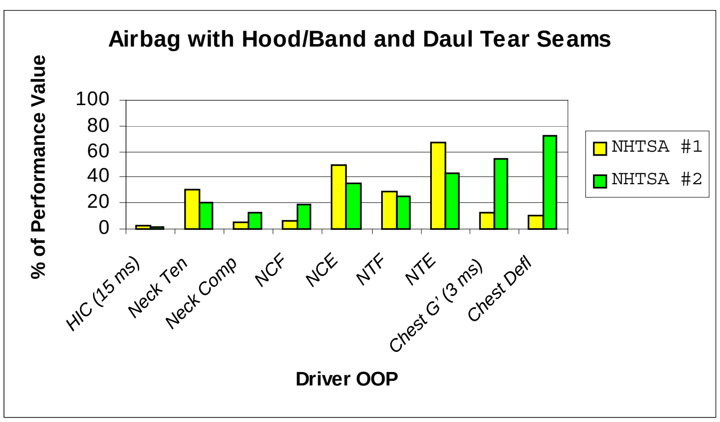

Figure 18 Simulation Results of OOP Performance with Hood and Dual Tear Seams