ADAPTIVE SIDE IMPACT RESTRAINTS USING INTRUSION BASED CRASH SENSING AND DISCRIMINATION

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ABSTRACT

State of the art frontal airbag systems provide adaptive features such as multi-stage deployment and active or passive venting based on occupant position, stature, crash mode and severity. Research was done to understand the potential of reducing injuries and fatalities by applying a similar methodology to side impact protection.

Adaptive restraints have been proposed for side impact protection, however, the sensors and discrimination methods available for side crash detection, have, in general, not provided sufficient time and information to effectively apply these adaptations. However, recent analysis of an alternative magnetic field based crash sensor (MSI) has shown that this sensing concept provides crash mode and severity at very fast times which could allow a second triggering event for situation adapted protection. Using CAE tools it is shown how the improved triggering times can be employed and how much potential protection benefit can be gained by using various active adaptive restraint concepts.

To demonstrate the concept, MSI sensor data was analyzed for a series of crash and abuse tests to determine estimates of crash severity and mode at practical airbag deployment times for several deployment situations. The paper reviews the techniques used to process the MSI Data. The derived deployment times, along with severity and mode estimates, are used to demonstrate the effectiveness of several candidate active adaptive restraints compared with standard restraints.

In conclusion it is seen that adaptive side protection is worth consideration, and not only because the future requirements are expected to become more complex and demanding. However, these improvements do not come free of cost and therefore the pro and cons will have to be balanced very well.

INTRODUCTION

Frontal occupant restraints have evolved steadily in time, as new restraint and sensing innovations have been introduced. This evolution has directly benefited car occupants through improved safety, despite increasing traffic volume, compatibility issues and increased speeds. New and useful crash sensor, occupant classification and vehicle status information is often available on cars which can be used to optimize occupant protection for classes of occupants, crash modes and impact severity. For example, dual frontal crash detection sensors are often mounted on cars to quickly detect impact location, mode and severity; weight based classification systems discriminate occupant class, and multi-stage or variable stage airbag inflation or venting systems can be controlled. Often, safety benefit can be obtained with minor system adaptations. Such improvements have been slowly and steadily introduced in the market, resulting in continuing reductions in death and injury [1,2,3]; this is the primary motivation for improved frontal protection through adaptation. However, an important secondary factor must also be considered. As car buyers increasingly use safety performance as a key factor in model selection, and regulatory agencies evolve test standards to match real-world trends, in parallel, OEMs and suppliers must continue to study cost effective ways to improve and distinguish frontal occupant protection.

Side impact adaptive restraints have also been considered. Lessons learned in frontal protection can be directly applied to designing improved side systems. However, the long and complex mechanical side structure and close proximity of occupants to impact barriers, makes it more difficult to quickly and accurately discriminate crash mode and severity. Due to the very fast door intrusion times experienced in side impacts, the algorithms and methods available to improve protection through adaptation have been limited.

This paper attempts to revisit the topic of improved side impact protection through airbag adaptation using an alternative sensor which discriminates side impact crashes through door intrusion in proximity to the occupant. The Magnetic Side Impact (MSI) sensor is described fully in [4]. Subsequent testing and CAE analysis has shown the potential of the MSI to provide faster average crash detection for deploying restraints than conventional accelerometer based crash detection systems. Because MSI senses average intrusion and not acceleration, CAE can be reliably used for analyzing not only the effectiveness of restraints, but also to derive the sensor signal early in the crash. To date, the effectiveness of CAE modeling of accelerometer data has been very limited, particularly in side impacts where even minor structural variations influence the detected signals early in the crash.

Additional analysis of actual crash data has shown that the MSI sensor provides information on crash mode and severity sufficiently soon after impact to consider side thorax airbag adaptation. CAE analysis was used to estimate the potential benefits of several basic forms of airbag adaptation including faster deployment, increased airbag volume and two stage inflation. Other forms of adaptation can be based on occupant classification, variable inflation, timed venting and variable venting. These are also discussed, but not yet supported through CAE analysis. In a similar way, adaptations could be considered for other forms of restraint such as belt pre-tensioners, side curtain airbags or reversible restraints (e.g. Motorized Seat Belts); however these topics fall outside the scope of this paper.

For completeness it should also be mentioned that there are passive methods to adjust restraint properties. In such cases, the settings are controlled by the variables that exist during the deployment of the airbag and progress of the crash and occupant. For example, an airbag may have a vent which is affected by the size and or stature of an occupant through direct or indirect interaction. In the case of passive adaptation, no additional sensors, signal processing or restraint actuators would be needed.

Figure 1 shows that the fatality rate per million vehicles that had been gradually decreasing over time has leveled off. This suggests that the current generation of restraint systems have reached the limits of their capabilities. At the same time demands for side impact protection are on the rise. New devices such as the Magnetic Side Impact (MSI) sensor allow for a breakthrough that can bring side impact protection to the next level. The earlier crash event detection and crash severity assessment offered by this sensor allow for more sophisticated and adaptable side restraint devices to be deployed. This will facilitate energy absorption at higher severity levels, providing better protection to more occupants in regulatory and consumer program testing as well as in real world accidents.

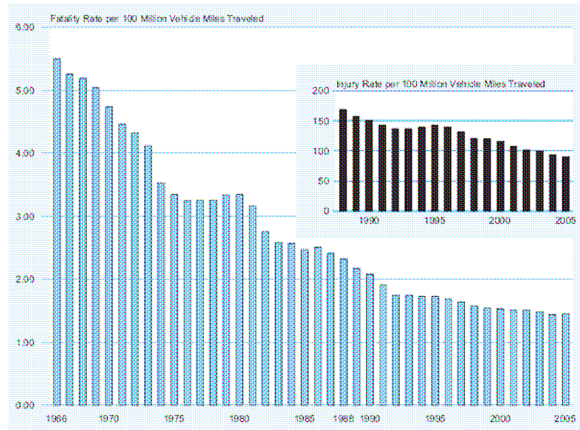

Figure 1. Fatality Rate per 100 Million Vehicle Miles Traveled, 1966-2005 [5]

REGULATORY FACTORS

Currently, the criterion for side protection varies globally. While harmonization is being pursued, it is not expected to take effect in the near future. Figure 2 depicts the wide range of requirements and priorities for regulatory tests in the future. Restraint designers must try to provide systems that function optimally for this wide range of tests and all classes of occupants. This can result in contradictory requirements, leading to different restraint systems for each global region. Selective adaptation provides a possible solution to achieve adequate protection over the widest range of tests and occupants with the same or similar system components.

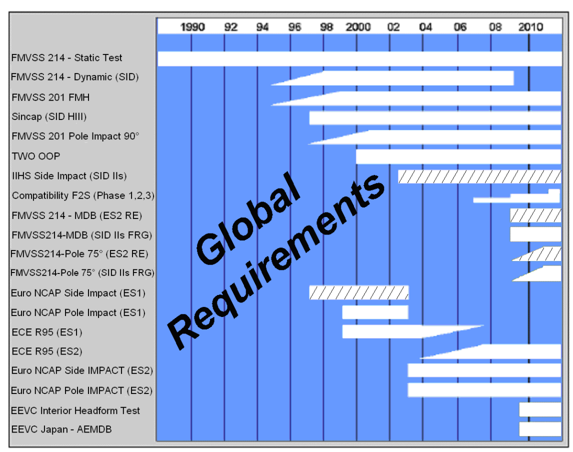

Figure 2. Plurality of global side crash requirement and new proposals [6]

As a first step in trying to meet this goal, a comprehensive investigation of the cooperation between adaptive restraints and side crash sensors using CAE is necessary. Crash simulations tend to be very time consuming, so the number of cases must be

selected in a systematic approach, to provide representative results in the end.
While other papers are available, which compare the benefits of different restraint systems for frontal crashes [7,8], this paper focuses strictly on side impacts.

The crash matrix considered in this paper is formed along two variables. The first variable is crash mode:

- 50km/h IIHS (90° IIHS MDB)
- 54 km/h FMVSS 214 MDB (27° crab)
- 50km/h ECE R95 (90° ECE R95 MDB)
- 32km/h FMVSS 214 NPRM pole (75°, 10 inch pole)

The crash modes from the above list are hashed in Figure 2, to allow an overview of which part of the global requirements is subject to investigation in this paper. The second variable combines sensor and protection type:

- standard airbag with accelerometer
- standard airbag with MSI
- enlarged airbag with MSI
- adaptive airbag with MSI (2nd stage)

DEFINITION OF TERMS

When talking about adaptive restraints, it is important to clearly define the key times in the sequence starting from first contact of the impacting barrier through deployment of the airbag and any adaptive components.

Time "0"

In a side impact it is the first contact of the impacting object with the vehicle (e.g. the falling edge of the trigger switch mounted on the vehicle door). This defines the origin for all subsequent times.

TTF1 (Time To Fire)

The time, when any crash detection system, detects a crash and deploys a protective restraint (airbag). Since this time can depend significantly on the kind of crash detection system, all deployment times originating from an accelerometer are labeled with the index A ($TTF1_A$), while all deployment times originating from the MSI sensor are labeled with the index M ($TTF1_M$). Any kind of restraint initiates at TTF1, a conventional restraint will be completely deployed, while an adaptive restraint will be deployed at its first stage.

TTS (Time To Severity)

This is the time when the MSI sensor can classify the crash mode (pole/barrier type) and estimate crash severity. For this paper, only the MSI is considered to provide this estimation.

TTF2

This is the time when a second stage of an adaptive restraint is deployed. Since knowledge about crash severity is important for the deployment of the second stage, the relation **TTF2 ≥ TTS** must hold. For lower speed crashes, a second restraint stage may not be needed, i.e. TTF2 $\rightarrow \infty$. There is no index necessary for TTF2, because in the scope of this paper, only MSI provides a TTF2.

Crash Severity

Side impact crashes are often categorized into severity levels. In fact, many crash sensor discrimination algorithms simply classify impacts as ON (restraints are deployed) or OFF (restraints are suppressed). To consider adaptive restraints, a more precise crash severity measure is required. For side impact crashes, the intruding door or impacting object poses the biggest injury threat to the occupant. MSI is a door intrusion sensor [4]. While regulatory barrier and pole tests are carried out to evaluate restraint performance because they are repeatable, it is useful to have a method to relate the intrusion (severity) of any real-world crash to that of a regulatory test. For this paper, the term ***equivalent speed*** will be used to define crash severity. It is defined as the speed that a standard regulatory reference test must be run to duplicate the intrusion profile that occurs in any crash. For example, if the severity of a real world car-to-car crash is rated with an ***equivalent speed*** of 50 km/h, then the intrusion profile (in the sensing timeframe) could be similarly reproduced in a FMVSS 214 MDB regulatory test at an impact speed of 50km/h. While any regulatory tests could be considered as a reference, for this paper, the FMVSS 214 MDB crash mode is the reference for barrier type crashes and the FMVSS 214 NPRM pole test is the reference for pole type crashes.

ESTIMATING TTF AND TTS

The MSI coil measures the distance to conducting material in its proximity. In a crash, as the outer door skin starts to move relative to the sensor, the MSI signal increases. Figure 3 shows the normalized MSI signal and slope response for a regulatory ECE R95 crash. Since the MSI coil measures average door intrusion, the slope of the MSI signal is a good indicator of crash severity (intrusion speed).

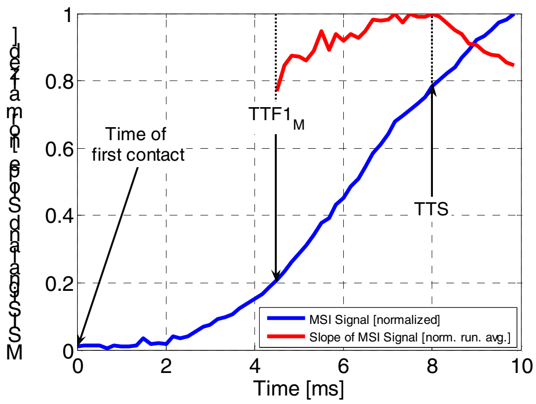

Figure 3. MSI Signal and Slope for an ECE R95 Crash Mode

The calculation of the slope starts right at TTF1 and is averaged over the ongoing signal. The calculation of the slope terminates at the derived TTS, if one of the following conditions is met:

1. The variance of the averaged slope is lower than a pre-determined, platform dependant threshold.

2. Time is greater than (TTF1 + 5ms)

3. A short term average of the slope decreases to zero. In this case the last 1ms of the signal is ignored for the final result, to make sure the result is not influenced by the plateau.

Table 1.
TTF1 and TTS for All Crash Modes Considered

Crash mode	$TTF1_M$	$TTF1_A$	TTS	equiv. speed
MDB Crashes:				
50km/h IIHS	3.0ms	5.8ms	7ms	50km/h
54km/h FMVSS 214 MDB	2.8ms	7.4ms	6ms	54km/h
50km/h ECE R95	4.5ms	7.0ms	8ms	34km/h
Pole crashes:				
32km/h FMVSS 214 NPRM pole	6.0ms	11.4ms	10ms	32km/h

Table 1 shows a compilation of TTF1 and TTS for sensors and crash modes considered in this paper. The table also shows the derived ***equivalent speed*** for each mode. All MSI slope calculations were terminated by the variation criteria (Condition 1). The TTF1 values in the table above were derived from full calibrations (crash and abuse tests included); the times were averaged over several crash series using mid-size sedans. The actual restraint deployment times that can be achieved on any specific platform must be derived through a full crash and abuse test set, where target TTF1 requirements vary by OEM and platform. The numbers used here are representative.
Further analysis of MSI signals shows the potential for classification of crash events into pole and barrier types, with unique ***equivalent speeds*** resulting from the dynamic differences in intrusion for poles and barriers. In practice, different adaptive restraint measures could be taken to reduce injury risk for each type.

CAE MODELS AND METHODOLOGY

A model of a typical mid size sedan, developed and validated for side impact studies in the research domain, was used for this study. The vehicle model comprises approximately 80,000 elements, providing a reasonable compromise between accuracy and computational efficiency.

Figure 4. Vehicle Model in Pole Impact

Individually validated barrier models, representative of the FMVSS 214 MDB, IIHS MDB and ECE R95 MDB were utilized as well as a model of the rigid pole of the FMVSS 214 NPRM dynamic oblique pole impact. The CAE analysis further incorporates dummy models representative of the Mid Size Adult Male (50^{th} percentile) and Small Adult Female (5^{th} percentile). While regulatory tests specify the size and type of dummy to be used, this study uses the same dummy models throughout for ease of comparing results.

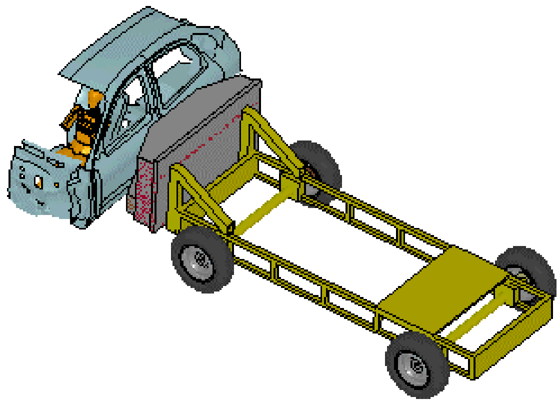

Figure 5. IIHS MDB Model

For Out of Position (OOP) injury risk assessments a model of the 3-year old Hybrid III dummy was used in ISO-2 position. The side airbag model used for this study is a typical single chamber airbag, typical for that used in vehicles of this class.

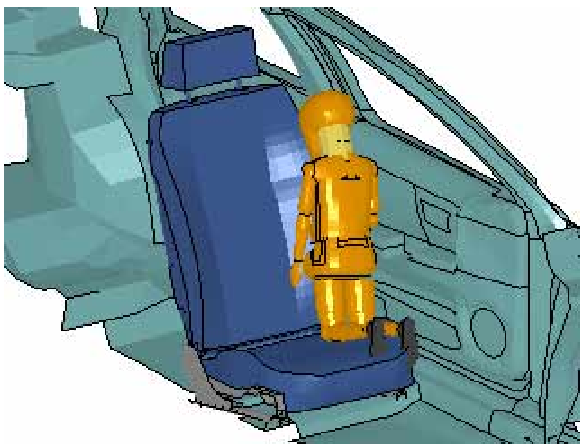

Figure 6. 3-Year Old Dummy in ISO-2 OOP

The airbag and inflator used in this study was designed to meet European regulatory MDB test standards and will not protect optimally in IIHS or the FMVSS 214 NPRM pole tests. For any airbag system, there is always a crash severity and/or occupant load where airbag protection potential is maximized. However, through active adaptation, the balance of internal pressure and venting can be controlled to best dissipate the impact energy.

The combination of two sensor types, four impact scenarios, and two adult dummy models allows for 16 permutations. Different restraint configurations and crash severity modes made for a total of 144 unique analysis models. To perform this study the LS-Dyna solver and an 8-node Linux cluster was utilized.

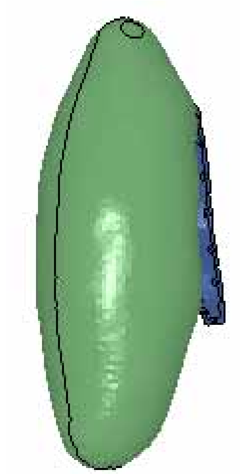

Figure 7. Baseline Side Airbag Model

CAE ANALYSIS

A first baseline CAE simulation set was performed to evaluate the possible benefits of the MSI sensor compared to an inertial sensor (accelerometer), using a standard airbag. Subsequent cases can be compared against the previous result to measure any level of incremental improvement. While many injury criteria are available to evaluate restraint effectiveness, rib deflection was chosen as the primary measure for this analysis. This measure is often the most critical for the vehicle size used in this analysis. A reduction in rib deflection represents an improvement in occupant protection. Note that in all subsequent figures, a value of one represents the peak rib deflection occurring on the Mid Size Adult Male dummy in the FMVSS 214 NPRM pole test. All other deflections are normalized to this level. Since this is a generic car, airbag and dummy model, absolute deflection levels cannot be cross validated against actual crash tests. Accordingly, normalization allows for a simple relative comparison of rib deflection levels across the crash, dummy and adaptation variables.

MSI Sensor and Accelerometer Comparison

The first question addressed in the CAE analysis was: would the faster MSI deployment times improve or degrade the performance of an airbag system designed for an inertial sensor? Keeping all other variables the same, the baseline airbag was deployed at $TTF1_A$ and $TTF1_M$ respectively.

Figure 8 and Figure 9 show the rib deflection measures, for Mid Size Male and Small Female respectively. Figure 8 shows that the earlier MSI deployment times reduce peak rib deflection for the less severe ECE R95 and FMVSS 214 MDB crash modes, while the values for the more severe IIHS and FMVSS 214 NPRM pole crash modes are almost identical. The bag has been optimized for all current global requirements which are less severe than the IIHS test, so faster deployment shows little benefit for the IIHS and FMVSS NPRM pole crash. Figure 9 shows the deflection situation for a Small Female and the faster MSI deployment times show some measurable benefit. However, for the lower severity crash modes the deflection results are nearly identical.

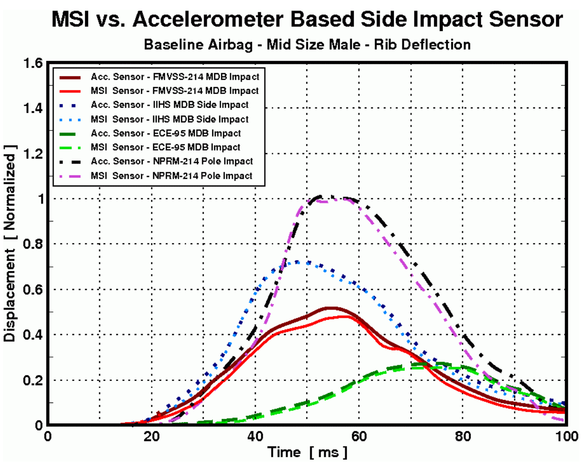

Figure 8. MSI vs. Inertial Sensor - Mid Size Male

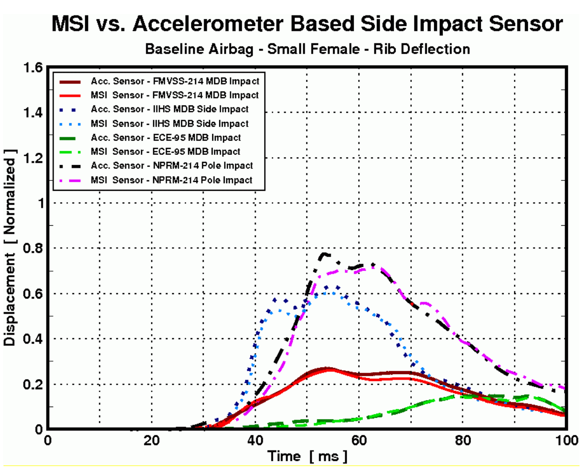

Figure 9. MSI vs. Inertial Sensor - Small Female

In no case analyzed, did a faster deployment result in higher peak rib deflections. This result suggests that the MSI could be effectively exchanged with an accelerometer in a conventional airbag system with no degradation in performance, and some measurable gains in reducing peak rib deflections.

Enlarged Bag Triggered by MSI

The second question addressed in the analysis is: Can a larger airbag deployed at the faster MSI TTF1 improve rib deflection? To simplify the analysis, only the width of the cushion was increased. Figure 10 shows the baseline cushion in red and the enlarged cushion in green. The resulting volume increase was 25%. Enlarging the cushion volume, while keeping the inflator constant results in a lower initial inflation pressure, and possibly less venting losses. With the larger contact area it was hypothesized that the overall contact forces of the higher volume airbag would be effectively the same as the original.

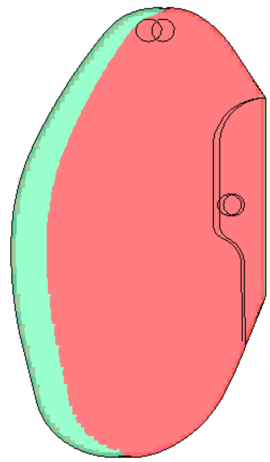

Figure 10. Baseline and Enlarged Cushions

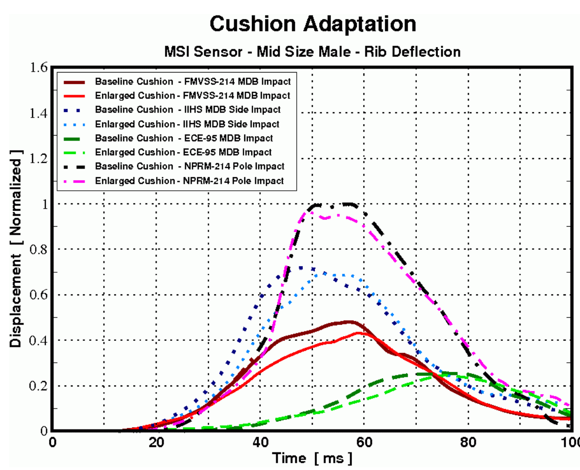

Figure 11. Cushion Adaptation - Mid Size Male

Figure 11 shows a comparison of dummy injury measures for the baseline cushion and enlarged cushion, both using MSI sensor trigger timing. A bigger bag is beneficial for all crash modes, except the low severity ECE R95 crash mode, where results are almost identical.

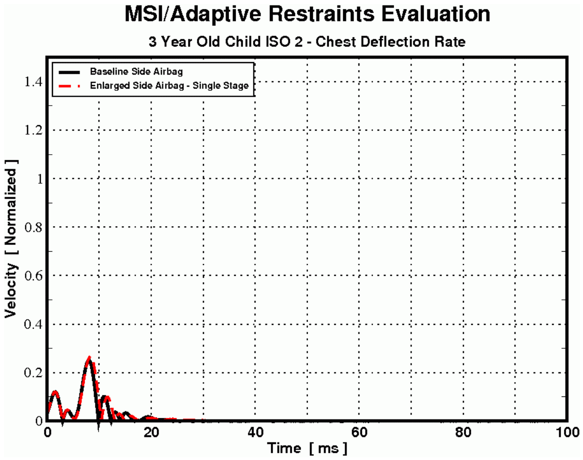

Figure 12. OOP Chest Deflection Comparison

One potential risk in simply enlarging the airbag cushion was how it would affect OOP performance. Therefore, a comparison was made, using the 3 year old child dummy in ISO-2 position. Figure 12 and Figure 13 show the comparative risk in terms of induced chest and head injury. In both figures, the solid black signal trace (Baseline Side Airbag) represents a known acceptable OOP performance. The dotted line represents the larger airbag.

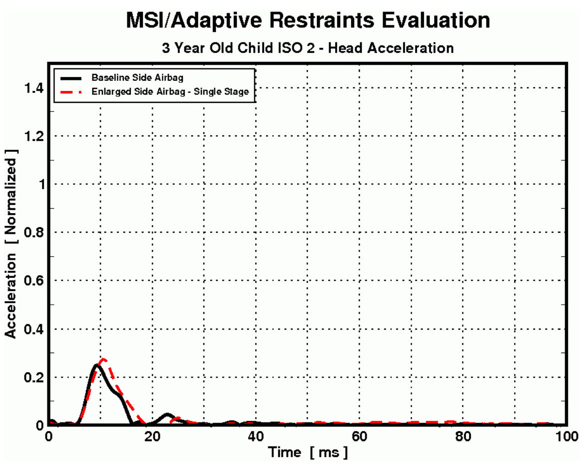

Figure 13. OOP Head Acceleration Comparison

Based on these figures, the effects of a larger airbag on OOP performance are minor and well within acceptable limits.

Enhanced Protection

Having established that the performance of the enlarged cushion is at least on-par with the baseline cushion, we next looked at further benefiting the occupants under high severity side impact conditions by adapting the restraints to the severity predicted by the MSI. Following the trends established for frontal impact restraints, the first adaptation considered here was the inclusion of a second inflation stage.
This approach brings many possible variables, including peak inflation level, stage delay, and active venting; where any or all of these are valid options for optimizing restraint effectiveness. As a first step, this study simply considered enhancing inflation through a second stage load at a level of 25% of the primary stage.

Figure 14 shows the rib injury measures for the Mid Size Male for the enlarged airbag cushions that were inflated by either the primary stage only or the primary and secondary stages. The secondary stage is deployed at the time the MSI has established crash type and severity. (i.e. TTF2 equals TTS) as shown in Table 1.

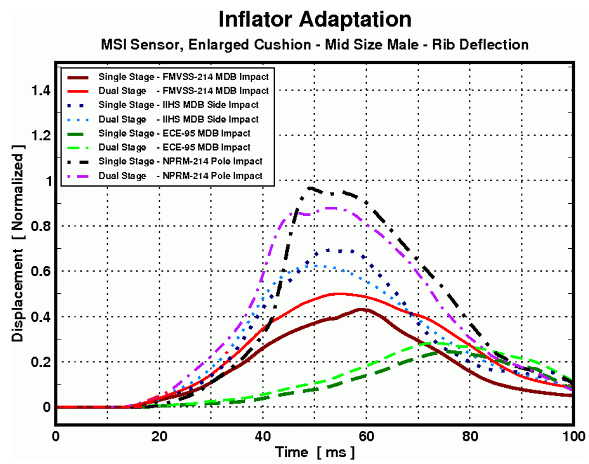

Figure 14. Inflator Adaptation - Mid Size Male

Clearly, the dual stage inflator shows a benefit for the higher severity cases (Pole and IIHS), while there is no perceived benefit for the lower severity cases. It is clear from Figure 14, that the threshold severity where a second stage should be deployed is somewhere between the severity of the FMVSS 214 MDB and the IIHS crash mode.

Aggravated and Real World Conditions

As discussed in [9,10], real world side impact severity on average may be considerably higher than current test conditions represent. We therefore explored the possibilities of the dual stage side airbag system under aggravated impact conditions. These comprise impacts with the same set of barrier objects but increased impact severity. Table 2 shows a compilation of the base line and aggravated speeds used in this paper.

Table 2.
Base Line and Aggravated Conditions

Base Crash Mode	Base Line Speed	Aggravated Speed
MDB Crashes:		
IIHS	50km/h	55km/h
FMVSS 214 MDB	54km/h	63km/h (SINCAP)
ECE R95	50km/h	55km/h
Pole crashes:		
FMVSS 214 NPRM pole	32km/h	35km/h

Figure 15 compares the rib deflections of the Mid Size Male for single and dual stage side airbags under these aggravated conditions. The figure shows that the second stage can be effectively used to improve protection in the three most severe tests.

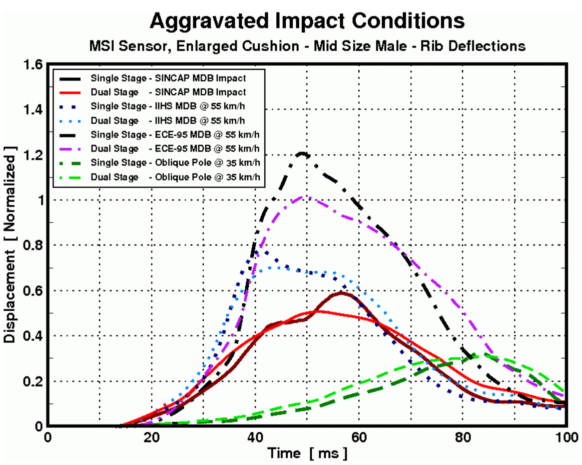

Figure 15. Aggravated Impact - Mid Size Male

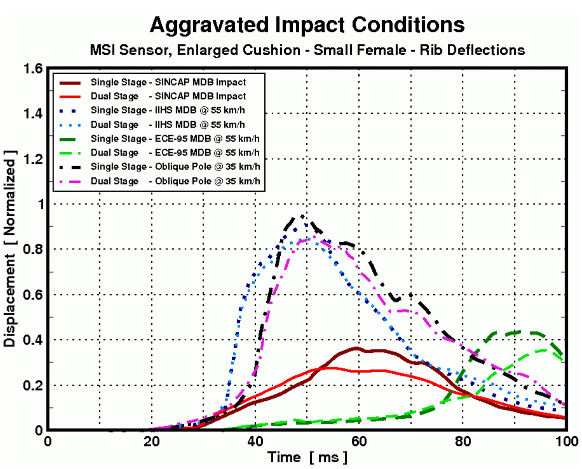

Figure 16. Aggravated Impact – Small Female

More benefit is obtained from the dual stage side airbag under more severe conditions, with little or no adverse effects on the performance for the lower severity tests. The peak rib deflection was reduced by 20% in the pole test with the use of the dual stage inflation. Figure 16 shows the results for the small female dummy under the increased speed impacts, which illustrate that the second stage improves the protection moderately for all tests.

DISCUSSION

The CAE analysis presented thus far intends to provide a basic starting point for the consideration of the potential benefits of adaptation in side impact protection. The results indicate that further analysis would be beneficial in order to optimize a second stage inflator by analyzing the tradeoffs for peak inflation levels in each stage, airbag volume, vent rate and other influencing factors. The achieved system must also show an improved benefit/cost ratio.

The MSI signal was used to estimate crash severity to derive a 2nd stage inflation decision and TTF2, from Table 1. From inspection of the results from figure 13-15, deployment of a second stage can be effective in reducing rib deflections in severe crash impacts. However, the severity threshold for deciding to deploy or not deploy the second stage must be carefully analyzed for each platform. For example, the MSI sensor location is chosen to balance fast TTF response over all regulatory tests. Inspection of Table 1 shows that the MSI effectively estimated severity for the FMVSS 214 MDB and the ECE R95 crash modes. The FMVSS 214 MDB (54km/h ***equivalent speed***) crash mode is rated slightly less than two thirds as severe as the ECE R95 crash mode (34km/h ***equivalent speed***). This same ratio is also approximately maintained in the peak values of the rib deflection values in those crashes. However, the MSI rates the FMVSS 214 MDB crash mode (63km/h ***equivalent speed***) more severe than the IIHS crash mode (50km/h ***equivalent speed***), but the IIHS crash mode produce more rib deflection. The reason for this is that the impact location of the IIHS barrier and the FMVSS 214 MDB are different. In the early phases of the crash, the IIHS barrier produces about the same average intrusion in proximity to the MSI sensor as the FMVSS 214 MDB. Therefore the IIHS ***equivalent speed*** is the same as the actual IIHS impact speed. This behavior can be tuned by optimal sensor placement to detect intrusion in the crash modes causing the worst injuries. This is an elegant way to allow the most protection for the most vulnerable point of the vehicle structure.

Real World Considerations

This analysis utilized a side airbag with greater width, which allows for a wider cover of the rib cage. This may provide additional benefits under real world impact conditions. For example, whereas the FMVSS 214 NPRM pole standard utilized an oblique impact angle of 75 degrees, recent NASS and FARS statistics on side impact suggest that the average "real world" impact incident angle for car-to-pole and car-to-car is approximately 63 degrees. The better thorax coverage of the enlarged airbag may afford additional benefits under such angled impact conditions. Not investigated in this study, but of equal perceived benefit is that the earlier trigger time afforded by the MSI sensor may allow for a more effective utilization of the side curtain restraints.

As shown in this paper the MSI can determine quickly whether a severe impact occurs. This information can be used to set various possibilities of adaptable restraints. For this paper, only a two-staged inflation of the side bag was considered. This was done to keep the number of simulation runs at an acceptable level. The ability of the MSI to detect and evaluate crash severity could be used for additional methods of restraint adaptation. Generally, adaptation of side restraints can be achieved by changing the properties of any of the following.

- **Bag shape variation** in x- or y- direction would adapt the cushion either to more absorption depth by the same deployment pattern compared to a side bag with a smaller depth or would improve the performance for oblique pole impacts. A challenging issue is to maintain the pressure at a balanced level during and after the extra expansion of the cushion shape.

- **Inflation method** by either having a 2-(or more) stage inflator or through by-passing a certain amount of gas generated from an "over-dimensioned" inflator can change the bag characteristics dramatically. This approach would cause differences in pressure level dependant on the demand necessary for a specific situation.

- **Active venting** on / off or even changing the size of the vent hole would generate a drastic improvement depending on the situation. It would have to be determined if an analog way or just a digital on/off function is sufficient. To optimize the restraint force-deflection characteristics an active adjustment of the vent hole seams to be most promising. [11]

Another potential method to improve side impact protection is by using information from occupant classification sensors in the car. As an example, seat weight classification systems can be used by the side protection system to selectively deploy or not deploy adaptive restraint functions. In the future, more sophisticated sensors can provide occupant position and stature information in real-time to continuously adapt the restraint optimally to the current conditions. Ultimately, fast deployment times and crash severity measures derived from MSI will be integrated as a key element in a holistic system safety approach.

CONCLUSIONS

In the introduction of this paper, a supporting case was made to consider new concepts for side impact crash protection. This paper has shown that the MSI provides fast restraint deployment as well as crash severity which can be used in improved protection adaptive side restraints.

This paper has also shown that there is still significant potential, for transferring more information from the crash sensor to the restraint system (e.g. crash severity) and by optimizing the restraint to make full use of the possibilities offered by the crash sensor (e.g. bigger cushion if faster TTF's are available).

If the crash sensor can also provide crash severity, adaptive restraints for side crashes are a first new path to follow, to further decrease fatalities and injuries, particularly in the case of more severe impact conditions which are expected to be reflected in future regulatory test standards.

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