A STUDY OF CURTAIN AIRBAG DESIGN FACTORS FOR ENHANCEMENT OF EJECTION MITIGATION PERFORMANCE

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ABSTRACT

A curtain airbag (CAB) plays a significant role in not only protecting an occupant head from side impact crashes, but also preventing an occupant being partially or totally ejected during rollover accidents. As the seriousness of rollover accident has been statistically studied and reported, the latter function of CAB become more emphasized than before. At last, NHTSA released FMVSS226 final rule in January 2011 which limits the linear travel of impactor headform by 100mm.
This paper focuses on how to meet the requirement by enhancing CAB design and on establishing design guideline through its parametric study. For this, 9 design factors are selected which have major effect on ejection mitigation performance and the effectiveness of each factor is analyzed. They are cushion pressure, amount of coating, cushion shape, cushion depth, overlapping area between door trim and cushion, strength of cushion mounting tab and tether, location of front tether and lastly, distance between impact target point (A3) and cushion mounting.
From this study, the parametric guideline of CAB design factors for satisfying the required excursion limit of 100mm is found out and the test result with the CAB module applied these parameter level shows that the goal is successfully achieved within the excursion of 80mm in all target locations with the test speed of 24kph in accordance with NPRM. At last part, the future work to optimize this for smaller glazing is mentioned.

INTRODUCTION

Rollover crash is a kind of accident which causes relatively more severe fatalities. According to the statistical research of NASS-CDS, although the ratio of rollover crash in all kind of the types is about 2~4% in USA in every year, the fatality rate in the rollover situation has been over 30% (31% in 2003), 33% in 2004, 35% in 2007). Especially, Figure 1 shows that 58% of the 10,378 fatalities in 2003 is due to being partially or fully ejected by rollover accident. From this annual report, we can come to the conclusion that it can be an effective method to help reducing fatalities that mitigating the occupant ejection through side windows. NHTSA (National Highway Traffic Safety Administration) recognized this seriousness of rollover accident and organized IPT (Integrated Project Team) in 2002, which published a guidebook[3)] in 2003 for safety-improving from the viewpoints of vehicle, roadway and behavioral strategies by conducting rollover and another kinds of tests. On the basis of this, rulemaking activity for mitigating the vehicle occupant ejection had been proceeded and NHTSA

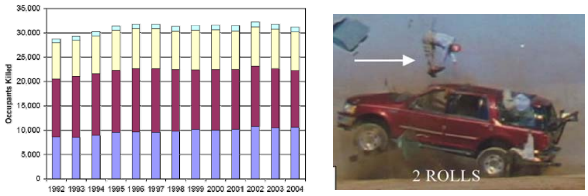


Figure 1. Statistical data of occupant fatalities and complete ejection in rollover crash accident.

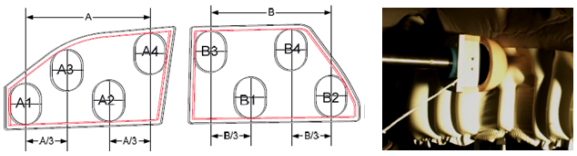


Figure 2. Target locations and test method.

released FMVSS 226 NPRM in December 2009, as well as its final rule in January 2011.
The NPRM limited the linear travel of the 18kg impactor headform by 100mm from the inside of the tested vehicle's glazing in all 4 or less locations when impacting it on curtain airbag with the speed of 24kph at 1.5 seconds after it deployed and 16kph at 6 seconds or on punched advanced glazing. But the final rule eased the regulation by reducing the impacting speed from 24kph to 20kph, and also tightened it rotating the headform and targets by 90 degrees to a horizontal orientation.

This paper proposes the curtain airbag design guideline for satisfying the FMVSS 226 by parametric study. For this, 9 design factors are selected which have major effect on ejection mitigation performance and then their effectiveness is independently analyzed assuming that they have no interactions with one another. They are cushion pressure, amount of coating, cushion shape, cushion depth, overlapping height between door trim and cushion, strength of cushion mounting tab and tether, location of front tether and distance between impact target point (A3) and cushion mounting. For some factors, ejection mitigation performance is evaluated by testing same kind of CAB modules which are made to have two or three parameter levels. And for the other factors, the effectiveness is analyzed using several CAB modules which are already developed and in production for their vehicles. Basically parametric values of guideline are drawn from the test speed of 24kph according to NPRM considering its severity of energy level and because of not enough test data under standards of final rule after it was released.

PRESSURE AND COATING

The performance of CAB's inner pressure can be evaluated by the capability to absorb the impact energy from side impact crash and to maintain high pressure as long as possible at 1.5 and 6.0 seconds after it is deployed when impactor headform hit the cushion. These two characteristics conflict with each other, so it would be the order of priority firstly to find the appropriate cushion pressure for side impact crash (SINCAP MDB and Pole test mode), secondly to keep the maximum pressure as can as possible making gas leakage minimized and then to modify the other design factors for reducing the excursion of headform.

Evaluation of Pressure in Cushion according to Coating Amount

Test method Inner pressure of three OPW(One Piece Woven) cushions is measured which have the same shape and size, only different silicon coating amount of 35g/mm^2, 75g /mm^2 and 95g/ mm^2 respectively. Three locations for fixing pressure port are selected on front, mid and rear cushion chamber in longitudinal direction for pressure monitoring as shown in Figure 3. The tests are conducted three times for each cushion having a coating amount.

Test result The average pressures in three locations have almost same level. The locational pressure property of cushion is closely related with the chamber design and deployment performance in case of first impact (side impact crash within 50ms) [8], but comparatively it have noting to do with ejection mitigation performance due to the enough time to fill the gas into entire cushion chamber.

Figure 3. The locations of pressure measuring port and its installation.

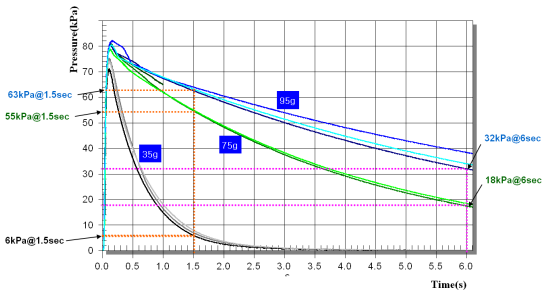


Figure 4. Inner pressure of cushion at 1.5s and 6s in different coating condition(35g, 75g, 95g).

Figure 4. shows that the average pressures are 63.3kPa(1.5s), 34.8kPa(6s) with the coating amount of 95g, and 55kPa(1.5s), 18kPa(6s) with that of 75g. The increase of coating amount by 20g(75g → 95g) results in the pressure increase of 15% at 1.5s and 93% at 6s. This means the coating factor become more important as times goes on.

Evaluation of Headform Travel According to Coating Amount

Test method The ejection mitigation tests are performed at 4 target locations(A1, A2, A3, A4) in 1st row using CABs with 75g, 95g coated. In this test, the cushions are filled with the gas in the same pressure as the lowest values of former pressure monitoring test using pressure controllable gas injection device instead of using inflator.

Test result The result shows that increase of coating amount is more effective when the impact time is at 6 seconds with the test speed of 16kph (See Table 1). This is due to that although the pressure loss at 6 seconds is more than at 1.5 seconds, the difference of gas leakage between the cushion having 75g and 95g coating also increases as time goes by.
In the aspect of target location, coating factor is most effective at A4 where the inflated cushion depth is thickest in all the test conditions and there are 7% and 16% improvement at the weak point of A1 and A3 respectively with the increase of 20g coating. The maximum improvement is 91% at 6 seconds at the location of A4 where the inflated cushion depth is biggest.
The decrease of excursions of all locations with the speed of 24kph(1.5s) or at A1 location with all test speed are around or under 10%, so cushion chamber shape or the other factors are to be modified to enhance the performance.

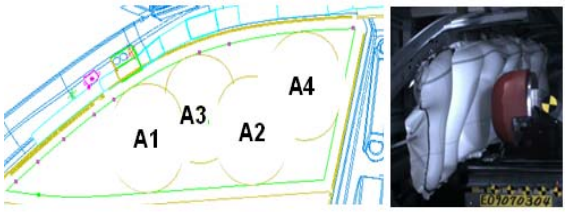


Figure 5. Target locations and tested cushion pressure.

Table 1.
Excursion and improvement according to coating amount.

Location	16kph, 6s			20kph, 1.5s			24kph, 1.5s		
	75g	95g	Excursion Difference (%)	75g	95g	Excursion Difference (%)	75g	95g	Excursion Difference (%)
A1	112.4	104.4	8 (7%)	125.5	123	2.5 (2%)	137.2	137.2	0
A2	55.9	26.5	29.4 (53%)	43.8	38.3	5.5 (13%)	79.3	71.9	7.4 (9%)
A3	107.8	91	16.8 (16%)	107.2	102.1	5.1 (5%)	137.2	132.4	4.8 (4%)
A4	35	3	32 (91%)	12.4	3	9.4 (76%)	35.7	40.1	4.4 (12%)

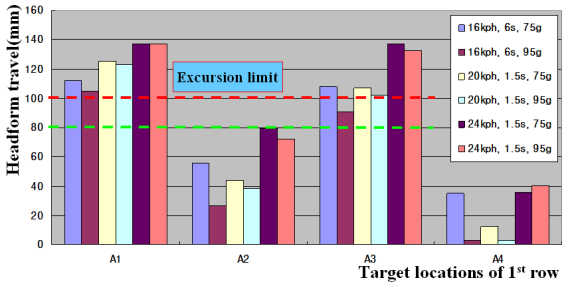


Figure 6. Headform travel according to target location and coating amount.

The Guideline of Cushion Pressure and Coating Amount of CAB

Generally, cushion pressure required for getting good head injury in side impact tests (SINCAP MDB and Pole test mode) ranges from 40kPa to 80kPa with varying vehicle segments and structural performances. But the CAB used in this test is SUV's and the guideline is that the cushion pressure needs over 65kPa at 1.5 seconds and 35kPa at 6 seconds with the impactor speed of 24kph and 16kph respectively and coating amount is 95g/mm^2 by OPW(One Piece Woven) fabric made of Nylon 66 material.

CUSHION CHAMBER SHAPE

Test Method

The excursions at A1 and B1 are compared each other according to active chamber, whose target point are comparatively far from the cushion mounting on body panel and are irrelevant to impact point of side crash test so that there usually have little inflated chamber. About A1 location, the test is carried out using two cushion designs as shown in

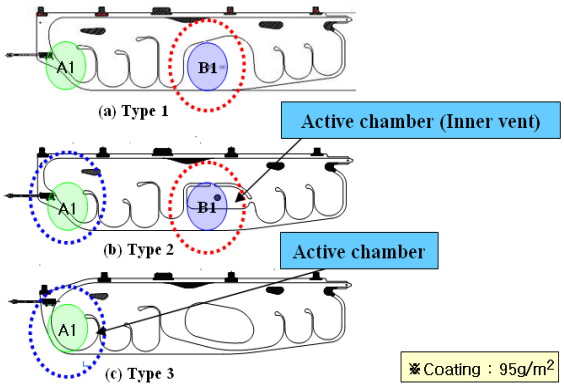


Figure 7. Cushion shape according to inflatable chamber at A1 and B1 target locations.

volume except different thickness at the point in conditions of 33kP and 40kPa (24kph, 1.5s). About B1 location, the test is conducted using two cushion designs as shown in Figure 7 (a)Type 1 and (b)Type 2 which have same volume but only type 2 have active chamber at the point in conditions of 33kP (24kph, 1.5s). All the CAB cushions have 95g/mm^2 coating.

Test Result

It is shown that there is improvement of 25~30mm between type 2 and type 3 at A1 location and that the higher the inner pressure is, the more effective the thicker cushion is (See table 2). Decrease of headform travel at B1 is 35mm from cushion type 1 to type 2. Especially, we applied inner vent to the chamber design on B1 location in type 2, which is also called delay chamber.

Table. 2
Headform travel according to inflatable chamber at A1 and B1.

Speed			24kph(1.5s)	
Location			A1	B1
TEST RESULT	Type #1	33kPa@1.5s(1.8 mol)	157	185
	Type #2	33kPa@1.5s (1.8 mol)	160	150
		40kPa@1.5s (2.0 mol)	152	
	Type #3	33kPa@1.5s (1.8 mol)	135	
		40kPa@1.5s (2.0 mol)	132	

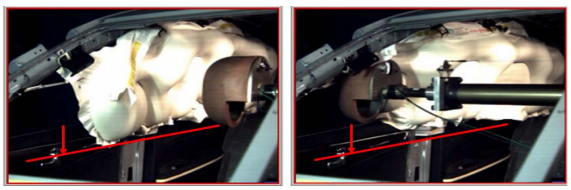


Figure 8. Ejection mitigation test of type 2 at A1.

This chamber is filled with inflator gas near after 1 second later than first impact time span (i.e. side crash impact) by narrowing the entrance to the aimed chamber. This design helps improving ejection mitigation performance without increasing inflator capacity (cost). Another example is shown in Figure 9.

The Guideline of Cushion Shape Design

Inflated chamber is needed at A1 and B1 location. The inflated chambers at A1 and B1 are to be set up so that they can include impactor headform projected area at A1 and target point (headform center point) as shown in Figure9. A-pillar structure cannot support CAB cushion at A1 location so that chamber needed to cover all of the headform. On the other hand, it is permitted that inflated chamber covers only B1 target point because B-pillar structure helps supporting the CAB cushion. In some cases of small glazing, the inflated chamber at B1 cannot be needed if the chamber depth of B-pillar area is thick enough to support CAB cushion. At both of A1 and B1 locations, inner vent design is applicable.

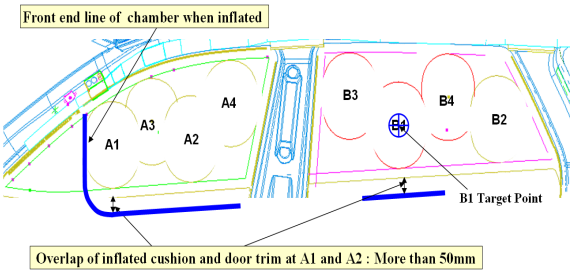


Figure 9. The area for inflated chamber

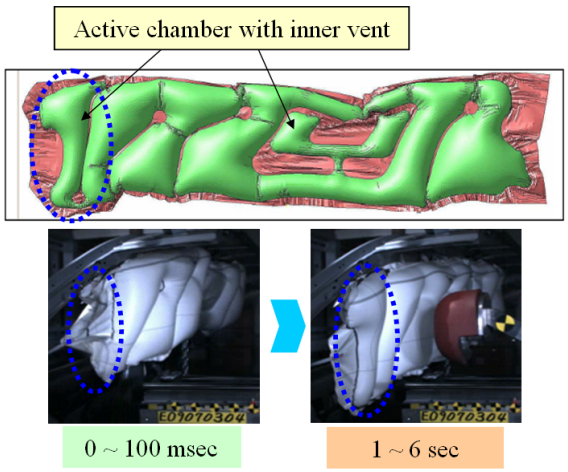


Figure 10. Inner vent (delay chamber) design.

DEPTH OF INFLATED CUSHION CHAMBER AT TARGET LOCATIONS

The depth of inflated cushion chamber is the design factor which directly affect to ejection mitigation performance so that the improvement is big when increasing its thickness in the state of high pressure level. But if it is increased without limit for only enhancing ejection mitigation performance, the inflator should be bigger and more expensive. In addition, the thickness is closely related with the development of rollover sensing system. The CAB firing time is determined predicting whether a vehicle is going to roll over or not considering roll-angle, roll-rate, lateral acceleration, occupant behavior, etc. In case of high speed roll-over situation like curb-trip mode, there cannot be enough time to determine TTF (Time to Fire) in order for CAB to be deployed stably before occupant head come to CAB cushion if its depth is too thick. Consequently, the guideline of cushion depth has only lower limit of 100mm without upper limit. The upper limit is depends on the behavioral characteristics of vehicle and occupant, and on CAB's deployment performance.

OVERLAPNG HEIGHT OF CUSHION AND DOOR TRIM

Test Method

The ejection mitigation performance according to overlapping height between door trim and cushion can be evaluated by using different CAB modules having different height in a vehicle. But if varying the cushion's height, it is very hard to make the CAB modules having same pressure property but only different height, and this result in interactions with another design factors. Thus, in this test, a CAB module is evaluated which is already developed and applied to two different vehicles which have same structural layout (CAB route and mounting position) but different height of door trim in second row. The target locations of second row are set to one vehicle and the coordinates are transferred to the other vehicle. And the overlap height is measured about the CAB module which satisfies the excursion limit of 100mm (20kph) in the inflated state.

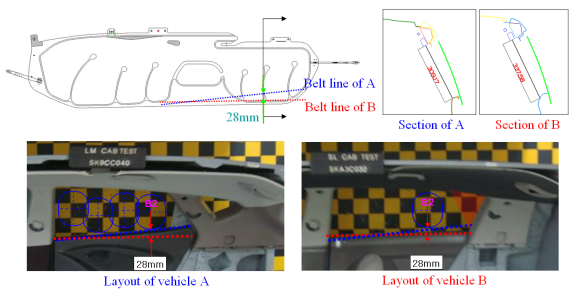


Figure 10. Two vehicles having same CAB module but different door trim height.

Test Result

The improvement of excursion is 21 mm at B1 location from the overlap difference of 28mm comparing the test results conducted in vehicle A and B as shown in Figure 11. This test seems to be reliable considering that excursion deviations at another location except A1 between two vehicles are within 1mm. It is thought that the difference at A1 is due to the A-pillar layout. It is expected that the overlapping height between door trim and cushion is effective at A1, A2, B1 and B2 which are close to door trim.

Another test result of CAB module whose maximum excursion is 79mm (24kph) also shows that the excursion decrease rapidly at the location which has the overlap height of over 50mm in the inflated state.

Table 3.
Test result according to overlap difference between two vehicles.

	80mm↓		100mm↓		Over 100mm↑

Vehicle	A				B			
Speed	24kph				24kph			
Location	A1	A2	A3	A4	A1	A2	A3	A4
First row	96			39	79			38
Location	B1	B2	B3	B4	B1	B2	B3	B4
Second row		112	56			133	55	

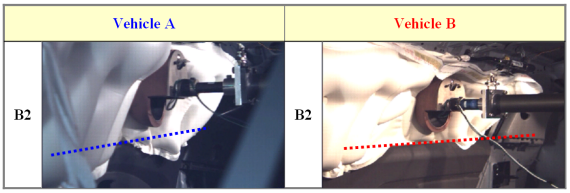
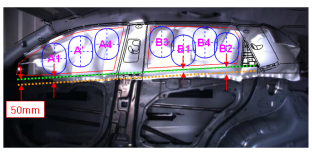


Figure 11. Ejection mitigation test at B2 location



Vehicle C	Speed	24kph	
	Location	A1	A'
	1st row	79	33.5
	Location	B1	B2
	2nd row	66	7

Figure 12. The cushion overlap with beltline and ejection mitigation test. **(Part of car body test)**

STRENGTH OF CUSHION MOUNTING TAB AND TETHER

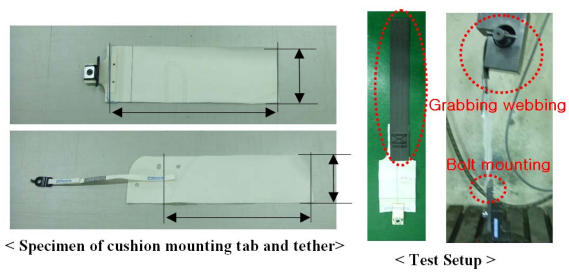
When the 18kg impactor headform is impacted to CAB cushion with the speed of 24kph, the energy of 400J is applied to the cushion exerting tensile force to the mounting tab and tether around the target location. Thus, they are needed to be designed not to be broken and easily stretched. Actually it sometimes happened that tether bracket was broken or cushion mounting tab was torn in ejection mitigation test increasing headform excursion or not containing it within vehicle's inboard side of CAB cushion.

Test Method

The specimens of seven kinds of cushion mounting tab-bracket and ten kinds of tether-bracket assembly were cut from six kinds of CAB modules and they were examined by grab test using UTM device. Each kind of specimen is tested three times with the speed of 100mm/min. The specimen and test setup method are shown in Figure 13. In this test, breaking strength (maximum tensile force in this paper) and stretched length at that point are simply used instead of tensile strength and elongation because the specimen is composed of more than two materials and doesn't follow the specimen standard.

Test Result

The breaking strength variously rages from 100kgf to 410kgf. The broken locations are also different in mounting tab, sewing line, tether bracket and tether itself. On the whole, cushion mounting has low breaking strength and short stretched length, while tether has the opposite properties. In ejection mitigation test of a vehicle, impactor headform stopped at almost same time when the mounting tab was broken, and this can tell us that 128kgf is the minimum required strength level against impactor energy, which is the breaking strength of this mounting tab in grab test.



< Specimen of cushion mounting tab and tether>

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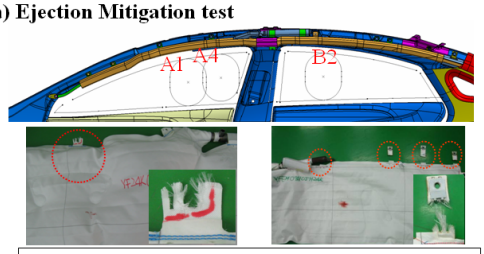
Figure 13. Test setup and specimen.

(a) Ejection Mitigation test



Tests at target points of A1 and B2 (24kph) : Mounting Tab broken and excursion increased

(b) Grab test : Breaking strength 128kgf with 36mm stretch

Cushion mounting Tab and bracket seperated

Figure 14. Breakage in ejection mitigation and grab test result.

The Guideline of Cushion Mounting Tab and Tether strength.

High breaking strength prevents the mounting parts being disconnected and the shorter the stretched length is, the better the ejection mitigation performance is. Therefore, as the ratio of breaking strength to stretched length (kgf/mm) is increased, so the excursion of headform is decreased at the point when reaching to the breaking strength.

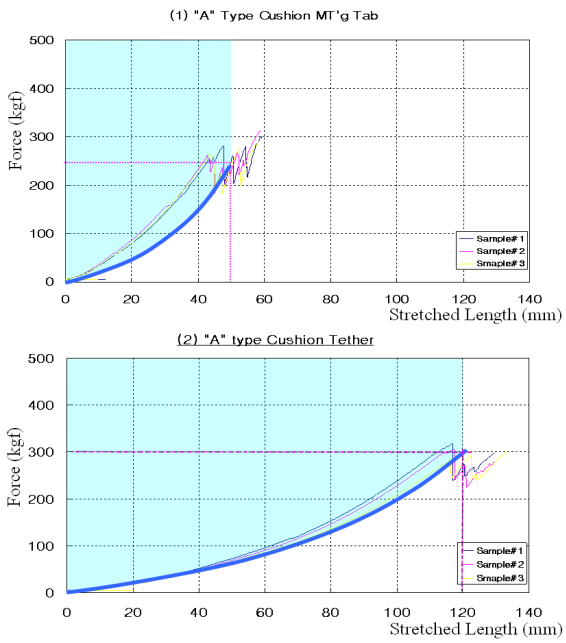


Figure 15. The result of grab test

The guideline for strength is determined so that mounting part can withstand the pulling force from impactor energy with the speed of 24kph and referring to the test result having high ratio of breaking strength to stretched length. The required parameter value for cushion mounting tab and tether is different. Mounting tab needs the breaking strength of over 250kgf and stretched length of below 50mm. Tether mounting needs the breaking strength of over 300kgf and stretched length of below120mm. The ratios of cushion mounting tab and tether are5kgf/mm, 2.5kgf/mm respectively as shown in Figure 15.

THE LOCATION OF FRONT TETHER MOUNTING

About the locations of A1 and A3, body structure of A-pillar cannot support CAB cushion because of the slanted feature of car body and the limit of cushion length in frontal direction. Therefore, tether is attached between A-pillar and front area of cushion in order to strongly grab the cushion against pushing force from headform to the outside of vehicle. In this case, the location of tether-cushion sewing and tether bracket mounting on A-pillar affect to ejection mitigation performance. As a result, their relative positions are determined so that the cushion can be constrained on body tightly as shown in Figure 16. Tether sewing is to be positioned below the A1 target point and location of tether bracket mounting, below the mid-height of cushion chamber when fully deployed.

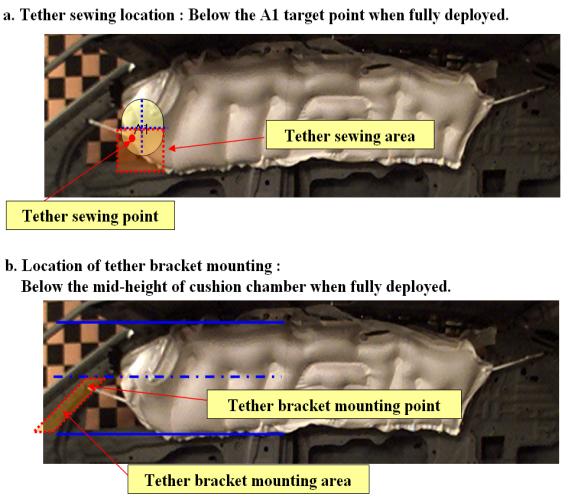


Figure 16. FRT The location of tether sewing and mounting.

THE DISTANCE BETWEEN A3 TARGET POINT AND ITS NEIGHBORING CUSHION MOUNTING

The relation between excursion and mounting distance from A3 target point is investigated for 5 vehicles. Mostly, the excursion limit of 100mm is satisfied except vehicle A at A3 and any clear correlation is not found (See Table 4.). It is thought that there are another design factors that affect more to ejection mitigation performance than this factor. Most of the distance ranges from 200mm to 300mm. It is recommended that the distance from A3 to its neighboring cushion mounting is below 300mm. It is expected that the closer the distance is, the smaller the excursion of impactor headform is.

CONCLUSIONS

Nine design factors are selected which have major effect on ejection mitigation performance and then their effectiveness is independently analyzed. With this, the curtain airbag design guideline is established for accomplishing the goal of 100mm limit of impactor headform's linear travel with the speed of 24kph (according to FMVSS226 NPRM). And the ejection mitigation test result for a CAB module of a SUV which this parameter level is applied to shows that the requirement of FMVSS226 NPRM is successfully achieved with the maximum excursion of 80mm as shown in Table 5.

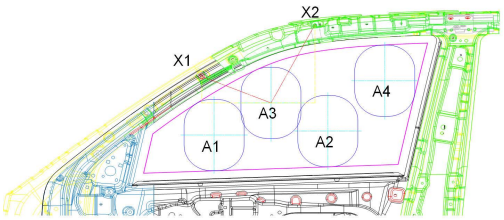
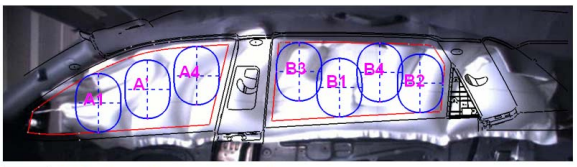


Figure 17. Distance between A3 target point and its neighboring cushion mounting.

Table. 4 Excursion according to mounting distance

Vehicle	A: A3~X1 (mm)	B: A3~X2 (mm)	A+B	Excursion(24kph)			
				A1	A2	A3	A4
A	221	281	501	138	27	**106**	29
B	413	286	699	85	35	**53**	-13
C	273	292	565	95	42	**72**	30
D	277	203 (346)	480 (623)	88	-45	**57**	-40
E	230	258	488	88	(13)	**(88)**	13

Table 5. Test result of the finally modified CAB.



: Eliminated target point

* : Skip considering the result of 24kph test

Location		A1	A2	A3	A4	A'
First Row	16kph	29			*	*
	24kph	80			-6	56
Location		B1	B2	B3	B4	
Second Row	16kph	*	*	*	*	
	24kph	46	-58	-24	*	

※ Test condition : Full vehicle
※ Dynamic friction : less than 0.25
※ Target locations according to NPRM and Final rule are same.

Nevertheless, the proposed CAB design specification may be reinforced for accomplishing the objective of FMVSS226 NPRM about SUV, resulting in the rise of cost.
Hence, it would be future work to optimize the parameters suitable for the vehicle which have smaller size of window glazing (having maximum of 2 or 3 target points per a glass in a vehicle) and to develop more improved technologies to approach higher ejection mitigation performance with reduced cost for satisfying FMVSS226 final rule.

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