THE APPLICATION OF CAE IN THE DEVELOPMENT OF AIRBAG RESTRAINT SYSTEM PERFORMANCE FOR A CERTAIN VEHICLE

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ABSTRACT

If vehicle manufacturers have an airbag sensing algorithm, they could use this algorithm to find optimal airbag sensor locations for the better airbag sensing performance, to get an optimal firing logic for their certain vehicle, and to get the overall good performance by considering both the vehicle structure and the airbag sensing algorithm. One study in this paper shows how to find the optimal locations of front impact sensors (FIS) using in-house airbag sensing algorithm, crash test data and CAE simulation models. For this purpose, three steps are fulfilled as follows. In the first step, the acceleration sensor signals of the crash tests are collected at several positions of the vehicle. In the second step, the full car crash simulations are made and correlated to the crash test data. Using these well defined crash vehicle models and crash test data, the acceleration signals of the FIS candidate locations, such as radiator, front side members, and bumper back beam, are obtained. In the final step, using these acceleration signals and airbag algorithm, the airbag sensing performance are evaluated, and the final candidate positions are selected. The robust FIS positions are selected effectively for various crash conditions and velocities via this approach.

The other study shows how to determine an airbag deployment logic using CAE. From simulation models which have several crash speeds, several crash modes, and several restraint conditions, the airbag deployment logic can be determined to minimize the occupant injury level. In addition, the roles and limitations of CAE simulations are demonstrated in the airbag algorithm calibration process and the airbag restraint system development.

INTRODUCTION

Out of several requirements for airbag sensing performance, it is very important to find the optimal locations of ACU (Airbag Control Unit) and FIS in the early phase of vehicle development. Besides the accelerometers in ACU near vehicle front tunnel, the FIS has very important role, too.

The current vehicle's FIS have various locations such as front side member, radiator upper or lower, bumper back beam and so on; therefore, further survey and research to find optimal sensor positions for airbag sensing must be carried out now and after.

The purpose of this paper is to find the optimal location of FIS in order to prevent airbag malfunctioning from inaccuracy of airbag sensibility under various crash modes and velocities. From this optimization point of view, airbag sensing algorithm and calibration technique were developed and various vehicle crash test data with various crash modes and speeds, and airbag sensing crash simulation data were handled to find our goal for sensor locations.

VEHICLE CRASH TEST DATA ANALYSIS

Requirements for Frontal Crash Airbag Sensing

The so-called advanced airbag system to meet the requirements of FMVSS208 should be able to discriminate crash severity with the help of frontal impact sensor(s) under multiple crash modes and impact speeds. In general, crash signal from FIS should survive at least up to 15ms for the high speed frontal impact and until over 40ms for the offset crash. That sensor survival time could be the necessities against the sensor damage and wiring cutting.

The peak of FIS signal must be larger and earlier than that of ACU. And for the ACU, the signal of lower crash severe modes must not be more than that of higher crash severe modes to prevent firing the airbag in case of Must Not Fire condition, and also to prohibit firing the airbag in case of Must Fire condition, on the contrary.

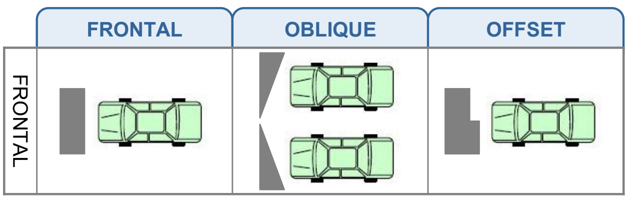


Fig.1 Crash Modes (Frontal, Oblique and Offset)

Crash Test Matrix and Test Conditions

Table.1 shows crash test matrix which has various crash modes and crash speeds for this project.

No.	Speed	Crash Mode	Purpose
1	Low	Frontal	Threshold
3	Low	Frontal	Threshold
2	Low	Frontal	Threshold
4	Low	Frontal	Threshold
6	Mid	Frontal	Threshold/Regulation
5	Mid (25mph)	Frontal	Threshold/Regulation
9	Mid (20mph)	Oblique	Regulation
7	Mid (25mph)	Offset	Regulation
11	High (35mph)	Frontal	Regulation
10	Mid (25mph)	Oblique	Regulation
8	High (40mph)	Offset	NCAP
12	Mid	Others	Due Care
13	Mid	Others	Due Care

Table.1 Crash Test Matrix

To minimize test numbers and costs, indispensable test items were selected from the past vehicle development test results by adjusting test speeds and distributing the number of tests, and using the past crash test data.

FIS Location Candidates

After surveying the FIS locations from many vehicle platforms in the real field, 3 points at the radiator support upper member (left, center, right), 3 points at the radiator support lower member (left, center, right), 3 points at the bumper back beam (left, center, right), 2 points at the front side inner member (left, right), and 2 points at the front side outer member (left, right) were selected and classified into 4 categories and 13 points per crash test. Fig.2 shows one of the FIS location candidates (radiator support upper member).

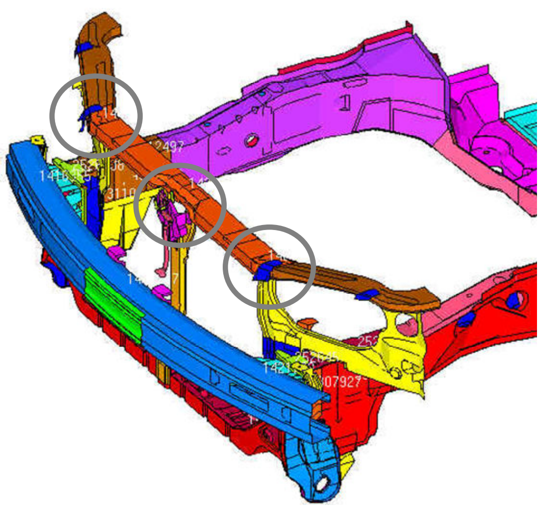


Fig.2 FIS Candidates - RAD SUPT UPR

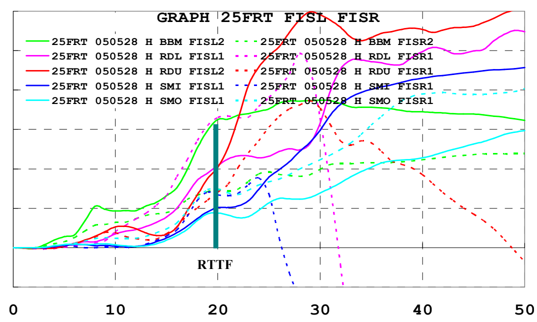
Validity Analysis of Crash Test Data

The numbers in Table.2 are signal failure number according to crash modes, crash speeds and FIS location candidates including left, center and right positions. Especially failure rate in central positions of radiator support lower panel and bumper back beam plate is higher than other positions, because those positions are the direct crash deformation area. And the rate of the front inner and outer side member is relatively higher than radiator support panels and bumper back beam.

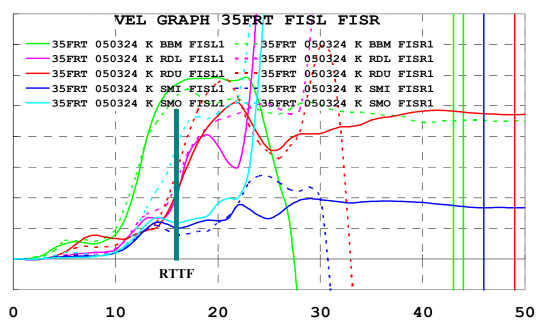
Mode	Speed	RAD SUPT UPR	RAD SUPT LWR	Bumper Back Beam	FR S/MBR INR	FR S/MBR OTR
Frontal	Low	-	-	-	-	-
	Low	-	1	2	-	-
	Low	1	1	4	3	4
	Low	2	1	5	3	4
	Mid	2	3	3	1	-
	Mid (25mph)	1	2	2	-	-
	High (35mph)	4	6	3	2	3
Offset	Mid (25mph)	-	1	1	-	1
	High (40mph)	-	3	-	1	1
Oblique	Mid (20mph)	-	1	-	-	-
	Mid (25mph)	-	-	-	-	-
Others	Mid	-	1	1	-	1
	Mid	-	1	1	-	-
Sum	Failure Rate	10/67	21/67	22/67	10/42	14/42

Table.2 Failure Rate according to Crash Modes and Crash Speeds at FIS Candidates

From a validity view with FIS signal observation, the failure numbers of frontal crash are proportional to the crash speed in the nature of thing. But because most of failure time is fortunately beyond the RTTF (Required Time To Fire) (Fig.3), it almost doesn't matter to airbag sensing performance of crash discrimination. And other crash modes such as oblique, offset etc. have lower failure rates than frontal impact.



(a) Mid Frontal FIS Signal Failure



(b) High Frontal FIS Signal Failure

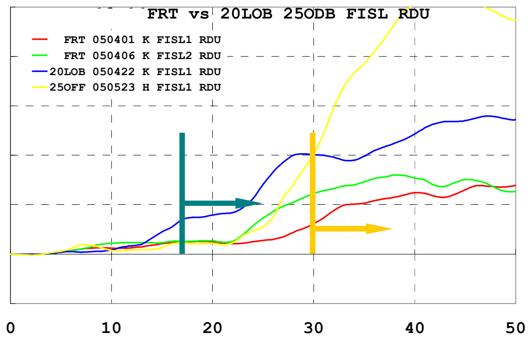
Fig.3 FIS Signal Failure Time Analysis

Threshold Analysis (Stage 1 and Stage 2)

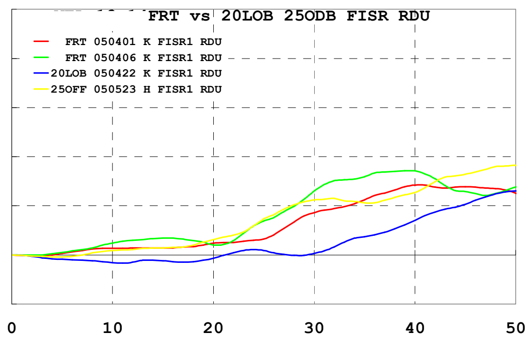
Table.3 and Fig.4 show the discrimination results of threshold stage1 with the crash test data including low speed frontal crash test modes, middle offset and middle oblique crash tests, and other crash modes. Where, ‘possible’ means that it is possible to discriminate the FIS signals according to the impact speeds, and ‘mixed’ means that the FIS signals are mixed one another, and ‘reverse’ literally means that the signals are reversed regardless of crash severity.

		Low Frontal Vs. Mid(25mph) Offset	Low Frontal Vs. Mid(20mph) Oblique	Low Frontal Vs. Other modes
RAD SUPT UPPER	FIS-L/R	Possible	Possible	Possible (Partly)
	FIS-C	Mixed	Mixed	Mixed
RAD SUPT LOWER	FIS-L/R	Possible	Possible	Possible (Partly)
	FIS-C	Offset Fail	Oblique Fail	Mixed
BACK BEAM	FIS-L/R	Possible	Possible	Possible
	FIS-C	Reverse	Reverse	Mixed
FR S/MBR INNER	FIS-L/R	Offset Fail	Possible	Reverse
FR S/MBR OUTER	FIS-L/R	Offset Fail	Possible	Mixed

Table.3 Threshold #1 Discrimination Results



(a) FIS-LH @ RAD UPR



(b) FIS-RH @ RAD UPR

Fig.4 FIS Signal Comparison between Low Frontal and Mid Oblique/Offset

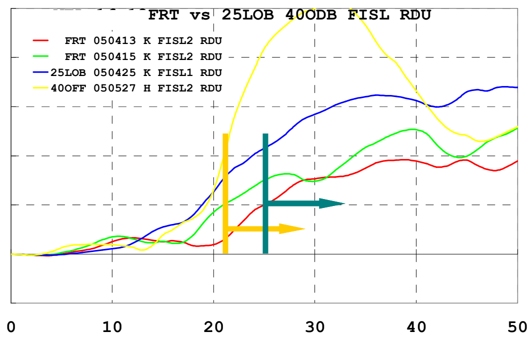
It is possible to classify FIS signals according to crash severity in the offset, oblique and other crash mode using crash test data of FIS-LH and RH at the radiator support upper member, the radiator lower member and bumper back beam. On the other side, it is difficult to divide crash data because of the FIS signal failure in the offset and oblique crash modes at the front side member which is the most general FIS locations, and also difficult to stand in line reversed crash test data according to crash severity. The crash signals from central FIS position can’t be arranged as crash severity throughout the crash data set.

Finally, bumper back beam plate is the most likely to discriminate in view of discrimination time, and radiator support lower member, radiator support upper member follows after that position

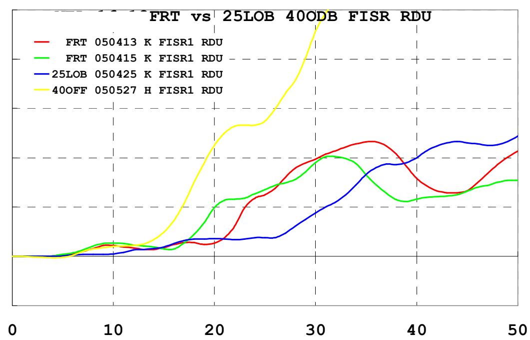
Table.4 and Fig.5 show the discrimination results of threshold stage2 with the crash test data including low speed frontal crash test modes, high offset and middle oblique crash test modes, and other crash mode.

		Low Frontal Vs. High(40mph) Offset	Low Frontal Vs. Mid(25mph) Oblique	Low Frontal Vs. Other mode
RAD SUPT UPPER	FIS-L/R	Possible	Possible	Possible
	FIS-C	Mixed	Mixed	Fail
RAD SUPT LOWER	FIS-L/R	Possible	Mixed	Reverse
	FIS-C	Mixed	Mixed	Mixed
BACK BEAM	FIS-L/R	Possible	Possible	Mixed
	FIS-C	Mixed	Mixed	Mixed
FR S/MBR INNER	FIS-L/R	Frontal Fail	Frontal Fail	Frontal Fail
FR S/MBR OUTER	FIS-L/R	Frontal Fail	Frontal Fail	Frontal Fail

Table.4 Threshold #2 Discrimination Results



(a) FIS-LH @ RAD UPR



(b) FIS-RH @ RAD UPR

Fig.5 FIS Signal Comparison between Low Frontal and Mid Oblique/High Offset

It is possible to divide FIS signals according to crash severity in the offset, oblique and other crash mode using crash test data of FIS-LH and RH at the radiator support upper member, and also possible to classify signals only in the offset mode using FIS crash data at the radiator support lower member, but impossible to discriminate in the oblique and other crash mode at that position. At the bumper back beam, it is possible to classify in the offset and oblique mode with FIS-LH and RH data. At the front side member, it is impossible to analyze the results because of the FIS signal failure of low speed frontal cash modes. Crash signals from central FIS position also have difficulties in arranging as crash severity from whole crash data set.

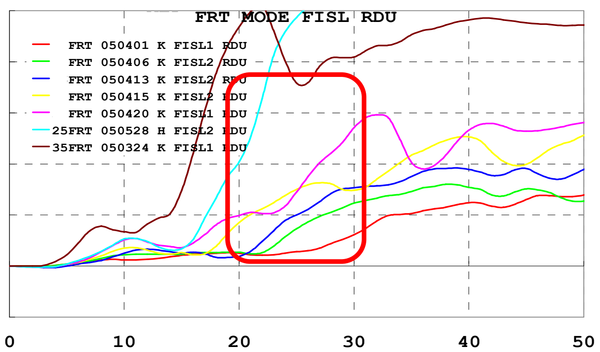
Parametric Study and Discussion

First, the evaluation results whether the FIS signal amplitude from various crash speeds is proportional to crash severity or not at the same FIS locations, are in Table.5. From the table, FIS signal discrimination performance from FIS-LH and RH is directly proportional to crash severity at the radiator support member locations (Fig.6), but FIS-CTR is not. Exceptionally, at the bumper back beam, whole FIS candidates have good proportionality.

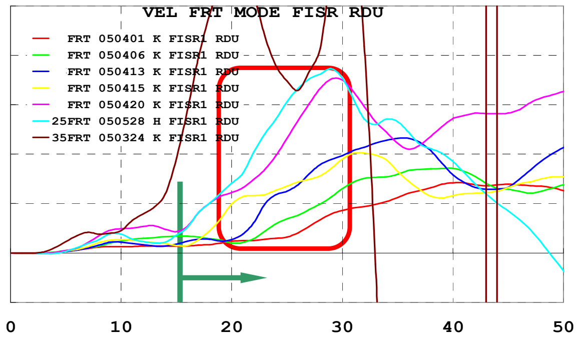
At the front side member, the FIS signal of low crash speed is bigger than that of high speed in reverse at some locations.

	FIS-LH	FIS-RH	FIS-CTR
RAD SUPT UPPER	Proportional	Proportional	Mixed
RAD SUPT LOWER	Proportional	Proportional	Mixed
BACK BEAM	Proportional	Proportional	Proportional
FR S/MBR INNER	Reversed	Proportional	
FR S/MBR OUTER	Reversed	Proportional	

Table.5 FIS Signals according to crash speed at the same FIS locations



(a) FIS-LH Signals @ RAD UPR



(b) FIS-RH Signals @ RAD UPR

Fig.6 FIS Signals of Frontal Crash Mode According to Impact Velocities @ RAD UPR

Signal amplitude from various locations is in good order at the same cash speed as follows: bumper back beam, radiator support upper and lower member, and front side inner and outer member.

It is noted that after reviewing the comparison results of FIS data analysis and parametric study, the radiator support upper member is the preferred location of FIS mounting.

CALIBRATOIN RESULTS OF FIS CANDIDATES

Calibration Data Set & Test Conditions

Airbag calibration controls the crash performance by decision of airbag firing at a proper time, so calibration results from whole the candidate locations, should be compared and analyzed to find the optimal positions.

Table.6 shows the test set and conditions for this project including 14 vehicle crash tests. And though not listed in Table.6, the other 94 rough road and misuse tests (25 constant road tests, 22 obstacle tests and 47 static tests) are also included in the calibration data set.

		Speed	Mode	Date	Purpose	Remark
Test Site 1	1	Low	Frontal	050401	THRESHOLD	
	2	Low	Frontal	050406	THRESHOLD	
	3	Low	Frontal	050413	THRESHOLD	S/MBR FISL DATA FAIL (S/MBR FISR)
	4	Low	Frontal	050415	THRESHOLD	S/MBR FISL DATA FAIL (S/MBR FISR)
	5	Mid	Frontal	050420	THRESHOLD / Regulation	
	6	High (35mph)	Frontal	050324	Regulation	
	7	Mid (20mph)	Oblique	050422	Regulation	
	8	Mid (25mph)	Oblique	050425	Regulation	
	9	Low	Frontal	030307	THRESHOLD	050401 Frontal FIS DATA
Test Site 2	10	Mid (25mph)	Frontal	050528	THRESHOLD / Regulation	
	11	Mid	Others	050526	DUE CARE	
	12	Mid	Others	050527	DUE CARE	
	13	Mid (25mph)	Offset	050523	Regulation	S/MBR FISL DATA FAIL
	14	High (40mph)	Offset	050527	NCAP	

Table.6 Calibration Data Set & Test Conditions

Calibration Results at Various Locations

(1) Bumper Back Beam

Over 80% (59 over 70, No.3) probability of No

Trigger exists at low speed frontal crash mode, which must be triggered into stage1 condition. And about 40% (42 over 70, No.5) probability of stage2 exists at another low speed frontal crash mode. And at the other modes such as mid speed oblique, mid speed offset, the calibration results couldn't satisfy the requirements. (Table.7)

Investigation of the misuse test margin, O17AS, O20AS and other 3 items have a margin of No Trigger less than 200%.

	SPEED/MODE	INFLATOR OUTPUT			REQ.	TTF's			RTTF
		NT	S1	S2		MIN	NOM	MAX	
1	Low Frontal	70	0	0	NT				
2	Low Frontal	64	6	0	GZ				
3	Low Frontal	59	11	0	S1				
4	Low Frontal	0	70	0	S1				
5	Low Frontal	0	42	28	S1				
6	Mid Others	0	70	0	S1				
7	Mid Oblique	0	16	54	S1				
8	Mid Frontal	0	0	70	S2				
9	Mid Frontal	0	0	70	S2				
10	Mid Oblique	0	0	70	S2				
11	Mid Offset	0	56	14	S1				
12	Mid Others	0	17	53	S2	Max. Delay : 13ms			
13	High Frontal	0	0	70	S2				
14	High Offset	0	0	70	S2				

	TEST	MARGIN
1	C09AS	185%
2	C11AS	180%
3	C15AS	190%
4	O08AS	180%
5	O17AS	125%
6	O20AS	130%

Table.7 Calibration @ Bumper Back Beam

(2) Radiator Lower Support Member

Table.8 shows that the calibration results can't fulfill the requirements at low speed frontal crash, mid oblique, mid offset and other conditions, and O17AS, O18AS, O20AS and the others at misuse tests, also can't meet the requirements.

	SPEED/MODE	INFLATOR OUTPUT			REQ.	TTF's			RTTF
		NT	S1	S2		MIN	NOM	MAX	
1	Low Frontal	70	0	0	NT				
2	Low Frontal	70	0	0	GZ				
3	Low Frontal	0	70	0	S1				
4	Low Frontal	0	70	0	S1				
5	Low Frontal	0	52	18	S1				
6	Mid Others	0	70	0	S1				
7	Mid Oblique	0	16	54	S1				
8	Mid Frontal	0	0	70	S2				
9	Mid Frontal	0	0	70	S2				
10	Mid Oblique	0	0	70	S2				
11	Mid Offset	0	56	14	S1				
12	Mid Others	0	17	53	S2	Max. Delay : 13ms			
13	High Frontal	0	0	70	S2				
14	High Offset	0	0	70	S2				

	TEST	MARGIN
1	C09AS	185%
2	C11AS	180%
3	C15AS	190%
4	O08AS	180%
5	O17AS	125%
6	O18AS	130%
7	O20AS	130%

Table.8 Calibration @ RAD SUPT LWR

(3) Radiator Upper Support Member

The calibration results at radiator upper support member can't satisfy the requirements at low speed frontal crash, mid oblique, mid offset and other conditions like the proceeding locations, and O17AS, O20AS, and so on at misuse tests, also can't meet the requirements. (Table.9)

	SPEED/MODE	INFLATOR OUTPUT			REQ.	TTF's			RTTF
		NT	S1	S2		MIN	NOM	MAX	
1	Low Frontal	70	0	0	NT				
2	Low Frontal	59	11	0	GZ				
3	Low Frontal	0	70	0	S1				
4	Low Frontal	0	70	0	S1				
5	Low Frontal	0	52	18	S1				
6	Mid Others	0	70	0	S1				
7	Mid Oblique	0	16	54	S1				
8	Mid Frontal	0	0	70	S2				
9	Mid Frontal	0	0	70	S2				
10	Mid Oblique	0	0	70	S2				
11	Mid Offset	0	52	18	S1				
12	Mid Others	0	16	54	S2	Max. Delay : 13ms			
13	High Frontal	0	0	70	S2				
14	High Offset	0	0	70	S2				

	TEST	MARGIN
1	C09AS	190%
2	C11AS	180%
3	C15AS	190%
4	O08AS	180%
5	O17AS	125%
6	O20AS	130%

Table.9 Calibration @ RAD SUPT UPR

(4) Front Side Inner Member

Many FIS crash signals are failed at low speed frontal crash test, and so the calibration was performed with other position signal from some other crash modes. As a result, at somewhat more crash types and speeds than other locations, couldn't meet the requirements especially mid speed offset crash mode.

	SPEED/MODE	INFLATOR OUTPUT			REQ.	TTF's			RTTF
		NT	S1	S2		MIN	NOM	MAX	
1	Low Frontal	70	0	0	NT				
2	Low Frontal	70	0	0	GZ				
3	Low Frontal	0	70	0	S1				
4	Low Frontal	0	70	0	S1				
5	Low Frontal	0	47	23	S1				
6	Mid Others	65	5	0	S1	No Trigger and Delay			
7	Mid Oblique	0	16	54	S1				
8	Mid Frontal	0	0	70	S2				
9	Mid Frontal	0	0	70	S2				
10	Mid Oblique	0	0	70	S2				
11	Mid Offset	0	56	14	S1				
12	Mid Others	0	17	53	S2	Max. Delay : 13ms			
13	High Frontal	0	0	70	S2				
14	High Offset	0	0	70	S2				

	TEST	MARGIN
1	C09AS	185%
2	C11AS	180%
3	C15AS	190%
4	O08AS	180%
5	O17AS	125%
6	O20AS	130%

Table.10 Calibration @ FR S/MBR INR

Discussion of Calibration Results

To summarize and compare the calibration results objectively according to FIS location candidates by numerical value, weighting factors are enforced into each crash mode. The weighting values vary from 1 to 5 as the importance of crash mode, requirement margin of crash and misuse test and so on as shown at Table.11

	ITEM	WEIGHT	BACK BEAM		RAD. LOWER		RAD. UPPER		S/MBR INNER	
				POINT		POINT		POINT		POINT
	Low Frontal Margin	5	1.48	5	1.48	5	1.48	5	1.59	5
	Low Frontal Margin	5	1.38	5	1.38	5	1.37	5	1.38	5
VIOLATED ITEMS	Low Frontal	3	40%	1	25.7%	3	25.7%	3	32.9%	2
	Mid Others	2	0%	5	0%	5	0%	5	91.4%	0
	Mid Oblique Margin	3	77.1%	0	77.1%	0	77.1%	0	77.1%	0
	Mid Offset Margin	4	20.0%	3	20%	3	25.7%	3	20.0%	3
	Mid Others	2	24.3%	3	24.3%	3	22.9%	3	24.3%	3
	Mid Others	1	84.3%	0	84.3%	0	85.7%	0	84.3%	0
	Σ W X POINT	-	81		87		87		74	
MISUSE MARGIN	C09AS	4	185%	4	185%	4	190%	4	185%	4
	C11AS	4	180%	4	180%	4	180%	4	180%	4
	C15AS	4	190%	4	190%	4	190%	4	190%	4
	O08AS	4	180%	4	180%	4	180%	4	180%	4
	O17AS	4	125%	2	125%	2	125%	2	125%	2
	O18AS	4	200%	5	130%	3	200%	5	200%	5
	O20AS	4	130%	2	130%	2	130%	2	130%	2
	Σ W X POINT	-	100		92		100		100	

Table.11 Summary of Calibration Results

The summary of calibration results explain that the radiator support upper and lower member are the best location for FIS mounting among candidates after investigation of airbag sensing crash test data, and that the locations except only the radiator support lower member get the same marks for the misuse test. In conclusion the radiator support upper member is proved again to be the better FIS candidate after considering all the calibration results.

OPTIMIZATION OF FRONTAL CRASH SENSING PERFORMANCE BY FIS SIMULATION PULSES

Robust Design Concept with Taguchi-Method

To prevent the reversal phenomenon of crash severity between frontal and offset crash pulses, the first peak of FIS signal from low speed frontal crash is defined as one variable, which has the smaller-the-better characteristics. On the other hand, the first peak of FIS signal from mid and high speed offset crash is defined as another variable, which has the larger-the-better characteristics.

After all, the smaller frontal FIS crash pulse and the larger offset FIS crash pulse are preferred, and which have an effect on the improvement of crash severity discrimination. On this method, control factors which have the highest signal to noise ratio are to be determined.

Selection of Control Factor and Noise Factor

For the optimization of FIS sensing performance, control factors with high priority are the number of FIS, position of FIS and the number of FIS mounting in relation to FIS, and other control factors are the material types and thickness of FEM (Front-End-Module). As shown in Table.12, all the control factors except the number of FIS have 3 control levels, and the umber of FIS has 2 levels.

	Design Variable	Level 1	Level 2	Level 3
A	Number of FIS	One	Two	-
B	Position of FIS	1	2	3
C	Number of FIS Mounting	1 pt	2 pt	3 pt
D	Material Type of FEM	All Plastic	All Steel	Hybrid
E	FEM Thickness	0.6mm	0.9mm	1.2mm

Table.12 Level of Design Variables

Table of orthogonal arrays for Taguchi method in this study are L_{18} (2^1X3^4), and the noise factors are like these: the distribution of vehicle weight which is a very important factor for frontal crash test, and that of stiffness and strength of bumper back beam, front side member which are the main parts for vehicle crashworthiness. The noise levels are ±100kg of vehicle weight distribution and ±10% stiffness and strength. The strategies of noise factor are composed of N1 which is toward improving FIS sensing performance and N2 in reverse.

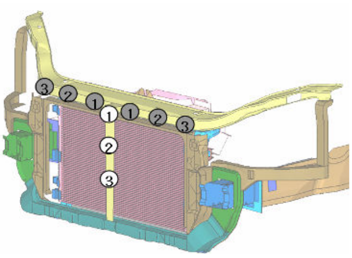


Fig.7 FIS Position According to the Level of Design

Variable

Crash Simulation of Orthogonal Arrays

Reduced crash simulation model was formulated to reduce the simulation time and cost as shown in Fig.8

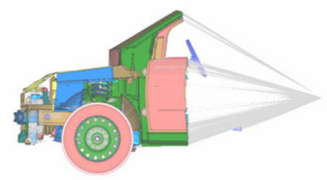


Fig.8 Reduced Crash Simulation Model

With reduced crash model, CPU time was reduced by 41% compared with full vehicle model in case of high speed offset crash simulation. Frontal and offset crash simulation results according to the impact velocities and noise factors represented in the table of orthogonal arrays are listed in Table.12. In general, the signal to noise ratio from radiator support upper panel is relatively higher than other positions.

No	A	B	C	D	E	Low Frontal1		Mid Offset		S/N Ratio
	1	2	3	4	5	N1	N2	N1	N2	
1	1	1	1	1	1	1195.0	1220.0	533.0	554.0	-6.9
2	1	1	2	2	2	1147.0	1119.0	217.0	193.0	-14.9
3	1	1	3	3	3	1196.0	1178.0	504.0	504.0	-7.4
4	1	2	1	1	2	1556.0	1543.0	441.0	656.0	-9.5
5	1	2	2	2	3	1702.0	1693.0	552.0	587.0	-9.5
6	1	2	3	3	1	1534.0	1538.0	555.0	720.0	-7.9
7	1	3	1	2	1	1550.0	1559.0	695.0	989.0	-5.7
8	1	3	2	3	2	1484.0	1482.0	740.0	930.0	-5.2
9	1	3	3	1	3	1474.0	1460.0	899.0	1015.0	-3.8
10	2	1	1	3	3	1054.0	799.0	1941.0	1861.0	6.2
11	2	1	2	1	1	1163.0	1220.0	2064.0	2052.0	4.7
12	2	1	3	2	2	943.0	743.0	1862.0	1949.0	7.0
13	2	2	1	2	3	862.0	626.0	2060.0	2020.0	8.7
14	2	2	2	3	1	1171.0	982.0	2210.0	2337.0	6.5
15	2	2	3	1	2	1062.0	957.0	2379.0	2217.0	7.1
16	2	3	1	3	2	1061.0	636.0	2212.0	2353.0	8.3
17	2	3	2	1	3	992.0	825.0	2110.0	2127.0	7.3
18	2	3	3	2	1	1061.0	773.0	2343.0	2309.0	8.0

(a) Low Frontal 1 vs. Mid Offset Crash

No	A	B	C	D	E	Low Frontal2		High Offset		S/N Ratio
	1	2	3	4	5	N1	N2	N1	N2	
1	1	1	1	1	1	1631.0	1598.0	1084.0	1171.0	-3.1
2	1	1	2	2	2	1698.0	1698.0	1410.0	1068.0	-3.0
3	1	1	3	3	3	1686.0	1774.0	1243.0	1332.0	-2.6
4	1	2	1	1	2	2008.0	2043.0	684.0	938.0	-8.3
5	1	2	2	2	3	2460.0	2341.0	1099.0	978.0	-7.3
6	1	2	3	3	1	2298.0	2285.0	981.0	1159.0	-6.7
7	1	3	1	2	1	2203.0	2241.0	1357.0	1614.0	-3.6
8	1	3	2	3	2	2094.0	2087.0	1308.0	1516.0	-3.5
9	1	3	3	1	3	1946.0	1937.0	1389.0	1587.0	-2.4
10	2	1	1	3	3	1510.0	1393.0	2392.0	2447.0	4.4
11	2	1	2	1	1	1755.0	2409.0	2612.0	3264.0	2.7
12	2	1	3	2	2	2039.0	2351.0	2463.0	3105.0	1.9
13	2	2	1	2	3	1782.0	2259.0	3078.0	3230.0	3.8
14	2	2	2	3	1	1350.0	1358.0	2809.0	3066.0	6.7
15	2	2	3	1	2	1536.0	1324.0	3060.0	3002.0	6.5
16	2	3	1	3	2	1054.0	1016.0	2750.0	3001.0	8.8
17	2	3	2	1	3	1358.0	1260.0	2729.0	2852.0	6.6
18	2	3	3	2	1	1131.0	744.0	2855.0	3033.0	9.7

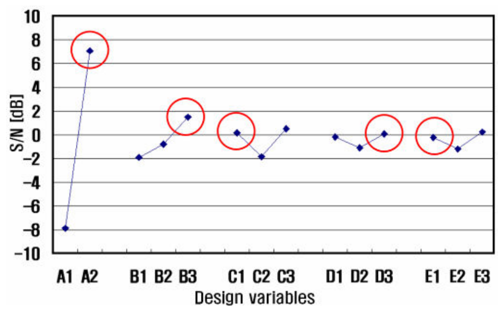
(b) Low Frontal 2 vs. High Offset Crash

Table.12 Orthogonal Arrays and Analysis Results as Regards the Frontal and Offset Crash

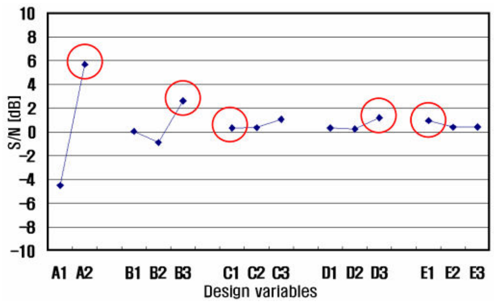
Selection of Robust Optimal Design Specification

From the results of Table.12, response charts of S/N to select the robust optimal design specification are shown in Fig.9. According to the impact velocity of frontal and offset crash, the degree and tendency by which each control factor level has an effect, can be figured out from Fig.9, and from that charts S/N is the most sensitive to the control factor of A(number of FIS) and B(position of FIS).

Therefore, the robust and optimal control factors are chosen as the number of FIS equals 'Two' and the position of FIS is '3(FEM UPR MBR). And the other factor C(number of FIS mounting) is 1 point, D(material type of FEM) is Hybrid, and E(thickness of FEM) is 0.6mm. The summary of these factors are listed in Table.13.



(a) Low Frontal 1 vs. Mid Offset Crash



(b) Low Frontal 2 vs. High Offset Crash

Fig.9 Response Chart of S/N

	Design Variable	Current Design	Robust Opt. Design
A	Number of FIS	One	Two
B	Position of FIS	2	3
C	Number of FIS Mounting	1 pt	1 pt
D	Material Type of FEM	Hybrid	Hybrid
E	FEM Thickness	0.9mm	0.6mm

Table.13 Comparison of Initial with Robust Optimal Design

Verification and Discussion of Robust Optimal Design Specification

To verify the FIS sensing improvement, additional crash simulation results which is performed with selected optimal control factors are in Table.14, in which S/N values are summarized from the first peak of each FIS signal.

Low Frontal 1 vs. Mid Offset Crash				
Current Design		Robust Optimal Design		Gain
Predicted	Verified	Predicted	Verified	
-8.03	-9.14	10.15	9.88	19.02
Low Frontal 2 vs. High Offset Crash				
Current Design		Robust Optimal Design		Gain
Predicted	Verified	Predicted	Verified	
-5.80	-8.30	8.43	9.40	17.70

Table.14 Summary of Optimization Results

When comparing between low frontal and mid offset FIS signal, S/N ratio are raised by 19.02dB from current design specification, and S/N ratio are also raised by 17.7dB in comparison between another frontal and high offset crash mode. These results explain that with current base design specification, the crash severity of low frontal crash may be larger than that of mid offset crash, but after optimization, the robust optimal design can drastically reduce the possibility of airbag malfunction. Fig.10 show the FEM sample of optimal FIS position.

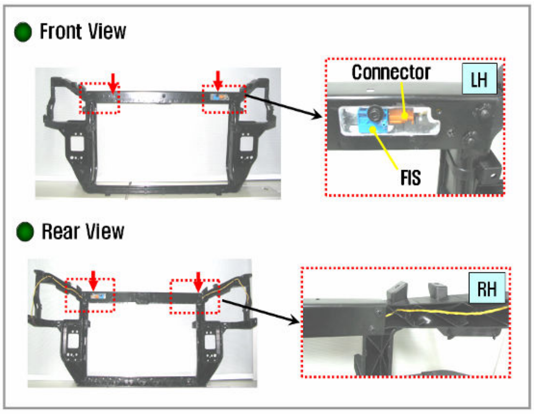


Fig.10 FEM Sample of Optimal FIS Position

DETERMINATION OF AIRBAG DEPLOYMENT LOGIC WITH CAE TECHNIQUE

Development of Unified Crash Simulation Model

Occupant injury simulation generally uses the different simulation model case by case for various crash modes. But in this study, to compare the crash severity between different crash modes in view of occupant injuries, unified occupant simulation model was developed and used. And the model was verified and confirmed through the correlation with the crash test results. Table.15 shows the notation for the unified simulation model used in this study.

Crash Mode / Restraints	Frontal	Offset	Oblique
Bag(Stage2)+PT	FRT bb2	OFF bb2	OBL bb2
Bag(Stage1)+PT	FRT bb1	OFF bb1	OBL bb1
Bag(Stage2) only	FRT bag2	OFF bag2	OBL bag2
Bag(Stage1) only	FRT bag1	OFF bag1	OBL bag1
PT only	FRT PT	OFF PT	OBL PT
Belt only(w/o PT)	FRT noPT	OFF noPT	OBL noPT
No Restraints	FRT nores	OFF nores	OBL nores

Table.15 Notation for the Unified Simulation Model

Fig.11 shows the development procedure of the unified occupant simulation model. Crash simulations with PAM-CRASH to acquire vehicle deceleration and deformation were performed, and as a result the unified occupant simulation with MADYMO followed after that.

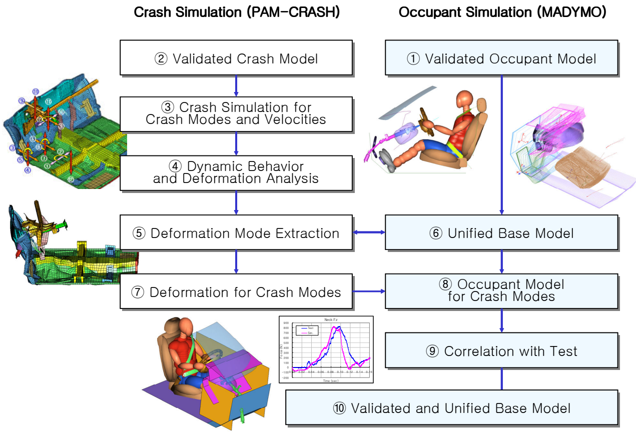


Fig.11 Development Procedure of the Unified Occupant Simulation Model

Based on old occupant simulation model for frontal crash, the unified occupant model was constructed with the utilization of crash simulation deformation results as follows, 1) model geometry and JOINT (vehicle structure, steering system, side plane), 2) lower leg contact model, 3) deformation scale factor. Validation results between the simulation and test using the unified simulation occupant model are listed in Table.16.

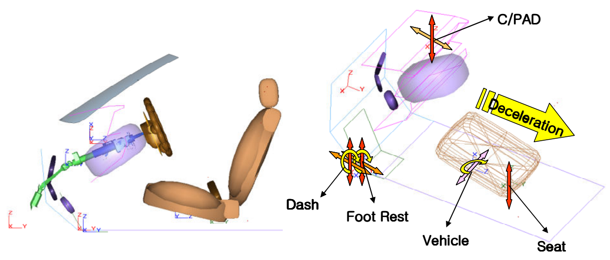
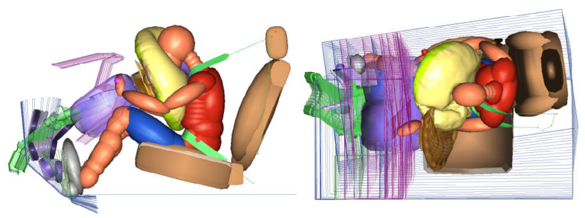
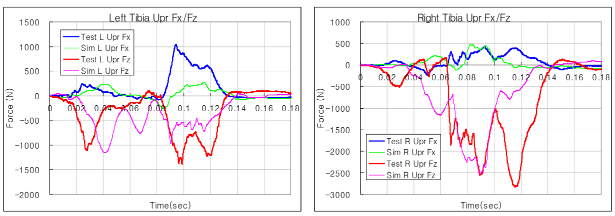


Fig.12 Unified Occupant Simulation Model



(a) Vehicle and Occupant Behavior



(b) Injury Graph

Fig.13 Validation Results (Offset Mode)

TEST		HIC			Chest G			Femur Load LH			Femur Load RH		
Mode	Speed	Test	Sim	Err	Test	Sim	Err	Test	Sim	Err	Test	Sim	Err
Frontal	Mid	154.4	179.1	16%	35.0	31.9	-9%	1229	1115	-9%	3137	4093	30%
Frontal	High	357.5	329.0	-8%	45.1	43.1	-4%	1344	1459	9%	4130	4771	16%
Others	Mid	377.2	234.5	-38%	34.4	38.7	13%	1952	1752	-10%	4609	4609	0%
Oblique	Mid	106.0	95.4	-10%	21.4	19.3	-10%	598	725	21%	1273	2090	64%
Oblique	High	240.9	341.3	42%	43.2	40.6	-6%	1148	2996	161%	5157	4535	-12%
Offset	High	235.0	408.0	74%	41.1	39.7	-3%	1251	3361	169%	2845	4828	70%

Table.16 Validation Results of the Unified Model

Discussion of Simulation Results with Variable Crash Modes and Velocities

As crash modes and velocities change, corresponding values are put into MADYMO input data file such as body pulse, vehicle deformation graphs, DAB/PT TTF, and so on. (Fig.14), and corresponding occupant simulation model can be classified into 7 groups according to restraint conditions: bagS2+PT, bagS1+PT, bagS2 only, bagS1 only, PT only, belt only and no restraints.

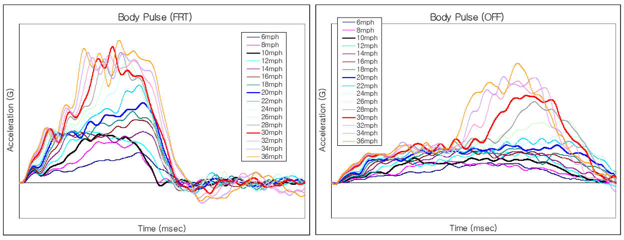
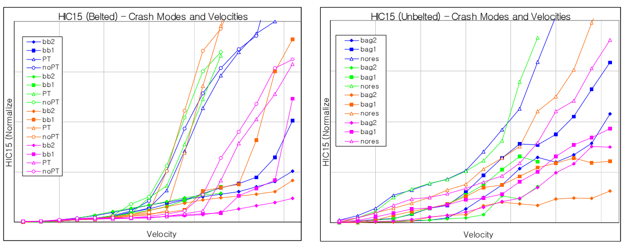
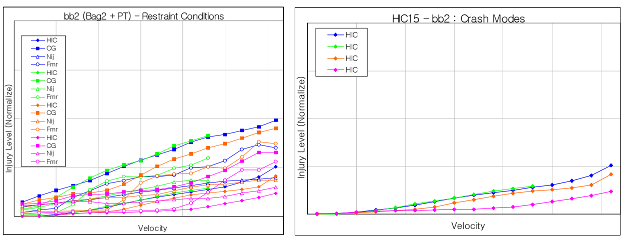


Fig.14 Crash Simulation Body Pulses according to Crash Velocities

After 525 crash and occupant simulations, occupant injuries of 21 items are extracted and selected as 4 representative injuries for this project as like: HIC15, Chest G, Nij and Femur Load, which represent the injury of head, chest, neck and lower leg. Fig.15 shows the injury results graph classified according to occupant injury levels, restraint conditions and crash modes.



(a) by Occupant Injury Level



(b) by Restraint Conditions and Crash Modes

Fig.15 CAE Simulation Results

Airbag Firing Decision Logic Determination

To determine airbag firing decision logic, the optimal restraint constraint condition which has a minimum occupant injury level for certain crash modes and impact velocities, must be found, but the optimal restraint varies as the injury items what we focus on.

To solve this problem, new dimensionless and combined injury severity index is used on this study, and which expresses multiple occupant injuries with one number by equation.

$$Index = a \times HIC_{15} + b \times ChestG + c \times N_{ij} + d \times Femurload$$

Where, a, b, c, d are weighting factors, and have different levels as belted and unbelted condition.

Two methods are proposed in this study as the manner to determine the weighting factors, one is an area weighting factor method and the other is a standard deviation weighting factor method.

Area weighting factor method means that the larger the area, the higher the weighing factor, that is the largest weighting factors are granted to the severest injury levels in order to reduce that injuries, so the firing time of airbag and P/T is determined by the weighting factor.

Standard deviation weighting factor method means that the larger the standard deviation of each restraint conditions, the higher the weighting factor, so to speak the largest weighting factors are given to the most sensitive injury levels to determine the firing time of airbag stage and P/T. Table.17 is the weighting matrix for combined injury severity index (where, 30 means the velocity range are from 0 to 30mph, and 24 means up to 24mph).

Belted

	Frontal				Offset				Oblique			
	HIC	CG	Nij	Fmr	HIC	CG	Nij	Fmr	HIC	CG	Nij	Fmr
Area30	0.22	**0.34**	0.20	0.24	0.15	**0.42**	0.28	0.15	0.28	**0.32**	0.20	0.20
Area24	0.12	**0.38**	0.23	0.27	0.07	**0.46**	0.36	0.11	0.13	**0.39**	0.26	0.22
Standard Deviation 30	**0.66**	0.13	0.17	0.04	**0.56**	0.18	0.23	0.03	**0.81**	0.07	0.12	0.01
Standard Deviation 24	**0.44**	0.19	0.28	0.09	0.13	0.26	**0.56**	0.05	**0.61**	0.12	0.24	0.03

Unbelted

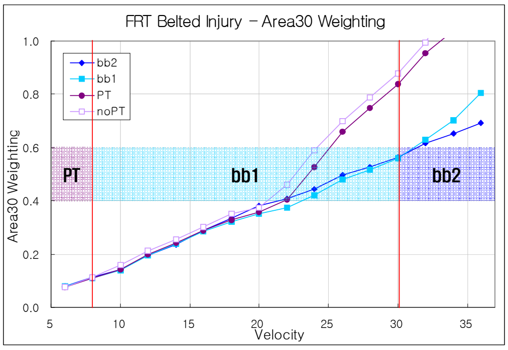
	Frontal				Offset				Oblique			
	HIC	CG	Nij	Fmr	HIC	CG	Nij	Fmr	HIC	CG	Nij	Fmr
Area30	0.16	0.20	0.28	**0.35**	0.12	0.21	**0.44**	0.23	0.12	0.19	**0.39**	0.31
Area24	0.13	0.20	0.32	**0.35**	0.09	0.19	**0.45**	0.27	0.10	0.18	**0.42**	0.31
Standard Deviation 30	0.36	0.11	**0.51**	0.03	0.23	0.15	**0.58**	0.03	0.30	0.13	**0.53**	0.04
Standard Deviation 24	0.31	0.10	**0.55**	0.03	0.19	0.15	**0.62**	0.04	0.24	0.12	**0.60**	0.04

Table.17 Weighting Matrix for New Index

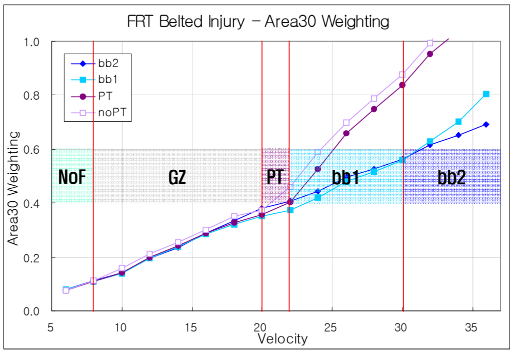
To determine the airbag deployment logic, first, crash and occupant simulation results are used, and various crash modes for example frontal, offset, oblique etc. and belt condition such as belted and unbelted are also used. And 6 injury indexes are also used: HIC15, Chest G, Nij, Star rate P_{comb}, and two indexes (area30 and standard deviation30). Methodologies of determination are divided into 2 categories

1) Airbag deployment logic to minimize injury level
2) Airbag deployment logic of Must Fire

Method of minimizing the injury level can use an ideal and definite restraint condition in a certain region, but the firing condition is somewhat lower velocity than needed, that is, restraint system is inclined to fire at lower velocities (Fig.16a). On the other side, the method of Must Fire uses a restraint condition without which the injury level increases rapidly. That condition seems to be the Maginot line for deployment, but the firing comes from higher velocities and is apt to be arbitrary because of indefinite basis (Fig.16b).



(a) Minimize Injury Level



(b) Must Fire

Fig.16 Airbag Deployment Logic

Discussion of Airbag Firing Decision Logic with P_{comb}

Apart from the new methodologies ahead proposed in this paper, however, the airbag deployment logic is constructed using NCAP star rate P_{comb} as an injury severity index, which is already verified and generally used, and with the method to minimize injury level. Fig.17 shows the final logic chart.

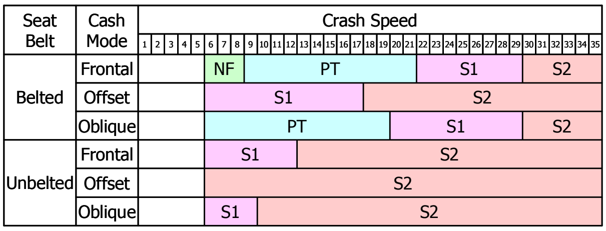


Fig.17 Proposed Final Airbag Deployment Logic Chart

CONCLUSIONS

To find out the optimal location of FIS which can enhance the airbag sensing and calibration performance, vehicle crash test results are used and 4 calibration set are carried out. As a result of FIS data analysis and airbag calibration, the relatively superior FIS locations are selected and proposed into the vehicle development process.

From now on, CAE simulation results which have a limitation in accuracy to use in the airbag calibration process must go further in comparison with test results.

To promote FIS sensing discrimination performance, CAE and Taguchi robust optimization design technique were used. At frontal and offset crash mode, the number of FIS and the positions of FIS are the most sensitive control factors for airbag sensing performance. And also the distribution of vehicle weight and stiffness/strength as a noise factor are also considered in this progress.

To determine the airbag deployment logic, crash and occupant simulation techniques are applied and adapted to this project, and as a result, the optimal restraint condition to minimize occupant injury level and to suppress the rapid increase of injuries are proposed. As an injury criterion to determine firing decision logic, two combined injury severity indexes are proposed. But at lower speed region less than about 20mph, there are few differences in injury levels irrespective of restraint condition.

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