Parameter Study on the Restraint System for Front-Seat Small Female Occupant Protection in Frontal Crashes

Libo CAO[1, 2, a], Kai ZHANG[1, b], Qian LUO[1, c],Lingbo YAN[1, d]andHuili YU[2, 3, e]

[1]State Key Laboratory of Advanced Design and Manufacture for Vehicle Body, HunanUniversity, Changsha, China, 410082

[2]State Key Laboratory of Vehicle NVH and Safety Technology, Chongqing, China, 400023

[3]Changan Automotive Engineering Institute, Chongqing, China, 400023

[a]hdclb@163.com,[b]zhangkai@hnu.edc.cn,[c]routina110@hnu.edc.cn, [d]milanylb@hotmail.com,[e]yuhl@changan.com.cn

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Abstract. Recent field data analyses have shown that the efficacy of restraint system for small female front-seated occupant protection is less remarkable than that for midsize males in motor vehicle crashes (MVCs). The objective of the study is to identify the major parameters of restraint system that have significant influence on responses of front-seat small female occupants and improve the efficacy of restraint system for small female occupants using optimization method.The results suggest that parameters of restraint system have greater influence on head responses and less influence on chest responses for front row occupants. For driver and front passenger, dominating factors for responses of each body region are different. For restrained driver, the main source of chest injury is the airbag, while the main source of chest injury is the seat belt for restrained front passenger.After parameter optimization, injury risks of head and neck for restrained front row occupant shave decreased, and the Euro-NCAP score of front row restraint increased by 37.3%.

Introduction

It is reported that the female fatalities in motor vehicle crashes accounted for about one-third (32%) of total fatalities while males accounted for 68% from 1996 to 2005[1].Despite lower fatality counts, the fatality risk was 22 ± 9%[2] to 28 ± 3%[3]larger for females than males in the same impact.Bose et al.[4] analyzed injury data and found that the 3-point belted female drivers had higher severe injury risks than male drivers in the similar crashes, about 47%.Chantal et al.[5] analyzed the NASS-CDS and concluded that the females had higher overall risks of serious injuries in all body regions except for the head and the abdomen.Though the injury concerns of small female occupants are fairly clear, research on enhancing the protection of small occupants is rare. Given the fact that advanced restraint features usually design for midsize male occupants, advanced restraint designs for small female occupants are needed.

Countries around the world continually update their NCAP testing program and evaluation procedures, respectively[6].In 2014, the Euro-NCAP Secretariat added the frontal full width impact test to its adult occupant protection assessment protocol and put into practice in 2015.

The small female occupants had higher serious injury risk and fatality risk, and HIII-05F has been used for the safety evaluation in the frontal impact test of NCAP of countries around the world. But rare efforts have been made to enhance the protection for small female occupants.Therefore, the objectives of the study were to determine main influencing parameters for responses of front-seat small female occupants and improve the protective effect of the occupants' restraint system through optimization based on Euro-NCAP assessment criteria.

Model Development and Validation

Multi-body models of frontal full width impact with HIII-05Fdummies seated in the driver position and front passenger position were established based on the date and description of an impact test under Euro-NCAP configurations.The front-seat compartment was established based on a compact vehicle.The front occupant model was integrated with a hybrid belt system model and a force-payout character was added to capture the film spool effect of the retractor.

To validate the models, a 50km/h frontal impact test using two HIII-05F dummies was conducted under Euro-NCAP.In the test,the seat was adjusted to the fore-most fore-aft adjustment position.In the simulations, the Hybrid III 5th percentile ellipsoid Q dummy was used, and MADYMO version 7.4.1 was used for all simulations. A comparison of the HIII-05Foccupants'injury indexes between the test and the simulation is shown inTable 1.Most of the differences between the test and the simulation are less than 10%.

Table 1 Comparison of the results of the test and simulation

Criteria	Driver			Front passenger		
	Test	Simulation	Difference [%]	Test	Simulation	Difference[%]
HIC_{15}	247.3	252.2	2.01	318.7	297.5	6.66
H3ms [g]	49.90	50.61	1.42	58.53	56.22	3.95
C3ms [g]	51.44	50.36	2.10	42.11	42.06	0.12
Left-FC [kN]	1.654	1.535	7.19	2.045	2.112	3.28
Right-FC [kN]	2.133	1.913	10.31	2.020	2.082	3.07

Parameters Sensitivity Analysis

A parametric study was performed to investigate the efficacy of restraint system, and input variables are listed in Table 2. The gas flow rate in Table2 is the scale of the gas flow rate curve in the original model. Friction coefficient of D-ring, gas flow rate, the area of air bleed and airbag volume is continuous.A uniform Latin Square design was used to sample uniformly and generate design table.

Table 2Parameters considered and the values used in the sensitivity analysis

Parameter	Driver	Right front passenger
Belt load limit [kN]	2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6	
Pretensioner stroke [mm]	40, 50, 60, 70, 80, 90, 100	
TTFof pretentioner [ms]	12, 13, 14, 15, 16, 17, 18	
Friction coefficient of D-ring	0.1~0.4	
TTF of airbag [ms]	13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30	
Gas mass flow rate of the inflator	0.8~1.2	
Area of air bleed [mm^2]	628~2513	628~4398
Airbag volume [L]	50~60	90~100

Student's t-test was used to determine whether or not a significant difference between the mean values of two groups exists. Difference of the two mean values could indicate the influence of the input factor onthe output. The plus or minus indicates the direction of influence (positive/negative), and the value indicates the level of influence. To compare influences on different injury criteria, all outputs of simulation were normalized with lower performance limit of Euro-NCAP before analysis.

Fig.1showsthe restraint parameters that have significant influence on responses of the HIII-05Fdriver. Belt load limit was the primary factor and affected response of all body parts of theHIII-05F driver and followed by is TTF of airbag.High belt load limits mitigated injuries of neck and chest.With the delay of airbag explosion, the driver head injuries decreased but tension force of neck increased. In general, responses of head were greatly influenced by the parameters of airbag and responses of neck and chest were greatly influenced by parameters of safety belt.

Fig.2shows the restraint parameters that have significant influence on responses of right front passenger's responses. TTF of airbag is the primary factor and have effects on all body parts of front small female passenger, and followed by the area of air bleed.Lager TTF of airbag led to increase of head and chest's injuries and decrease of neck's extension moment. Increasing the area would result in decrease of head injuries and the extension moment of neck and increase of shear force and tension force of passenger's neck.

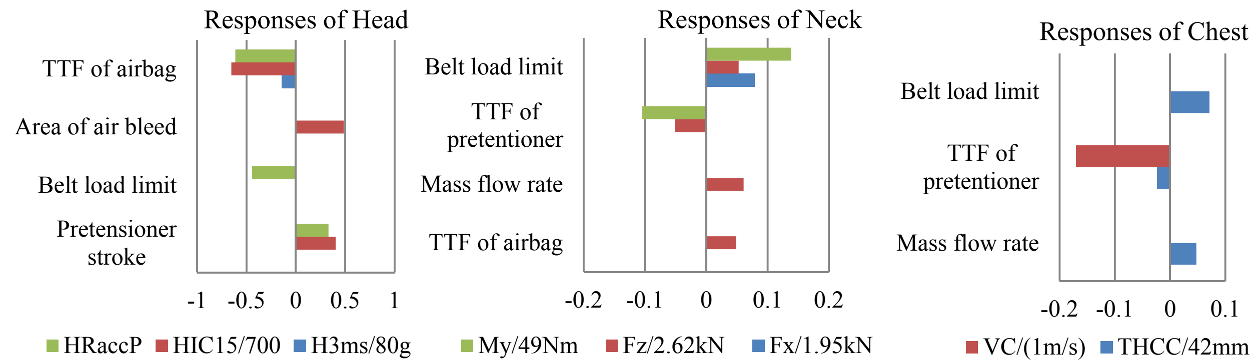

Fig.1Parameters that have significant influence on driver'sresponses ($p<0.05$)

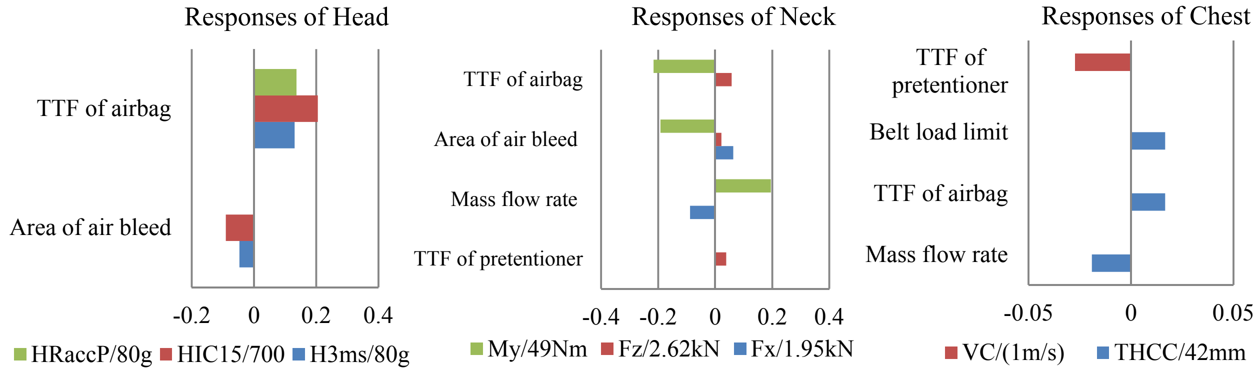

Fig.2Parameters that have significant influence on right front passenger's responses ($p<0.05$)

Optimization of Restraint System

According to the sensitivity analysis above, TTF of airbag, the area of air bleed, belt load limit and the TTF of pretensioner were selected to be optimization variables.

OptimizationObjectives.HIII-05F driver's chest compression and right front passenger's neck extension moment and chest compression caused severe loss of points. Thus, those injury parameters have the top priority to reduce.

Constraints. Eq.1 is Weighted Injury Criterion (WIC), defined based on the assessment protocol of adult occupant protection of Euro-NCAP. According to the sensitivity analysis, some parameters have conflicting effect on the different body regions. So WIC was limited less than 1 to ensure similar levels of protection forall body regions.

$$\mathrm{WIC} = 0.25\left[\left(\frac{\mathrm{HIC15}}{700}+\frac{\mathrm{H3ms}}{80}\right)/2.0+\left(\frac{\mathrm{Fx}}{1.95}+\frac{\mathrm{Fz}}{2.62}+\frac{\mathrm{My}}{49}\right)/3.0+\left(\frac{\mathrm{THCC}}{42}+\mathrm{VC}\right)/2+\left(\frac{\mathrm{L-FC+R-FC}}{6.2}\right)/2.0\right]. \quad (1)$$

According to Euro-NCAP, a hard contact is assumed, if the peak resultant head acceleration (HRaccP) exceeds 80g, and where the shoulder belt load measured, exceeds 6kN a two point penalty is applied. The two cases are not conducive to occupant protection.

Response Surface. Uniform Latin Hypercube method was used to distribute points randomly and uniformly over each variable dimension. 50 parameter combinations were selected for run simulations. Simulations were performed automatically in MODE FRONTIER.Kriging was used to compute response surface. Non-dominated Sorting Genetic Algorithm Ⅱ (NSGA-Ⅱ) was used for optimizations.

Optimization Result. To check the reliability of response surface, the optimal design parameters that obtained from optimization were assigned into MADYMO models. The greatest relative error between true simulation and virtual simulation is only 7.49%，indicating that response surfaces created above is reliable.

After parameter optimization, the score of front row restraint increased by 37.3%, which provided better protection performance. Through optimization, the score of driver increased by 3.8%, that of front passenger increased by 28.9%. After optimization, front passenger's neck extension moment dropped to below higher performance limit. Thorax compression reduced 2.8mm and 0.26mm for driver and right front passenger respectively. Table 3lists the restraint system parameters before and after optimization. Reducing belt load limit and delaying TTF of pretensioner reduced thorax compression of HIII-05F driver. Increasing the area of air bleed reduced passenger's neck extension moment apparently. For both driver and front passenger, thorax compression was not reduced significantly. These results were in consistent with parameter sensitivity analysis.

Table 3Combination of input values before and after optimization

Input variable	Driver		Right front passenger	
	Before optimization	After optimization	Before optimization	After optimization
TTF of airbag [ms]	18	22	20	20
Area of air bleed [mm^2]	628	1347	2513	3998
Belt load limit [kN]	3	2.5	2.5	2.5
TTF of pretensioner [ms]	18	18	17	13

Conclusions

The findings from this study are as follows:

1. For driver and front passenger, primary factors that affect the responses of each body region are different: belt parameters have significant influence on responses of driver's head but no significant influence on responses of front passenger's head.
2. The main source of chest injuries for restrained driver is the airbag. The main source of chest injuries for restrained front passenger is the seat belt.
3. Within scope, reasonable matched belt load limit, TTF of pretensioner, TTF of airbag and area of air bleed could reduce head and neck injuries for restrained front row 5^{th} percentage occupants.

Acknowledgements

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