Research on the Safety of Rear Seat Female Occupant in the 50km/h Frontal Collision

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Abstract. In order to improve the safety of rear seat occupant in the 50km/h car frontal collision, the simulation model of the rear occupant restraint system based one car was established by crash simulation software MADYMO and verified by the crash test, studying the effect of the design parameters of the front seat and the safety belt on the various injuries of rear seat female occupant. Results show: 1) head injury criterion HIC15 and occipital stretching moment Myoc have a clear downward trend as the headrest stiffness of the front seat decreases from 70N/mm to 30N/mm, 2) HIC36, Myoc, left femur force Fleft, right femur force Fright and thorax 3ms resultant acceleration T3MS declines by 29.7%, 75.1%, 24.7%, 52.2% and 6.9% respectively as the backrest stiffness of the front seat drops from 84N/m to 36N/mm, 3) HIC36, Myoc, T3MS, Fleft and Fright fall obviously and the variation of D is negligent as the recliner rotational stiffness of the front seat backrest lessens compared to the original value, 4) HIC15, Myoc, T3MS and Fright drops by 18.6%, 24.0%, 6.2% and 11.7% respectively, D arises by 9% as the webbing friction coefficient of the safety belt rises from 0.2 to 0.8, 5) HIC36 and T3MS experience the obvious decline with the decrease of the retractor locking feature of the safety belt, 6) HIC15, Myoc, T3MS and Fright show a significant upward trend and Fleft falls obviously with the forward movement of the buckle location.

1. Introduction
With the rapid development of Chinese automobile industry, the quantity of cars is very large. Automobile road traffic accident has become a serious social problem. In China, the rear-seat sitting rate of cars is quite high, especially the vulnerable crowd including the elderly and the child prefer to sit in the rear-seat. The death toll in rear-seat reaches ten thousand people every year. However, the death toll in rear-seat is only two hundred in Japan. As a result, rear-seat occupant safety is paid more and more attention recently.

Atkinson et al. [1] suggested that the design of rear seat occupant protection systems should consider means to reduce the injury risk for older adults.

In a 10-year set of crashes from Australia, Mitchell et al. [2] utilized a matched cohort of front and rear seat occupants to identify age, model year, airbag deployment and roadways with higher speed limits as contributing to a higher likelihood of the rear seat occupant experiencing the more serious injury in the pair.

Hong et al. [3][4] putted forward a new automobile front safety seat for protecting rear occupant and indicated the new front seat can all provide rear occupant with better protection in the frontal collision and the frontal offset collision.
Durbin et al. [5] extended the prior research on the relative safety of the rear seat occupants as compared with the front by examining restraint system performance in a more contemporary fleet of vehicles and indicated the increased risk of serious and fatal injuries for occupants 55 and older highlights the challenges for vehicle and restraint system manufacturers in providing optimal protection to a wide range of rear seat occupants.

Sahraei et al. [6] indicated the front-end stiffness of vehicle is a possible factor causing the decrease of rear seat occupant protection; found out an increase in stiffness can increase the risk of AIS3+ head injuries from 4.8% in the original model (with a stiffness of 1,000 N/mm) to 24.2% in a modified model (with a stiffness of 2,356 N/mm), an increased risk of chest injury from 9.1% in the original model to 11.8% in the modified model by simulations. Distribution of injuries from real world accident data confirms the findings of the simulations.

Matsui et al. [7] analysed the injury risks of the rear AF05 dummy and AM50 dummy with the safety belt in the full-frontal rigid barrier and the frontal offset deformable barrier impact test to find that the injury risks of the AF05 dummy were greater than those of the AM50 dummy in the full-frontal test. Especially, the AIS3+ neck injury risk was larger by 27% to 31% and the AIS3+ chest injury risk was almost twice than those of the AM50 dummy. In the frontal offset test, the injury criteria measured from the AM50 dummy seated on the barrier-impacted side were higher than those measured from the AF05 dummy seated on the non-impacted side in the rear seat.

Mizuno et al. [8] conducted full car crash tests to point out that the injury values of rear belted female occupants and 3-year-old children would be relatively low because the seatbelt prevents their contact with the car interior; the knees and head of the unbelted female occupants would make contact with the front seatback and the head of front seat occupants respectively.

Sundararajan et al. [9] evaluated the biomechanical performance of a rear-seat inflatable seatbelt system and compared it to that of a 3-point seatbelt system, pointed out an inflatable seatbelt system would offer additional benefits to some occupants in the rear seats.

Bohman et al. [10] analysed rear seat occupants injury using NASS-CDS database to find that of all AIS3+ injured restrained 13 years and older occupants, 59% had AIS3+ thoracic injuries and 38% had AIS3+ head injuries; the thoracic injuries were distributed to lungs (60%), skeletal fractures (38%) and injuries to arteries (1.26%) and heart (0.1%); for AIS3+ injured 4-12 years old children, 51% had AIS3+ thoracic injuries and 54% had AIS3+ head injuries; compared to adults, children sustained less fractures and more lung injuries.

The aims of the work presented in this paper are evaluate the influence of the headrest stiffness, the backrest stiffness and the backrest recliner rotational stiffness of the front seat on HIC15 (head injury criterion), Myoc (occipital stretching moment), T3MS (thorax 3ms resultant acceleration), D (thorax compression displacement), Fleft (left femur force) and Fright (right femur force) of rear seat occupant; the influence of the webbing friction coefficient, the buckle longitudinal location, the retractor locking feature of the safety belt on HIC15, Myoc, T3MS, D, Fleft and Fright of rear seat occupant in the 50km/h frontal collision through MADYMO analytical simulation software.

2. Research Method and Experimental Verification

In the study, the simulation model of the rear occupant restraint system based one car was established through crash simulation software MADYMO that simulates the dynamic behaviour of physical systems emphasizing the analysis of vehicle collision and assessing the injury sustained by rear seat occupant.

The MADYMO simulation model contains the front and rear seat, the vehicle floor, the 3-point safety belt, the rear occupant (Hybrid III 5th percent female dummy model) and so on, defines the acceleration field, the contact and the other features.

The computer crash simulation can not substitute the actual vehicle crash test completely, therefore the MADYMO simulation model must be verified for its reliability on the basic of the 50km/h frontal collision test performed previously.

Figure 1 shows the comparison between the dummy model response curves in the MADYMO simulation model and the dummy injury curves in the 50km/h frontal collision test. It is shown that the
simulation curves are basically consistent with the test curves, therefore the MADYMO simulation model can reflect the actual vehicle crash test on the whole, and can be studied further as a basic model.

![Simulation curves](image1.png)

(a) Head X-acceleration curve  
(b) Head Z-acceleration curve  
(c) Thorax X-acceleration curve  
(d) Pelvis X-acceleration curve

Figure 1. The comparison of rear occupant injury response curves in test and simulation

3. Results

3.1 Research on the Design Parameters of the Front Seat

The seat is one of the most components to protect the occupants in the vehicle as collision occurs. Automobile seat mainly consists of the headrest, the backrest, the cushion and the backrest recliner which is used to adjust the angle of backrest. In the car frontal collision, rear seat occupant would dash forward in the inertia force, resulting in the second crash between the head and the headrest or backrest of front seat, the second crash between the femurs and the backrest of front seat. Therefore, it is necessary to study the influence of the headrest stiffness, the backrest stiffness, the recliner rotational stiffness of front seat on rear female occupant injury in the frontal collision.

(1) Headrest Stiffness Analysis

The study substituted the stiffness value 30N/mm, 35N/mm, 40N/mm, 45N/mm, 50N/mm, 55N/mm, 60N/mm, 65N/mm, 70N/mm of the front seat headrest into the MADYMO simulation model to examine the effect on the rear female occupant injury. Table 1 indicates when the headrest stiffness decreases from 70N/mm to 30N/mm, HIC15 drops from 1079.3 to 835.7, Myoc drops from 41.1Nm to 26.8Nm, HIC15 and Myoc show a clear downward trend, T3MS drops from 387.0m/s² to 357.5m/s². In addition, the thorax compression displacement D, the left femur force Fleft and right femur force Fright change slightly with the variation of the headrest stiffness.
Table 1 The effect of headrest stiffness on rear occupant injury

| Injury criterion | Front seat headrest stiffness/(N/mm) |
|------------------|-------------------------------------|
|                  | 30  | 35  | 40  | 45  | 50  | 55  | 60  | 65  | 70  |
| HIC15            | 835.7 | 859.9 | 883.1 | 913.5 | 948.1 | 982.6 | 1014.1 | 1046.1 | 1079.3 |
| Myoc/Nm          | 26.5  | 29.2  | 32.0  | 34.7  | 36.8  | 38.1  | 39.0  | 40.4  | 43.1  |
| T3MS/(m/s²)      | 357.5 | 363.9 | 368.4 | 371.9 | 376.2 | 380.3 | 382.6 | 389.1 | 391.8 |

The headrest becomes softer as the headrest stiffness decreases from 70N/mm to 30N/mm, its energy absorption capacity enhances, the headrest could absorb the impact force more effectively when rear occupant head collides with the headrest, leading to the decrease of HIC15, Myoc and T3MS. However, the softer headrest would amplify the neck whiplash injury of front occupant in the rear collision. As a result, it is necessary to choose the optimum headrest stiffness through the synthetical consideration of the frontal collision and the rear collision.

(2) Backrest Stiffness Analysis

The original backrest stiffness value 60N/mm and the other value 36N/mm, 42N/mm, 48N/mm, 54N/mm, 66N/mm, 72N/mm, 78N/mm, 84N/mm were selected into the MADYMO simulation model to inspect the effect on the rear female occupant injury. Table 2 shows HIC36, Myoc, Fleft and Fright experience the significant decline and the variation of D is little with the decrease of the backrest stiffness, HIC36, Myoc, Fleft, Fright and T3MS declines by 29.7%, 75.1%, 24.7%, 52.2% and 6.9% respectively as the backrest stiffness drops from 84N/m to 36N/mm.

Table 2 The effect of backrest stiffness on rear occupant injury

| Injury criterion | Front seat backrest stiffness/(N/mm) |
|------------------|-------------------------------------|
|                  | 36  | 42  | 48  | 54  | 60  | 66  | 72  | 78  | 84  |
| HIC15            | 683.2 | 740.7 | 784.4 | 833.1 | 948.1 | 950.6 | 952.6 | 956.6 | 971.7 |
| Myoc/Nm          | 10.7  | 11.4  | 13.1  | 17.6  | 36.8  | 37.3  | 39.4  | 41.4  | 43.0  |
| T3MS/(m/s²)      | 361.5 | 363.9 | 368.0 | 371.1 | 376.2 | 380.7 | 380.0 | 384.2 | 388.6 |
| Fleft/N          | 2934.7 | 3017.9 | 3055.2 | 3151.1 | 3775.3 | 3817.4 | 3855.5 | 3899.0 |
| Fright/N         | 1141.8 | 1308.4 | 1503.0 | 1678.8 | 2260.4 | 2328.7 | 2345.3 | 2390.3 |

The softer backrest could absorb more impact energy when the head and femurs of rear occupant collide with the backrest, resulting in the decline of the head injury, neck injury, thorax injury and femur injury of rear occupant. But the head would hit against the internal backrest frame as the material stiffness of backrest is very low, leading that rear occupant injury enhances. Therefore, the backrest stiffness should be considered comprehensively.

(3) Recliner Rotational Stiffness Analysis

The backrest recliner is used to adjust the longitudinal angle of backrest. The study substituted the original rotational stiffness value of the backrest recliner and a difference of ±10%, ±20%, ±30%, ±40% into the MADYMO simulation model to examine the effect on the rear female occupant injury. Table 3 illustrates HIC36, Myoc, T3MS, Fleft and Fright fall obviously and the variation of D is negligible when the rotational stiffness of the backrest recliner lessens compared to the original value. On the contrary, increasing the rotational stiffness makes the head injury, neck injury, thorax injury and femur injury of rear occupant go up surprisingly.

Table 3 The effect of recliner rotational stiffness on rear occupant injury

| Injury criterion | Recliner rotational stiffness/(N/mm) |
|------------------|-------------------------------------|
|                  | -40%  | -30%  | -20%  | -10%  | Original value | +10%  | +20%  | +30%  | +40%  |
| HIC15            | 585.7  | 689.3  | 745.2  | 885.3  | 948.1  | 1010.5 | 1049.2 | 1112.2 | 1208.7 |
| Myoc/Nm          | 13.1   | 16.4   | 25.6   | 31.0   | 36.8   | 37.3   | 39.1   | 41.8   | 42.6   |
| T3MS/(m/s²)      | 331.8  | 355.4  | 360.9  | 368.4  | 376.2  | 380.1  | 390.2  | 393.5  | 398.9  |
| Fleft/N          | 2556.6 | 3144.8 | 3337.6 | 3512.7 | 3730.3 | 3784.5 | 3835.7 | 3895.5 | 3945.3 |
| Fright/N         | 2075.1 | 2137.4 | 2201.1 | 2243.4 | 2260.4 | 2315.3 | 2365.0 | 2407.6 | 2481.8 |
When rear occupant hits against the headrest and backrest of the front seat, the rotational stiffness of the backrest recliner are lower, the forward rotational angle of the backrest is larger, absorbing the more forward impact energy of rear occupant to reduce the injury. Nevertheless, the front seat with the very low recliner rotational stiffness has a bad effect on the ride comfort of front seat occupant. Summarily, lowering the recliner rotational stiffness by the fitting amount relative to the original value could mitigate the injury sustained by rear occupant largely under the premise of the ride comfort of front occupant.

3.2 Research on the Design Parameters of the Safety Belt
The safety belt contains the webbing, the retractor, the buckle and the anchor. NHTSA indicates the safety belt can reduce death and serious injury by 45% to 65%, the safety belt can save 5500 lives each year in Europe. Front occupant would be multi-protected by the safety belt, the safety airbag and the energy-absorbing steering column. However, rear occupant would be protected only by the safety belt. Therefore, it is essential to study the influence of the friction coefficient of webbing, the locking feature of retractor, the longitudinal position of buckle on rear female occupant injury in the frontal collision. In the MADYMO simulation model, the buckle is on the right side of Hybrid III 5th percent female dummy model.

(1) Webbing Friction Coefficient Analysis
The original friction coefficient 0.5 of the safety belt webbing and the other value 0.2, 0.3, 0.4, 0.6, 0.7, 0.8 were selected into the MADYMO simulation model to study the effect on the rear female occupant injury. Table 4 shows HIC15, Myoc, T3MS and Fright drop gradually and D ascends gradually as the friction coefficient of the webbing rises from 0.2 to 0.8, HIC15, Myoc, T3MS and Fright cuts down by 18.6%, 24.0%, 6.2% and 11.7% respectively, D arises by 9%.

| Injury criterion | Webbing friction coefficient |
|-----------------|-----------------------------|
|                 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 |
| HIC15           | 1087.2 | 1008.4 | 971.9 | 948.1 | 924.5 | 898.0 | 884.8 |
| Myoc/Nm         | 40.5 | 39.3 | 38.2 | 36.8 | 35.4 | 33.3 | 30.8 |
| T3MS/(m/s²)     | 398.1 | 385.1 | 379.9 | 376.2 | 375.5 | 374.5 | 373.6 |
| D/mm            | 29.8 | 30.7 | 30.7 | 30.7 | 30.9 | 31.9 | 32.5 |
| Fleft/N         | 3489.7 | 3634.0 | 3715.2 | 3730.3 | 3710.2 | 3695.3 | 3675.3 |
| Fright/N        | 2459.6 | 2360.1 | 2306.9 | 2260.4 | 2227.5 | 2197.1 | 2171.1 |

The increase of the webbing friction coefficient could reduce efficiently the forward displacement of rear occupant head, thorax and pelvis, resisting the head from colliding with the front seat or mitigating the second crash between the head and the front seat. Therefore HIC15, Myoc and T3MS would drop. However, excessive friction coefficient would aggravate thorax compression to make D raise. In summary, rear occupant could obtain the comprehensive protection when the webbing friction coefficient is optimum.

(2) Retractor Locking Feature Analysis
After the retractor locks, some amount of the safety belt webbing would still pull out from the retractor in the collision, the webbing output is defined as the retractor locking feature. The original webbing output and a difference of ±10 %, ±20%, ±30%, ±40% were selected into the MADYMO simulation model to inspect the effect on the rear female occupant injury. Table 5 illustrates HIC36 and T3MS experience the significant decline with the decrease of the webbing output, HIC36 and T3MS falls by 76.5% and 29.6%. Compared to the original value, Myoc descends from 38.5Nm to 7.0Nm as the webbing output drops, reducing by 81.8%. In addition, Fleft and Fright shows upward and downward trend respectively when the webbing output cuts down gradually. When the webbing output decreases, the safety belt provides rear occupant with more reliable "binding" effect, lowering the strength of the impact between rear occupant and front seat.
Table 5  The effect of retractor locking feature on rear occupant injury

| Injury criterion | Retractor locking feature/mm | -40%  | -30%  | -20%  | -10%  | Original value | +10%  | +20%  | +30%  | +40%  |
|------------------|-------------------------------|-------|-------|-------|-------|----------------|-------|-------|-------|-------|
| HIC15            |                               | 420.2 | 538.2 | 722.8 | 827.2 | 948.1          | 1080.4| 1274.7| 1462.6| 1784.4|
| Myoc/Nm          |                               | 7.0   | 9.4   | 21.9  | 31.2  | 38.5           | 39.4  | 41.1  | 40.3  | 37.3  |
| T3MS/(m/s²)      |                               | 312.6 | 332.2 | 350.5 | 369.6 | 376.2          | 386.4 | 403.6 | 434.9 | 444.1 |
| Fleft/N          |                               | 3816.8| 3828.3| 3808.7| 3775.6| 3730.3         | 3688.7| 3663.6| 3646.8| 3642.2|
| Fright/N         |                               | 2163.2| 2214.6| 2237.2| 2251.2| 2260.4         | 2285.7| 2329.3| 2361.2| 2402.9|

(3) Buckle Longitudinal Location Analysis

In order to study the effect of the longitudinal location of the safety belt buckle on rear female occupant injury in the frontal collision, the original longitudinal location, the 25mm, 50mm, 75mm forward (+25mm, +50mm, +75mm), the 25mm, 50mm, 75mm backward (-25mm, -50mm, -75mm) were selected into the MADYMO model. Table 6 indicates HIC15, Myoc, T3MS and Fright show a significant upward trend and Fleft falls obviously with the forward movement of the buckle location. Furthermore, forward moving the buckle location would bring down D. Considering of the various injuries of rear occupant, it is necessary to move the buckle location backwards to a suitable place.

Table 6  The effect of buckle longitudinal location on rear occupant injury

| Injury criterion | Buckle longitudinal location | -75mm | -50mm | -25mm | original location | +25mm | +50mm | +75mm |
|------------------|------------------------------|-------|-------|-------|-------------------|-------|-------|-------|
| HIC15            |                              | 860.5 | 863.0 | 881.2 | 948.1             | 1070.2| 1350.1| 1934.7|
| T3MS/(m/s²)      |                              | 368.4 | 369.0 | 372.4 | 376.2             | 386.2 | 413.4 | 437.1 |
| D/mm             |                              | 33.3  | 32.4  | 31.4  | 30.7              | 29.9  | 29.1  | 28.1  |
| Fleft/N          |                              | 3832.2| 3811.3| 3772.6| 3730.3            | 3667.2| 3586.4| 3434.1|
| Fright/N         |                              | 2187.4| 2172.8| 2184.0| 2260.4            | 2439.4| 3005.5| 3313.4|

4. Conclusions

In order to improve the safety of rear seat occupant, this paper studied the effect of the design parameters of the front seat and the safety belt on the injury of rear seat female occupant in the 50km/h car frontal collision by the MADYMO simulation model.

(1) As the front headrest stiffness decreases, the head and the neck injury of rear seat female occupant would drop obviously. But the softer front headrest would raise the neck whiplash injury of front occupant in the rear collision.

(2) The softer front backrest could cut down the head injury, neck injury, thorax injury and femur injury, but the head may hit against the internal backrest frame as the stiffness of backrest is very low, leading that the various injuries rise.

(3) Lowering the recliner rotational stiffness of the front seat by the fitting amount relative to the original value could mitigate the injury sustained by rear occupant obviously under the premise of the ride comfort of front occupant.

(4) Increasing the webbing friction coefficient could reduce the head injury, neck injury and thorax injury, however, excessive friction coefficient would enhance thorax compression displacement.

(5) When the retractor locking feature declines, the safety belt provides rear occupant with more reliable "binding" effect, lowering the strength of the impact between rear occupant and front seat.

(6) Considering of the various injuries of rear occupant, it is necessary to move the buckle location backwards to a suitable place.

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Reference

[1] Atkinson T, Gawarecki L, Tavakoli M 2016 Accident Analysis & Prevention. 89 88-94.
[2] Mitchell R J, Bambach M R, Toson B 2015 Accident Analysis & Prevention. 82 171-179.
[3] Hong L, Ge R H 2015 Automotive Engineering. (11) 1277-1283.
[4] Hong L, Ge R H 2016 Automotive Engineering. (10) 1206-1212.
[5] Durbin D R, Jermakian J S, Kallan M J, et al. 2015 Accident Analysis & Prevention. 80 185-193.
[6] Sahraei E, Digges K, Marzougui D, et al. 2014 Accident Analysis & Prevention. 66(66C) 43-54.
[7] Matsui Y, Tanaka Y, Hosokawa N 2011 INT J CRASHWORTHINES. 16(3) 263-273.
[8] Koji M, Yasuhiro M, Takahiro I, et al. 2011 INT J CRASHWORTHINES. 16(1) 63-74.
[9] Sundararajan S, Rouhana S, Board D, et al. 2011 Stapp Car Crash J. 55 161-197.
[10] Bohman K, Rosén E, Sunnevang C, et al. 2009 Ann Adv Automot Med. 53 3-12.