# Parameter Analysis and Design Optimization of child restraint system in Vehicle Frontal Impacts

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**Abstract:** The aim of the paper is to improve the protecting performance of the child restraint system and reduce the injury risk of child occupants using the MADYMO software. The mathematical model of the seat and the child was used to investigate the injury risk influenced by the design of the booster seat. In the simulations the pulse prescribed in regulation of frontal impact (ECER 44/04) was used. Furthermore, design optimization of the main parameters was carried out by applying iSIGHT software. The results indicate that seat belt stiffness and overall angle of booster seat have a strong influence on head and neck injury risks. Furthermore, the influence of design parameters on thorax injury risks in a frontal crash was confirmed as follows: seat belt stiffness, stiffness of booster seat, position of belt guide hole of booster seat, overall angle of booster seat, base angle of booster seat and friction coefficient between dummy and booster seat. This study demonstrated that the optimized CRS design can reduce child occupant injury risk in crash accident.

**Key Words:** CRS, safety of child passenger, simulation, design optimization

## 1 Introduction

In recent years, the number of new registration of the passenger cars in China is increasing strongly. The 2006 data from the Police Traffic Administration Bureau shows that the total number of death resulted from traffic accidents is 89,455; of these 4.67% are victims below 12 years old. If we consider the fatalities inside the car, victims below 12 years old account for 16.4% of all traffic fatalities in this group [1]. Therefore, the issue of crash safety of child occupant is important.

Although the risk of death and also injury can be reduced by correct use of child restraint system (CRS), the CRS still can be improved. At present, the studies performed in many countries on CRS focus on: the design of this system, the methods of test analysis, the evaluation criteria and improvement of correct usage. In China, the safety issue of child occupants is not yet recognized as important topic. The emphasis should be put on the popularization of CRS, design and production of these systems based on experiences from foreign countries [2].

From the perspective of design of CRS, in the current paper the parameters influencing the protection of booster seat in frontal impact are analyzed. Furthermore, design optimization of the main parameters is carried out.

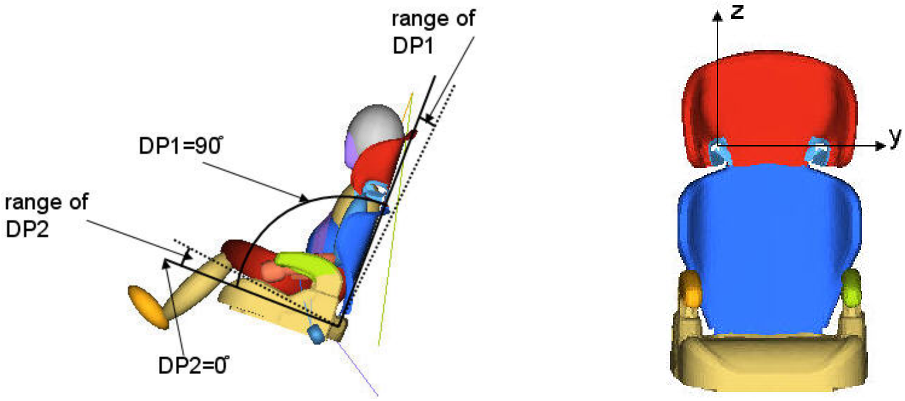
## 2 Method

### 2.1 Selection of design parameters

The automobile child restraint environment is influenced by properties of both the vehicle and the child restraint system. To improve child restraint environment, design parameters from both the vehicle system and child restraint system (CRS) must be considered. Based on the published papers [3,4,5,6], we decided to select eight following parameters（see Table 1）to study their influence on protection level of children. Three parameter regarding the geometry of booster seat were varied from original position (*) to one or two other levels. Parameters related to stiffness and friction also selected at three different levels. The schematic pictures of geometrical parameters 1, 2 and 3 are shown in Figure 1.

**Table 1 Levels of the Design Parameters**

| Design parameter | | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| **DP1** | Overall angle of booster seat | 90* | 100 | - |
| **DP2** | Base angle of booster seat | 0 | 5 | 10* |
| **DP3** | Position of belt guide hole of booster seat (y-direction) | 0* | -0.04 | -0.06 |
| **DP4** | Friction coefficient between booster seat and vehicle seat | 0.2 | 0.5 | 0.7 |
| **DP5** | Friction coefficient between dummy and booster seat | 0.1 | 0.3 | 0.6 |
| **DP6** | Booster seat stiffness coefficient | 0.2 | 1.0 | 5.0 |
| **DP7** | Vehicle seat stiffness coefficient | 0.2 | 1.0 | 5.0 |
| **DP8** | Seat belt stiffness coefficient | 0.5 | 1.0 | 2.0 |




a）Parameter 1 and 2 b）Parameter 3

**Figure 1 Parameters related to geometry of the booster seat**

## 2.2 Selection of method of simulation

Because we selected eight parameters and three levels for most of them, it was necessary to use Design of Experiment (DOE) methodology $L_{18}$（$2^1 \times 3^7$）to reduce the number of simulations. The orthogonal experimental design is shown in Table 2.

**Table 2 Orthogonal experimental design**

| Test NO. | DP1 | DP2 | DP3 | DP4 | DP5 | DP6 | DP7 | DP8 |
|---|---|---|---|---|---|---|---|---|
| **1** | 1 | 1 | 1 | 3 | 2 | 2 | 1 | 2 |
| **2** | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 |
| **3** | 1 | 3 | 1 | 2 | 3 | 3 | 3 | 3 |
| **4** | 1 | 1 | 2 | 2 | 1 | 2 | 3 | 1 |
| **5** | 1 | 2 | 2 | 3 | 3 | 1 | 1 | 3 |
| **6** | 1 | 3 | 2 | 1 | 2 | 3 | 2 | 2 |
| **7** | 1 | 1 | 3 | 1 | 3 | 1 | 3 | 2 |
| **8** | 1 | 2 | 3 | 2 | 2 | 3 | 1 | 1 |
| **9** | 1 | 3 | 3 | 3 | 1 | 2 | 2 | 3 |
| **10** | 2 | 1 | 1 | 1 | 1 | 3 | 1 | 3 |
| **11** | 2 | 2 | 1 | 2 | 3 | 2 | 2 | 2 |
| **12** | 2 | 3 | 1 | 3 | 2 | 1 | 3 | 1 |
| **13** | 2 | 1 | 2 | 3 | 3 | 3 | 2 | 1 |
| **14** | 2 | 2 | 2 | 1 | 2 | 2 | 3 | 3 |
| **15** | 2 | 3 | 2 | 2 | 1 | 1 | 1 | 2 |
| **16** | 2 | 1 | 3 | 2 | 2 | 1 | 2 | 3 |
| **17** | 2 | 2 | 3 | 3 | 1 | 3 | 3 | 2 |
| **18** | 2 | 3 | 3 | 1 | 3 | 2 | 1 | 1 |

## 2.3 Selection of child injury related parameters

In the paper of de Jager K. et al. [7] described that EEVC WG18 concluded that when the booster seat and adult seatbelt (group II/III) is used the head is the most important body area in terms of frequency of injury. They are also concluding that the chest does not seem to be a priority in terms of frequency of injuries, nevertheless, as the chest cavity protects vital organs, it remains an important body segment from the protection point of view. Focusing on severe injuries, ribs fractures are not very common because of the child chest compliance, but internal injuries occur by compression of the chest by the seatbelt. They didn’t noticed injuries due to inertial loading for children in booster seat. They also concluded that pelvis region is not in priority in frontal impact. And limb fractures are numerous for children on booster seats and booster cushions, but not severe and are not in priority in terms of child protection for the moment.

Based on their study and also EEVC WG18 recommendations, the parameters of the dummy head, neck and thorax are selected as objectives of current study. We selected the following parameters: HIC15 value, peak value of head resultant acceleration, thorax resultant acceleration both $T_{3ms}$ value and peak value, peak value of thorax vertical acceleration, peak value of neck force in Z-direction and peak value of neck moment in Y-direction.

### 2.4 Model preparation for simulation

The simulation model was developed (see Figure 2). It includes four parts: vehicle seat, booster seat, child dummy and seat belt. The vehicle seat contains of three hyperellipsoids and is defined as a rigid body. They represent seat cushion, seat back and seat headrest. The booster seat was developed based on some brand product. This seat is recommended to children whose age is from 3 to 10 years, weight from 13.6 to 45 kg and height from 96 to 145 cm. The validated P6 dummy from the MADYMO database was selected to simulations. The seat belt used is a hybrid belt; it is composed with multi-body and FE part. The contact characteristics of vehicle seat, booster seat and seat belt from a validated model in MADYMO. The pulse used in simulations representing the frontal crash is shown in Figure 3.

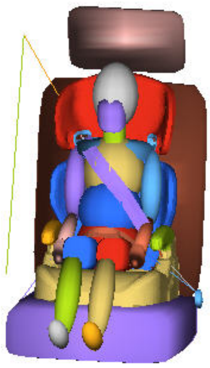


**Fig.2 Simulation Model**

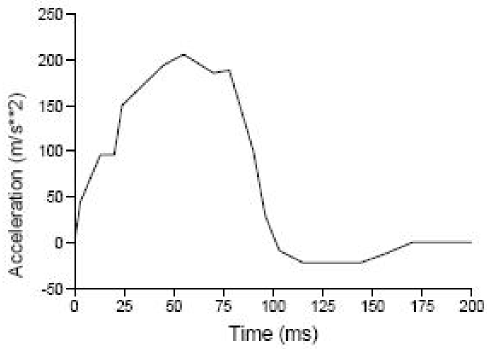



**Fig.3 Simulation Pulse**

## 2.5 Parameter analysis

For each design parameter selected to analysis (8 parameters) we analyzed its influence on selected injury criteria (7 criteria). The results of orthogonal experimental design can be analyzed by two methods. One is the direct-viewing analytical method; the other is the analysis of variance. In the first method, the range value is used to evaluate the influence of the design parameter on the injury related parameter. However we haven't any criteria to evaluate the range value. So the analysis of variance is necessary to prove the significance of factorial effect and interaction effect.

The analysis of variance was applied. We calculated sum of square, degree of freedom, mean square, F-test, P value. The significance of the parameters is correlative with P value. Usually two levels of significance are used: $p \leq 0.01$ indicates the factor that is strongly significant, $0.01 < p \leq 0.05$ indicates the factor is significant. In our study the level of $p \leq 0.05$ is used to select parameter to further optimization. In this optimization the importance of injury criteria was also considered.

## 2.6 Optimization

In the ECE R44[8] and FMVSS213 [9], the HIC value and thorax resultant acceleration $T_{3ms}$ value are chosen as child injury evaluation criteria. Therefore we also selected these criteria as optimization objectives. By the previously described analysis of variance, the parameters influencing the dummy HIC and T3ms were defined.

The optimization model was defined as follows:

$$\mathrm{MinHIC} = f_1(x_1, x_2, x_3)$$

$$\mathrm{MinT}_{3ms} = f_2(x_1, x_2, x_3)$$

Where, $x_1, x_2, x_3$ are levels of design parameters selected from parameter analysis.

In order to obtain the MADYMO simulations results of the combination of different design parameter levels, the Full Factorial design (FFD) was used. Results from the MADYMO simulations were used in the stepwise regression method in order to obtain the regression equations of the three parameters. And then, the iSIGHT software was introduced to obtain the optimized values of the regression equations.

# 3 Results and Discussions

## 3.1 Influence of design parameters on injury related parameters

### 3.1.1 Analysis of variance of design parameters on HIC15 value

The influence of the parameters on the HIC15 is shown in Table 3. It shows that the order of this influence is as follows:

seat belt stiffness>overall angle of booster seat>friction coefficient between booster seat and vehicle seat>friction coefficient between dummy and booster seat>booster seat stiffness>position of belt guide hole of booster seat>vehicle seat stiffness >base angle of booster seat.

The seat belt stiffness (DP8) and overall angle of booster seat (DP1) are significant parameters. This can be explained that the motion of dummy is mainly influenced by the initial posture and belt restraint, especially the motion of head and neck. Other parameters are at lower significance levels than requirements of the study.

**Table 3 Analysis of variance of the HIC15 value**

| | DP1 | DP2 | DP3 | DP4 | DP5 | DP6 | DP7 | DP8 |
|---|---|---|---|---|---|---|---|---|
| SS（A-H） | 14168.1 | 609.3 | 10030.3 | 12441.3 | 12049.3 | 11124.0 | 3265.3 | 46281.3 |
| df | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| MS | 14168.1 | 304.7 | 5015.2 | 6220.7 | 6024.7 | 5562.0 | 1632.7 | 23140.7 |
| F | 11.84 | Error | 4.19 | 5.20 | 5.04 | 4.65 | 1.36 | 19.35 |
| P value | 0.03 | — | 0.10 | 0.077 | 0.081 | 0.09 | 0.35 | 0.01 |

When the seat belt stiffness increases (DP8), the HIC15 value also increases from 163.5 to 284.8, see Figure 4. This is because when the seat belt stiffness is increased, the restraint forces on the thorax and abdomen and the relative motion of head also increase. When the overall angle of booster seat (DP1) increases from 90° to 100°, HIC15 value increases from 188.4 to 244.6. This is because that the distance between head and the center of gravity of dummy's body in motion direction also increases, and the relative motion of head increases by inertial forces.

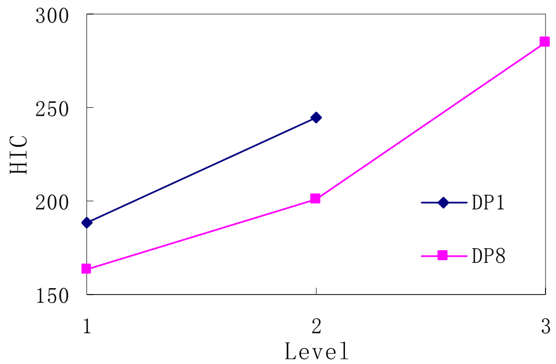



**Figure 4 Level trendines of HIC15 of significant design parameters**

### 3.1.2 Analysis of variance of design parameters on peak value of head resultant acceleration

The influence of the design parameters on the peak value of head resultant acceleration is shown in Table 4. The order of the influence is as follows:

seat belt stiffness>position of belt guide hole of booster seat>friction coefficient between dummy and booster seat>friction coefficient between booster seat and vehicle seat>vehicle seat stiffness>overall angle of booster seat>booster seat stiffness>base angle of booster seat.

The seat belt stiffness (DP8) is only significant parameter. Other parameters are at lower significance levels than requirements of the study.

**Table 4 Analysis of variance of the peak value of head resultant acceleration**

| | DP1 | DP2 | DP3 | DP4 | DP5 | DP6 | DP7 | DP8 |
|---|---|---|---|---|---|---|---|---|
| SS（A-H） | 1458.0 | 1598.8 | 27691.4 | 9048.1 | 18843.4 | 2905.4 | 5588.1 | 89734.1 |
| df | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| MS | 1458.0 | 799.4 | 13845.7 | 4524.1 | 9421.7 | 1452.7 | 2794.1 | 44867.1 |
| F | 1.10 | 0.60 | 10.44 | 3.41 | 7.10 | 1.10 | 2.11 | 33.83 |
| P value | 0.40 | 0.62 | 0.09 | 0.23 | 0.12 | 0.48 | 0.32 | 0.03 |

As the HIC value is computed from the head resultant acceleration, the influence of all design parameters on head resultant acceleration is similar to that observed in case of HIC value. When the seat belt stiffness (DP8) is increasing, the peak value of head resultant acceleration also increases from 453.2m/s$^2$ to 615.5 m/s$^2$, see Figure 5.

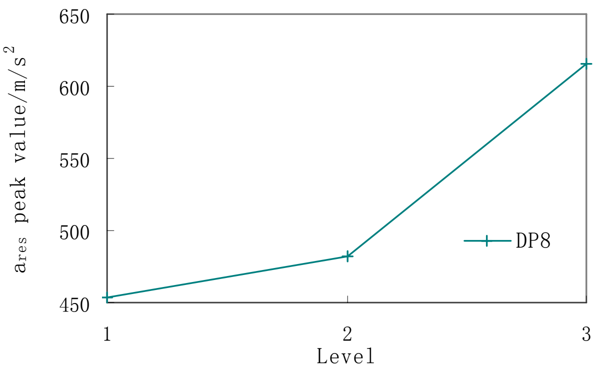



**Figure 5 Level trendline of the peak value of head resultant acceleration**

### 3.1.3 Analysis of variance of design parameters on thorax resultant acceleration T3ms

The influence of the design parameters on $T_{3ms}$ is shown in Table 5. The order of this influence is as follows:
booster seat stiffness>seat belt stiffness>overall angle of booster seat>position of belt guide hole of booster seat>vehicle seat stiffness>friction coefficient between dummy and booster seat>friction coefficient between booster seat and vehicle seat>base angle of booster seat.

The booster seat stiffness (DP6) is only significant parameters because booster seat stiffness influences the relative motion of dummy. The seat belt stiffness (DP8) and overall angle of booster seat (DP1) are at lower significance level. Others parameters are insignificant.

**Table 5 Analysis of variance of the thorax resultant acceleration T3ms**

| | DP1 | DP2 | DP3 | DP4 | DP5 | DP6 | DP7 | DP8 |
|---|---|---|---|---|---|---|---|---|
| SS（A-H） | 3528.0 | 644.8 | 5128.8 | 2870.8 | 4459.1 | 20998.1 | 4602.1 | 12693.8 |
| df | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| MS | 3528.0 | 322.4 | 2564.4 | 1435.4 | 2229.6 | 10499.1 | 2301.1 | 6346.9 |
| F | 1.87 | Error | 1.36 | Error | 1.18 | 5.57 | 1.22 | 3.37 |
| P value | 0.2 | — | 0.33 | — | 0.37 | 0.04 | 0.36 | 0.10 |

Figure 6 show that when the booster seat stiffness (DP6) is increasing, the thorax resultant acceleration $T_{3ms}$ also increases from 332.8 m/s$^2$ to 409.8 m/s$^2$. This is because stiffer booster seat absorbs less energy, so the thorax resultant acceleration $T_{3ms}$ is increased.

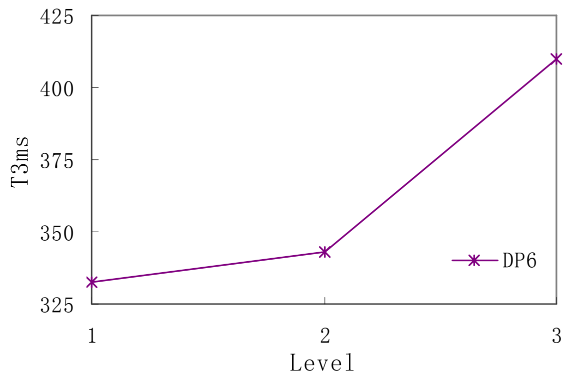



**Figure 6 Level trendline of the thorax resultant acceleration $T_{3ms}$**

### 3.1.4 Analysis of variance of design parameters on peak value of thorax resultant acceleration

The influence of the design parameters on the peak value of thorax resultant acceleration is shown in Table 6. It shows that the order of this influence is as follows:

seat belt stiffness>booster seat stiffness>position of belt guide hole of booster seat>overall angle of booster seat>base angle of booster seat>friction coefficient between booster seat and vehicle seat>vehicle seat stiffness> friction coefficient between dummy and booster seat.

Seat belt stiffness (DP8), booster seat stiffness (DP6), position of belt guide hole of booster seat (DP3), overall angle of booster seat (DP1) and base angle of booster seat (DP2) are significant parameters. These parameters influence the motion of dummy upper trunk. Other parameters are at lower significance levels than requirements of the study.

**Table 6 Analysis of variance of the peak value of thorax resultant acceleration**

| | DP1 | DP2 | DP3 | DP4 | DP5 | DP6 | DP7 | DP8 |
|---|---|---|---|---|---|---|---|---|
| **SS（A-H）** | 5868.1 | 10543.4 | 20177.4 | 8251.4 | 3272.1 | 28800.8 | 6660.1 | 56668.1 |
| **df** | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **MS** | 5868.1 | 5271.7 | 10088.7 | 4125.7 | 1636.1 | 14400.4 | 3330.1 | 28334.1 |
| **F** | 22.48 | 20.19 | 38.65 | 15.80 | 6.27 | 55.16 | 12.76 | 108.54 |
| **P value** | 0.04 | 0.05 | 0.03 | 0.06 | 0.14 | 0.02 | 0.07 | 0.01 |

Figure 7 show that when the seat belt stiffness (DP8) is increasing, the peak value of thorax resultant acceleration first decreases and then increases. This is because the seat belt stiffness level 1 is too small, and when the seat belt stiffness increases from this level, the dummy is better restrained causing the decrease of thorax acceleration, whereas, when the seat belt stiffness continues to increase, the harm of seat belt to thorax becomes distinct.

When the booster seat stiffness (DP6) is increasing, the peak value of thorax resultant acceleration also first decreases and then increases. This is because softer booster seat causes “submarining phenomenon” of dummy. When the booster seat stiffness increases, dummy can retain good sitting posture and the relative motion of thorax decreases. However, when the booster seat stiffness continues to increase, this seat reduces the energy absorbed and causes the increase of thorax resultant acceleration.

When the position of belt guide hole of booster seat (DP3) is increasing, the peak value of thorax resultant acceleration also first decreases and then increases.

The peak value of thorax resultant acceleration is increasing with the increase of the overall angle of booster seat (DP1).

When the base angle of booster seat (DP2) is increasing, the peak value of thorax resultant acceleration also first decreases and then increases.

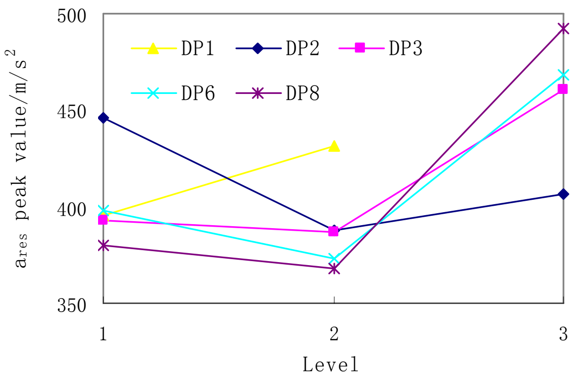



**Figure 7 Level trendlines of the peak value of thorax resultant acceleration**

### 3.1.5 Analysis of variance of design parameters on peak value of thorax vertical acceleration

The influence order of the design parameters is as shown in Table 7:

overall angle of booster seat> friction coefficient between dummy and booster seat > booster seat stiffness> friction coefficient between booster seat and vehicle seat> seat belt stiffness> vehicle seat stiffness>position of belt guide hole of booster seat > base angle of booster seat.

Overall angle of booster seat (DP1) and friction coefficient between dummy and booster seat (DP5) are significant parameters.

**Table 7 Analysis of variance of the peak value of thorax vertical acceleration**

| | DP1 | DP2 | DP3 | DP4 | DP5 | DP6 | DP7 | DP8 |
|---|---|---|---|---|---|---|---|---|
| **SS（A-H）** | 20672.2 | 40.4 | 49.8 | 3580.1 | 13160.4 | 4186.8 | 1617.4 | 2357.4 |
| **df** | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **MS** | 20672.2 | 20.2 | 24.9 | 1790.1 | 6580.2 | 2093.4 | 808.7 | 1178.7 |
| **F** | 47.22 | Error | Error | 4.09 | 15.03 | 4.78 | 1.85 | 2.69 |
| **P value** | 0.0005 | — | — | 0.08 | 0.005 | 0.06 | 0.24 | 0.15 |

The peak value of thorax vertical acceleration when the overall angle of booster seat (DP1) is 100° is higher than when this angle is 90°. When the friction coefficient between dummy and booster seat (DP5) increases, the peak value of thorax vertical acceleration is reduced, see Figure 8. It can be explained that if the friction coefficient between dummy and booster seat is increasing, the motion of dummy in vertical direction decreases.

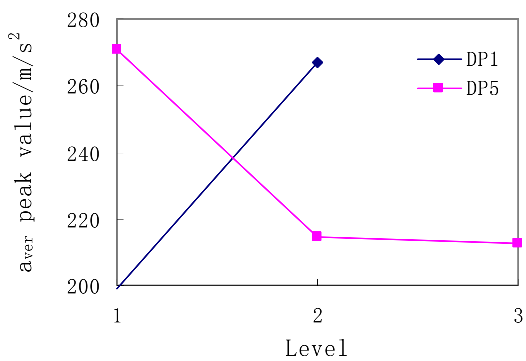



**Figure 8 Level trendlines of the peak value of thorax vertical acceleration**

### 3.1.6 Analysis of variance of the design parameters on the peak value of neck force in Z-direction

The influence order of the design parameters is as shown in Table 8:

seat belt stiffness>friction coefficient between booster seat and vehicle seat>overall angle of booster seat> position of belt guide hole of booster seat >booster seat stiffness>friction coefficient between dummy and booster seat>vehicle seat stiffness>base angle of booster seat.

The seat belt stiffness (DP8) is only significant parameter.

**Table 8 Analysis of variance of the peak value of neck force in Z-direction**

| | DP1 | DP2 | DP3 | DP4 | DP5 | DP6 | DP7 | DP8 |
|---|---|---|---|---|---|---|---|---|
| **SS（A-H）** | 83913.4 | 4496.4 | 107854.8 | 207165.4 | 74675.4 | 77575.1 | 27754.1 | 791952.8 |
| **df** | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **MS** | 83913.4 | 2248.2 | 53927.4 | 103582.7 | 37337.7 | 38787.6 | 13877.1 | 395976.4 |
| **F** | 12.32 | 0.33 | 7.91 | 15.20 | 5.48 | 5.69 | 2.04 | 58.11 |
| **P value** | 0.07 | 0.75 | 0.11 | 0.06 | 0.154 | 0.149 | 0.33 | 0.02 |

When the seat belt stiffness (DP8) is increasing, the neck force in Z-direction force also increases, see Figure 9. This can be explained when the seat belt stiffness is increasing, the belt force on the dummy, head relative motion and finally the neck force in Z-direction also increase.

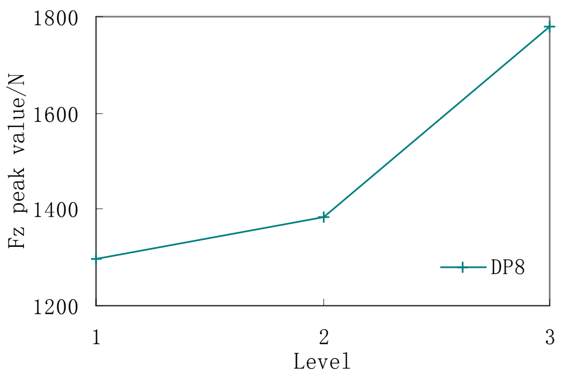



**Fig.9 Level trendline of the peak value of neck force in Z-direction.**

### 3.1.7 Analysis of variance of the design parameters on the peak value of neck moment in Y-direction

The influence of parameters on neck moment in Y-direction peak value is shown in Table 9. It shows that the order of this influence is as follows:

overall angle of booster seat>base angle of booster seat >booster seat stiffness and vehicle seat stiffness>friction coefficient between dummy and booster seat>seat belt stiffness>friction coefficient between booster seat and vehicle seat>position of belt guide hole of booster seat.

The overall angle of booster seat (DP1) is only significant parameter.

**Table 9 Analysis of variance of the peak value of neck moment in Y-direction**

| | DP1 | DP2 | DP3 | DP4 | DP5 | DP6 | DP7 | DP8 |
|---|---|---|---|---|---|---|---|---|
| **SS（A-H）** | 26.9 | 18.8 | 1.4 | 5.4 | 10.8 | 11.1 | 11.1 | 7.4 |
| **df** | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **MS** | 26.9 | 9.4 | 0.7 | 2.7 | 5.4 | 5.6 | 5.6 | 3.7 |
| **F** | 10.52 | 3.67 | Error | 1.07 | 2.11 | 2.17 | 2.17 | 1.46 |
| **P value** | 0.03 | 0.12 | — | 0.43 | 0.24 | 0.23 | 0.23 | 0.33 |

When the overall angle of booster seat (DP1) is 100°, the peak value of neck moment in Y-direction is 10.3 Nm. When the overall angle is reduced to 90° the peak value of neck moment in Y-direction decreased to 7.9 Nm.

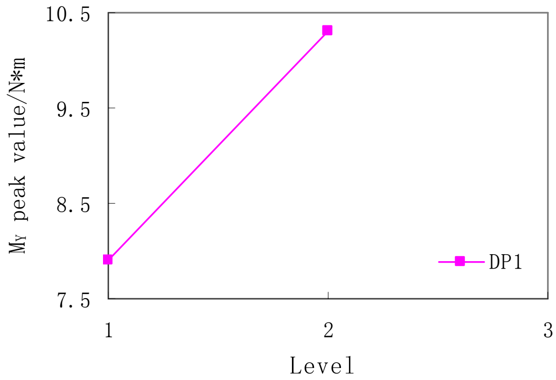



**Fig.10 Level trendline of the peak value of neck moment in Y-direction**

## 3.2 Design Optimization of Parameters

Based on the parameters analysis, the following design parameters has been selected to FFD: overall angle of booster seat (DP1), booster seat stiffness (DP6) and seat belt stiffness (DP8). The simulation matrix for FFD is shown in Table 10.

**Table 10 FFD**

| Test No. | DP1（X1） | DP6（X2） | DP8（X3） | HIC15 | T3ms |
|---|---|---|---|---|---|
| **1** | 90 | 0.2 | 0.5 | 82.5 | 276.2 |
| **2** | 90 | 0.2 | 1 | 136.8 | 292.3 |
| **3** | 90 | 0.2 | 2 | 129.1 | 349.8 |
| **4** | 90 | 1 | 0.5 | 144.3 | 351.6 |
| **5** | 90 | 1 | 1 | 203.8 | 291.2 |
| **6** | 90 | 1 | 2 | 211.4 | 376.4 |
| **7** | 90 | 5 | 0.5 | 127.9 | 356.0 |
| **8** | 90 | 5 | 1 | 145.8 | 319.3 |
| **9** | 90 | 5 | 2 | 182.4 | 377.5 |
| **10** | 100 | 0.2 | 0.5 | 86.0 | 291.5 |
| **11** | 100 | 0.2 | 1 | 135.7 | 328.1 |
| **12** | 100 | 0.2 | 2 | 176.1 | 313.9 |
| **13** | 100 | 1 | 0.5 | 139.5 | 271.9 |
| **14** | 100 | 1 | 1 | 177.8 | 299.6 |
| **15** | 100 | 1 | 2 | 182.9 | 374.0 |
| **16** | 100 | 5 | 0.5 | 166.5 | 352.8 |
| **17** | 100 | 5 | 1 | 188.9 | 357.5 |
| **18** | 100 | 5 | 2 | 231.2 | 374.6 |

The regression equations based on the simulations according to Table 11 are as follows:

$$HIC15=84.5-3.3x_2+62.5x_3-13.8x_2^2-40x_3^2+0.9x_1x_2+0.8x_1x_3+0.3x_2x_3 \quad \text{(Eq.1)}$$

$$T3ms=342.8-2.1x_2-37.5x_3-3.4x_2^2+33.6x_3^2+0.4x_1x_2-0.1x_1x_3-4.2x_2x_3 \quad \text{(Eq.2)}$$

The determination coefficient $R^2$ of the regression equation of HIC15 is 95.8%. And the $R^2$ of the regression equation of thorax resultant acceleration T3ms is 90.3%. Therefore we can say that the two regression equations are credible.

From iSIGHT software we obtained the following optimized values of the regression equations. When $x_1$ equals 90, $x_2$ equals 0.2 and $x_3$ equals 0.704289, thorax resultant acceleration T3ms achieves minimum of 272.769. For the same values of $x_1$, $x_2$ and $x_3$, HIC15 is 104.416; this is not minimum but less than 700, which is the tolerance for children.

When we proved the regression equation credibility and used following values for design parameters 90, 0.2 and 0.704289 with the MADYMO code, we obtained from the simulation the value of thorax resultant acceleration $T_{3ms}$ equaling 259.88 with the relative error of 4.9%. The value of HIC15 was 100.69 and the relative error was 3.7%. We can see that regression equations are credible.

# 4 Conclusions

Seat belt stiffness and overall angle of booster seat are significant parameters influencing child occupant head and neck injury risks.

Seat belt stiffness, stiffness of booster seat, position of belt guide hole of booster seat, overall angle of booster seat, angle of booster seat base and friction coefficient between child and booster seat are significant parameters influencing child occupant thorax injury risks.

Overall angle of booster seat, booster seat stiffness and seat belt stiffness are the parameters influencing dummy thorax resultant acceleration $T_{3ms}$ and HIC15 values simultaneously. When overall angle of booster seat is 90 degree, booster seat stiffness coefficient is 0.2 and seat belt stiffness coefficient is 0.704289, the thorax resultant acceleration T3ms value reaches minimum and HIC15 value is less than 700.

The approach of mathematical simulations combined with optimization procedures is very usable in design of child seats providing an effective protection.

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