Responses of Hybrid III 3YO and Q3 Dummies in Various CRSs Tested Using ECE R44 Impact Conditions

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Paper Number 09-0242

ABSTRACT

There are various types of child restraint systems (CRSs), and the child kinematic response behavior during a crash is different according to which CRS type is being used. In general, P3, Q3 and Hybrid III 3-year-old (3YO) dummies are used to evaluate the performance of the forward-facing CRSs in sled and crash tests. In this study, the Hybrid III 3YO and Q3 dummies were seated in 7 types of CRSs and were tested under the impact conditions specified in ECE R44. The tested CRSs include a 5-point harness and an impact shield, and their installations on the vehicle seat were accomplished by using the seat belt or the ISOFIX with a top tether. The dummy response and injury measures were compared.

The neck flexed in the 5-point harness CRS and the chest deflection was small due to the shoulder harness restraint. In the impact shield CRS, the chest was loaded and the chest deflection was large. The chest deflection in the impact shield CRS depends on the shield structure, and it was small when the shield supported the pelvis. For the 5-point harness CRS, the injury measures of the dummy were smaller in the ISOFIX CRS with a top tether than in the seat belt installed CRS, especially that for the head excursion. For the impact shield CRS, the injury measures were comparable between the ISOFIX CRS with a top tether and in the seat belt installed CRS.

The global dummy kinematic behavior was comparable between the Hybrid III 3YO and Q3 dummies, though the Q3 showed more flexible behavior. This less-stiff characteristics of the Q3 affected the head kinematic behavior. In the 5-point harness CRS, the neck tension force of the Q3 was higher than that for the Hybrid III 3YO, possibly because the Q3 head severely contacted the chest due to its less-stiff neck. The chest deflection of the Q3 was larger than that of Hybrid III 3YO. This large chest deflection was more prominent for the impact shield CRS where the chest was directly loaded. The bottoming-out of the chest occurred for the Hybrid III 3YO seated in the impact shield CRS.

INTRODUCTION

There are various types of child restraint systems (CRSs) such as 5-point harness and impact shield CRS. Langwieder et al. [1] have shown that the injury risks to children were low in the impact shield CRS. This likely is due to less frequent misuse of the impact shield CRSs. However, in an impact shield CRS tested in the Japan New Car Assessment Program (JNCAP) CRS test, the chest deflection of the Hybrid III 3YO dummy was so large that a bottoming-out of the chest occurred.

In Japan, the Japan Automobile Federation (JAF) examined CRS usages in the field. Seventy percent of CRSs were misused, and most of the misuse was due to seat belt slack that was introduced during installation of the CRS on the vehicle seat. An ISOFIX installation reduces this kind of misuse. On the other hand, since the ISOFIX CRS with a top tether is tightly connected to the vehicle seat, the impact response of a child seated in the ISOFIX CRS with a top tether could be affected by the vehicle acceleration.

In the ECE R44, a P dummy is specified for use in the dynamic test of the CRS. However, it is indicated that the measurement capacity of the P dummy is limited. Therefore, a new child dummy, the Q dummy, was developed and is under investigation. Meanwhile, in the US, the Hybrid III 3YO (3-year-old) dummy is used in the FMVSS 213. In Japan, the Hybrid III 3YO dummy is used in JNCAP to evaluate the dynamic performance of forward facing CRSs.

There are some studies that have compared the Hybrid III 3YO, P3 and Q3 dummies. Ratingen [2] compared the P3 and Q3 behavior in the ECE R44 test. He concluded that the injury measures of both dummies were comparable if the injury criteria prescribed in the ECE R44 were used. Crandall et al. [3] identified the mechanical characteristics of the neck of the Hybrid III 3YO and Q3 dummies based on laboratory testing, and indicated that the Hybrid III 3YO neck has a stiffer spring constant than that of the Q3. Berliner et al. [4] examined the dummy responses of the Hybrid III 3YO and Q3 dummies in dummy calibration tests and static out-of-position airbag tests. In the dummy thorax pendulum impact calibration test condition, the Q3 showed stiffer chest characteristics than the Hybrid III 3YO. Based on finite element (FE) simulations, Kapoor et al. [5] compared the kinematic behavior of the Hybrid III 3YO and Q3, under the FMVSS 213 test condition. The acceleration of the head and chest was comparable between the Hybrid III 3YO and the Q3. The neck of the Hybrid III 3YO was stiffer than that of the Q3. The head excursion of the Q3 was larger than the Hybrid III 3YO. They also compared the Hybrid III 3YO and Q3 dummy responses with a child FE model, and found that the Q3 responses are more comparable with the child FE model with respect to the head excursion and neck stiffness.

In this study, sled tests were carried out using Hybrid III 3YO and Q3 dummies seated in 7 types of CRSs. The dummy responses were compared for a 5-point harness CRS and an impact shield CRS under install conditions on the vehicle seat by a seat belt and by an ISOFIX with a top tether. The Hybrid III 3YO and Q3 kinematic behavior and injury measures were compared for these various types of CRSs.

METHOD

Test Conditions

Figure 1 and Table 1 show the tested CRSs and their specifications. In classification of child restraint type, CRSs A, B, C are an impact shield CRS, and the CRSs D, E, F, G are a 5-point harness CRS. In classification of CRS installation on vehicle, the CRSs A, B, D, F are installed by the seatbelt, and CRSs C, E, G are an ISOFIX with a top tether type CRS. The CRSs B and C, CRSs D and E, or CRSs F and G are models made by the same manufacturer, and the difference between the two models is the car seat installation of the CRS with a seat belt or with an ISOFIX and a top tether. In a CRS A tested in JNCAP, the chest deflection of the Hybrid III 3YO was so large that the chest was bottomed out. The CRSs A and B are an impact shield type CRS, and the shield height of CRS B was higher than that of CRS A, which covered an area ranging from the thorax to the pelvis of the dummy. The two types of 5-point harness CRS were tested in order to confirm that the same type CRS has comparable performance of dummies kinematic behavior and injury measures.

Figure 2 shows the tested dummies. As indicated above, Hybrid III 3YO and Q3 dummies were used in the tests.

Test conditions with CRS and dummy are presented in Table 2. An acceleration-type sled facility was used in the tests (Figure 3). The tests were conducted in accordance with ECE R44 with the exception that the Hybrid III 3YO and Q3 dummies were used instead of the P3 dummy. The acceleration of the sled and its corridors are shown in Figure 4. Table 3 shows the injury assessment reference values (IARVs). HIC15, neck tension force, chest deflection, and head excursion are checked as dummy injury criteria. The dummy injury measures were compared with the IARVs. For the Hybrid III 3YO, the acceptance levels of FMVSS 208 were used. For the IARVs of the Q3, the AIS 3 at a 50% risk level was used as based on the logistic regression (LR) injury risk curves from the EEVC report [6].

(a) A (b) B (c) C

(d) D (e)E

(f) F (g) G

Figure 1. Tested CRSs

Table 1. Type of tested CRSs

CRS	A	B	C	
type of restraint	impact shield	impact shield	impact shield	
type of anchorage	seat belt	seat belt	ISOFIX + top tether	
CRS	D	E	F	G
type of restraint	5-point harnes	5-point harness	5-point harness	5-point harness
type of anchorage	seatbelt	ISOFIX + top tether	seat belt	ISOFIX + top tether

(a) Hybrid III 3YO (b) Q3

Figure 2. Tested dummies

Table 2. Test conditions

Test No.	1	2	3	4	5
CRS	A	B	C	D	E
Dummy	Hybrid III 3YO	Hybrid III 3YO	Hybrid III 3YO	Hybrid III 3YO	Hybrid III 3YO
Test No.	6	7	8	9	10
CRS	F	G	A	B	C
Dummy	Hybrid III 3YO	Hybrid III 3YO	Q3	Q3	Q3
Test No.	11	12	13	14	
CRS	D	E	F	G	
Dummy	Q3	Q3	Q3	Q3	

Figure 3. Sled system

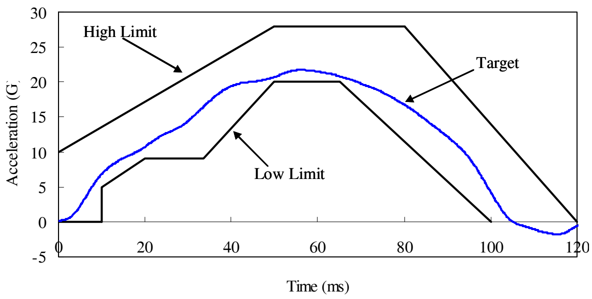


Figure 4. Sled acceleration

Table 3. Injury criteria

injury criteria	IARV	
	Hybrid III 3YO (FMVSS208)	Q3 (EEVC report)
HIC15	570	1000
Neck tension force	1130 N	1705 N
Chest deflection	34 mm	53 mm
Head excursion	550 mm	550 mm

FE Simulation

To examine the interaction of the shield with a dummy, an FE simulation with a Hybrid III 3YO dummy model using LS-DYNA was carried out. The FE models of CRS A and B were developed because they have difference in the shield shape. Figure 5 shows the CRS model.

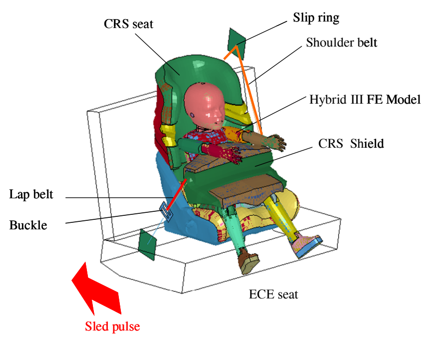


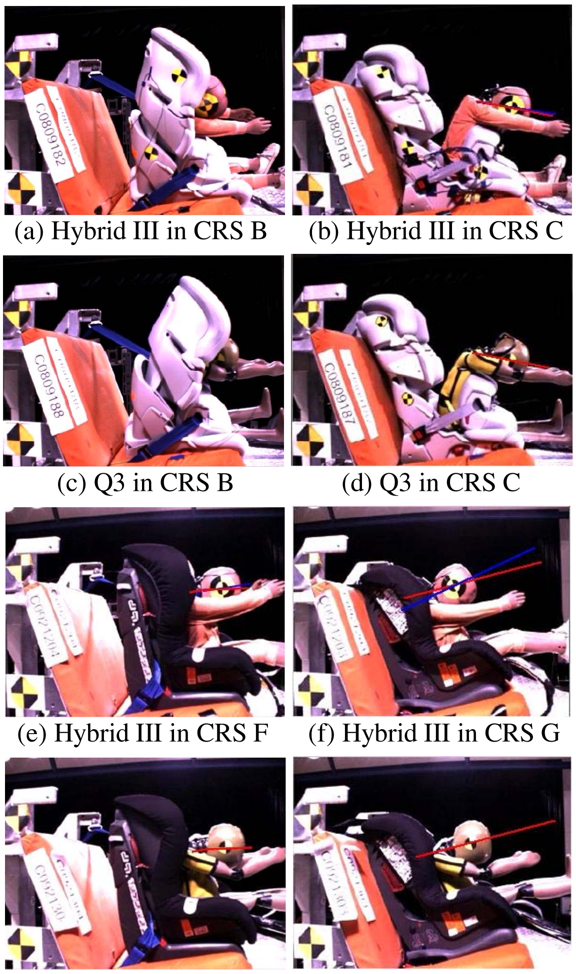
Figure 5. FE model for the CRS sled test

RESULTS

Sled Tests

<u>Dummy Kinematic Behavior</u>

The dummy showed different kinematic behavior according to which CRS type was being used. Figure 6 shows the kinematic behavior for a dummy seated in the impact shield CRSs (CRS B and C) and the 5-point harness CRSs (CRS F and G) at the point in time during the test when the head excursion was at its maximum. In the impact shield CRSs, the dummies were restrained by the shield and the torso flexion angle was large. The head made contact with the shield. The dummies in the CRSs installed with a seat belt had substantial yawing rotation while the dummies in the ISOFIX CRSs with a top tether had no yawing rotation. The dummies' forward movement in the impact shield CRSs was similar for both the CRS installed by a seat belt and the ISOFIX CRS, though the forward movement of the CRS installed by a seat belt was much larger than that for the ISOFIX CRS. In the 5-point harness ISOFIX CRS with a top tether, the CRS forward movement was small with the ISOFIX attachment, and the CRS forward pitching was small with the top tether. In the 5-point harness CRS installed with a seat belt, the CRS forward movement and forward pitching were large because of the stretch of seat belt. As a result the dummy's forward movement in the CRS installed seat belt was larger than that in the ISOFIX CRS with a top tether. The flexion angle of the dummy torso was small since the dummy was restrained by the CRS shell with shoulder harness. The Hybrid III 3YO and Q3 dummies showed almost similar behavior. In the impact shield CRS, the head flexion angles were similar between the Hybrid III 3YO and the Q3. In the 5-point harness CRS, the head rotation angle of the Hybrid III was smaller than that of the Q3, which indicated that the Q3 is more flexible than the Hybrid III 3YO.



(a) Hybrid III in CRS B (b) Hybrid III in CRS C

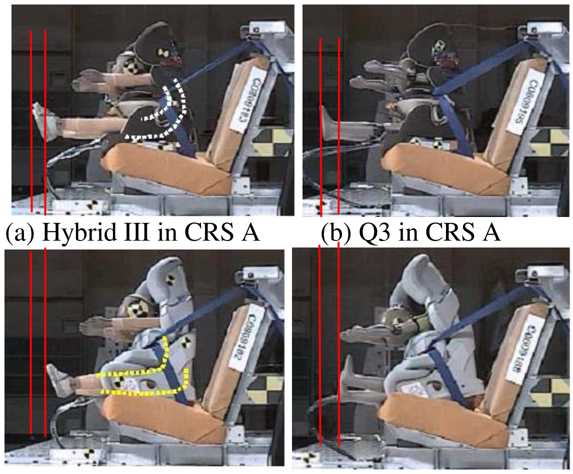
(c) Q3 in CRS B (d) Q3 in CRS C

(e) Hybrid III in CRS F (f) Hybrid III in CRS G

(g) Q3 in CRS F (h) Q3 in CRS G

Figure 6. Dummy behaviors at the time of head maximum excursion

The difference in dummy behavior was also observed for the impact shield CRSs A and B of which the shield shape was different. Figure 7 shows the dummy kinematic behavior in CRS A and B at a point during the tests when the chest deflection was at its maximum. The dummy foot forward motion was larger in the CRS A than in the CRS B, which indicates that the pelvis restraint was different between CRSs A and B.

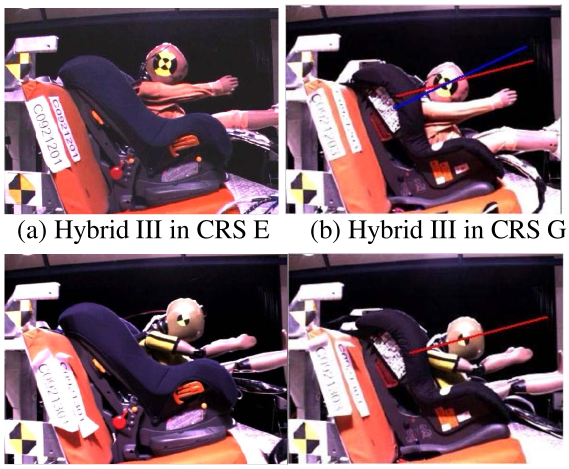


(a) Hybrid III in CRS A (b) Q3 in CRS A

(c) Hybrid III in CRS B (d) Q3 in CRS B

Figure 7. Dummy behavior at the time of maximum chest deflection in impact shield CRS A and B

Figure 8 shows the dummy behavior in CRSs E and G at the time during the test when the head excursion was maximal. The dummy behavior of the different 5-point harness CRSs was similar.



(a) Hybrid III in CRS E (b) Hybrid III in CRS G

(c) Q3 in CRS E (d) Q3 in CRS G

Figure 8. Dummy behaviors at the time of head maximum excursion in 5-point harness CRS E and G

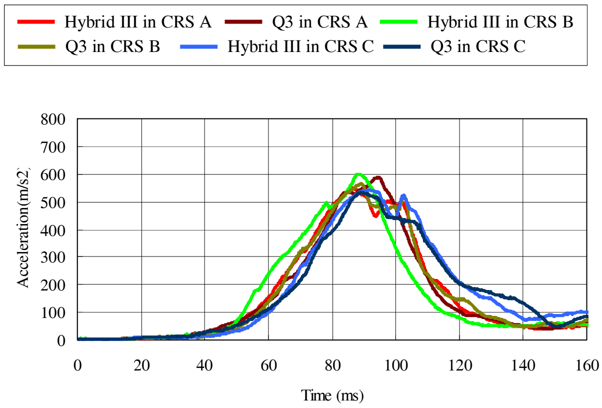
Dummy Readings

Figures 9 and 10 shows the head, chest, and pelvis acceleration time histories for the impact shield CRSs and the 5-point harness CRSs, respectively. In the impact shield CRSs, the chest and head accelerations were similar in the tests even though the CRS type and dummy types were different. For the impact shield CRSs, the pelvis and the chest accelerations started to increase almost simultaneously, and finally the head acceleration increased. The pelvis acceleration was delayed in the CRS A as compared with CRSs B and C for Hybrid III 3YO and Q3. In the impact shield CRSs, the accelerations of head, chest, and pelvis were similar for Hybrid III 3YO and Q3. The delay of the pelvis acceleration in CRS A as compared to the responses in CRSs B and C occurred because of the shield structure.

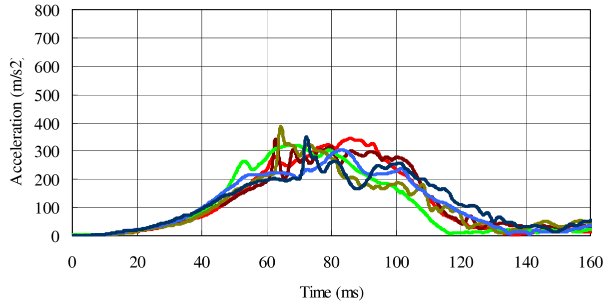
The acceleration of each body region started later in the 5-point harness CRS than in the impact shield CRS. For the 5-point harness CRSs, the pelvis acceleration stared to increase with the lap harness restraint, then the chest acceleration increased with the shoulder harness, and finally the head acceleration increased. In the 5-point harness CRSs, the accelerations of each body regions were different by the CRSs. By comparison with the CRS manufacturer, the acceleration of the dummy in the CRS F or G started earlier than that for the CRS D or E. The pelvis accelerations were comparable between the Hybrid III 3YO and Q3 dummies. The chest acceleration of the Q3 dropped temporarily around 80 ms though this phenomenon was not observed for the Hybrid III 3YO. The head acceleration of Q3 also dropped during its increase. The Q3 head acceleration had a sharp peak which was not observed in the acceleration of the Hybrid III 3YO.

The accelerations of the dummy were compared by the CRS installation method on the vehicle seat, such as the seat belt installed CRS and the ISOFIX CRS with a top tether. The accelerations of each body region were comparable in the impact shield CRSs. For the 5-point harness CRS, the accelerations increased earlier for the ISOFIX CRS with a top tether than for the seat belt installed CRS in both Hybrid III 3YO and Q3 dummies. In comparison of the 5-point harness CRS with the same manufacturer (CRS D, E or CRS F, G), the peak accelerations of the dummy were smaller in the ISOFIX CRS with a top tether than that in the seat belt installed CRS.

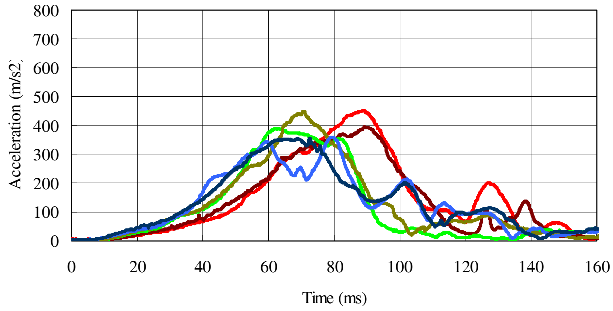
The dummy accelerations start times were comparable between the impact shield CRSs and the 5-point harness ISOFIX CRSs with a top tether.



(a) Head Acceleration

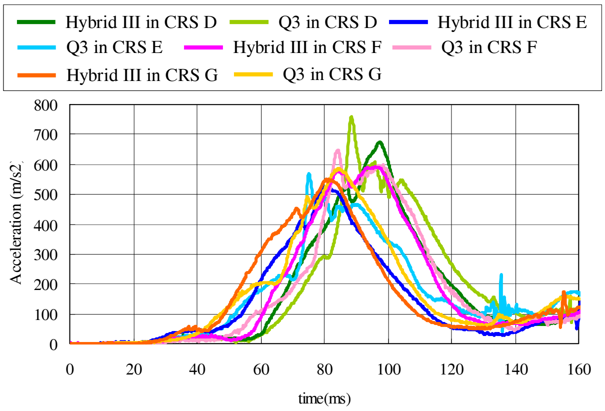


(b) Chest Acceleration

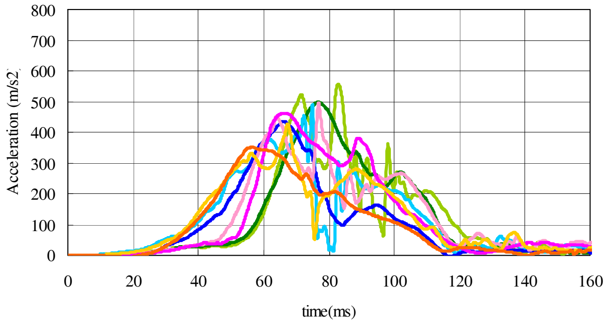


(c) Pelvic Acceleration

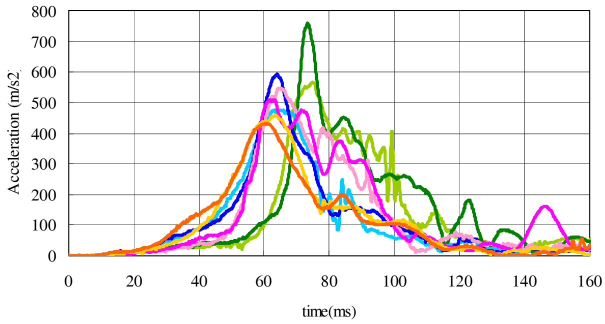
Figure 9. Dummies in impact shield CRSs acceleration time histories



(a) Head acceleration



(b) Chest acceleration



(c) Pelvic acceleration

Figure 10. Dummies in 5-point harness CRSs acceleration time histories

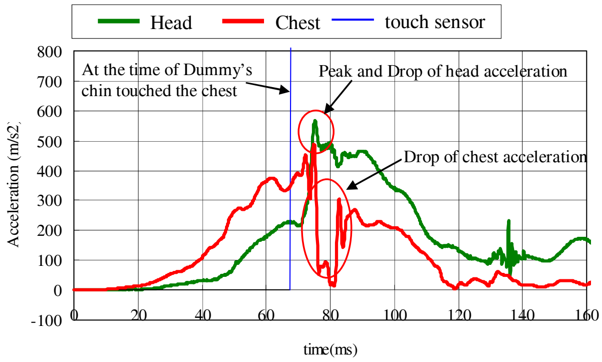


Figure 11. Head and chest acceleration time histories of dummy in CRS E

Figure 12. Q3 behavior at 70ms in CRS E

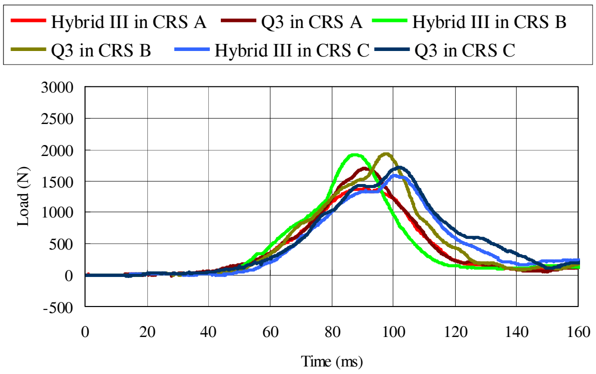
Figure 13. Touched sign of Q3 Dummy clavicles and spine after the test of 5-point harness CRSs

Figure 11 shows the accelerations of the head and chest, and the chin/chest contact sensor of the Q3 seated in CRS E. The Q3 kinematic behavior at 70 ms is shown in Figure 12. After the chin and chest contacted, the head acceleration increased and the chest acceleration decreased. But it is unknown whether there is a correlation between the contact of the chin to the chest and the decrease in chest acceleration. Figure 13 shows the Q3 after Test 12. As can be seen, there were traces of contact of chin/clavicle and clavicle/spine (by noting the blue grease paint).

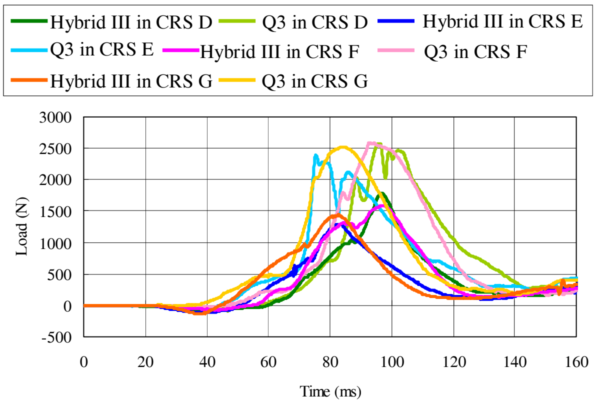
Figure 14 shows the upper neck tension force time histories. Figure 15 shows the upper neck shear force time histories. In all CRSs, the upper neck tension force of the Q3 was larger than that of the Hybrid III 3YO. In the impact shield CRSs where the dummy head impacts the shield, the difference of the upper neck force between the Hybrid III 3YO and the Q3 was small. For the 5-point harness CRSs, there was a large difference of upper neck tension force between the Hybrid III 3YO and the Q3. The upper neck shear forces were small in the 5-point harness CRSs for the Q3, while they were large for the Hybrid III 3YO. Accordingly, for the 5-point harness CRSs, the flexion angle of the dummy torso was small, so the difference of the neck stiffness between the Hybrid III 3YO and the Q3 dummies had a large influence.

The tension and shear force of the dummy were comparable in the seat belt installed CRSs and the ISOFIX CRSs with a top tether.

Figure 16 shows the upper neck moments. The neck moment was larger for the 5-point harness CRSs than for the impact shield CRSs because the neck flexion angle was larger in the 5-point CRSs. In all CRSs, the upper neck moment of the Hybrid III 3 YO was larger than that of the Q3.

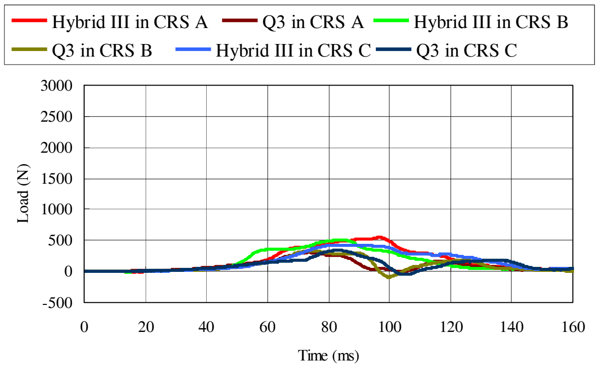


(a) Impact shield CRSs

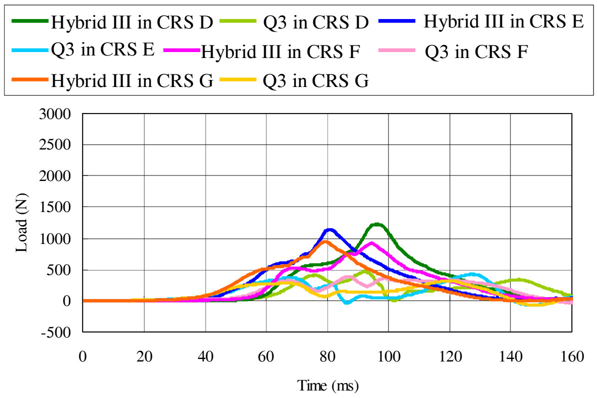


(b) 5-point harness CRSs

Figure 14. Time histories of upper neck tension force

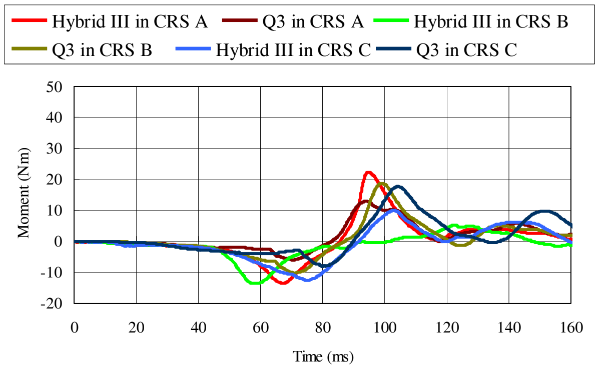


(a) Impact shield CRSs

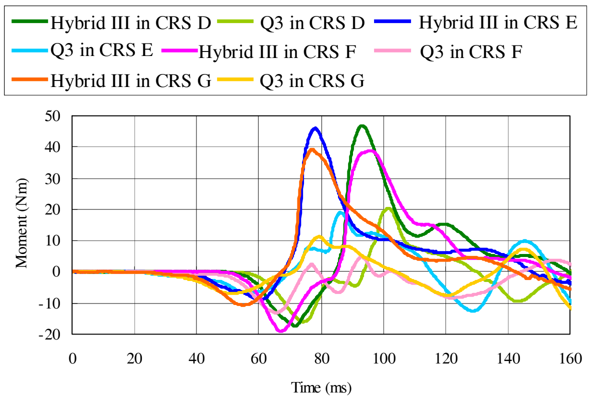


(b) 5-point harness CRSs

Figure 15. Time histories of upper neck shear force



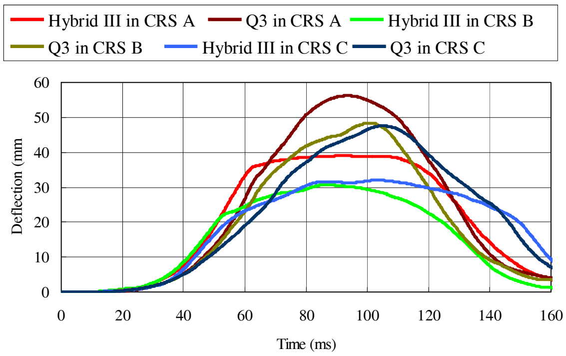
(a) Impact shield CRSs



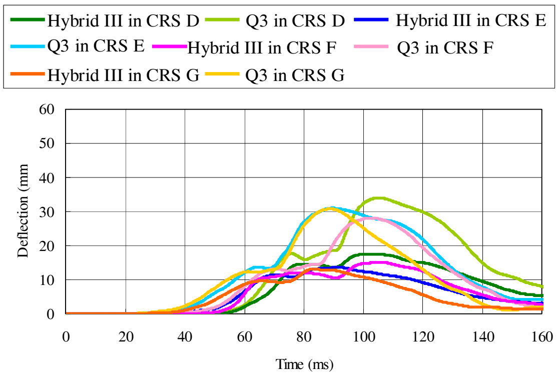
(b) 5-point harness CRSs

Figure 16. Time histories of upper neck moment

Chest deflection time histories are shown in Figure 17. The chest deflection was larger in the impact shield CRSs than that in the 5-point harness CRSs. The Q3 had larger chest deflections than the Hybrid III 3YO. For the Hybrid III 3YO seated in the CRS A, a flat top occurred in the chest deflection. In the CRSs B and C, it did not occur.



(a) Impact shield CRSs



(b) 5-point harness CRSs

Figure 17. Time histories of chest deflection

Injury Measures

Table 4 presents the HIC15, neck tension force, chest deflection, and maximum head excursion. Figure 18 shows the ratio of the injury measures to the IARVs for the Hybrid III 3YO and Q3 dummies. The HIC15 was less than the IARV for all tests. The HIC15 ranges from 237 to 426 with the various CRS types, and the differences of HIC15 between the Hybrid III 3YO and the Q3 dummies were small.

The neck tension forces exceeded the IARV in all tests except Test 8 (CRS A with Q3). In Test 8, the neck tension force was 1704 N, which was comparable with IARV (1705 N). In comparing the responses of the Hybrid III 3YO and Q3, the neck tension forces of the Hybrid III 3YO and Q3 were comparable for the impact shield CRSs (CRS A, B, C). However, on the other hand, the neck tension forces of the Q3 were larger than those of the Hybrid III 3YO for the 5-point harness CRSs (CRS D, E, F, G).

The chest deflections of the dummies in the impact shield CRSs (CRS A, B, C) were substantially larger than that for the dummies in the 5-point harness CRSs, and they were close or exceeded the IARVs. The chest deflections of the Q3 were larger than those of the Hybrid III 3YO by 13-18 mm. In CRS A, the chest deflections were over the IARVs for both the Hybrid III 3YO and the Q3 dummies.

The head forward excursions were less than the IARV (i.e., 550 mm) for all tests. Head excursions were about 500 mm for all the seat belt installed CRSs. For the 5-point harness ISOFIX with a top tether CRSs (CRS E, G), the head excursions were far smaller than the 550 mm. However, even for the ISOFIX with a top tether CRSs, the head excursion in the impact shield ISOFIX and a top tether CRS (CRS C) was slightly larger than that in the CRS B, which was installed by the seat belt.

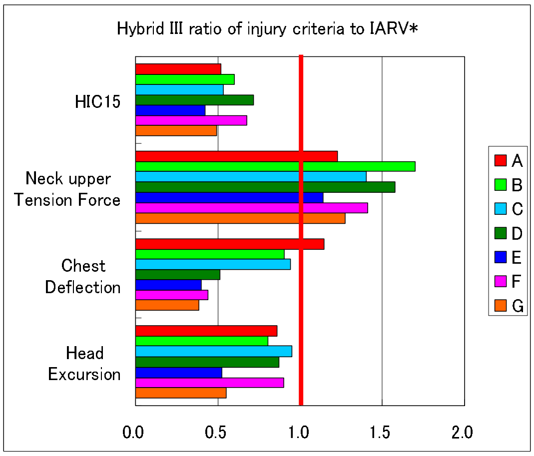
The injury measures of the dummy were compared between the seatbelt installed CRSs and the ISOFIX and a top tether CRSs. For the 5-point harness CRSs, the injury measures of the dummy seated in the ISOFIX and a top tether CRSs were comparable or smaller than those in the CRSs installed by the seat belt. For the impact shield CRSs, the injury measures were comparable between the seatbelt installed CRSs and the ISOFIX and a top tether CRSs.

The rank order of the injury measures was almost similar between Hybrid III 3YO and Q3.

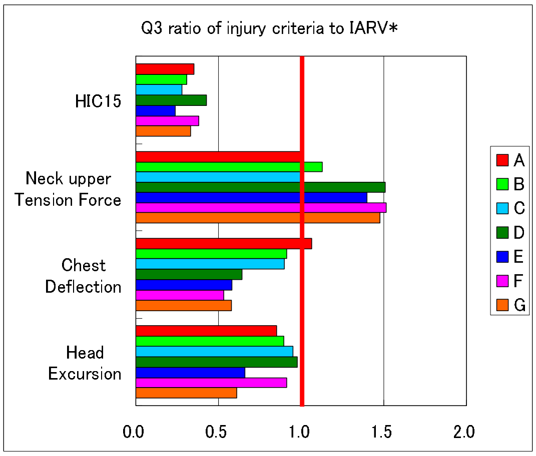
Table 4. Injury Measures

Dummy	Hybrid III 3YO							
CRS	A	B	C	D	E	F	G	IARV*
HIC15	295	344	305	410	242	384	280	570
Chest Deflection (mm)	**39**	31	32	18	14	15	13	34
Neck upper tension force (N)	**1385**	**1920**	**1586**	**1783**	**1290**	**1594**	**1437**	1130
Head excursion (mm)	474	442	523	481	289	495	303	550

Dummy	Q3							
CRS	A	B	C	D	E	F	G	IARV*
HIC15	354	306	279	426	237	383	329	1000
Chest Deflection (mm)	**56**	48	48	34	31	28	31	53
Neck upper tension force (N)	1704	**1923**	**1716**	**2574**	**2382**	**2584**	**2515**	1705
Head excursion (mm)	470	493	522	536	363	503	336	550



(a) Hybrid III 3YO

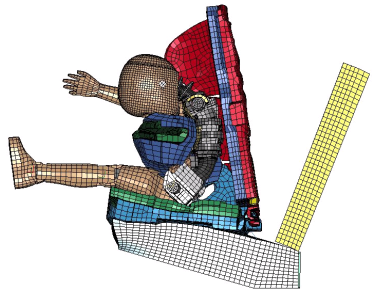


(b) Q3

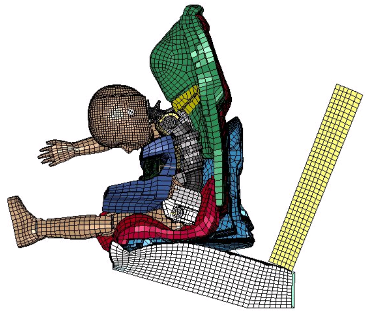
Figure 18. Ratio of injury criteria to IARV

FE Analysis

The kinematic behavior of the Hybrid III 3YO in the CRSs A and B from the FE simulation is shown in Figure 19. In CRS A, the pelvis rotated and only the upper edge of the ilium made contact with the shield. Therefore, the inertial forces of the lower extremities were not supported by the shield. As a result, loading of the Hybrid III 3YO was concentrated on the thorax. On the other hand, in CRS B, the shield interacted with the ilium, and thus prevented forward motion of the pelvis. Accordingly, the shield shape has a large influence on the pelvis interaction



(a) Hybrid III 3YO in CRS A



(b) Hybrid III 3YO in CRS B

Figure 19. Dummy kinematic behavior in FE analysis

DISCUSSION

The Q3 dummy showed more flexible behavior in flexion than the Hybrid III 3YO. The head of the Q3 flexed at a large angle as compared to the Hybrid III 3YO dummy. This flexible behavior of the Q3 affected the head acceleration and neck forces. In the 5-point harness CRSs, the head acceleration of the Q3 increased later during the crash than that of the Hybrid III 3YO (see Figure 10(a)). The shear forces of the Hybrid III 3YO were larger than that of the Q3 (see Figure 15). The stiffness of the Q3 is smaller than that of the Hybrid III 3YO. Then, during head swing motion, the transfer force of the neck would be small for the Q3, which leads to small head acceleration. Since the Q3 chin made contact with the thorax more severely than that for the Hybrid III 3YO, the upper neck tension of Q3 was larger. For the Q3, due to chin/thorax contact, the clavicles interacted with the spine, which might cause oscillations in the chest acceleration. In the impact shield CRSs, the neck force was similar between the Hybrid III 3YO and the Q3. This is because the head made contact with the shield and there were no chin/thorax contacts.

The chest deflection was different in the dummy types (Hybrid III 3YO and Q3) as well as in the CRS types. The chest deflections of the dummy in the impact shield CRSs were larger than those in the 5-point harness CRSs since the shield restrained and loaded the chest in the impact shield CRSs. In all tests, the chest deflection of Q3 was larger than the Hybrid III 3YO by 13-18 mm. The likely reason is that the Q3 thorax is less-stiff than the Hybrid III

3YO, and the rib cage of the Q3 is cone-shape. In CRS A, a flat top was observed in the chest deflection time history for the Hybrid III 3YO. This is likely due to the bottoming-out of the chest. For the Q3 seated in the CRS A, the chest deflection was larger than the Hybrid III 3YO, though the bottoming-out of the chest did not occur. The upper limit of the measurement of the chest deflection of the Q3 is larger than that for the Hybrid III 3YO. Thus, the Q3 could be used in tests where there are more severe loading conditions to chest.

Even for the impact shield, the bottoming-out of the Hybrid III 3YO chest did not occur in the CRSs B and C. This is likely due to the structure of the shield. As shown in Figures 7 and 19, the shield of the CRS B restrained the pelvis as compared to the CRS A. As the pelvis forward motion was limited in the CRS B, the shear force transferred from the pelvis to the chest was small, which led to a small chest deflection. The pelvis restraint condition was also reflected in the pelvis acceleration which started late in the CRS A (see Figure 9). Based on the tests, it was demonstrated that the chest deflection could be less than the IARV with the structure of the impact shield CRS, even though the chest was loaded by the shield.

In the impact shield CRS, the dummy was restrained by the shield and the torso flexion angle was large and the neck flexion angle was small (see Figure 6). As a result, the influence of the less-stiff characteristic of the neck was small and the accelerations of the head, chest, and pelvis were similar for the Hybrid III 3YO and Q3 dummies.

In this study, the ISOFIX CRSs with a top tether and the seat belt installed CRSs were compared. The injury measures of the Hybrid III 3YO and Q3 dummies were smaller in the ISOFIX CRSs with a top tether than in the seat belt installed CRSs, especially for the head excursion. Since the seat belt slack is smaller in the ISOFIX CRS with a top tether than in the seat belt installed CRSs, the child dummy moved earlier in the ISOFIX CRSs with a top tether. Thus, as shown in Figure 10, the dummy acceleration started early in the ISOFIX CRS with a top tether. As a result, the difference of speed between the dummy and CRS at the start of dummy movement was smaller in the ISOFIX CRSs with a top tether than in the seat belt installed CRSs, and the necessary energy for the dummy to catch up with the CRS was small. Accordingly, the loading to the dummy was small. In the impact shield CRSs, the injury measures of the dummy were comparable between the ISOFIX CRSs with a top tether and the seat belt installed CRSs. In the impact shield CRSs, the shield is installed by the belt. Therefore, the dummy loadings would be strongly affected by the belt characteristics in the impact shield CRSs. The 5-point harness CRSs have two belt systems which consist of harness and seat belt. The ISOFIX CRSs with a top tether and impact shield CRSs have one belt system. The number of belt systems can affect the restraint start time of the dummy.

In all tests, the neck injury measures exceeded the IARV for the Hybrid III 3YO and Q3 dummies. In accidents, neck injuries of children are not frequent if head contact does not occur. The neck stiffness and the chin/chest contact characteristic of the dummy can affect the neck injury measures. Accordingly, research is needed to investigate the dummy characteristics as well as the IARV of the child neck.

The Q3 dummy used in this study was a first edition device. In the current generation of Q3s, the characteristics of the Q3 may have been improved.

SUMMARY

The Hybrid III 3YO and Q3 dummies seated in a 5-point harness CRS and an impact shield CRS were tested using ECE R44 impact conditions. The results are summarized as follows:

1. The dummies showed different kinematics by the CRS types. The neck flexed in the 5-point harness CRSs, whereas the torso flexed around the shield in the impact shield CRSs.

2. In the impact shield CRSs, the chest deflection was large, since the chest was directly loaded. The chest deflection could be less than the IARV, which is dependent on the shield structure and on the shield supporting the pelvis.

3. For the 5-point harness CRSs, the injury measures of the dummy were smaller in the ISOFIX CRS with a top tether than in the seat belt installed CRSs. The head excursion was far smaller than 550 mm in the 5-point harness ISOFIX CRS with a top tether. For the impact shield CRSs, the injury measures were comparable between the ISOFIX CRSs with a top tether and the seat belt installed CRSs.

4. In general, the kinematic behavior was comparable between the Hybrid III 3YO and Q3 dummies, though the Q3 showed more flexible behavior.

5. The chest deflection of the Q3 dummy was larger than that of Hybrid III 3YO dummy. This large chest deflection was more prominent for the impact shield CRS. The bottoming-out of the chest occurred for the Hybrid III 3YO seated in one type of impact shield CRS.

6. In all tests, the neck injury measures exceeded the IARVs. Further research is needed for

investigating the dummy neck characteristics and IARVs.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Mr. Masami Kubota (JARI) for his technical advice.

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THE ROLE OF VERTICAL ROOF INTRUSION IN PREDICTING OCCUPANT EJECTION

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ABSTRACT

The purpose of the current study is to investigate whether there was a statistically significant relationship between vertical roof intrusion and the probability of occupant ejection in rollovers that are likely to be covered by Federal Motor Vehicle Safety Standard No. 216 (FMVSS No. 216). If such a relationship did exist, FMVSS No. 216 might affect the number of occupant ejections in rollovers.

The study applies thirty six different statistical models to crash data to model the probability of occupant ejection using a number of explanatory variables, including the amount of vertical roof intrusion. The data is on vehicle occupants who were involved in relevant rollover crashes, and is taken from NASS CDS for years 1997 to 2006 (n = 5,562). Though the study considers a number of different models, it does not find a statistically significant relationship between vertical roof intrusion in relevant rollovers and the probability of complete occupant ejection. When ejections of any degree are considered (whether complete, partial, or of unknown degree), there was a statistically significant relationship in some subpopulations.

Given that no relationship has been found between the amount of vertical roof intrusion and the probability of complete occupant ejection, increasing roof strength is unlikely to impact the number of complete occupant ejections. The study is limited to occupants in rollovers that are likely to be covered by FMVSS No. 216, and to occupants for whom key data, such as the amount of vertical roof intrusion, are available.

INTRODUCTION

Purpose. Austin et al. (2005) and Strashny (2007) have established the existence of a statistically significant relationship between the maximum severity of head, neck, and face injuries due to occupant roof contact that occurred in rollovers that were likely to be covered by Federal Motor Vehicle Safety Standard (FMVSS) No. 216 and the amount of vertical roof intrusion. The occupants considered in those reports were belted and not completely ejected. The purpose of the current report is to investigate whether there was also a statistically significant relationship between vertical roof intrusion and occupant ejection. The rollovers considered ("relevant rollovers") are those likely to be covered by FMVSS No. 216, with the exception that this report is not placing restrictions on occupant seat belt use or ejection status.

Data. The data is from the National Automotive Sampling System Crashworthiness Data System (NASS CDS) for years 1997 to 2006. NASS CDS is a complex, random sample of crashes involving at least one passenger car or "light truck or van" (LTV), defined by a gross vehicle weight rating of 4,536 kilograms (10,000 pounds) or less, that was towed due to damage. The beginning year of 1997 was selected because it was the first year that NASS CDS coded continuous vertical roof intrusion measures. Prior to that year, NASS CDS coded intrusion in categories with ranges that were too wide to be of use in this study. The ending year of 2006 was the most current year available at the time of this analysis. Note that the database codes intrusion in centimeters. For this report, measurements have been converted to inches.

This study analyzes occupants of automobiles, utility vehicles, light-duty pickup trucks, and light-duty vans that were involved in single-vehicle rollover crashes. The following vehicles were excluded from the analysis: (1) convertibles; (2) vehicles that rolled only one quarter-turn to the side, since they did not have roof-to-ground exposure; and (3) vehicles that had been towing a trailing unit or that were multistage or certified altered vehicle, because changes may have been made to the roof structure in such vehicles. To be consistent with the target population used in the FMVSS No. 216 regulatory analyses, the occupants of interest were seated in one of the two outboard front seats (seating positions 11 and 13) and were 13 years old or older. Unlike in Austin et al. (2005) and Strashny (2007), occupants were not excluded from the analysis based on their seat belt use status, ejection status, or the model year of their vehicle.

Method. Probability of ejection was analyzed using the probit model. Thirty-six statistical models were estimated. These models differed in the dependent variables, independent variables, and the data subset used. Two different dependent variables were used to indicate ejection status. These were:

1. "complete ejection" (C), indicating whether the occupant was completely ejected or not; and
2. "any ejection" (A), indicating whether the occupant was ejected (to any degree, including completely, partially, and to unknown degree) or not.

Some models contained a continuous intrusion variable, measured in inches, as an independent variable. Other models contained a dichotomous intrusion variable. In this case, the dichotomous variable was set to 0 if there was no intrusion and to 1 if there was intrusion.

Some models contained intrusion, whether continuous or dichotomous, as the only independent variable. These are called "unadjusted" as they have not been adjusted for potentially confounding factors. "Adjusted" models, on the other hand, control for a number of potentially confounding factors. The following independent variables were used in all of the adjusted models: occupant age, whether the vehicle was an LTV or a passenger car; and whether the rollover was end-over-end or to the side. For sideways rollovers, rollover severity was controlled by using either the number of quarter turns or the number of roof-to-ground exposures.

There does not appear to be a logical connection between occupant age and ejection status. Indeed, occupant age was not statistically significant in most of the models. In the models in which it was statistically significant, it is possible that the statistical significance was due to an artifact of the data, as discussed below. Thus, the only reason that occupant age is included as an independent variable is for consistency with other recent reports that included it in their models of occupant ejection, such as Lund (2008) and Padmanaban and Moffatt (2008), and because it was statistically significant in some models.

Occupant sex was not statistically significant in any of the estimated models. Because of this, and because there does not appear to be a logical connection between occupant sex and ejection status, this independent variable was not used in the final versions of any of the models.

According to Eigen (2003), while there is no universally accepted measure of sideways rollover severity, some studies use the number of quarter turns for this purpose. Digges and Eigen (2003) and Eigen (2005) found that, in some cases, the number of roof-to-ground exposures is a good measure of sideways rollover severity. Specifically, Digges and Eigen (2003) found that "for belted occupants and unbelted ejected occupants in single vehicle crashes, the number of [roof-to-ground exposures] is an appropriate severity indicator." Following Eigen (2005) and Strashny (2007), the number of roof-to-ground exposures in a sideways rollover is defined as the number of times that the vehicle roof faced downward, toward the ground, regardless of the number of times that the roof physically contacted the ground. Strashny (2007) found that, other things being equal, as the number of quarter turns or the number of roof-to-ground exposures increased, the severity of injuries considered by that report also tended to increase. Therefore, the current report uses both of these measures to control for sideways rollover severity.

Some models were estimated using all the occupants. In these cases, the adjusted models controlled for seat belt use. Other models were estimated only on the subpopulation of belted occupants or on the subpopulation of unbelted occupants. Note that only the occupants who are known to have been belted are considered as such, whereas the occupants who were either unbelted or whose seat belt use status is unknown are considered to be unbelted.

Thus, there were two possible dependent variables (C and A), two possible intrusion variables (continuous and dichotomous), three possible types of models (unadjusted, quarter turns adjusted, and roof-to-ground exposure adjusted), and three data subsets (all occupants, belted occupants only, and unbelted occupants only), leading to a total of 36 models.

DATA DESCRIPTION

Error! Reference source not found. is a description of the variables used in this report. The first sub-table shows the sample size and the weighted annual average of all occupants, as well as the unbelted and the belted subsets. The second sub-table describes categorical variables. As all of the categorical variables used in this report only have two categories, the table shows only one category for each variable. Values for the other category can be obtained by subtraction. For example, among all occupants, 4.3 percent were complete ejected. This means that 95.7 percent [= 100% - 4.3%] were not completely ejected. The third sub-table describes interval scale variables. For each variable, it gives the minimum, maximum, and the weighted mean.

Table 1.

A description of the variables used in this report

Occupants	**All**	**Unbelted**	**Belted**
Sample size	5,562	1,951	3,611
Weighted annual average	251,245	51,297	199,949

	All occupants			**Unbelted occupants**			**Belted occupants**		
Variable	WP	WAA	Sample	WP	WAA	Sample	WP	WAA	Sample
Intrusion > 0 (vs. no intrusion)	58.2%	146,205	3,686	59.4%	30,461	1,290	57.9%	115,744	2,396
Complete ejection (C) (vs. partial or no ejection)	4.3%	10,863	793	20.0%	10,252	765	0.3%	612	28
Any ejection (A) (vs. no ejection)	6.9%	17,250	1,199	25.4%	13,009	948	2.1%	4,241	251
End-over-end rollovers (vs. lateral rollovers)	0.7%	1,689	76	1.5%	779	34	0.5%	910	42
Vehicle = LTV (vs. vehicle = passenger car)	54.8%	137,729	3,135	47.9%	24,553	1,086	56.6%	113,177	2,049
Belted occupants (vs. unbelted or unknown)	79.6%	199,949	3,611						

		All occupants			**Unbelted occupants**			**Belted occupants**		
Variable		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Intrusion	(inches)	0	44.1	3.5	0	44.1	3.7	0	38.6	3.4
# roof exposures	(end-over-end = 0)	0	4	1.2	0	4	1.2	0	4	1.2
# quarter turns	(end-over-end = 0)	0	17	3.6	0	17	3.8	0	17	3.6
Occupant age	(years)	13	95	29.6	13	93	28.5	13	95	29.9

Note: “WP” = weighted percent; “WAA” = weighted annual average; “Sample” = sample size.
Source: NHTSA, NCSA, NASS CDS 1997-2006.

Both complete ejection and any ejection were much more likely among unbelted occupants as compared to belted occupants. One way of measuring differences in probabilities is using odds ratios (OR). The odds ratio for complete ejection for unbelted occupants as compared to belted occupants was 81.4 [=(0.2 / (1-0.2)) / (0.003 / (1-0.003))]. For any ejections, the odds ratio was 15.7.

For categorical variables, the sample sizes of some of the categories were relatively small. For example, for unbelted occupants, the sample size of those who were in the end-over-end rollover vehicles was 34; for belted occupants, the sample size of those who were completely ejected was 28.

One potential issue with models of belted occupants is that there were few belted occupants who were ejected. This could affect the accuracy of these models. That is why Padmanaban and Moffatt (2008) only develop models of ejection for unbelted drivers. Table 2 shows selected variables and statistics for the subpopulation of belted occupants.

Table 2.

Selected variables and statistics for the subpopulation of belted occupants

	WP	WAA	SP	Sample
Complete ejection (C)	0.31%	612	0.78%	28
Any ejection (A)	2.12%	4,241	6.95%	251
End-over-end	0.46%	910	1.16%	42
Complete ejection (C) and end-over-end	0%	0	0%	0
Any ejection (A) and end-over-end	0%	0	0%	0

Odds ratio for age >= 50	WAA	Sample

Complete ejection (C)	12.71	0.59
Any ejection (A)	2.17	1.08

Note: "WP" = weighted percent; "WAA" = weighted annual average; "SP" = sample percent; "Sample" = sample size.
Source: NHTSA, NCSA, NASS CDS 1997-2006.

As the table shows, annually, only an estimated 0.31 percent of belted occupants were completely ejected. End-over-end rollovers were a rare event in belted occupants as well – only an estimated 0.46 percent of belted occupants were in such rollovers annually. Finally, there were no occupants who were belted, involved in an end-over-end rollover, and ejected, either completely or to any degree.

The second sub-table of Table 2 shows the odds ratios of ejection for older occupants (50 years old or older) as compared to younger occupants. The first column gives the odds ratios based on the weighted annual averages, while the second column gives them based on the sample. The table shows that, while there were relatively few belted older occupants who were ejected in the sample, the weighting was such that the estimated annual average for these occupants was large. This means that, in the belted subpopulation, the observations of a few older occupants could have a large effect in modeling the probability of ejection.

For example, consider complete ejections. In the sample, there were only 3 older occupants who were completely ejected, as compared to a total of 28 occupants who were completely ejected, giving odds of ejection of 0.12 [=(3/28)/(1-3/28)] for older occupants. Among the occupants who were not completely ejected, the odds were 0.20. Thus, the odds ratio was 0.59 [=0.12/0.20], indicating that relatively more occupants in the sample were younger than 50. However, using the estimated annual averages, the odds ratio was 12.71, indicating that, based on the weighting, there were relatively many more older ejected occupants. For instance, while the estimated annual average of completely ejected occupants was 612 based on 28 observed occupants, just one observation of an occupant who was 59 years old had a weighted annual average of 310, or about 50 percent of the total.

It might appear that the number of quarter turns variable and the end-over-end indicator might be highly correlated and that using both of them as explanatory variables in the same model might cause near multicollinearity. This is because there is a relationship between the two variables: whenever the end-over-end indicator is equal to 0, the number of quarter turns is greater than or equal to 2; whenever the end-over-end indicator is equal to 1, the number of quarter turns is equal to 0. In fact, the correlation coefficient between the two variables is just -0.20, which means that the variables are not strongly correlated at all and using both of them as explanatory variables at the same time would not cause near multicollinearity. Likewise, the correlation coefficient between the number of roof exposures and the end-over-end indicator is -0.26, which means that these two variables are not strongly correlated either and can both be used in the same model as explanatory variables without causing near multicollinearity.

Table 3 shows the ejection route for ejected occupants as a function of ejection degree, seat belt use, and rollover type. The table shows weighted annual averages and weighted percents. The patterns shown in the table might help explain the results of the statistical analysis below. For example, it is at least conceivable that some routes could be enlarged during some rollovers, while other routes could be restricted.

Table 3.

Ejection route for ejected occupants as a function of ejection degree, seat belt use, and rollover type

Ejection	Complete		Partial	
Windshield	1,398	12.9%	166	2.6%
Side window	5,708	52.5%	5,096	79.8%
Backlight	582	5.4%	74	1.2%
Roof window	585	5.4%	707	11.1%
Door	1,178	10.8%	69	1.1%
Other/ Unknown	1,412	13.0%	275	4.3%

Seat belt use	Unbelted		Belted	
Windshield	1,253	9.6%	311	7.3%
Side window	7,441	57.2%	3,364	79.3%
Backlight	593	4.6%	64	1.5%

Roof window	1,161	8.9%	132	3.1%
Door	1,141	8.8%	106	2.5%
Other/ Unknown	1,421	10.9%	266	6.3%

Ejection type	End-over-end		Sideways	
Windshield	278	54.6%	1,286	7.7%
Side window	134	26.4%	10,670	63.7%
Backlight	7	1.3%	650	3.9%
Roof window	0	0.0%	1,292	7.7%
Door	10	1.9%	1,237	7.4%
Other/ Unknown	80	15.8%	1,607	9.6%

Source: NHTSA, NCSA, NASS CDS 1997-2006.

The distribution of ejection routes varied by the categories considered in the table. For example, of the occupants who were completely ejected, 10.8 percent were ejected through the door, while of those who were ejected but not completely, only 1.1 percent were ejected through the door. For ejections through the door, the odds ratio for complete ejections versus ejections that were not complete was 11.1 [= (0.108 / (1-0.108)) / (0.011 / (1-0.011))]. As another example, considering end-over-end rollovers as compared to sideways rollovers, relatively more of the ejected occupants were ejected through the windshield in end-over-end rollovers (OR = 14.5).

ANALYSIS RESULTS

Table 4 shows the statistical significance of the coefficient on the vertical roof intrusion variable in the models analyzed in this report. In the table, “yes” means that the coefficient is statistically significant at the 0.05 level; “weak” means that the coefficient is statistically significant at the 0.10 level, but not at the 0.05 level; and “no” means that the coefficient is not statistically significant, even at the 0.10 level.

Table 4.

Statistical significance of the coefficient on the vertical roof intrusion variable in several probit models of occupant ejection.

	Intrusion:		Continuous		Dichotomous	
	Ejection:		Complete (C)	Any (A)	Complete (C)	Any (A)
All occupants	Adjustment	# roof exp.	No	Weak	No	No
		# q.t.	No	Yes	No	No
	Unadjusted model		No	Yes	No	No
Unbelted occupants	Adjustment	# roof exp.	No	No	No	No
		# q.t.	No	No	No	No
	Unadjusted model		No	Weak	No	No
Belted occupants	Adjustment	# roof exp.	No	Yes	No	No
		# q.t.	No	Yes	No	No
	Unadjusted model		No	Yes	No	Weak

Yes = statistically significant at the 0.05 level.
Weak = statistically significant at the 0.10 level, but not at the 0.05 level.
No = not statistically significant, even at the 0.10 level.
Source: NHTSA, NCSA, NASS CDS 1997-2006.

As the table shows, in the 18 models of complete ejection, the coefficient on the vertical roof intrusion variable was never statistically significant. This means that this report does not find evidence of a statistical relationship between the vertical roof intrusion in relevant rollovers and complete occupant ejection. As for the statistical relationship between the vertical roof intrusion and any occupant ejection, it varies depending on the statistical model used. For example, among belted occupants, the report does find such a statistical relationship. However, among unbelted occupants, it does not.

Table 5 and **Error! Reference source not found.** show the coefficient estimates for the models analyzed in this report. Estimates in bold are statistically significant at the 0.05 level. Percent concordant and c are two popular measures of association between estimated probabilities and observed outcomes. Percent concordant can be anywhere between 0 and 100; c can be anywhere between 0 and 1. Higher values of each measure indicate better association.

Table 5.

Coefficient estimates for probit models of occupant ejection in relevant rollover crashes (continuous intrusion).

		Complete ejection (C)			Any ejection (A)		
		All	Unbelted	Belted	All	Unbelted	Belted
Intercept		**-1.77**	**-0.91**	**-2.64**	**-1.60**	**-0.74**	**-2.22**
Intrusion	(inches)	0.0146	0.0184	-0.0406	**0.0285**	0.0205	**0.0428**
% concordant		44.1	47.1	40.3	47.9	47.4	50.8
c		0.529	0.535	0.573	0.544	0.538	0.572
Sample size		5,562	1,951	3,611	5,562	1,951	3,611

Complete ejection (C)		All occupants		Unbelted occupants		Belted occupants	
Adjustment		Roof exp	QT	Roof exp	QT	Roof exp	QT
Intercept		**-1.88**	**-1.91**	**-1.73**	**-1.77**	**-4.14**	**-4.19**
Intrusion	(inches)	-0.0038	-0.0009	0.0040	0.0074	-0.0628	-0.0591
# quarter turns	(end-over-end = 0)		**0.172**		**0.173**		**0.181**
# roof exposures	(end-over-end = 0)	**0.549**		**0.553**		**0.584**	
End-over-end	(1 = yes/0 = no)	**1.52**	**1.54**	**1.67**	**1.68**	**-1.98**	**-1.91**
Occupant age	(years)	0.0003	0.0011	-0.0087	-0.0076	**0.0197**	**0.0193**
Seat belt status	(1 = belted/0 = not belted)	**-2.01**	**-2.09**				
Vehicle	(1 = LTV/0 = car)	**0.592**	**0.563**	**0.701**	**0.675**	0.089	0.040
% concordant		87.8	89.7	63.8	68.9	51.5	53.2
c		0.888	0.903	0.643	0.691	0.640	0.667
Sample size		5,562	5,562	1,951	1,951	3,611	3,611

Any ejection (A)		All occupants		Unbelted occupants		Belted occupants	
Adjustment		Roof exp	QT	Roof exp	QT	Roof exp	QT
Intercept		**-1.66**	**-1.59**	**-1.60**	**-1.54**	**-3.10**	**-3.02**
Intrusion	(inches)	0.0245	**0.0273**	0.0083	0.0125	**0.0395**	**0.0415**
# quarter turns	(end-over-end = 0)		**0.149**		**0.170**		**0.129**
# roof exposures	(end-over-end = 0)	**0.528**		**0.607**		**0.463**	
End-over-end	(1 = yes/0 = no)	**1.46**	**1.39**	**2.00**	**1.91**	**-2.84**	**-2.91**
Occupant age	(years)	0.0029	0.0033	-0.0078	-0.0068	**0.0109**	**0.0106**
Seat belt status	(1 = belted/0 = not belted)	**-1.40**	**-1.42**				
Vehicle	(1 = LTV/0 = car)	**0.248**	**0.206**	**0.608**	**0.563**	-0.104	-0.145
% concordant		81.0	81.7	62.7	66.2	59.9	60.5
c		0.814	0.821	0.631	0.664	0.618	0.622
Sample size		5,562	5,562	1,951	1,951	3,611	3,611

Note: Bolded estimates are statistically significant at the 0.05 level.
QT = quarter turns adjusted model.
Source: NHTSA, NCSA, NASS CDS 1997-2006.

Table 6.

Coefficient estimates for probit models of occupant ejection in relevant rollover crashes (dichotomous intrusion).

		Complete ejection (C)			Any ejection (A)		
		All	Unbelted	Belted	All	Unbelted	Belted
Intercept		**-1.71**	**-0.85**	**-2.56**	**-1.54**	**-0.68**	**-2.15**
Intrusion?	(1 = yes/0 = no)	-0.005	0.009	-0.403	0.094	0.036	0.197
% concordant		N/A	22.9	28.5	23.3	23.2	24.7
c		N/A	0.506	0.546	0.512	0.508	0.533
Sample size		5,562	1,951	3,611	5,562	1,951	3,611

Complete ejection (C)		All occupants		Unbelted occupants		Belted occupants	
Adjustment		Roof exp	QT	Roof exp	QT	Roof exp	QT
Intercept		**-1.82**	**-1.85**	**-1.70**	**-1.74**	**-4.10**	**-4.13**
Intrusion?	(1 = yes/0 = no)	-0.179	-0.128	-0.090	-0.036	-0.648	-0.612
# quarter turns	(end-over-end = 0)		**0.171**		**0.173**		**0.185**
# roof exposures	(end-over-end = 0)	**0.554**		**0.559**		**0.617**	
End-over-end	(1 = yes/0 = no)	**1.51**	**1.53**	**1.66**	**1.67**	**-1.93**	**-1.88**
Occupant age	(years)	0.0005	0.0012	-0.0083	-0.0073	**0.0214**	**0.0212**
Seat belt status	(1 = belted/0 = not belted)	**-2.02**	**-2.09**				
Vehicle	(1 = LTV/0 = car)	**0.621**	**0.587**	**0.728**	**0.697**	0.040	-0.015
% concordant		87.8	89.8	64.0	68.5	42.8	44.4
c		0.888	0.903	0.644	0.688	0.596	0.620
Sample size		5,562	5,562	1,951	1,951	3,611	3,611

Any ejection (A)		All occupants		Unbelted occupants		Belted occupants	
Adjustment		Roof exp	QT	Roof exp	QT	Roof exp	QT
Intercept		**-1.65**	**-1.58**	**-1.58**	**-1.53**	**-3.04**	**-2.94**
Intrusion?	(1 = yes/0 = no)	0.038	0.092	-0.028	0.032	0.100	0.155
# quarter turns	(end-over-end = 0)		**0.153**		**0.172**		**0.135**
# roof exposures	(end-over-end = 0)	**0.557**		**0.615**		**0.506**	
End-over-end	(1 = yes/0 = no)	**1.48**	**1.40**	**2.00**	**1.91**	**-2.53**	**-2.62**
Occupant age	(years)	0.0032	0.0034	-0.0075	-0.0065	**0.0103**	**0.0097**
Seat belt status	(1 = belted/0 = not belted)	**-1.39**	**-1.41**				
Vehicle	(1 = LTV/0 = car)	**0.283**	**0.234**	**0.632**	**0.582**	-0.065	-0.109
% concordant		80.6	81.5	62.4	65.9	57.6	58.3
c		0.813	0.819	0.629	0.662	0.602	0.603
Sample size		5,562	5,562	1,951	1,951	3,611	3,611

Note: Bolded estimates are statistically significant at the 0.05 level.
QT = quarter turns adjusted model.
Source: NHTSA, NCSA, NASS CDS 1997-2006.

The intercept is lower in models of belted occupants as compared to corresponding models of unbelted occupants. Also, in the adjusted models of all occupants, the seat belt status indicator is negative. Both of these factors indicate that, other things being equal, the probability of ejection for belted occupants was lower than for unbelted occupants.

In the cases when it is statistically significant, the coefficient of the vertical roof intrusion variable is positive, indicating that greater vertical roof intrusion was associated with a greater probability of ejection. Note again, however, that the coefficient is not statistically significant in any of the models of complete ejection. In fact, in several of the models of complete ejection, the coefficient estimate is negative. Thus, if these models were used to describe the relationship between intrusion and complete ejection, which they shouldn't be because of the lack of statistical significance, they would be saying that greater vertical roof intrusion is associated with a *lower* probability of ejection.

The coefficients on both the number of quarter turns and the number of roof exposures are positive and statistically significant in all of the adjusted models. This means that in sideways rollovers, occupant ejection was more likely in more severe rollovers, as measured by these criteria.

The coefficients on the end-over-end indicator are statistically significant in all of the adjusted models. In the models of all occupants and unbelted occupants, the coefficients are positive. Let β_E be the coefficient on the end-over-end indicator; let S be a sideways rollover severity measure (that is, either the number of quarter turns or the number of roof-to-ground exposures); and let β_S be the coefficient on S. Then, the rollover severity measured in terms of occupant ejection S^* for which, other things being equal, an end-over-end rollover is hypothetically equivalent to a sideways rollover is

$$S^* = \frac{\beta_E}{\beta_S}.$$

See Strashny (2007) for a more detailed discussion of this calculation. Thus, for example, considering the continuous intrusion/complete ejection/all occupants/quarter turns adjusted model, the number of quarter turns that would make a rollover hypothetically equivalent to an end-over-end rollover in terms of occupant ejections, other things being equal, was 9.0 [=1.54/0.172].

Interestingly, the coefficients on the end-over-end indicator in models of belted occupants were negative. The reason for this is that there were no belted occupants in end-over-end rollovers who were also ejected. See Table 2 and its discussion. Because of this, the presence of an end-over-end rollover in belted occupants indicated the absence of ejection, producing a relatively large negative coefficient on the end-over-end indicator.

The coefficient on occupant age is positive and statistically significant in models of belted occupants. This means that, according to the models, for belted occupants, higher occupant age was associated with a greater probability of ejection in a relevant rollover. Lund (2008) found the opposite effect in a model of any ejections of drivers regardless of seat belt use. However, the model in that report did not control for rollover severity, with which driver age could be correlated. One explanation for why the coefficient is positive in the current report is that the weights on a few belted ejected older occupants were relatively large. See Table 2 and its discussion.

The coefficient on the vehicle indicator is statistically significant and positive in the models of all occupants and unbelted occupants, indicating that, for these occupant groups, being in a relevant rollover in an LTV as opposed to a passenger car was associated with a higher ejection probability.

According to both the percent concordant measure and the c measure, of the models considered, the models that have the best association between estimated probabilities and observed outcomes are the quarter turns adjusted/all occupants/complete ejection models. Among models of any ejection, the models that have the best association between estimated probabilities and observed outcomes are the quarter turns adjusted/all occupants/any ejection models.

CONCLUSION

This report does not find evidence of a statistical relationship between vertical roof intrusion in relevant rollovers and complete occupant ejection. The report models the probability of occupant ejection in relevant rollovers as a function of vertical roof intrusion using 36 different statistical models. According to the models considered, there was no statistically significant relationship between complete ejection and vertical roof intrusion. However, in some cases, a statistically significant relationship did exist between any ejection and vertical roof intrusion.

The report finds that, other things being equal, an increase in the number of quarter turns or an increase in the number of roof-to-ground exposures increased the probability of both complete and any ejection. This finding lends further support to using either the number of quarter turns or the number of roof-to-ground exposures as a measure of sideways rollover severity.

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SAFER CHILD RESTRAINTS FOR CHILDREN 6 to 10 Years

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ABSTRACT

Other studies have identified, and recent studies in Australia and the U.S. have confirmed, that whilst the 1970's concept of boosters to try to improve adult seatbelt geometry for growing children is a good one, many of the currently available boosters do not provide children with optimal restraint.

This paper recommends a new category of CRS booster with the intention of providing more effective restraint to children in the 6 to 10 age group.

Recommended features include:-

- a mandatory requirement for side wings with performance based requirements.
- lap belt guides
- sash belt guides
- top tether strap
- anti-submarining features
- that the base of the booster seat be narrower so that three of these child restraints can fit across the rear seat of a typical mid size car's rear bench seat and allow for arm rests from car doors
- the seat incorporate 'ride height' lines.

Furthermore, this category of booster should have more demanding assessment procedures to ensure booster seats coming onto the market actually achieve improved protection for the children using them.

What this paper offers that is new is a safer class of booster to take older children through till they safely fit an adult seatbelt.

This paper explains the need for each component and shows the suggested dimensions of an exemplar restraint.

INTRODUCTION

There have been a number of recent studies demonstrating the typical three point (lap/sash) seatbelt restraints in the rear seats of cars are not an optimal restraint system for children until they are approximately 11 or 12 years of age [1-3].

Depending on the country, infants are generally restrained in rearward facing restraints up to six months or several years of age. Children then typically move from the rearward facing infant restraint into a forward facing child seat with an inbuilt five or six point harness. These restraints are attached directly to the car, and then the child is attached to the restraint through the five or six point harness.

These first two categories of restraint have been proven to be highly effective when used correctly [4-6].

Top tether anchorage points and later anchor fittings were compulsorily introduced into new vehicles in Australia over a number of years, starting with sedans in July 1976, and station wagons and hatchback vehicles in January 1977. It consequently became mandatory practice to secure child restraints using both the lap part of the adult seatbelt and a top tether strap in the rear seat. Most authorities in Australia advise that children should stay in these forward facing child seats with in-built harnesses until they physically will no longer fit, i.e. shoulders too wide. Depending on the child's rate of growth (and these days, obesity) children typically outgrow these restraints between the age of 4 and 6 years.

Once they outgrow these restraints, they mostly become reliant upon restraint from an adult seatbelt. The problem with this is that the geometry of adult seatbelts is generally not suited to children. This can be potentially rectified, by adjusting the path of the seatbelt webbing to try and better transfer the loads onto the strong bony structures of the child. This is generally done with what is called a booster seat. Booster seats raise the child up with the intention of making the webbing of the lap parts of the seatbelt more vertical so that they apply a higher downward force on the child's thighs. This makes the seatbelt less likely to ride up into the abdomen. Boosters also raise the child higher so that the sash part of the seatbelt is more likely to be take a pathway over their shoulder, rather than across their face or neck.

Children seated on seat cushions with a length greater than their femur, tend to take a slouched position increasing the likelihood of the lap part of the seatbelt riding up the abdomen [1]

For these reasons the use of a booster seat is recommended and sometimes regulated for children once they outgrow forward facing child restraints. However, booster seats and booster cushions design mass limits (in regulatory standards) effectively (based on mass alone) limit booster seat use to children up to approximately age 8. Currently the upper most mass limit for boosters is in the vicinity of 36 kg. Based on anthropometric data [7] this would mean that 11% of 8 year olds, 22% of 9 year olds, and more than half of children over age 10 would be above the design mass limit (personal communication Michael Paine). In many instances the upper most design limit is 26kg, and this equates approximately to the 50th percentile 8 year old [7]. Furthermore in a recent study that looked at seat back height and seat width in boosters, the authors reported that some boosters would not accommodate children between 6 and 8 years [3]. Therefore, for many children over the ages of 6- 8 years, the lap sash belt is the only available restraint.

Booster seats vary considerably in what they offer and the effectiveness of their design. Some booster seats have no back which means the child (especially a sleeping one) is not given any lateral support. Moreover, recent studies have demonstrated that many booster seats currently on the market do not achieve the objective of improving belt fit for the child occupants who would be using them [8-9].

There is therefore a need for a new class of child restraint that caters for children from approximately the age of 6 to 10, and ensures a better match between seat belt geometry and these child occupants.

WHAT IS NEEDED

Based on the deficiencies observed in the current generation of boosters the desirable qualities of a new class of child restraint primarily designed to suit children in the 6 to 10 year age range include qualities of:-

- low strength lateral support to keep a sleeping child in position so that in the event of a crash, they are correctly positioned

- stronger lateral support (e.g. wings) of a sufficient height to provide crash energy absorbing padding protection for the child's head in a side impact

- raised base of the restraint to make the angle of the seatbelt lap webbing more vertical, so that it applies a higher downward load to the thighs, and has less opportunity or likelihood of slipping up over the relatively unformed front pelvis structure of the child into the abdomen

- a narrower base, that is, not much wider than a child's buttocks, to assist in more downward vertical application of force over the child's thighs, and less likelihood of the seatbelt slipping rearward into a submarine position

- a belt guide at the shoulder level to position the seatbelt so it passes over the child's shoulder and departs the child's shoulder in an approximately horizontal angle. This can provide some lateral stability to the child and ensures the sash belt does not pass over the child's neck or face

- anti-submarining features. That is design features to prevent the webbing of the lap part of the seatbelt sliding over the child's pelvis into its abdomen.

One of the difficulties with booster seats is that because they further raise the child above the seat base, the seat bite and hence seatbelt buckles are more difficult to reach. There is a need to provide better access to the seatbelt buckle below the booster's base, so that adults can easily find the buckle part of the seatbelt and fasten it to the sliding latch plate. This is assisted by having a narrow base on the booster, which in turn provides an opening for the adults hand to reach down to the seat bite.

SIDE WINGS

In lateral impacts, then, the two primary safety goals of a child restraint system are to:-

- retain the child's head within the child restraint
- provide energy absorption for better head protection in the side wings of the child restraint.

Head retention within the restraint requires three things. Firstly there must be a barrier or side wing to contain the head. Secondly by good top and base tethering of the child restraint, rotation of the child restraint towards the side door or oncoming object can be prevented or minimised, and thirdly the motion of the torso should also be controlled to prevent undesirable motion towards the impact and in rebound. Energy absorption within the side wings or lateral structure of the restraint is desirable if there is direct impact between the child restraint and the adjacent vehicle door or incoming object.

In Australia, thanks to enhanced regulatory protocols that assess the likelihood of a head strike with a static door in 90 degree impacts, and consumer testing (CREP) at 90 or 66 degrees, the head retention capacity of many restraints including high back boosters has improved. However, in current model booster seats we still see many high back booster seats that do not provide adequate torso control in side impact, particularly in rebound. More importantly in many restraints the side wing height is insufficient for children at the upper limits of the mass limit.

LAP BELT GUIDES

Whilst many jurisdictions' have mandatory requirements for good front seat belt geometry, many jurisdictions do not have the same demanding requirements for rear seat belt geometry.

As a result of this, it is not uncommon to encounter poor rear seat belt lap geometry in popular cars. This can include very shallow angles of the lap part of the adult seatbelt that makes it easier for the seatbelt to slip up over the pelvis of a wearer into the abdomen. Sometimes there is also poor lateral spacing of the lower ends of the lap parts of the seatbelt.

Because a booster raises the child's buttocks and pelvis above the seatbelt anchorages, it is possible to use lap belt guides which provide a more vertical downward angle of the lap parts of the seatbelt which can then better engage with the child's pelvis and reduce the likelihood of "submarining".

A narrower base on the booster can also assist more vertical downward application of loads from the lap webbing of the seat belt across the upper aspects of the child's thighs, again leading to significantly lower likelihood of "submarining".

SASH BELT GUIDES

Again, because rear seat geometry is less tightly regulated than front seat belt geometry, it is more common to experience poor sash belt geometry in the rear seats of vehicles.

This poor sash belt geometry can be even worse for shorter rear seat occupants with sashes taking angles that may slip off because they do not engage well with the shoulder, or the webbing may pass across the child's face or neck in a potentially hazardous manner.

Boosters can incorporate either structural or non-structural seatbelt webbing guides that reposition the sash belt in a more optimal location for the size of the intended occupant of the booster.

Non structural guides rely upon good positioning of the seatbelt early in the crash when loading commences, and then hope that the occupants shoulders and upper torso will "wrap" around the sash part of the seatbelt and keep the seatbelt in a good position on the child's shoulder.

Structural belt guides can make use of the structural rigidity of the back of the booster cushion achieved by the use of a tightly adjusted top tether strap. These structural sash belt guides are less dependent upon early loading for engagement from the occupant and "wrapping" of the child's shoulder and upper torso around the webbing, and, as such, provide more reliable and robust protection in multiple impacts or impacts where the directions of primary force or loading can vary during the impact.

TOP TETHER STRAPS

As stated earlier, mandatory provision of top tether anchorages in new passenger cars commenced in Australia in 1976. This was subsequently extended to include other passenger vehicle types, including coaches (long distance buses).

What this means is, as at the date of ESV 2009, Australia has had 33 years of experience of the performance of top tether straps with child restraint systems in the real world of crashes on public roads. This has been backed up by extensive research into the performance of top tethers in crash sled tests and some full scale barrier tests by NSW RTA Crashlab.

What has been learnt is that top tethers can provide:-

- good lateral stability of the portion of the child restraint containing the child's shoulders
- excellent limitation of forward displacement of the child's head.

ANTI SUBMARINING FEATURES

Anti-submarining features have the purpose of keeping the lap belt positioned over the child's thighs during crashes and preventing the seatbelt slipping up over the child's pelvis into their abdomen

A dramatic demonstration of the need for and the benefits of anti-submarining features (that is, the function often performed by crotch straps or anti-submarining clips) was experienced in Australia in the late 1970's.

A new style of forward facing child seat was introduced into the market with a four point harness not incorporating any crotch strap. Within a short time there was an unfortunately significant number of child fatalities recorded, not just in crashes, but also in stationary mode. The child could slide down under the harness to the extent that the cause of death was blockage of an airway and suffocation.

The lack of collation of a national data system meant that in the order of more than 9 deaths were recorded before action was taken.

The first recorded death in New South Wales was investigated jointly by the then New South Wales Traffic Accident Research Unit and Standards Australia. An immediate recall and addition of a crotch strap appeared to entirely eliminate the problem. There were no more reports of deaths associated with this (previously) crotch strap less four-point harness.

It was not until some years after that, that Australian researchers came to a good understanding of the submarining phenomenon and what kind of seatbelt geometry was required to reduce the likelihood of submarining.

Again, it has been the consumer program, CREP, which has led to better identification and understanding of the submarining phenomenon in different types of forward facing booster seats.

As is now well known in adults, the prospect of submarining can be, amongst other means, reduced by:-

- an anti-submarining pan which engages with the buttocks of the adult and, in conjunction with the downward pressure of the lap part of the seatbelt, provides forward restraint

- ensuring a more vertical angle of the lap part of the seatbelt, so that it applies pressure across the tops of the upper thighs of the adult.

What has been learnt in the consumer child restraint program, CREP, is that some booster seats appear to inadvertently have an anti-submarining base. That is, the bases of those booster seats are a blow moulded shell, with the horizontal seating surface of the shell sufficiently thin so that under the forces of a crash, the area under the buttocks deflects downward while the front lip maintains its height because of the front vertical panel. The combination of the central downward deflection and the undeformed front lip appears to form an impromptu anti submarining pan and provides some restraint on the front of the buttocks of the child occupant.

Whilst this attribute appears to be accident of manufacture and was initially viewed as poor design, the downward depression of the seat base was very effective in preventing submarining in the consumer program (CREP) sled tests.

This seemingly inadvertent, but effective feature had the significant benefit that it did not require the parent or carer to undertake the extra action of fastening a crotch strap (anti submarining clip).

If all parents and carers consistently used all components of a child restraint in complete accordance with the manufacturer's instructions then one of the most reliable methods of preventing a child's pelvis sliding forward would be to have a crotch strap that attaches to the lap part of the seatbelt, that is, an anti-submarining clip. However in the real world of poor behavioural compliance, an engineering feature which automatically does the task of preventing submarining is more likely to result in consistently safer restraint use and less submarining injuries to children.

REQUIREMENTS FOR THREE BOOSTERS PER REAR SEAT

An issue of considerable debate in Australia is that wider child restraints can mean that only two will fit across the rear seat of medium size passenger cars and many large family sedans. This means that a family with more than two children, or that wants to carry more than five occupants, needs to move into a vehicle with three rows of seating. (This is also a perceived problem with ISOFIX and LATCH). The most commonly chosen, and the cheapest style of vehicle with three rows of seating, is a four-wheel drive vehicle (4WD/SUV).

As a generalisation, 4WDs/SUVs are more prone to rollover, more prone to single vehicle run off road crashes, and are heavier and more aggressive vehicles in the road mix. When 4WDs roll, their roll rate is generally more violent **than a car** and the likelihood of serious injury is greater. Overall then anything which pushes families into four wheel drives can lead to an overall degradation of the safety of not just them, but other road users.

Therefore, it is desirable to keep as many families as possible within standard family sedans.

One way to do this is to try and revise the design of child restraints so that three can be comfortably fitted in the rear seat of medium and large family sedans.

Two of the most significant problems in accommodating three child restraints in a vehicles rear seat are the arm rests which protrude from the lower rear corner of many car doors and the reduction in seat width between intruding wheel arches.

It would assist installation of child restraints if vehicle manufacturers reviewed the need for these adult armrests, made them retractable or, at least made them easy to detach.

Nevertheless, booster seats be made to fit above rear door arm rests, if the boosters have a narrower base, and the booster's lateral side wings do not commence until approximately 200mm or so above the seat base

The 200mm dimension was arrived at by inspecting the rear seat of a number of popular sedan cars. Some photographs of typical armrests are shown in adjacent Figures 1 and 2.

Figure 1 – Arm rest in Honda Civic mid/small sedan

Figure 2 – Arm rest in Australia's most popular family size station wagon

It is of limited use to provide energy absorbing side wings and lateral support, if the back and the sides of the child restraint are not held in position in impacts which have lateral components. The best way to provide this lateral stability is to have a top tether strap which firmly secures the top rear of the booster seat against the vehicle's seat back, that is, not just in a fore and aft direction, but also in a sideways/lateral direction.

One of the difficulties with booster seats is that because they raise the child further above the seat base, the seat bite where the seatbelt buckles are located are more difficult to reach. Better access for adults to these buckles below the booster's base can be provided if the boosters have a narrower base. The adult can then more easily locate the buckle part of the seatbelt and then fasten it to the sliding latch plate.

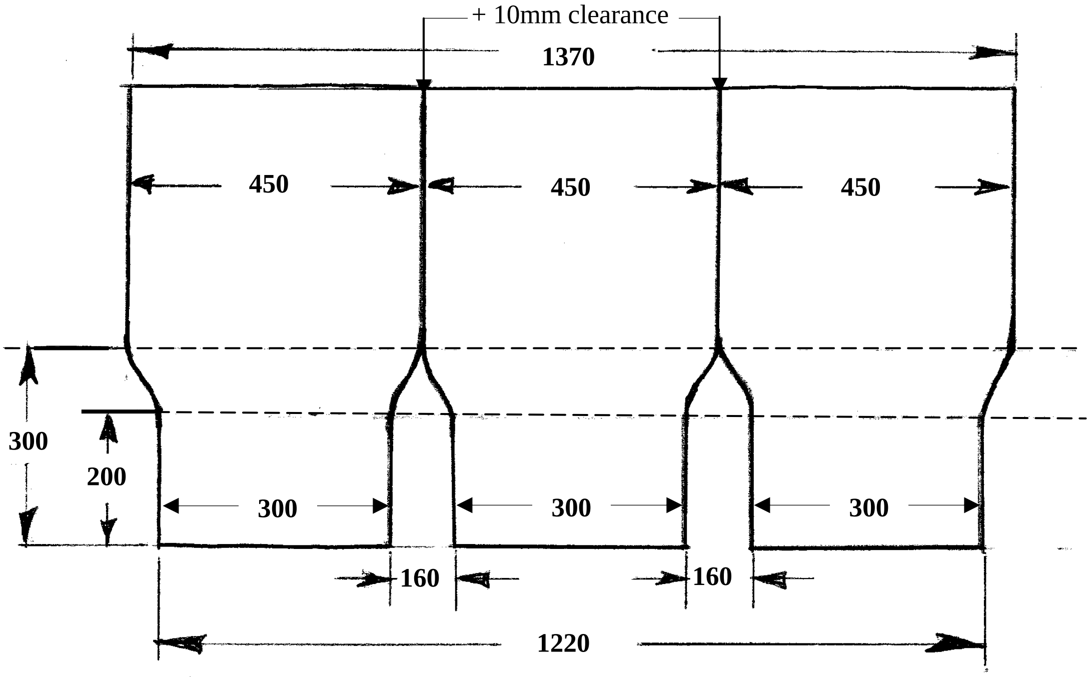

Figure 3 – Author's initial concept sketch depicting possible front elevation of three Type F seats. Shows the narrow base cut outs to allow for seatbelt buckle access and car door arm rests. Further development on these dimensions is underway.

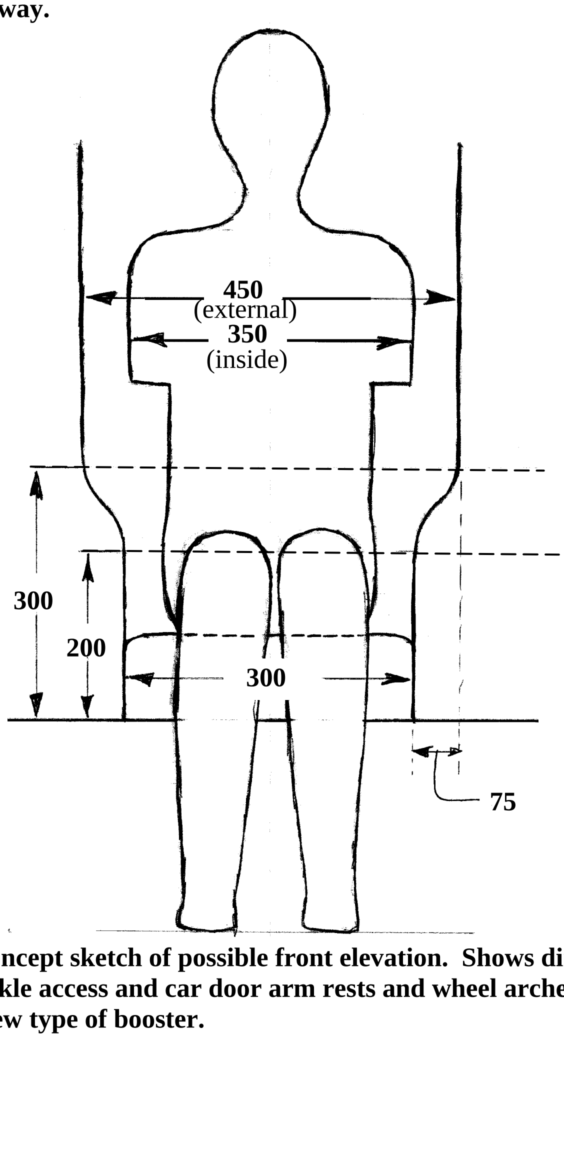

Figure 4 – Author's initial concept sketch of possible front elevation. Shows dimensions of seat base cut outs to allow for seatbelt buckle access and car door arm rests and wheel arches. Work is continuing on optimal dimensions of this new type of booster.

SAFE RIDE HEIGHT LINES

The concept of safe ride height lines is explained in greater detail in the authors' paper ESV 09-0354.

There is a considerable amount of research which has arrived at a degree of consensus as to at what dimensions a child can safely use an adult seatbelt, and at what dimensions a child should remain in a forward facing six point harness.

A similar volume of research has documented the greater exposure to risk of injury to children who prematurely graduate into boosters from forward facing child seats, and from boosters into adult seats.

The concept of 'safe ride height' lines as applied in booster seats consists of:-

- a lower line across the rear of the booster seat back and sides which indicates the minimum shoulder height for a child to safely ride in the booster. If the child's shoulders are below that line, then they should be in a forward facing six point harness child seat

- an upper line across the booster seat back and sides which indicates the shoulder height at which a child could safely use a seatbelt.

PATHWAY TO A STANDARD

Once all these desirable features had been identified, the next task was to see whether it was technically possible to satisfy all of these in a real product.

A number of requests had been made to Standards Australia by many organisations seeking better and safer restraint systems for children in the 5 to 10 year age bracket.

As a result of these requests, the task of designing a standard for this new category of restraint system was taken on to the work program of Standards Australia Child Restraint Systems committee.

Unlike many new Standards, this was not one where there was existing product and the task was to develop a Standard which discriminated between those which offer good protection and those which offer less than adequate protection.

In this instance the authors were not aware of any existing product which satisfied consumer or researcher expectations.
This meant that the design and performance specifications had to be developed in the absence of any current product.

Because of the strong motivation to be able to fit three of these child restraints in the rear seats of cars, there was inherently going to be some dimensional design restrictive requirements as part of the Standard.

CHOICE OF A TEST TOOL

In terms of evaluating the fit and crash test performance of a child restraint, the best kind of tool is an anthropomorphic, biofidelic test dummy.

To a degree, what was available in the way of dummies had a large influence on the ultimate design specifications for the upper end of this new category of booster. The most suitable, and the largest child test dummy, was the 50^{th} percentile 10 year old Hybrid III

A review of anthropomorphic data revealed that a child restraint which fitted a 50^{th} percentile 10 year old Hybrid III should also fit 95^{th} percentile 8 year old children.

What this meant was that in terms of mandatory use, it was possible for Authorities to mandate use of this kind of booster for children up to the age of 8 years, in the knowledge that there would not be a need for widespread exemptions.

When there is a need for widespread exemptions, laws become unenforceable, because Police officers will not enforce laws where they are frequently overturned by the courts.

CONCLUDING REMARKS

In conclusion, there is a widely agreed need amongst researchers and carers for a new style of restraint system to provide more effective protection for children in the 6 to 10 years age group.

This paper summarised and discussed both the safety and usability issues that this new type of restraint system would need to both offer good protection to children, and be user friendly for parents and carers.

The Australian Standards Committee on Child Restraint Systems has the development of a Standard for this new type of booster on its current work program, and development of the new standard is reportedly well advanced.

It is hoped to be able to produce a prototype of this new class of restraint at the ESV 2009 Conference.

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A STUDY OF THORACIC INJURY CRITERIA FOR ELDERLY KOREAN OCCUPANT

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Paper Number 09-0367

ABSTRACT

According to 2005 national census, more than 65 year older population is about 10% of total 48millions population. In 2030, the elderly rate will be reached up to 23%. The statistical analysis of elderly traffic accident from the national policy report, the elderly fatalities was 2,183 (33.3% of 6,563) in 2004. This was the double increase compared with 14 year years ago. In 1994, elderly fatality was 1,748 (17.3%). Elderly driver and passengers have a disproportionately higher crash involvement rate and commonly sustain more severe injuries than the other generation.

The current frontal impact regulation of Korean safety standard (KMVSS 102) is based on the FMVSS 208 to protect the motor vehicle occupant in the event of frontal crash type accidents. The injury criteria utilized in the regulation is based on 50%tile Hybrid III dummies in both driver and passenger sides. Therefore, no motor vehicle standards in Korean are designed to specially address the needs of elderly persons. Since the elderly population is rapidly increasing, it is more important to improve the safety standard to mitigate elderly casualties.

A primary objective of the study is to develop a guideline or standard for elderly occupants protection with new injury criteria on the frontal impact regulation and to promote design of restraint system or so call silver vehicle for elderly in the domestic market. The physical characteristics of elderly Korean occupant are relatively small and lighter than that of western elderly. Data from the SizeKorea database (total surveyed number of subjects in SizeKorea database was 14,200 between 0 to 90 years old), the 50th %tile height and weight of the subjects in target group (527 male samples) were 162.8cm and 62kg, respectively.

From the in-depth study of recent years vehicle-to-vehicle frontal crash accidents, the elderly occupant sustain more thorax rib fracture injury within MAIS <2. More than MAIS >3 case, elderly suffers more hemo/pneumo thorax injury than younger occupant.

In this study, as an assessment tool with scaling methods 50%tile Korean elderly Hybrid III type

simulation model was developed to mitigate elderly thorax injury.

INTRODUCTION

Each nation has it's own vehicle safety standard as a regulation to protect the peoples. Therefore, a vehicle must meet the requirements of specific safety standards as minimum requirements such as structural performances and occupant protections. For assessing the occupant protection of the vehicles, the various types of standardized Anthropomorphic Test Devices (ATDs) are used. The first regulation utilizing full scale frontal crash testing of vehicles with test dummies is the FMVSS 208 in 1973. The crash test dummy used was the Hybrid II dummy, developed by General Motors in 1972, mainly to assess the integrity of lap and shoulder belt restraint system. Hybrid III dummy has the size, shape and mass distribution of a 50th percentile American adult male. Currently, world-widely using new dummy called the Hybrid III, was developed by G.M. with substantial improvement in biofidelity over the Hybrid II dummy in all parts of the dummy. In 1984, the Hybrid III dummy has become the only dummy that can be used for compliance purposes. Frontal Crash Regulations in Korea has also accepted the Hybrid III dummy as the test device with controls over the measured dummy responses.

Beside as a regulation tool, the dummy can be used as a Occupant injury assessment tools to research and development of advanced occupant restraint systems. Traditionally, Anthropomorphic Test Devices (ATDs) have been used in laboratories to evaluate the restraint system performance with built-in various types of sensors attached in the most frequently injured body parts such as head, neck, chest, femur and lower extremity.

In Korea, the occupant protection standard for the frontal crash test is KMVSS 102. In the regulation, Hybrid III 50%tile dummies are used to assess the safety of a vehicle.

From 2000 national census, the population of 65 year and more (65+) was reached 3.4 million (7.2%) and entered aging society. Due the current extremely lower birth rate, the aging rate is rapidly increased. The most demographic forecasts indicate the proportion of Korean over 65 years of age by the year 2019 will be more than 14% of total population as a aged society. Therefore, it will become increasingly more important that safety standards be optimized to mitigate elderly casualties. Currently, no motor vehicle safety standards in Korea are designed to specifically address the needs of elderly persons. Elderly drivers and passengers have a disproportionately higher crash involvement rate and commonly sustain more severe injuries than the general population. From the National Police Reported Accident Data for the years 1994 to 2006, the fatality of the age group 61 and older (61+) was continuously increased 1,748 (17.3%) to 2,136 (33.8%). Still, the majority of elderly fatality is coming from the pedestrian casualty, however, the fatalities of elderly occupants (driver or passenger) is continuously increasing year by year.

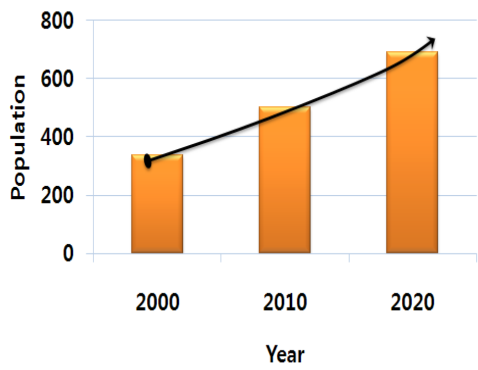

Figure 1. Elderly Population in Korea.

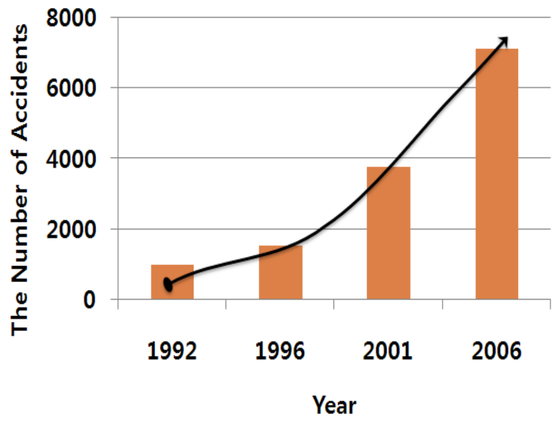

Figure 2. The Number of Korean Elderly Involved in Accidents.

Therefore, providing mobility as well as improvement of safety for older occupants is essential for aging society by the means of development of older occupant friendly vehicle. NHTSA launched "Safer Mobility for a Maturing Society: Challengers and Opportunities" program in 2003. The program shows the target and strategic plans for older drivers and pedestrian to promote safer mobility. Due to the global trend of the societal aging with more than 20% of elderly population, auto manufactures in the advanced nations such as US and Japan concentrate their endeavors on the development of the technologies for the elderly friendly vehicle. The research group includes Korean government (MLTM) and domestic auto makers are putting their enormous efforts to develop key technologies for the elderly friendly vehicle. In the project, the target was set for the comfort and safety improvements of the transportation with vulnerable people, preparing the aging society, consists of the following 5 categories that will provide a safe and convenient transportation to elderly population and also comfort ingress and egress (boarding and un-boarding) to the disabled.

To provide the safety for the elderly occupants, it will be necessary to review the safety standards to mitigate elderly casualties. Currently, the injury criteria in KMVSS are determined by Hybrid III 50%tile dummy readings similar to other countries. In the project, the best suitable injury criteria for Korean elderly occupant will be developed. It is almost impossible to develop a physical Korean elderly dummy to assess the injury mitigating performance of the so called "elderly friendly vehicle" and the restraint system. Since the Hybrid III 50%tile male dummy is only the dummy regulatory body accepted, the main objective of the research is focus developments of converting table or equation. This scale method will be convert Hybrid III 50% dummy tested injury values to the Korean elderly injury values.

In this paper, the traffic accident patterns and injury types of elderly occupants suffered are examined and analyzed using the insurance company database. To investigate the converting equation, the standard 50%tile Korean elderly Hybrid III model is developed by scaling method in MADYMO model.

INJURY CHARACTERISTICS OF ELDERLY OCCUPANTS

Literature Survey

Although older drivers are involved in relatively few collisions due to limited exposure, once involved in a crash they are more likely to sustain severe injuries or death. Several studies have confirmed that as people age, they are more likely to sustain serious or fatal injuries from the same severity crash (Evans, Evans, Bedard *et al*., Mercier *et al*). Elderly drivers and occupants are especially at risk of thoracic region injuries due to increased bone fragility (University of Michigan, Wang *et al*., Wang, Augenstein *et al*., Foret-Bruno, Schiller, Sjogren *et al*., Bulger *et al*.). Currently, no motor vehicle safety standards in Canada are designed to specifically address the needs of elderly persons. Results from S.C Wang, the head injury is the most frequent in younger age group, while the older age group is suffered from mostly thoracic injury as shown in Figure 3. It is clearly show that in the Figure 4, the older age group, the more numbers of rib fracture is occurred in the frontal collision.

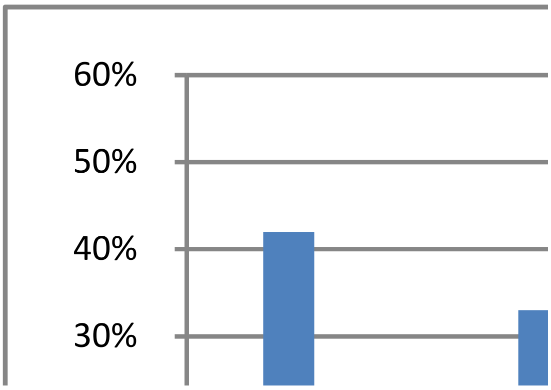

Figure 3. Incidence of Thoracic and Head Injury by Age.

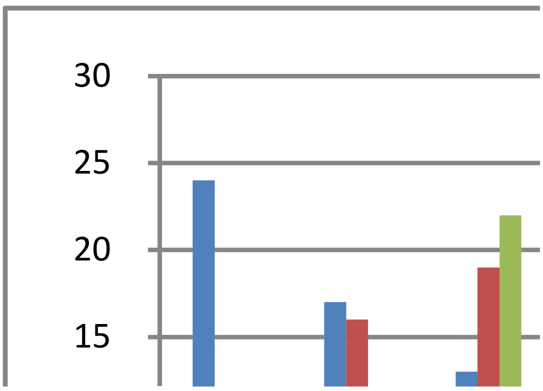

Figure 4. Age Distribution of Rib Fractures in Frontal Crash Occupants age 20~79, NASS 1993-1996.

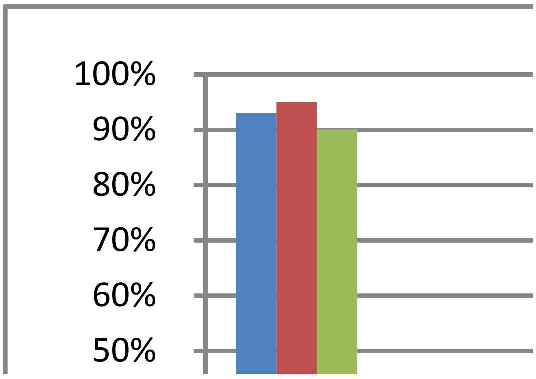

Figure 5. Head and Chest MAIS by Driver Age Group - Frontal Impacts.

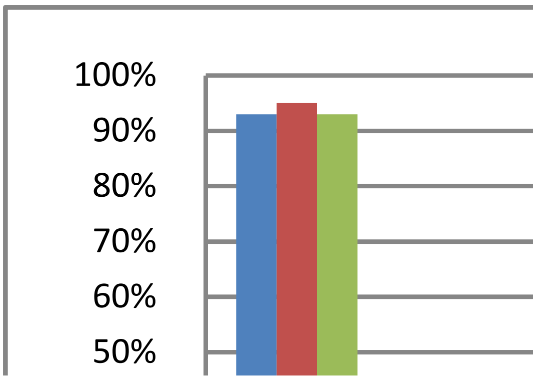

Figure 6. Head and Chest MAIS by Passenger Age Group - Frontal Impacts.

According to the R. Welsh paper, there is no significant difference in MAIS 2 or less head injury among the different age group selected frontal collision accident database of seatbelt restrained driver and passenger only. But, older age group was more experienced in sever thoracic injury.

Korean Elderly Occupant Accident Characteristics

7 years period of accident database (2000-2007) was statistically evaluated to examine the elderly occupant's accident patterns and injury types. The total 64,424 car-to-car type frontal accidents was scanned but injury involved 32,195 accidents (injured person: 61,645) was collected as 1st data set. After eliminate the improper data not provide sufficient information, the final data set was targeted 26,057 injured accidents. The data was categorized 4 different age group, such as less than 25 year old, 25 year to 54 year, 55 year to 64 year and 65 year and older. The injury characteristics were classified by 9 AIS injured body segment classes. The 3 highly injured body parts compared with other age groups were carefully investigated to find any statistical significant. From results, the elderly occupants exposed higher risk in thorax, head and abdomen. The thoracic injury risk is 2.6 time higher than other ages. The head injury is 1.3 time higher and abdomen injury is 1.9 time higher. The abdomen of male elderly injury is 26.2% higher than that of female elderly occupant. But, female elderly has higher potential risk in head and lower extremity 57% and 11.6% respectively more than those of male elderly. In seating position, driver side is 2.9 time more suffered thorax injury compared with 25 - 54 year old age group. The elderly occupant seated in front passenger seat or rear seats reveals 1.4 - 1.8 times higher injuries in abdomen and lower extremity as well as thorax injury.

Regardless the type of vehicles, the thorax injury of the elderly occupant is more than 1.7 - 2.1 times more frequently occurred. The elderly seated in SUV and RV vehicles are more injured than sedan type vehicle during the car-to-car frontal collisions. The seat belted elderly is more suffered thorax, abdomen and upper extremity injuries than other age groups. However, compared with non belted occupants, there are no differences in terms of injury between different age groups. Even the airbag equipped vehicle cases, still elderly occupants exposed 12.9% more sever thorax injury compared with other age group.

Table 1. Injury Patterns with Different Age Group in Car-to-Car Frontal Accidents

	MAIS 3↑				**MAIS 2↓**			
Age	~ 24	25 ~ 54	55 ~ 64	65 ~	~ 24	25 ~ 54	55 ~ 64	65 ~
Head	28	194	34	20	736	4,316	505	220
Neck	52	420	84	37	2,078	11,719	1,265	473
Lumber	19	219	47	27	179	1,142	136	55
Thorax	25	325	55	41	14	1,91	36	24
Abdomen	37	192	31	21	59	212	29	21
Arm	53	402	54	40	316	1,613	156	87
Leg	41	244	33	21	177	810	83	38
Whole Body	21	86	18	14	45	275	30	13
Total	227	1,408	246	153	3,508	19,314	2,248	987

KOREAN ELDERLY HYBRID III TYPE DUMMY MODEL

Dimension of Korean Elderly

In order to develop the elderly friendly vehicle and special injury criteria for elderly occupant, it is need to define the standard elderly person. In this study, 65 year and older male is defined as the elderly. The SizeKorea database was applied to develop the computer simulation model. The physical characteristics of elderly Korean occupant are relatively small and lighter than that of western elderly. Data from the SizeKorea database (total surveyed number of subjects in SizeKorea database was 14,200 between 0 to 90 years old), the 50th %tile height and weight of the subjects in target group (527 male samples) were 162.8cm and 62kg, respectively. Table 2 show the height, weight and seated height of 50%tile Korean elderly male standard.

Table 2. Body Dimensions of Korea Elderly

	50%tile	Mean
Weight (kg)	62.1	62.34
Height (mm)	1627.5	1629.62
Seated Height (mm)	973.5	971.57

Development of Korean Elderly Hybrid III Type Dummy

The MADYMO / Scaler has been created to scale occupant models in MADYMO (DE LANGE, 2005). It allows the user to scale a model in three different ways:

1) Specifying gender, mass and standing height for creating a model based on the GEBOD anthropomorphic database (BAUGHMAN, 1986)

2) Specifying a data set of 35 anthropomorphic values.

3) Specifying direct scaling factors λ_x, λ_y, λ_z and λ_{xyz} for each dimension of the 14 scalable body sections.

The definitions of the anthropomorphic values are given in the MADYMO Utilities Manual Release 6.3.1 (2006). With respect to the dimensions, x is always referring to the depth of a body section (e. g. “chest depth” for body region “thoracic spine”, y to its lateral width (e. g. “head breadth ”for region “head” and z to its height (e. g. “knee height seated” for region “lower leg”).

In this study, using SizeKorea database for 65 year and older person's body dimension, the second scaling method is taken to develop the Korean elderly Hybrid III 50% male dummy model. The 35 body dimension list is shown in Table 3. The dimensions of item 5, 14, 15 and 22 were not listed in the SizeKorea database. These dimension were generated using GEBOD program by input the weight and standing height. With given dimensional data, the Korean elderly size dummy is created as shown in Figure 7.

The results of the converted dimension for Korean elderly 50%tile is shown in Table 4 with high accuracy.

Table 3. Anthropomorphic data set for scaling

No.	Items	Hybrid Ⅲ	Korean Elderly
1	Weight (kg)	77.14	62.1
2	Standing Height (mm)	1,690	1,6275
3	Shoulder Height (mm)	1,396	1,328
4	Armpit Height (mm)	1,301	1,2105
5	Waist Height (mm)	1,007	962.9
6	Seated Height (mm)	902	873.5
7	Head Length (mm)	209	188

8	Head Breadth (mm)	146	146.5
9	Head to Chin Height (mm)	228	201.5
10	Neck Circumference (mm)	370	371.5
11	Shoulder breadth (mm)	437	369.5
12	Chest Depth (mm)	260	220.5
13	Chest Breath (mm)	316	294.5
14	Waist Depth (mm)	223	208
15	Waist Breadth (mm)	280	284.9
16	Buttock Depth (mm)	236	234.5
17	Hip Breath, Standing (mm)	366	321.5
18	Shoulder to Elbow Length (mm)	341	330.5
19	Forearm-Hand Length (mm)	460	440.5
20	Biceps Circumference (mm)	286	280.5
21	Elbow Circumference (mm)	286	271.5
22	Knee Height, Seated (mm)	563	489.5
23	Forearm Circumference (mm)	276	267
24	Wrist Circumference (mm)	174	168.5
25	Thigh Circumference (mm)	541	506.5
26	Upper Leg Circumference (mm)	534	465.5
27	Knee Circumference (mm)	416	356.5
28	Calf Circumference (mm)	358	339.5
29	Ankle Circumference (mm)	223	250.5
30	Ankle Height, Outside (mm)	120	67.5
31	Foot Breath (mm)	92	99.7
32	Foot Length (mm)	267	246.5
33	Hand Breadth (mm)	96	82.5
34	Hand Length (mm)	168	182.5
35	Hand Depth (mm)	50	26.5

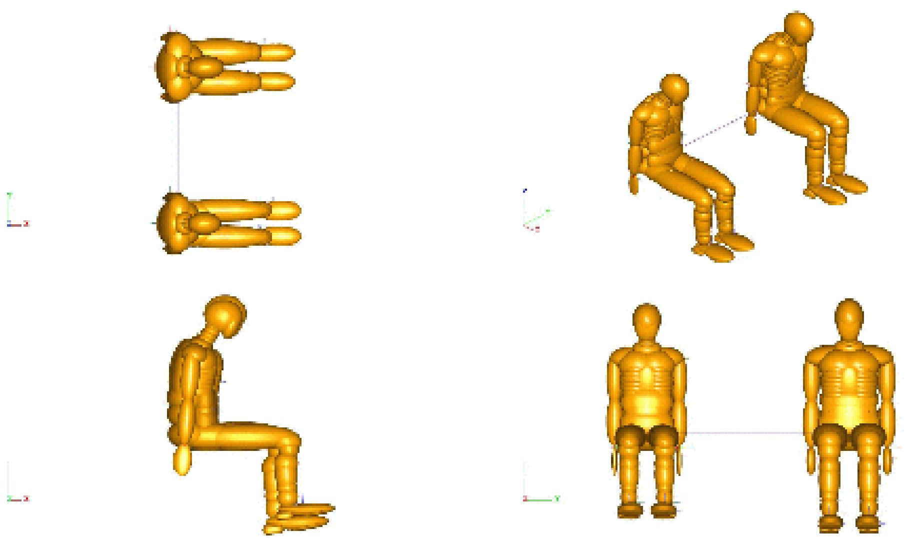

Figure 7. Comparison of the Original Hybrid Ⅲ 50%ile Dummy(right) and the Scaled Hybrid Ⅲ Korea Elderly Dummy(left).

Table 4 Results of Model Scaling

Parameters	Requested	Modeled	Ratio (%)
Weight	62.1	62.1199	100.03
Standing Height	1.6275	1.6279	100.02
Seated Height	0.8735	0.8734	99.99
Shoulder Breadth	0.3695	0.3696	100.03

Computer Simulation Analysis

<u>Occupant Simulation Model</u> - The converted Korean Elderly 50%tile Hybrid III Dummy model has been constructed with sled test model to compare with 50%tile standard Hybrid III model. In the simulation, occupant kinematics and injury values are examined to find relationship between two dummy models. From the accident data analysis and literature survey, since the most sever injury for the elderly occupant is thoracic injury, the detailed seat belt and airbag model are added in the typical sled model. In the seat belt model, load-limiter and pre-tensioner are also adopted as shown in Figure 8.

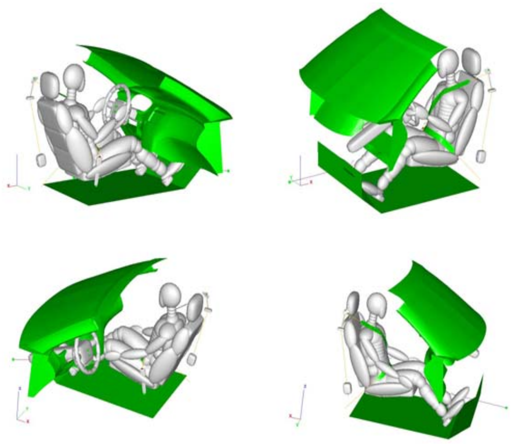

Figure 8. Configurations of the Frontal Sled Simulation model with A/bag and Seat Belt

<u>Simulation Results</u> - In the simulation, the various force level of load-limiters were examined to define the influence of belt force level. Table 6 shows the simulation results of driver side and Table 7 is results of passenger side. The current 2+1kN dual stage load-limiter is optimized to protect Hybrid III 50%tile male dummy both in driver and passenger side. The lower force load-limiter can help to reduce chest deflection in standard 50%tile Hybrid III, but the other injuries were getting worse.

In other hand, since the load-limiter and pre-tensioner is not intended to design for elderly occupant, there are rooms for improvements.

Table 6 Results of Elderly Driver Dummy Model

Driver	Original Dummy (50%ile)			Scaling of Dummy (Only size)		
Load-limiter (DLL) kN	1.5+1	2+1	3+1	1.5+1	2+1	3+1
Head (HIC36)	380.31	357.65	396.09	371.28	385.44	467.5
Chest def. (mm)	33.37	35.74	40.7	26.4	30.44	35.02
Chest acc (g)	47.11	46.14	49.38	46.82	45.06	49.51
Femur (kN)	5.50	5.3	5.21	9.95	8.87	9.33

Table 7 Results of Elderly Passenger Dummy Model

Passenger	Original Dummy (50%ile)			Scaling of Dummy (Only size)		
Load-limiter (SLL) kN	1.5	2	3	1.5	2	3
Head (HIC36)	361.44	323.87	301.25	321.87	286.17	305.05
Chest def. (mm)	31.67	26.88	30.54	18.02	21.11	26.15
Chest acc (g)	45.59	42.08	43.29	37.51	38.45	45.08
Femur (kN)	8.30	8.17	9.19	9.71	9.61	9.68

As given same crash severity, the Korean elderly model is less weight and height. Due to the small moment of inertia during the ride-down stage, the force acting on the head and trunk is less than standard size Hybrid III dummy. Therefore, except femur load, the injury, HIC, Chest deflection, Chest acceleration is less than standard size Hybrid III dummy.

It is also well established that the human injury tolerance decreases as the age increases. An aging person becomes increasingly susceptible to sustain thoracic injuries, primarily rib fractures, during a car crash. In the development of the human injury tolerance criteria for automotive crashes, only a few researchers have paid attention to age effects. About age-related changes occurred in the thorax, the degeneration of human bones and soft tissues is an important factor which modified significantly their mechanical properties. The material properties of the bone obviously have a significant influence on the condition at which fractures occur. In general, all humans begin to lose progressively bone mass at the age between 30 and 40 as a result of a physiologic inability to maintain a positive balance between the removal of old bone and the replacement of new bone. After 55 years old, the decrease in bone mineral content becomes more pronounced, and the negative skeletal balance increases significantly between ages of 60 to 70. The chest deflection injury threshold is strongly dependent upon the age of the subject as shown in Figure 9. From R. Kent's curve, the chest deflection of standard size Hybrid III dummy is 35.74 mm with 260 mm chest circumference and the percentage of deflection rate is about 13.74. Korean elderly occupant has been experienced 30.44 mm chest deflection who has 220.5 mm chest circumference size. Although the chest deflection was less than the standard Hybrid III, the chest deflection rate is about equal. From Figure 9, 13.8 % of chest deflection rate is 5% of probability which 0+ number of rib fractures injury for the 30 year old adult. But 13.8% of chest deflection rate for the elderly occupant may occur 50% of .0+ number of rib fractures injury probability. The same rate chest deflection, but the different level of injury can be expected.

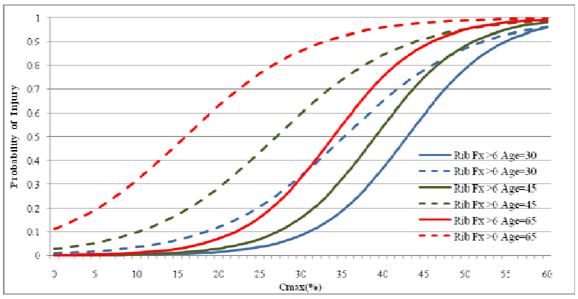

Figure 9. Thoracic Injury Probability Curves in Deflection Rate of Rib Based on Kent (7).

CONCLUSIONS

Analysis of traffic accident data, the fatality and injury of elderly occupants are continuously increasing. As entering the aging society, safety issues for elderly driver and passenger must be carefully studied to provide the best possible protections or special safety regulation for elderly occupants. To provide optimal restraint system for the elderly, the scaled Korean elderly occupant dummy model was developed. With this model, the sled type simulation was conducted to examine the elderly injury and to find the suitable converting table for injury criteria for the safety standard.

ACKNOWLEDGEMENTS

The project was funded by the Korea Ministry of Land, Transport and Maritime Affairs.

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Opportunities for Protecting the Right Front Passenger in Frontal Crashes

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Paper Number: 09-0410

ABSTRACT

This paper explores opportunities to better protect belted right front passengers during frontal crashes. Paired comparisons of using NASS CDS 2000-2007 data showed that, across all ages and genders, belted passengers carried a 34% higher serious injury risk than belted drivers. In an effort to explain this difference, we explore crash configurations where right front passengers most often sustain serious injuries. We also identified primary attributes of right front passengers including age and weight to determine how they differ from drivers when serious injuries occur.

When involved in the same crash, right front passengers more often sustain MAIS3+ injuries compared to drivers. However, there are fundamental differences between these populations. First, a higher percentage of right front occupants are injured during angled collisions with a 1 o'clock principle direction of force. These crashes are more serious for occupants seated on the nearside or passenger side of the vehicle. Often these crashes occur at intersections where the struck vehicle initiates a turn.

A second reason for this difference in risk is principally due to the presence of occupants in the passenger location who are more vulnerable to injury than the driver. While only 1 in 10 right front seat occupants involved in frontal crashes are age 65 and older, the elderly population makes up more than 1/3 of the MAIS3+ injured group. When both front seat occupants are elderly, the most vulnerable in terms of age or gender is in the passenger position 85% of the time. The GES data showed that when two elderly occupants (age 65+) were present, the female occupied the right front passenger position 73% of the time.

Analysis of NASS GES data suggests that, when an elderly male occupies the passenger seat he is frequently older than the driver. When investigated further, there was no significant difference in the fatal injury risk of young belted drivers and young belted right front passengers in frontal crashes.

INTRODUCTION

An earlier study found that when both driver and right front passenger were elderly, the right front passenger was more likely to have a lower injury tolerance [Augenstein 2008]. It was noted that the right front passenger has more ride-down room than the driver. Consequently, the safety system for the right front passenger could utilize the additional distance and be more benign than for the driver. The earlier study focused primarily on the needs of the elderly right front passenger. This study is intended to examine the needs of a wider range of belted right front occupants involved in frontal crashes.

Numerous studies have shown higher vulnerability to injury and death for older occupants involved in motor vehicle crashes [Augenstein, 2001; Fildes, 1991; and Mackay 1994, 2001]. Other studies of gender differences indicate that females, like older occupants, are more vulnerable to injury than males of the same age [Lenard 2001; Welsh, 2001]. Evans found that the same physical insult was three times more likely to fatally injure a 70 year old compared with a younger person age 15 to 45. He further showed that women age 15 to 45 were 25% more likely to be killed from a similar physical insult than their male counterparts [Evans 2001, 1991].

Studies of serious injuries by body region for restrained occupants in frontal crashes have shown that for belted occupants age 65+, the chest is the body region most frequently injured at the MAIS 3+ level [Augenstein, 2005]. Similar results were found for belted fatally injured older drivers in frontal crashes [Kent, 2005].

Earlier studies examined changes in chest injury propensity using cadaver testing and found a significant decrease in injury tolerance by age [Zhou, 2001]. For frontal crashes, belt loading was found to more significantly increase the risk of injury compared with loading by air bags. When compared to 16-35 year old occupants or the "young" group, the chest injury threshold for bag loading was reduced to 84% for the 36-65 year old age group and to 79% for the 66-85 year old age group. For belt loading, the reduction was to 47% for the 36-65 year old age group and to 28% for the 66-85 year old age group.

Recent evaluations of NASS CDS data identified that for a given stature, an obese occupant (BMI ≥30) has a 97% higher risk of fatality and 17% higher risk of MAIS3+ injury compared to occupants with a normal Body Mass Index (BMI) [Viano 2008]. The Viano study applied a matched pair methodology controlling for occupant age and gender however safety belt usage and crash type were not considered. A study by Mock et. al. (2002) similarly found that the risk of fatal injury increased 1.013 (95% CI: 1.007, 1.018) for each kilogram increase in body weight. This study controlled for age, gender, seatbelt use, seat position and vehicle curb weight.

Earlier research supports the thesis that females and older occupants of both genders could benefit from restraint systems that apply forces at lower levels than the force allowable for young males. However, restraints design must also adequately treat a population of occupants whose weight is steadily increasing.

METHODS

The 2000-2007 National Automotive Sampling System, Crashworthiness Data System (NASS CDS) data was used to compare the relative injury risk of belted drivers and right front passengers during frontal crashes. The analysis included restrained occupants involved in frontal crashes by crash severity, gender and age. Subsequently, a comparison of the occupancy of the driver and right front passenger seats by gender and age was made using General Estimates System, GES (2003-2005), data to better understand the demographics of right front seat occupants. We also explored NASS CDS data to further compare differences in driver and right front passenger size for those who are injured and uninjured.

For the NASS data analysis, frontal crashes were defined as any crash where the principal direction of force (PDOF) was 1, 11, or 12 o'clock or the PDOF was 10 or 2 o'clock with the highest deformation location coded as front (F). Typically, crash severity is determined using the coded change in velocity or deltaV. For those cases where delta-V was missing, the NASS researcher supplied estimated delta-V was used. These estimates are available for those cases where delta-V cannot be accurately computed during crash reconstruction. Estimated delta-V values can be partitioned into 3 categories which are 0-15 MPH, 15-25 MPH and 25+ MPH.

The NASS database provided 23,124 raw cases of belted front seat occupants 16 and older exposed to frontal crashes with known or estimated delta-V. Of these occupants, 2,437 suffered MAIS 3+ injuries. When weighted, these cases expanded to 11,768,366 occupants with 189,034 MAIS 3+ injured. Table 1 shows the population of drivers and right front passengers used in the analysis.

Overall, few differences exist in the attributes shown in Table 1 comparing driver crash distributions with those of right front passengers. In terms of crash severity (deltaV), vehicle type and age, the distributions are similar. As discussed in more detail below, the NASS CDS reflects the fact that more females ride in the right front passenger seat while more males are driving when a tow-away crash occurs.

Table 1. Crash exposure of belted front seat occupants involved in frontal crashes (source: NASS CDS 2000-2007)

Front Seat Occupant Category	Drivers		Right Front Passengers	
	Count	%	Count	%
All	9,414,686 80%		2,350,643 20%	
DeltaV (mph)				
0-14	5,993,720	64	1,574,201	67
15-24	3,091,409	33	720,926	31
25+	305,898	3	55,516	2
Vehicle Type				
Cars	6,463,688	68	1,574,813	67
SUVs	1,185,574	13	294,122	14
Pickups	1,111,366	12	292,366	12
Vans	614,111	7	188,699	8
Age Group				
16-34	4,965,589	53	1,068,143	54
34-65	3,547,415	38	708,879	36
65+	792,518	9	186,784	10
Gender				
Male	5,078,752	54	989,060	43
Female	4,252,315	46	1,324,584	57

Conversely, Table 2 identifies a few key differences between crashes where drivers are injured and those where right front passengers are injured. Fewer injured right front passengers are pickup truck occupants while a higher proportion ride in cars. When a passenger is injured, Table 2 indicates that higher proportions are age 65+. Seventeen percent (16%) of drivers who sustain an MAIS3+ injury were age 65 and older while over 31% of right front passengers fell into this category. Sixty nine (66%) of injured right front passengers are females compared to only 47% of injured drivers.

Table 2. MAIS3+ injury counts for belted front seat occupants involved in frontal crashes (source: NASS CDS 2000-2007)

MAIS3+ Injured Occupant Category	Drivers		Right Front Passengers	
	Count	%	Count	%
All	156,630 82.9%		32,404 17.1%	
DeltaV (mph)				
0-14	30,024	19	5,766	18
15-24	68,657	44	14,527	45
25+	57,949	37	12,111	37
Vehicle Type				
Cars	108,429	69	23,418	72
SUVs	19,125	12	3,504	11
Pickups	20,725	13	2,695	8
Vans	8,260	5	2,753	9
Age Group				
16-34	59778	38	10,185	35
34-65	71,138	45	9,868	34
65+	25,495	16	8,881	31
Gender				
Male	82,759	53	10,943	34
Female	73,871	47	21,435	66

Matched Pair Analysis

In order to evaluate the difference in MAIS3+ injury risk for passengers relative to drivers while controlling for the influential factors identified above, a matched pair analysis using NASS CDS 2000-2007 data was performed. Only those belted drivers involved in frontal crashes with a belted right front passenger present at the time of the crash were retained. In total 11,066 unweighted occupant pairs representing 2,350,643 weighted occupant pairs were available for evaluation.

To adequately treat the stratified sampling design of NASS CDS, odds ratio estimates, standard errors and 95% confidence intervals (95% CI) were calculated using Stata Software Version 9.0 (Stata Corporation, 2005).

Odds of right front passenger injury are 34% higher than drivers for belted occupants in frontal crashes. When the sample was further stratified by PDOF, for the risk of MAIS3+ injury for right front passengers it was not statistically different than drivers for 11 or 12 o'clock crashes when age, gender and crash deltaV are controlled for. However, the effect for 1'oclock PDOF crashes is significant having a 2.43 times higher risk of MAIS3+ injury for right front passengers compared to drivers.

The odds of serious injury for female right front passengers relative to female drivers is 1.39 (95% CI: 1.13, 1.69). For elderly passengers versus elderly drivers, the odds of injury were substantially higher at 1.89 (95% CI: 1.29, 2.78).

Table 3. Odds ratios based on matched pairs analysis- Odds of MAIS3+ injury for belted right front passengers in frontal crashes compared with drivers (NASS CDS 2000-2007)

Category	Odds Ratio (95% Conf. Limits)
All Frontal Crashes	**1.34 (1.16, 1.55)**
11 o'clock PDOF	0.86 (0.62, 1.19)
12 o'clock PDOF	1.20 (0.96, 1.50)
1 o'clock PDOF	**2.43 (1.76, 3.36)**
Female Passengers	**1.39 (1.13, 1.69)**
Elderly Passengers	**1.89 (1.29, 2.78)**

Crash configurations for two vehicle crashes where drivers and right front passenger sustain MAIS 3+ injuries are shown in Figure 1. This plot shows results for the crashes used for the matched pair analysis so that the population of crashes where a right front passenger was present is identical to those for the drivers in terms of deltaV, vehicle type and crash configuration. The non-collision category indicates a single vehicle crash event has occurred.

Overall, drivers more often sustain injuries during head on collisions with other vehicles. Right front passengers are injured more frequently than drivers during angled collisions. The vast majority (more than 88%) of angled crashes where right front passengers were injured occurred while turning or at intersections.

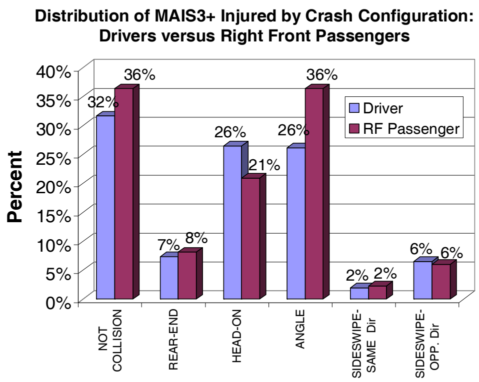

Figure 1. Comparison of crash configurations where drivers and right front passengers sustained one or more MAIS3+ injuries (for crashes where both occupants were present).

Figure 2 shows the distribution of injured occupants by seating position and specific PDOF for the frontal crash event. As mentioned above, right front passengers are more frequently injured in angled collisions associated with turns at intersections supporting the elevated frequency of injuries where the PDOF of the primary impact was 1 o'clock.

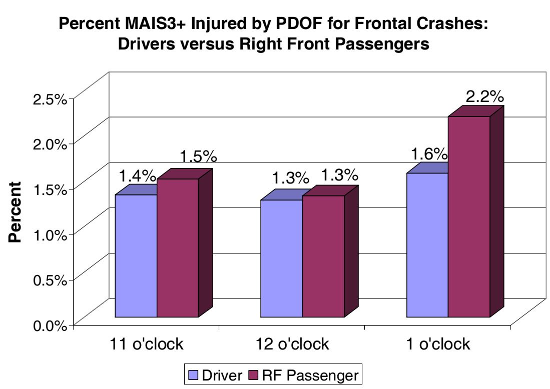

Figure 2. Comparison of primary impact PDOF where drivers and right front passengers sustained one or more MAIS3+ injuries (for subset of crashes where both occupants were present).

Figure 3 indicates that a higher proportion of right front passengers sustaining MAIS3+ injuries are age 65 and older than in the driver position. Although only 10% of tow-away crash involved right front seat occupants are age 65 and older as shown in Table 1, more than 35% of those who sustain one or more MAIS3+ injury are age 65+. For drivers, the proportion of occupants age 65 and older who sustain MAIS3+ injuries is 16% while the driver position is occupied by those 65 and older 9% of the time.

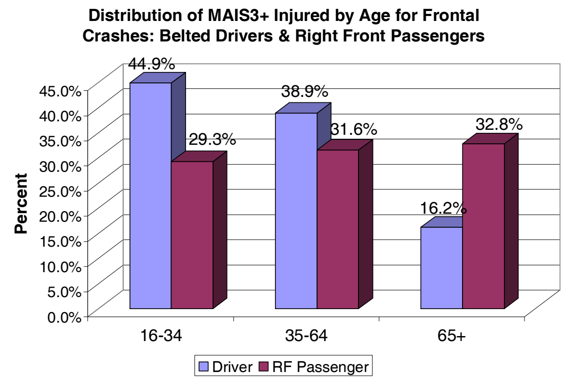

Figure 3. Distribution of occupant ages where driver or right front passenger was MAIS3+ injured (for subset of crashes where both occupants were present).

Figure 4 indicates 16% of adult females seated in the right front passenger seat during any NASS CDS crash were similar in weight to the 5th Percentile Female Dummy (the 5th percentile female weighs 46.7 kg or 102 lbs). A total of 41% were slightly heavier than the 5th Percentile female yet lighter than the 50th Percentile Male dummy. Overall, the 5th percentile female does not represent female occupants most often seated in the right front position well.

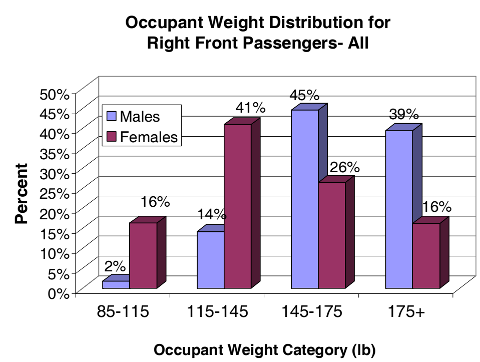

Figure 4. Occupant weight distributions for all NASS CDS crashes.

Within the MAIS3+ injured population, shown in Figure 5, increased percentages by weight for all categories for both males and females can be seen. It should be noted that Figure 5 includes only belted right front passengers involved in frontal crashes while Figure 3 includes the complete NASS CDS population.

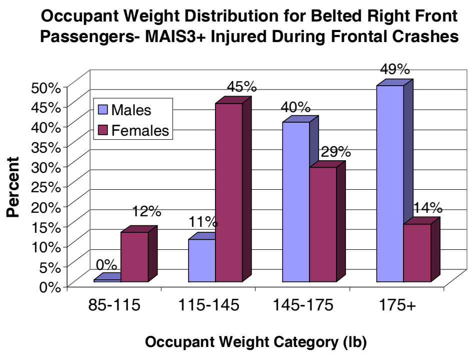

Figure 5. Occupant weight distribution for MAIS3+ injured, belted right front passengers in frontal crashes.

General Estimates System (GES)- Seat Occupancy

Figure 6 shows the distribution of occupants by seating position based on NASS GES data. This data was reviewed to understand frequency of front seat occupancy by age and gender. The subpopulation reviewed includes police reported, crash involved vehicles where the driver and passenger seat were occupied. The analysis considers both injured and non-injured occupants. There were 153,936 unweighted pairs of occupants included representing 1,556,533 drivers in crashes from 2000-2007. Figure 6 shows the percent of crashes where a female driver or male driver was accompanied by a female passenger or male passenger. This data suggests that overall, female passengers occupied the passenger seat during 56% of the crash events.

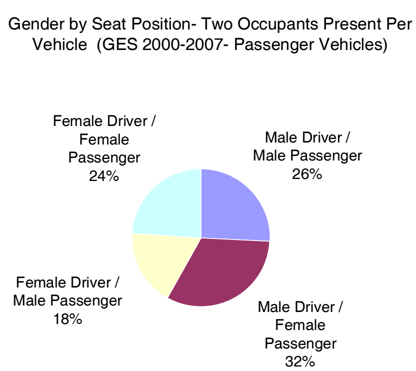

Figure 6. All occupants by seating position (GES 2000-2007).

Figure 7 indicates that, when both front seat occupants were 65 and older, a female occupied the right front passenger seat 73% of the time. Both driver and passenger were elderly males in 10% of these cases.

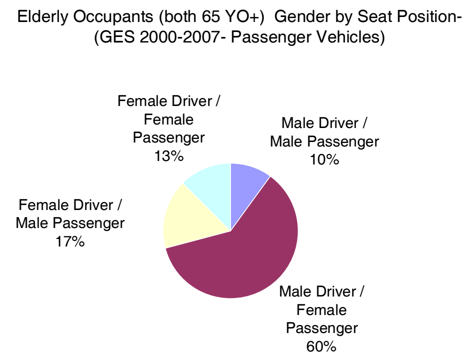

Figure 7. Elderly occupants by seating position (GES 2000-2007).

DISCUSSION

In this study, the risk of MAIS3+ injury was compared for right front passengers and drivers using matched pairs analysis. Crashes where both the driver and right front passenger were present and restrained were retained.

Fundamental differences in crash configurations appear to impact the frequency that right front passengers are injured. As may be expected, the right front passenger is much more likely than the driver to be injured in a 1 o'clock crash. When examining the 11 o'clock crash the driver would be expected to have a higher risk. However, the driver's increased risk was not statistically significant. The right front passenger's increased frequency of injuries is further illustrated in Figures 1 and 2. The energy absorbing steering column may provide some benefit to the driver in the angular collision that is absent for the right front passenger. Further, compartment intrusions at the right front passenger position could impact injury risk. This result suggests the need to provide some additional protection to the right front passenger in the 1 o'clock frontal angular collisions.

Table 2 shows the predominance of females and elderly females among right front passengers with MAIS 3+ injuries.

The analysis of GES (Figures 7 and 8) indicates that, when all ages are considered, 56% of the right front passengers are female. In NASS CDS, 57% of the right front passengers in tow-away crashes are female. However, when examined by age, the female occupancy rate increases dramatically for older occupants. GES (Figure8) shows that when both front seat occupants were 65 and older, a female occupied the right front passenger seat 73% of the time. This result is consistent with NASS data that shows that among right front passengers age 65 and older, 81% are female. For age 50 and older, the percentage of female passengers in NASS remains about the same.

An earlier study using paired comparison analysis of FARS for belted drivers and right front passengers showed that when all ages of occupants were considered, the passenger position had a slightly higher risk of being fatally injured [Augenstein 2008]. There was no difference in the risk when both occupants were young. However, when both occupants were 65 and older, the odds ratio for the passenger was much higher – 1.42. This result further supports the hypothesis that when elderly occupants occupy both front seats, the most vulnerable to injury is the passenger, not the driver.

It is interesting to examine the injuries and fatalities that occur to belted elderly occupants in the lower severity crashes. An earlier study found that 58% of the frontal crash fatalities among belted front seat occupants aged 65+ occurred in crashes less severe than 25 mph [Augenstein, 2006]. The earlier paper showed that, for an elderly occupant, sustaining an MAIS 3+ injury carries a much higher risk of death compared with the same injury in a younger occupant. The paper suggested that reductions of chest injuries in lower severity frontal crashes offered a large opportunity for improvement.

Figure 3 shows the weight distribution for injured males and females in the right front occupant position. The distribution suggests the need for tests with a dummy heavier than the 5^{th} percentile female. It also suggests the need to tailor the restraint system for both the weight of the occupant and the severity of the crash.

These results suggest that an opportunity exists for providing age, weight and gender appropriate restraint systems for the right front passenger. These restraint systems could be more focused on reducing the forces on the body in low severity crashes while maintaining the current level of safety in high severity crashes.

CONCLUSIONS

Occupants of the right front passenger position have different restraint needs compared with the driver. The NASS paired comparison analysis indicates that the right front passenger is more vulnerable to frontal angular crashes than the driver. Additional protection for the 1 o'clock angular crash would be beneficial.

The right front passenger is more likely to have a lower injury tolerance than the driver. This difference suggests the need for a more benign restraint system. However, occupants of the right front passenger position exhibit a wide range of sizes. The broad population suggests the need for tests with a variety of dummy sizes.

ACKNOWLEDGEMENT

The authors would like to thank the Takata Corporation for sponsoring the analysis that led to this paper. However, the discussion and conclusions of the paper are those of the authors and not those of the Takata Corporation.

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MISUSE OF AIRBAG DEACTIVATION WHEN CHILDREN ARE TRAVELLING IN THE FRONT PASSENGER SEAT

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Paper Number 09-0351

ABSTRACT

Within the process of integrating passenger airbags in the vehicle fleet a problem of compatibility between the passenger airbag and rearfacing child restraint systems was recognised. Especially in the US several accidents with children killed by the passenger airbag were recorded. Taking into account these accidents the deactivation of a present passenger airbag is mandatory if a child is carried in a rearfacing child restraint system at the front passenger seat in all member states of the European Union. This rule is in force since the deadline of 2003/20/EC at the latest.

In the past a passenger airbag either could not be disabled or could only be disabled by a garage. Today there are a lot of different possibilities for the car driver himself to disable the airbag. Solutions like an on/off-switch or the automatic detection of a child restraint system are mentioned as an example. Taking into account the need for the deactivation of front passenger airbags two types of misuse can occur: transportation of an infant while the airbag is (still) enabled and transportation of an adult, while the airbag is disabled, respectively. Within a research project funded by BASt both options of misuse were analysed utilising two different types of surveys amongst users (field observations and interviews, Internet-questionnaires). In addition both analysis of accident data and crash tests for an updated assessment of the injury risk caused by the front passenger airbag were conducted.

Both surveys indicate a low risk of misuse. Most of the misuse cases were observed in older cars, which offer no easy way to disable the airbag. For systems, which detect a child seat automatically, no misuse could be found. The majority of misuses in cars equipped with a manual switch were caused by reasons of oblivion.

Also the accident analysis indicates a minor risk of misuse. From more than 300 cases of the GIDAS accident sample that were analysed, only 24 children were using the front passenger seat in cars equipped with a front passenger airbag. In most of these cases the airbag was deactivated. When misuse occurred the injury severity was low. However, when analysing German single accidents the fatality risk caused by the front passenger airbag became obvious.

From the technical point of view, there were important changes in the design of passenger airbags in recent years. Not only volume and shape were modified, but also the mounting position of the entire airbag module was changed fundamentally.

Even if these findings do not allow obtaining general conclusions, a clear tendency of less danger by airbags could be identified. For future vehicle development a safe combination of airbags and rear faced baby seats seems to be possible in the long term. This would mean that both types of misuse could be eliminated. For parents an easier use of child seat and car would be the result.

INTRODUCTION

During the integration of passenger airbags into the vehicle fleet a problem of incompatibility between the passenger airbag and rearfacing child restraint systems was recognised. Especially in the US several accidents with children killed by the passenger airbag were recorded. Taking into account these accidents the deactivation of a present passenger airbag is mandatory in all member states of the European Union if a child is carried in a rearfacing child restraint system on the front passenger seat. This rule is in force since the deadline of 2003/20/EC (April 2008) at the latest.

In recent years the possibilities of airbag deactivation have changed considerably. While the only way to disable the airbag was the general deactivation by a garage several years ago, some techniques are offered today allowing the deactivation and reactivation in a simple way. The most common one is an on/off-switch integrated in the car. It can be designed as a key switch, which is used with the car key to switch off the airbag. This comparatively simple way to deactivate the airbag for the front passenger seat facilitates the use of that seat for rearfacing child restraint systems (CRS), which is an important relief for parents.

However, with this method two types of misuse can occur: transportation of an infant while the airbag is enabled (first kind of misuse) and the transportation of an adult, while the airbag is still disabled (second kind of misuse). With systems of automatic airbag deactivation, which are able to detect the presence of a child restraint system, both types of misuse should be prevented.

ACCIDENT DATA

This analysis is based on data from the GIDAS (German In-Depth Accident Study), NHTSA as well as data of a small number of single accidents. In 337 GIDAS cases with children in cars 58 were transported on the passenger seat. In 24 of them an airbag was present. In 15 accidents the airbag was not deployed, which can be caused by deactivation or by technical failure. In one out of the 9 cases in which the airbag deployed the child was transportted in a baby shell. This is the only clear documentted case of misuse out of 337 situations with children transported in a car. In this accident the child received only minor injuries, which were classified as AIS 1.

Second data retrieval to the GIDAS data was related to the second type of misuse. However, no accident with a non-deploying airbag was detected.

Comparing the injury severity for with and without airbag deployment indicates a higher injury risk with airbag deployment, see Figure 1. However, the accident severity is also an important factor influencing the injury risk. In cases with active airbag the airbag deployment depends on the accident severity. That means that the cases with airbag deployment are generally of higher accident severity than those without. Looking at the GIDAS data the average delta-v for the cases with airbag deployment is higher than for those cases without. Furthermore the injury severity in this sample did not exceed AIS2.

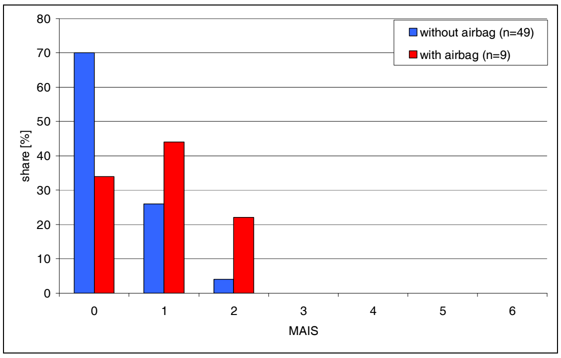

Figure 1. Comparison of injury severity for children with and without deployed airbag.

In addition the risk associated with the front passenger seat compared to the rear seats was analysed, see Figure 2. There seems to be a slightly higher risk at the front seat compared to the rear seats. However, in the sample the injury severity did not exceed AIS 2 for both configuration and the sample is rather small. Therefore the results are not significant.

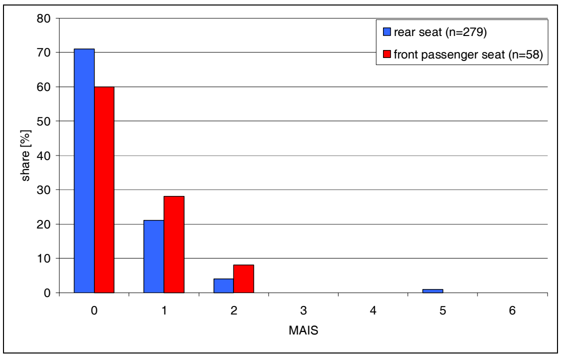

Figure 2. Comparison of injury severity for children using a rear seat or the front passenger seat.

Lesire et al. [Lesire, 2007] also compared the injury severity for children in the front seat with those in the rear seat. Based on French and UK data they came to the conclusion that there is no difference between front and rear seats with respect to the injury severity. However, the UK data indicates a higher CRS usage in the front seat compared to the rear, which may not be neglected when comparing the injury risk.

The analyses of single accidents showed two fatal accidents in Germany, both with low accident severity and cars equipped with the first generation of passenger airbags. In one case the low mount Eurobag deployed even so it was disabled by a garage, while in the other case there was no possibility to deactivate the mid mount full-size airbag. In both accidents the babies received fatal head injuries due to the deploying airbag.

NATIONAL CENTER FOR STATISTICS AND ANALYSIS
SPECIAL CRASH INVESTIGATIONS
CHILDREN FATALLY INJURED BY PAB
NORMALIZED BY VEHICLE REGISTRATIONS
Confirmed and Unconfirmed*
January 1, 2008

Vehicle Model Year (in millions of vehicles)

	1987-88	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	Total
Registered Passenger Air Bag Equipped Vehicles	0.000	0.061	0.144	0.037	0.405	1.311	5.918	9.987	10.240	13.690	14.491	16.070	17.065	16.402	16.883	15.575	15.570	15.516	15.516	15.516	15.516	215.913

Vehicle Model Year

Crash Date	1987-88	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	Total
Sep 87 to Aug 88																						0
Sep 88 to Aug 89																						0
Sep 89 to Aug 90																						0
Sep 90 to Aug 91																						0
Sep 91 to Aug 92																						0
Sep 92 to Aug 93						1																1
Sep 93 to Aug 94						1	1															2
Sep 94 to Aug 95						1	2	4														7
Sep 95 to Aug 96					1		6	9	3													19
Sep 96 to Aug 97							4	12	7	5												28
Sep 97 to Aug 98							4	15	5	8	2											34
Sep 98 to Aug 99							2	7	3	3	3	1										19
Sep 99 to Aug 00							1	4	6	2	2	1										16
Sep 00 to Aug 01							1	5	5	2		1		1								15
Sep 01 to Aug 02						1	1	1	2	2			1									8
Sep 02 to Aug 03								2	2	4			1	1								10
Sep 03 to Aug 04							1	1		3		1				1						7
Sep 04 to Aug 05							1		1	3	1		1									7
Sep 05 to Aug 06					1		1	3	1			1										7
Sep 06 to Aug 07							1				1											2
Sep 07 to Aug 08																					0	0
Total	0	0	0	0	2	4	26	63	35	32	9	5	3	2	0	1	0	0	0	0	0	182
Fatalities/Million Vehicle Years	0.000	0.000	0.000	0.000	0.402	0.254	0.382	0.572	0.329	0.242	0.070	0.038	0.024	0.019	0.000	0.014	0.000	0.000	0.000	0.000	0.000	

*Confirmed cases are those where the air bag has been confirmed to be the injury mechanism. Unconfirmed cases are crashes under active investigation where the air bag is suspected of being the injury mechanism.

Figure 3. US children killed due to airbag deployment [NHTSA, 2008].

Finally NHTSA data show that fatal injuries in children due airbag deployment has significantly reduced by information campaigns (resulting in a general decreasing trend since 1995) and airbag improvement (resulting in lower figures for newer cars compared to older ones), see Figure 3.

AIRBAG TECHNOLOGY

In the beginning of the introduction of airbags these were developed for the frontal impact of the driver only. The driver airbag was an important step towards reduced injuries, which were often caused by the small distance between the occupant and the steering wheel resulting in a hard contact even for belted drivers. The airbag needs to inflate rapidly after the detection of a severe accident to have the airbag completely inflated before the occupant contacts it.

As a second step airbags for front seat passengers were introduced. Due to the larger distance between the passenger and the instrument panel front seat passenger airbags need to be larger and faster than the driver airbags. In addition the seating position of the front seat passenger is not as well defined as for the driver, who needs to operate the car. The combination of the more aggressive size and inflation procedure of passenger airbags on the one hand and the risk of dangerous position of front seat passengers on the other hand resulted often in serious injuries. Therefore NHTSA introduced regulations (modification of FMVSS 208) aiming at reducing the risk caused by airbags. Both low risk deployment and automatic detection of dangerous situation and disabling of airbags are addressed. For assessing the low risk deployment several static airbag deployment tests need to be conducted. One of them utilises a CRABI 1 YO dummy using rearfacing CRS. The CRS is positioned in a way that it is just not touching the instrument panel.

While the driver airbag is mounted at the steering wheel since its introduction the mounting position of the front seat passenger airbag changed during time. In the beginning most passenger airbags were mounted in the low mount position and replaced the glove box. Due to package requirements and the low risk deployment strategies the mounting position changed to the mid mount and later top mount position. Today almost all new cars are equipped with front seat passenger airbags in the top mount position. While the low mount position airbags inflated directly in the direction of the occupant, the top mount positioned airbag starts with the inflation in the direction of the wind screen and the movement in the direction of the occupant follows with a lower energy input.

Finally it is important to note that there are considerable differences in the airbag design depending on the region of use of the car. While airbags are meant to be an additional safety device for belted occupants in Europe they are designed to be used without the seat belt in the US: This difference requires larger airbags for the US market.

TECHNIQUES OF AIRBAG DEACTIVATION

In general, three different types of airbag deactivation are available: the deactivation using a switch, the automatic detection of a CRS and the permanent deactivation by a garage.

Deactivation by a switch

Today, this possibility to activate the airbag is the most common. Most of the European car manufactures offer this integrated systems in cars as a standard or it can be ordered as optional equipment. For the customer this system is easy to use: he can disconnect the airbag either by a key or manually himself. If the airbag is disabled, its status is shown to occupants by a warning light. Depending on the car, the switch is integrated in the glove compartment, dashboard or in the transmission tunnel.

Automatic detection

This system, called CPOD (Childseat Presence and Orientation Detection) detects the existence of a child seat in a car and its orientation. The system, which is available in Germany, is called AKSE (Automatische Kindersitzerkennung; automatic detection of CRS). Even if it is nearly identical to CPOD it is originally not designed to detect the orientation of the CRS. A special transponder at the CRS is necessary, which is identified by the AKSE. In Germany, there are two car manufactures which offer this system: Mercedes and Opel. Even if the systems of both manufactures are nearly equal, Opel seats can only be used in Opel cars and Mercedes seats in Mercedes cars only. There are ongoing activities by an ISO-working group to define an international standard for such systems.

Durable deactivation by a garage

A further possibility to disconnect the airbag is its deactivation by a garage. There the airbag is deactivated permanently. Thus, the airbag can’t be enabled by the driver himself if required. Usually, the occupants are informed by a warning decal. Today, this way of deactivation is less common than some years ago. Compared to the deactivation by a switch, with this method there is a high risk of an adult on the passenger seat while the airbag is disabled.

No possibility of deactivation

Even if it is mandatory to disable the front airbag if a child is transported in a rearfacing CRS on the passenger seat, there are still some car manufacturers not offering any possibility to switch-off the airbag. Even the deactivation by a garage is impossible. The outcome is that rearfacing CRS have to be mounted on the rear seat.

To summarise the available techniques for airbag deactivation the majority of old cars do not offer any possibility for deactivation or the durable deactivation by a garage, while recent cars normally offer the possibility by a switch. However, there are still models in production, which do not offer any possibility.

RISK POTENTIAL OF PASSENGER AIRBAGS

Due to recent developments with respect to the airbag geometry, size and mounting position a number of tests was conducted to be able to reassess the risk resulting from airbag deployment.

The first public available tests, e.g. published by GDV [GDV, 2003] mainly focused on video analysis. In contrast this study emphasised on dummy readings. The tests included a number of sled tests with a body in white of a recent mid-size class car with different airbags, one static airbag deployment test with the same car body and a number of dynamic and static tests with old cars offering the first generation of passenger airbag technology. All tests utilised the same ECE R44 group 0+ CRS and the same Q1.5 dummy.

One of the first problems recognised within this study was the question how to assess the dummy readings. Looking at the accident data described above the main problem seems to be head injuries. However, compulsory tests according to FMVSS 208 mainly rate the neck loads with a combined assessment of neck forces in Z direction and neck moments along the Y axis. This so called Nij (neck injury criterion) requires the knowledge of critical neck tension and neck compression forces as well as critical neck flexion and neck extension moments. These values were defined for the Hybrid III series of dummies including CAMI and CRABI. For the dummy used in the tests, the Q1.5, the Nij reference values have not been defined. Based on the results of the CHILD project [Palisson, 2007] critical neck tension force and neck flexion moments can be derived from the calculated injury risk functions for the Q3 using scaling technologies. As the critical neck tension differs from the critical neck compression and the critical neck extensions differs from the critical neck flexion the ratio as used for Hybrid III dummies was utilised for the Q1.5. The other IARV are based on the results of the CHILD project. Taking into account that the critical forces and moments for the used dummy have not been officially defined the used neck injury criterion is called Nij*.

Table 1.
Injury criteria and corresponding load limits used for assign the different tests

Criterion	**IARV**
Head a_{3ms}	79 g
HIC15	585
Neck tension force	1550 N
Neck compression force	1126 N
Neck flexion moment	61 Nm
Neck extension moment	27 Nm
Nij*	1.0

The static airbag deployment tests with cars offering the first generation of passenger airbags showed different results for different cars – or to be more precise between cars with different airbag sizes, see Table 2. The results indicate that the risk resulting from the small airbags in car1, car2 and car3 is relatively low, while it is high for the cars with the larger airbags (car4 and car5). However, one needs to take into account that only one CRS has been tested and that the results of the static airbag deployment does not necessarily represent realistic loading conditions.

Table 2.
Results of static airbag tests

criterion	**car1**	**car2**	**car3**	**car4**	**car5**
position	low	low	low	mid	mid
size	~ 50 l	~ 65 l	~ 65 l	~ 110 l	~ 130 l
head a_{3ms}	8 g	12 g	14 g	30 g	49 g
HIC_{15}	1	6	6	43	137
neck F_Z	148 N (comp.)	371 N (comp.)	299 N (tens.)	730 N (comp.)	322 N (comp.)
neck M_Y	4 Nm (flex.)	11 Nm (flex.)	10 Nm (flex.)	22 Nm (flex.)	54 Nm (ext.)
Nij*	0,15	0,44	0,29	0,99	2,86
chest a_{3ms}	3 g	10 g	6 g	9 g	38 g

The video analysis clearly shows the differences between the tests with low dummy loadings and those with high dummy readings. While the smaller airbags hit the CRS directly from the front when the airbag is almost completely inflated, the larger airbags caused two impacts (firstly from the front with high energy input and then from the top). Figure 4 shows the airbag when it is completely inflated for car1 and car5 as an example.

Figure 4. Maximum airbag deployment: car 1 (top) and car 5 (bottom).

As a next step car model 2 was used for dynamic tests with and without the passenger airbag. Due to the age and therefore different histories of the two cars there were slight differences in the car acceleration but overall the tests are comparable. The main characteristics of the tests are listed below:

- full frontal, rigid wall,
- 55 km/h,
- front passenger seat in mid position.

Table 3.
Results of dynamic tests with old cars

criterion	with airbag	without airbag	static airbag test
head a_{3ms}	92 g	93 g	12 g
HIC_{15}	1061	989	6
neck F_Z	677 N (comp.)	2020 N (tens.)	371 N (comp.)
neck M_Y	21 Nm (ext.)	39 Nm (ext.)	11 Nm (flex.)
Nij*	0,96	3,06	0,44
chest a_{3ms}	73 g	83 g	10 g

Although the CRS and Q1.5 kinematics was completely different in both tests the dummy readings, except the neck are almost the same, see Table 3.

The neck loads within this comparison are much higher without airbag deployment than with. Looking at the kinematics the babyshell turns after the impact of the airbag by 90° along the Y axis while it stays stable in the test without the airbag.

When comparing the tests with the fatal injuries recorded in German accidents it becomes evident, that the chosen test severity might be too high. It could be that the airbag mainly causes harm in accidents with a moderate severity level and does not changes much in high severity accidents. Within the tests described above the dummy readings already exceeded the proposed load limits for the head.

Finally recent and future airbag designs have been tested in sled tests in a body in white of a mid size car of today. The main characteristics of these tests are listed below:

- 60 km/h,
- pulse according to NPACS frontal impact protocol,
- front passenger seat in most forward position.

Non of the airbag tested in this series have been calibrated for the car, therefore better results can be expected in the field. The following airbags have been tested:

Airbag A

- designed for the European market
- volume 60 l
- 1 gas generator

Airbag B

- designed for the US market
- volume 120 l
- 2 gas generators

Airbag C

- based on airbag B
- prototype
- special venting technology with additional vents, which are open at the beginning of the inflation and will normally be closed except the airbag get in contact to anyone or anything
- volume 120 l
- 2 gas generators

Airbag D

- prototype

- special venting technology with additional vents, which are open at the beginning of the inflation and will normally be closed except the airbag get in contact to anyone or anything
- 2 chambers connected in the centreline resulting in a geometry which emphases at restraining the shoulders and reducing the loads at the head
- volume 100 l
- 2 gas generators

In addition to the airbag tests two reference tests without airbag and one static airbag deployment test with airbag D were conducted.

Analysis of the test data shows that the test without airbag already has a considerable high severity and that the Nij* shows the worst repeatability, see Table 4. The head acceleration and HIC value is considerably higher in the airbag tests as in the reference tests. The best results amongst the airbag tests was obtained in the test with Airbag C. Especially the neck loads expressed by Nij* were lower in the test with Airbag C than the average of both reference tests. The static airbag deployment tests with Airbag C did induce minor loads only.

Again it is important to note, that the tests showed a considerable high impact severity, causing already critical neck loads in the reference tests. Probably a lower impact severity would be better to assess the risk resulting from the airbag.

SURVEY AND FIELD STUDY

To evaluate the risk of misuse of airbag deactivation during the transportation of children in rearfacing CRS it is important to include the user's point of view. Level of knowledge, stance on child safety and risk assessment should be considered as well as the marginal conditions which make misuse more likely.

For this analysis a field study and an internet survey were carried out and accident data were evaluated.

Field study – first type of misuse

The central approach of this study was to interview people on the spot, who were just transporting a child in their car. Typical interview mistakes and response biases were excluded by this real time procedure. Furthermore, the interviewer had the possibility to check the airbag state in the car himself. Because of the more frequent use of the back seat for child transportation, it was time-consuming for the interviewer to find the desired situation of transport. Based on results of Fastenmeier et al. [Fastenmeier, 2006] only one of seven children is using the front passenger seat.

The survey has been conducted in Munich, Berlin, Stuttgart and Saarbrücken. The interviews were carried out at places where parents with young children or babies could be expected, e.g.: nursery schools, baby swimming courses, etc. Using this procedure of different places at different times of day the interviewer could ensure that with the survey there was a variation in trip purpose. Within this survey 140 interviews took place (54 in Munich, 21 in Berlin, 25 in Stuttgart, 40 in Saarbrücken). More than three-quarter of the interviewees were women and in 97% the people asked were the parents of the child.

The most important aim of this investigation was to find out how often the airbag is activated when a child is transported on the passenger seat. In 20 out of 140 cases the airbag was not deactivated, which corresponds to a rate of 15% of misuse. If misuse was detected parents were asked whether they think that this combination is dangerous, which was confirmed by 62.5% of the parents. This suggests that 7% of all interviewees consciously accepted the risk of a deploying airbag.

Table 4.
Results of dynamic tests with new airbags

Criterion	reference 1	reference 2	airbag A	airbag B	airbag C	airbag D	airbag C static test
Head a_{3ms}	62 g	61 g	73 g	78 g	72 g	76 g	13 g
HIC_{15}	362	405	572	572	517	560	5
Neck F_Z	474 N (comp.)	400 N (comp.)	1126 N (comp.)	1255 N (comp.)	1121 N (comp.)	916 N (comp.)	207 N (comp.)
Neck M_Y	27 Nm (ext.)	36 Nm (ext.)	18 Nm (ext.)	15 Nm (ext.)	9 Nm (ext.)	20 Nm (ext.)	7.5 Nm (ext.)
Nij*	1,26	1,40	1,60	1,65	1,29	1,54	0,23
Chest a_{3ms}	63 g	67 g	74 g	68 g	65 g	69 g	3.6 g

The replies to further questions reveal a considerable coherence between airbag deactivation and age of the car: the newer the car the less misuse occurred (p<0.001, Chi-square-test), see Figure 5.

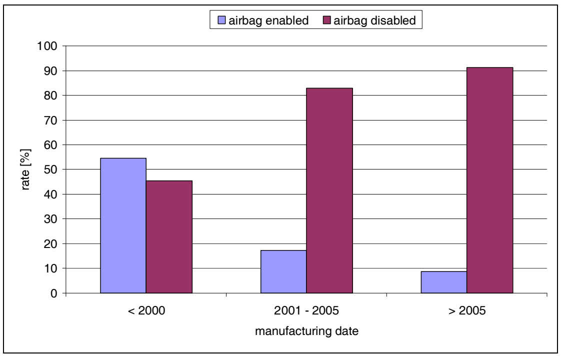

Figure 5. Misuse depending on year of manufacture.

This leads to the question of the airbag deactivation technique in dependence of the car's age. It seems obvious that newer cars offer easier deactivation possibilities, (e.g. a switch) than older ones, in which the airbag could deactivated at most by a garage. As Figure 6 shows, there is coherence between misuse rate and airbag deactivation technique. Especially the relation between deactivation and misuse in connection with the garage shows that this comparatively complicated way of deactivation leads to a high rate of misuse.

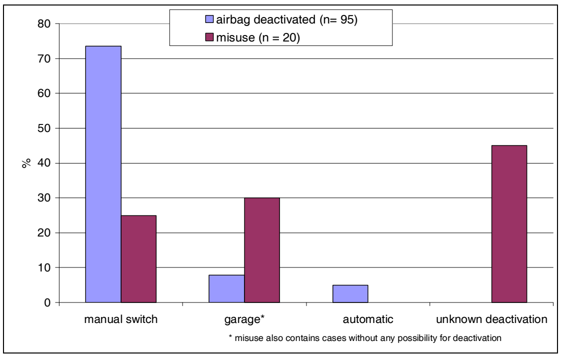

Figure 6. Misuse compared to different airbag deactivation techniques.

In cases of automatic airbag deactivation (CPOD) no misuse was detected.

The age of the interviewees had no significant influence on the misuse rate. Trip duration showed a tendency for increasing misuse for short distances. By contrast, the coherence of misuse and frequency of child transportation is highly significant (p < 0.01, Chi-square test). Trips that take place several times per week show a clearly lower misuse rate than trips which take place rarely. Apparently, it is more common to switch off the airbag if it is part of a daily routine procedure.

Surprisingly, the largest explicit effect is regional differences: there is a clear coherence between misuse and the city of survey (p<0.05, Chi-square test), see Figure 7.

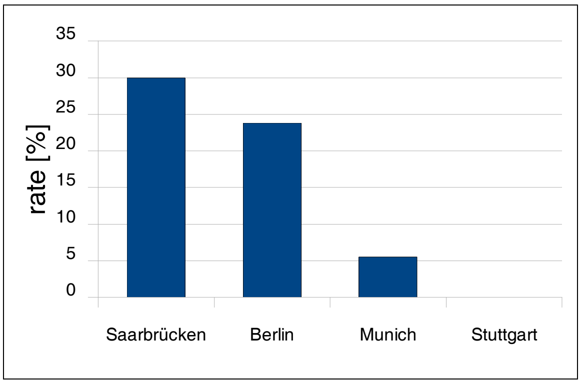

Figure 7. Percentage of misuse in different cities.

While the rate of misuse is 5.6% in Munich, it is approximately 24% in Berlin and 30% in Saarbrücken – in Stuttgart no misuse case was observed at all. The possibility that these differences are due to differences in interview strategies can be excluded because of an exactly defined questionnnaire and a defined interview situation. Possible reasons for these variations may be the following facts: in Munich the newest car fleet was part of the interview and the highest rate of female interviewees occurred. However, the car fleet does not show any important differences between Berlin, Saarbrücken and Stuttgart.

These varieties might be attributable to differences in social backgrounds of interview participants. Social differences usually lead to differences in educational standards, safety attitudes and knowledge structures. As social status was not controlled for in the interviews, differences in this respect may explain the large regional differences in behaviour.

Field study – second type of misuse

In 58 out of 140 cases an adult person was transported on the passenger seat after the first airbag deactivation. In 6 of these cases the airbag was not reactivated for the adult passenger, which results in a misuse quote of 10%.

Internet study – first type of misuse

The internet survey was online from January to March 2009. Links to the survey were placed on popular automotive websites like the automobile club "ACE" or the magazine "auto motor und sport". In addition child seat manufacturers were asked to link the questionnaire. In total, 309 questionnaires were collected. All participants had transported a child on the passenger seat, which was equipped with an airbag. In 194 cases the child was seated in a rearfacing CRS. The following data analysis is based on these cases.

Note that online surveys are less representative than compared to field studies, which was confirmed in the present study. 54% of the participants were men, while in the field study 75% of the interviewees were women. The education level of the participants was also above-average: 74% of the interviewed people had a general university qualification (Abitur), while only 4% had a low education level. This does not correspond to the average education level in Germany.

In 20 out of 194 analysed cases of rearfacing CRS on the passenger seat the airbag was not deactivated, resulting in a misuse (rate) of 11%. This quote is surprisingly low compared to the field study with 15% of misuse. However, the rate corresponds to the average of all analysed cities. The aberration from the average in Munich and Stuttgart was hypothetically explained by variables of social positions. According to the high education level of the respondents, this explanation is consistent with the results of the internet survey. The analysis of the survey shows that the rate of misuse decreases with increasing level of education. Considering the fact that participating in this online survey was voluntary and that it was impossible to control whether the participants answered honestly, the result above seems to be plausible. However, a detailed analysis of these correlations cannot be carried out due to a low number of cases.

With respect to the car's year of manufacture the results of the field study are confirmed: in newer cars with easier airbag deactivation devices less misuse occurs than in older ones. In five out of eight cases misuse occurred in cars where the deactivation was impossible or only practicable by a garage. There was only one case of misuse in which a switch was present.

Internet study – second type of misuse

In 14% of the situations in which an adult was transported on the passenger seat the airbag was not reactivated. This quote is slightly higher than in the field study. Interviewees justified this misuse with a supposedly low risk of a deactivated airbag and with the fact that the airbag could only be deactivated by a garage.

CONCLUSION

Looking at accident data and the results from the field investigation it becomes evident that children are transported on the rear seats in most of the cases – especially in those cars equipped with a passenger airbag. That is the main reason why the misuse risk with respect to the deactivation of the front passenger airbag is very low. If children are using the front passenger seat in cars with passenger airbag mostly the airbag is deactivated. The share of misuse mainly depends on the possibility of airbag deactivation. While minor rates of misuse where observed in cars offering a switch or automatic deactivation (the latter one without any case of misuse), misuse is more common in cars which do not offer any deactivation or require durable deactivation by a garage.

In several accidents the fatal risk resulting from the combination of rearfacing child restraint systems and deploying passenger airbags was proven. However, other accidents indicate that there is no certain risk coming from the passenger airbag. The real risk seems to depend on the airbag itself, the seating position and the accident severity. Looking at the airbag itself especially the mounting position and the size are important parameters defining the risk. Today's top mount airbags result in lower risk than the earlier airbags in low mount and mid mount position. Taking into account the differences with respect to the mounting position of the airbag larger airbags cause higher injury risks than smaller ones. It is obvious that proximate seating positions expose the passengers to a higher risk than farther seating positions. Finally there are indications that the main risk resulting from modern passenger airbags is connected with a moderate severity level.

Summarising the results of the study manual switches for the airbag deactivation are good practise. Within this study no evidence for the commonly feared misuse risk for the automatic deactivation (i.e., CPOD / AKSE) could be found. In contrast, no misuse occurred in the rare cases of cars offering automatic deactivation. Finally it seems to be possible to design airbags which avoid any risk in the long term.

ACKNOWLEDGEMENTS

The presented study has been funded by Bundesanstalt für Straßenwesen (BASt) under contract no. FE 82.310/2006 and supported by TAKATA-PETRI Berlin.

In addition the authors want to thank among others ACE Auto Club Europa", "ADAC", "auto motor und sport", "Britax Römer", "Concord", "Eltern", "Maxi Cosi", "Recaro" for "advertising" the online questionnaire.

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CONTINUOUS RESTRAINT CONTROL SYSTEMS: SAFETY IMPROVEMENT FOR VARIOUS OCCUPANTS

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ABSTRACT

Occupant safety can be significantly improved by continuous restraint control systems. These restraint systems adjust their configuration during the impact according to the actual operating conditions, such as occupant size, weight, occupant position, belt usage and crash severity. In this study, the potential of a controlled restraint system is demonstrated. First, an overview is given of the problems concerning the sensors, actuators and control strategy of such a system, and solutions are given. Next, a numerical demonstrator is developed, which includes a dummy and vehicle model, and a realistic implementation of the components of the controlled restraint system. The demonstrator is subjected to different loading conditions, and the results are compared to a reference model. This reference model contains a conventional restraint system with optimized settings, and it has been validated against sled test experiments. Simulation results with the demonstrator indicate that significant injury reduction can be achieved with continuous restraint control systems.

INTRODUCTION

In high-speed vehicle crashes, the occupant is subjected to high forces, typically resulting in severe injuries. The forces depend on the actual loading condition, which reflects the severity and complexity of the impact, and the occupant's size, weight, behavior and posture. The seat belt and airbags, referred to as the restraint systems, are designed to reduce these forces. For the most effective reduction, the settings of the restraint systems should be geared towards the loading condition. Current restraint systems, however, have typically one level of operation, and this level is a compromise between several loading conditions. It implies that the benefits of current restraint systems may not be fully exploited (Holding et al., 2001). This fundamental shortcoming of current safety systems makes that not every vehicle occupant will be optimally protected under all possible conditions.

Nowadays, an increasing number of sensors and electronics is being integrated in vehicles, and this allows the use of advanced safety systems with adjustable components. An example is the adaptive restraint system, which can adjust its configuration during the crash, but typically only once. A large number of studies on adaptive passive safety focuses on the adjustment of the tension in the safety belt. Adaptive belt forces lower thoracic injury especially for occupants or collisions that deviate from the average (Iyota et al., 2003; Adomeit et al., 1997). For example, the dual-stage load limiter can significantly improve thoracic injury mitigation (Miller et al., 1996; Paulitz et al., 2006; Mertz et al., 1995; Clute et al., 2001).

Compared to adaptive restraint systems, a near optimal protection can be delivered when the seat belt force can be continuously adapted during impact. In two similar studies, by Crandall et al. in 2000 and by Kent et al. in 2007, a time-varying belt force is applied in open-loop. The optimal input is found through optimization using an elementary chest model. More robust solutions are presented in Habib et al., 2001; Cooper et al., 2004; Hesseling et al., 2006; van der Laan et al., 2009, where the belt force is applied in a feedback configuration, and optimal values are obtained by solving a control problem. These types of systems, in which restraint settings can be continuously adapted during the crash, are referred to as *Continuous Restraint Control (CRC)* systems. CRC systems will be the main focus of future restraint system development, and this paper contributes to the development.

Objective and Contributions

The aim of this paper is to demonstrate the potential of CRC systems to mitigate injuries in frontal impacts. This is achieved with a *numerical demonstrator*, which is a simulation model of an occupant, vehicle interior and a CRC system, subjected to various loading conditions. The outcome of the numerical demonstrator is compared with the results of a validated *reference model,* consisting of a conventional restraint system, albeit with optimized settings.

Previous studies have already shown the evident benefit of CRC systems (Hesseling et al., 2006; Shin et al., 2007; and references therein), but an idealized implementation of the system was assumed in those studies. In this study, the properties and limitations of the various components of the CRC system are shortly discussed, and their limitations and properties are explicitly incorporated in the numerical demonstrator. This leads to a model that closely resembles a CRC system that could be implemented in future vehicles.

The CRC system proposed in this paper controls the seat belt force to lower thoracic and head injury criteria, based on measurements of the vehicle and the occupant. In this study, the airbag settings are not adapted to the loading condition, as control of the belt force makes the forward movement of the occupant more predictable, which in turn may already improve the airbag performance.

This paper is structured as follows. In Section 2, a set of frontal MADYMO dummy models with a conventional restraint system is developed, and validated against experimental data from sled tests. Subsequently, the restraint settings are tuned to obtain a reference model that achieves optimal injury reduction with non-adaptive or fixed restraint systems. In Section 3, the four components of the proposed CRC system are shortly discussed. This includes (i) the control strategy, (ii) the state estimator, since sensors to directly measure injury related occupant responses are not available, (iii) a simple, low-order occupant model to be used in the controller and estimator, and (iv) the design and construction of the belt force actuator. The properties of these components are used in Section 4 to develop the numerical demonstrator. The result in injury criteria achieved by the conventional and the controlled restraint system are compared and evaluated for several loading conditions. Finally, in Section 5 conclusions and outlook are presented.

REFERENCE MODEL

In this section, the vehicle and occupant model will be described. It is developed in MADYMO (TNO, 2005), and it forms the baseline model in this study. It serves two purposes. Firstly, it is used as a reference model with conventional restraints. To show that this reference model has sufficient resemblance to the real world, it is validated against results from sled test experiments. Secondly, the baseline model is used in the numerical demonstrator, now with the CRC system, to demonstrate the benefit of the CRC system.

Validation

Several car models are developed representing averages of classes of cars during the European PRISM project (Bosch-Rekveldt et. al., 2005). This approximation of an "average" car consists of a multi-body belt, compartment model and hybrid III dummy model. The belt characteristics are obtained from an experimental test. This MADYMO model is validated against sled test experiments, performed at TNO, the Netherlands. The geometrical aspects (like distance to steering wheel) are adjusted so they coincided with the geometry of the car on the sled. Since the belt rollout will be used to estimate several dummy responses, a belt rollout sensor is added to the standard test setup. Additionally, belt forces are measured at three different locations (between shoulder and D-ring, between hip and buckle, and between hip and attachment point). The belt forces are used to estimate friction coefficients in the buckle and D-ring, which can then be implemented in the friction models.

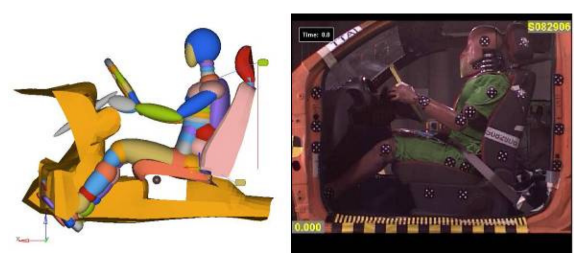

Figure 1. MADYMO simulation model (left) versus experimental setup (right).

The experimental sled test is based on a supermini car as shown in Figure 1. The acceleration pulse (in longitudinal direction) is shown in Figure 2. The experimental sled test does not include an airbag, since this reduces the number of unknown parameters like airbag frictions, flow rate, vent size, and volume. Of course, future research should include the airbag in the validation, since it is part of the baseline restraint configuration in today's consumer vehicles.

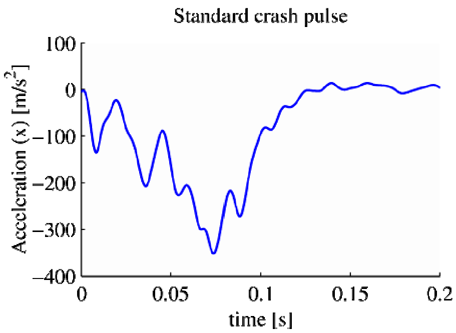

Figure 2. Vehicle acceleration (x) pulse used in the sled test (referred to as the standard pulse).

The following injury responses are obtained from the sled test dummy and from the simulations:

1. head acceleration in longitudinal (x) direction,
2. chest acceleration in longitudinal (x) direction,
3. chest deflection,
4. neck force in z direction (vertical compression),
5. neck torque in y direction (flexion/extension),
6. pelvis acceleration in longitudinal (x) direction.

The results of the validation are shown in Figure 3.

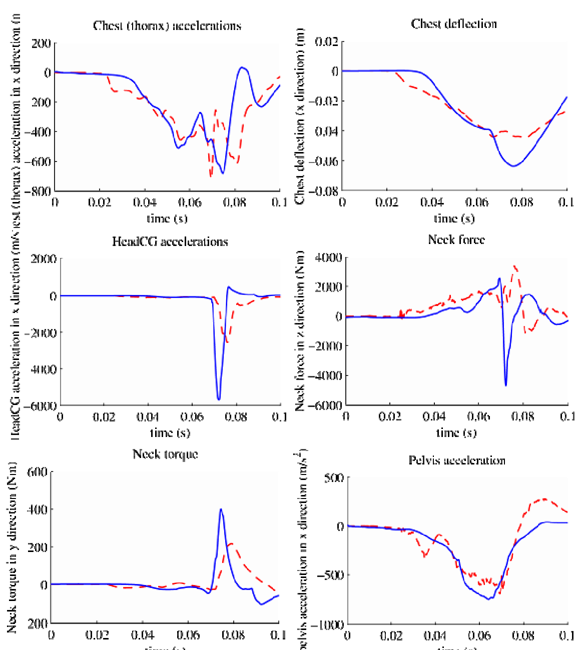

Figure 3. Injury responses MADYMO average car model simulation (blue solid line) versus sled test (red dotted line).

An objective rating is used, which is based on the weighted integrated factor method (WIF), global peak value (GPV), global peak time (GPT), and difference in area under curve (DUC) of these responses, see Twisk et al, 2007. The conclusion is that on average the derived MADYMO model mimics the sled test phenomena sufficiently, at least for the considered responses, as shown in Figure 3. When the neck injuries are not included in the simulation, the results are more accurate, as shown in Figure 4. The belt forces and rollout fit the measurement very accurate. The model can be further improved when the characteristics of the steering wheel, seat model and dashboard are known more precisely.

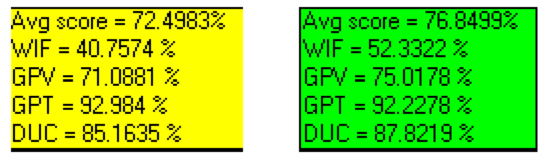

Figure 4. Average score for relevant injury parameters (left) and average score for relevant injury parameters without neck parameters (right).

Optimization

The validated model is now used as a reference model in the comparison with the CRC system. It contains a pretensioner and load limiter for the belt system, and a conventional airbag is added to the model. To make a useful comparison, the reference model should mitigate injuries maximally. Therefore, the following three restraint parameters are optimized:

1. scaling of the airbag flow rate,
2. airbag timing,
3. load limiter value.

The optimization is based on a minimal total injury parameter. This total injury parameter is defined as a weighted sum of all relevant injury parameters. The 50th Hybrid III model, seated in the position as used for the sled test (according to EURONCAP norms) is used for this optimization. A full factorial optimization is done, using three different values for each parameter.

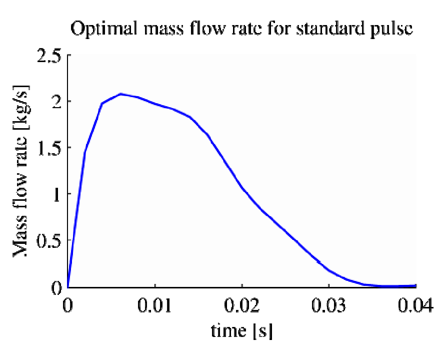

Figure 5. Optimal mass flow rate.

The airbag flow rate is found to be optimal when no additional scaling was applied with respect to the original flow rate, which is shown in Figure 5. The optimal airbag timing for the standard pulse is 25 ms and the optimal load limiter value is found to be 4.5 kN.

COMPONENTS OF THE CONTINUOUS RESTRAINT CONTROL SYSTEM

In the previous section, a MADYMO model for the 50th percentile HIII dummy was developed and validated with experimental data from a sled test. The objective of this paper was previously formulated as to demonstrate the potential of realistic CRC systems, which aim at reducing neck and thoracic injuries of this numerical dummy model by control of the seat belt force. In this section, the components of this CRC are discussed.

1. Semi-active belt force actuator in an experimental setup

The requirements for a restraint actuator that can effectively be used in a controlled seat belt system are very challenging. Numerical simulations performed previously, (van der Laan et. al, 2009), indicated that peak belt forces of 7-10 kN are required for optimal injury reduction. The bandwidth of the local control system of the actuator has to be around 300 Hz. Finally, the dimensions of the actuator are limited, as it ultimately has to be fitted in a vehicle's B-style. Up until today, no devices exist that can deliver these high belt forces during a crash, and can actually be used in a commercial vehicle.

This has led to the decision to design and develop such an actuator at the Eindhoven University of Technology. The concept of the actuator is based on a semi-active hydraulic damper, where semi-active refers to the fact that the velocity and force vectors have opposite directions, so the actuator does not have to deliver energy to the system. Due to the desired forces and displacements, fully active systems would require a large amount of energy storage. , which is for non-chemical sources difficult to realize in commercial vehicles.

The hydraulic damper consists of a custom-made cylinder, piston and valve. The belt is attached to the piston, and the cylinder is mounted to the vehicle. During frontal impact, the relative forward movement of the occupant makes the piston to extent from the cylinder, thereby inducing flow through the valve. By restricting the valve orifice, the cylinder pressure and hence the belt force increases.

The valve design is fundamentally different from most conventional hydraulic servo-valves. The latter have typically too low a bandwidth for this application. In conventional servo-valves, the motion of the spool valve is perpendicular to the hydraulic pressure, such that the force needed to close the valve does not have to counteract the (large) hydraulic force. The valve developed in this study is deliberately designed to counteract this force.

The advantage is that the force needed to prevent the spool body from accelerating equals the force from the hydraulic pressure. If these forces are not equal, the spool body starts to move, thereby changing the restriction, until there is a force balance. Hence, the nonlinear relations for flow through an orifice do not play a part in the control law, which is advantageous from a control point of view. The constructed valve is shown in the left part of Figure 6. Fluid from the cylinder enters the valve through the opening on top, and it is led to a container via the tubes on the side. The hydraulic cylinder with the valve is shown on the right side.

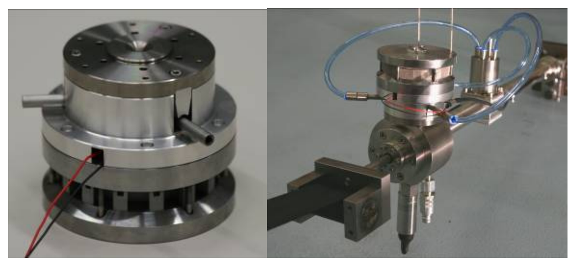

Figure 6. The hydraulic valve (left) of the semi-active hydraulic damper (right), which is used to control belt forces during the crash. The device is developed at the Eindhoven University of Technology.

The belt actuator is tested in the sled setup, which shown in Figure 7. The sled is accelerated up till 10 m/s, and it impacts then against a deformable crumple bar (not shown). During this impact, the actuator is used to control the acceleration of a sliding mass of 30 kg, representing the torso of a human body.

The results of the experiments with the sled test setup have provided information on the performance of this specific actuator, such as semi-active behavior, force limits, bandwidth and delay. This information is used in the numerical demonstrator, such that the actuator model reflects an actual device.

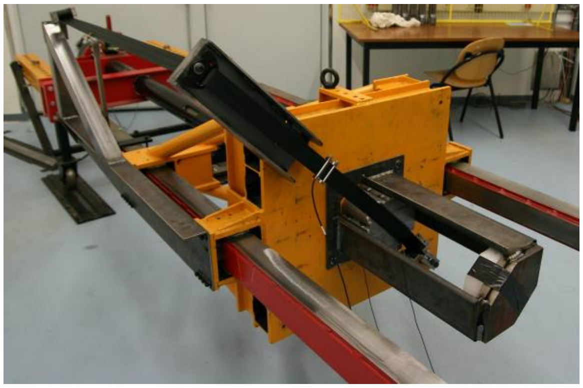

Figure 7. Sled crash setup used to test the belt force actuator during impact.

2. Design Model

In the development of CRC systems, it is essential to have manageable, low-order models of the occupant. Most of the relevant occupant responses, for instance the chest compression, cannot be measured directly with current sensors, for instance the chest compression. An accurate, but low-order model of the occupant may be used to estimate this compression in real-time, given some measurable signals and the loading conditions. Additionally, in the design of the control algorithms of the CRC system, it is convenient to have knowledge on the input-output behavior of the system. A low-order model for this behavior is therefore very useful.

The low-order models, referred to as design models, have been developed in a previous study. More details on theses models can be found in (van der Laan, 2009). The knowledge obtained from a sensitivity analysis on MADYMO Hybrid III dummies has been used to construct and parameterize the design model. The analysis has resulted in a 2D model of the dummy, with 11 rigid bodies and 14 degrees of freedom, see Figure 8. The model parameters such as masses, dimensions, initial conditions, are directly linked to parameters in the MADYMO model, which makes scaling of the design model very straightforward.

Outputs of this model are biomechanical responses that are used to assess injury risk to thoracic and neck regions. These are chest acceleration, chest compression and its time derivative, neck bending moment and neck axial and shear forces. Additionally, the belt rollout is added as a model output, as a belt rollout sensor will be used to estimate injury responses later on.

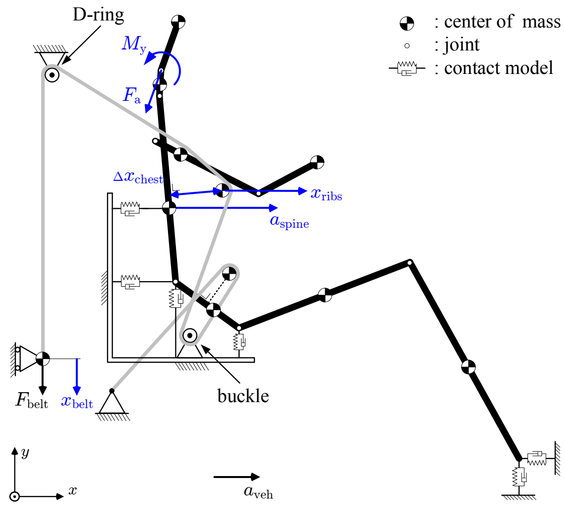

Figure 8. Representation of the multi-body design model of a 50th %-ile Hybrid III dummy.

Simulations show that the design model generates the biomechanical responses related to injury predictors for the chest and neck region remarkably well. The models are validated for a broad range of frontal crash scenarios, and for three different adult Hybrid III dummies. For all these tests, it was shown that the low-order model includes all relevant dynamics of the reference model. An example of the results is shown in Figure 9.

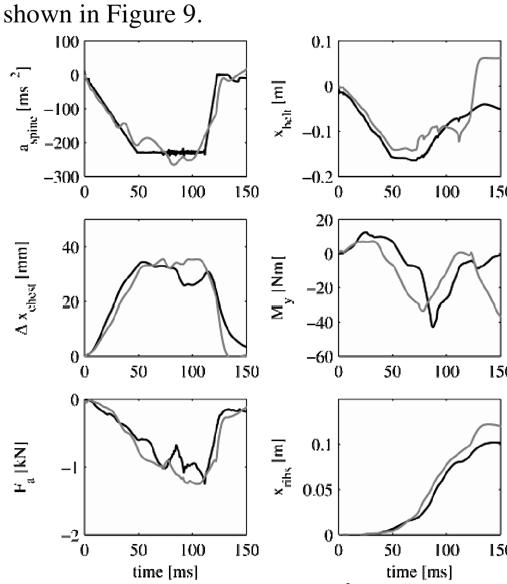

Figure 9. Responses of the 50th %-ile MADYMO reference model (grey) and design model (black) in a 40% ODB frontal impact at 64 km/h.

The linearized version of the presented design model is used in the design of the CRC controller and of the state estimator. These topics are discussed in the remainder of this section.

3. Reference Governor

A control strategy has been developed to solve the control problem formulated at the beginning of this section. In previous studies on controlled belt restraint systems (Hesseling et al., 2006), the control problem was formulated as a tracking problem, where biomechanical responses of the occupant are measured and forced to follow a predefined reference trajectory. This trajectory results in a minimum risk of injury, while satisfying certain constraints. However, the reference trajectories are constructed assuming full a priori knowledge of the crash pulse, constraints and occupant characteristics, which is in practice clearly not realistic.

To harvest the advantages of using CRC systems, these limitations have to be overcome. This indicates the compelling need for the development of a control algorithm that - based on the available measurements from the sensors - computes the optimal control signals for the belt restraint actuator. This includes the incorporation of the following requirements:

1. the algorithm must be computationally feasible in order to meet the real-time requirements,
2. a priori knowledge of the crash pulse is not available, and
3. the algorithm must be based on on-line measurement data.

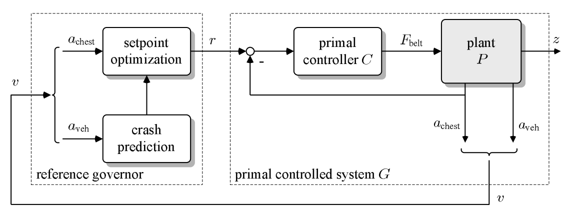

Figure 10. Control strategy based on Reference Governors. On the left, the modified RG, on the right a primal controlled loop.

A novel control strategy has been proposed to this challenging design problem (van der Laan et al., 2008; 2009a). The control method consists of a combination of a primal controlled system, which achieves good tracking properties, and a modified reference governor (RG), (Bemporad et al., 1998). The layout of the method is graphically shown in Figure 10, where *r* indicates the setpoint, *v* the measurements, and *z* injuries. The RG finds an optimal setpoint for the spinal acceleration, while satisfying constraints and without having a priori knowledge of the upcoming crash. It includes a crash prediction procedure of the vehicle motion to provide good estimates of its position during the crash.

The setpoint optimization problem is robustified with respect to the estimation errors. Moreover, the whole design procedure is generic in nature. For instance, multiple injury criteria can be easily included in the design process. In addition, different primal controllers and plant dynamics can be accounted for. This enables the incorporating of various additions, such as future improvements in the actuator and sensor technologies.

An example of the results obtained with the RG is given in Figure 11. It shows a reduction of 45% of the 3ms acceleration criterion with respect to conventional restraint systems (EuroNCAP pulse), while still meeting the real-time computational requirements.

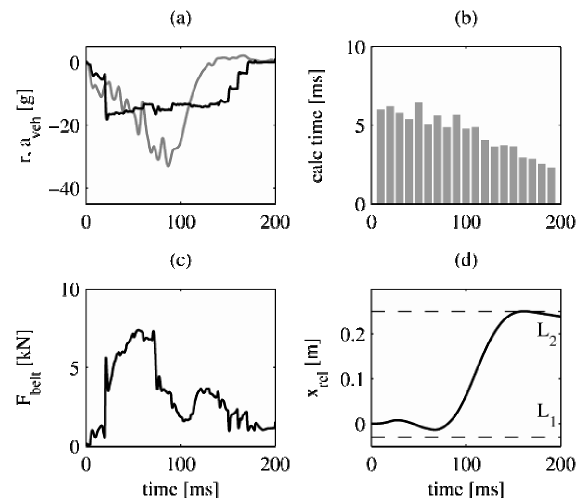

Figure 11. (a) Optimal setpoint for the chest acceleration (black), without a priori knowledge of the crash pulse (grey); (b) calculation times per optimization step; (c) required belt force in the primal controlled loop; and (d) constraint on the relative chest position with respect to the vehicle.

The RG control strategy is believed to be an important step towards real-time implementation of controlled passive safety systems. The strategy is used to evaluate the performance of CRC in the numerical demonstrator, presented in the next section.

4. State Estimator

The primal feedback controller from the previous section has to ensure that the spinal acceleration tracks the setpoint generated by reference governor. Obviously, the acceleration of the human spinal cord cannot be obtained directly as a measurement signal from the occupant. Furthermore, it is considered to be cumbersome to develop such a type of sensor, as it should be robust, 'foolproof' (each driver must be able to use it, preferably without his or her awareness), cheap and crash safe. Hence, it is proposed to employ a set of more conventional sensors, and then estimate the state of the system using a model of the system.

Many types of occupant sensors are available in today's cars, both contact as well as non-contact, see e.g. (Fleming, 2008). Non-contact sensors are not preferable, since the "line-of-sensing" may be easily blocked during an impact, e.g. by the airbags. Since the occupant typically has uninterrupted contact with the seat belt during an impact, it is chosen to attach sensors to the belt: one acceleration sensor to the shoulder belt in the center of the torso, and one displacement sensor to measure the belt rollout where usually the load limiter is placed. As mentioned in Section 2, this belt rollout sensor has also been attached to the belt in the sled experiments, in order to validate the belt displacement signal from the reference model. The acceleration sensor measures the absolute acceleration of the sternum in forward direction; the accuracy of this sensor could however not be checked with sled test measurements.

Since a manageable design model is available, as well as inputs and measurements, it is obvious to choose a model-based recursive estimation method. Besides that, much experience is already gained with recursive estimation methods in other automotive applications. More specifically, the Kalman filter approach was chosen as a candidate to set up an estimator for the chest acceleration. Since the proposed estimator estimates all states of the (human) model, it is referred to as "human state estimator".

The behavior of the occupant, which is subject to belt forces and a vehicle acceleration pulse, can be approximated by the following linear state-space system:

$$x_k = Ax_{k-1} + Bu_{k-1} + w_{k-1}$$
$$z_k = Hx_k + v_k \quad (1).$$

In Equation 1, u is the input vector consisting of the vehicle deceleration in forward direction, and the seat belt force. The measurement vector z consists of the sternum acceleration, a_{ribs}, and the belt rollout, x_{belt}. The vectors w, v are the (uncorrelated) measurement and process noise, respectively.

The Kalman filter setup is shown in Figure 12. The gain for the filter correction K is calculated from the measurement noise covariance R, the process noise covariance Q, and the linearized system matrices A and H, see for example (Gelb, 1974).

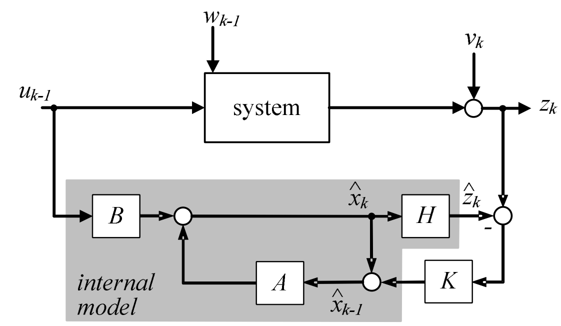

Figure 12. Kalman filter setup.

First, a fully linear approach was set up and tested against MADYMO results. However, this linear approach did not give satisfactory results under all conditions, whereas the non-linear model fits the MADYMO results very well. So the linear internal model in the Kalman filter was replaced by the non-linear design model whereas the gain calculation K is still based on the linear system. This approach resembles the Extended Kalman Filter, albeit that the A and H matrices are constant. Measurement data from the reference model are used to estimate a number of occupant responses. In Figure 13, the estimated responses are compared with true responses from the reference model.

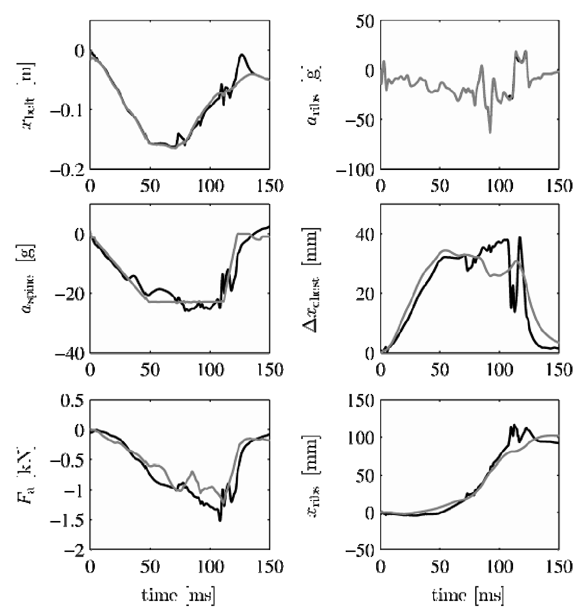

Figure 13. Results of the human state estimator (black) applied to the reference model (gray), with both measurements in the top figures.

NUMERICAL DEMONSTRATOR

This section shows the benefit of the CRC system above the conventional system by means of a simulation study. Note that the conventional restraint system is optimized as described on page 3. Several cases are investigated, which are shown in Table 1. Original seat angle and original D-ring height represent the settings that are obtained from the model validation with the sled test results. Variation is applied in these settings and in the size of the dummy model. Three crash pulses are simulated: One standard crash pulse (obtained from the sled test, see page 3) and two non-standard crashes, based on an offset frontal collision between two cars, as shown in Figure 14. For the two non-standard crash pulses, the reference model is also optimized (italics in Table 1), using the same method as described on page 3.

Table 1.
Investigated cases

Seat Angle	D-ring height	Seize	Crashpulse
orig	*orig*	*50%*	*standard*
orig+10deg	orig	50%	standard
orig	orig	95%	standard
orig	orig	5%	standard
orig+10deg	orig	95%	standard
orig	orig-10cm	5%	standard
orig+10deg	orig-10cm	50%	standard
orig	orig-10cm	50%	standard
orig	*orig*	*50%*	*nonstandard1*
orig+10deg	orig	95%	nonstandard1
orig	orig-10cm	5%	nonstandard1
orig+10deg	orig-10cm	50%	nonstandard1
orig	orig-10cm	50%	nonstandard1
orig	orig	5%	nonstandard1
orig	*orig*	*50%*	*nonstandard2*
orig	orig	95%	nonstandard2
orig	orig	5%	nonstandard2
orig+10deg	orig	50%	nonstandard2

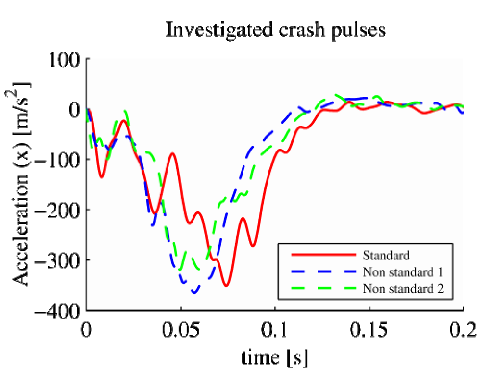

Figure 14. Investigated crash pulses.

Figure 15 shows that the chest acceleration tracks the setpoint from the reference governor sufficiently well. Hence, the control system is robust against disturbances from the crash pulse and the airbag, and has good tracking performance. It should be noted that the state estimator as described op page 7 is not included at this point.

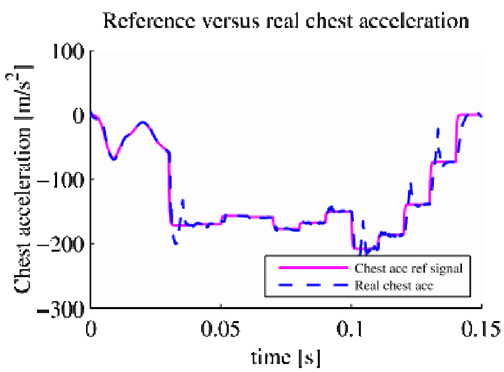

Figure 15. Reference chest acceleration (solid) versus simulated chest acceleration (dashed).

The results are shown in Figure 16 and Figure 17 for two following cases:

- original seat angle, original D-ring height, 50% dummy, standard crash pulse,
- original seat angle, original D-ring height, 5% dummy, nonstandard crash pulse 2.

Figure 16 and Figure 17 present three different curves:

- The red solid line describes the result for the conventional restraint,
- The dotted blue line shows the CRC with an ideal actuator. The optimization done by the RG is based on chest acceleration only,
- The dotted green line shows the CRC result with a realistic actuator.

The properties of the realistic actuator, which are implemented in the demonstrator, are:

- Maximum belt force: 8kN
- Rate limit: 10^6 N/s
- Time delay: 0.2 ms

Note that the actuator is semi-active, in a sense that the actuator does not have to deliver energy to the system. This is indeed the case after a short period of pretension.

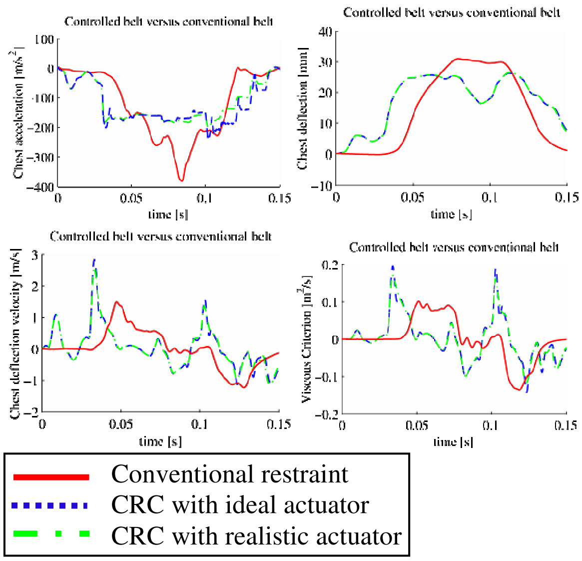

Figure 16. Results for several injury parameters for 50% dummy, standard crash pulse.

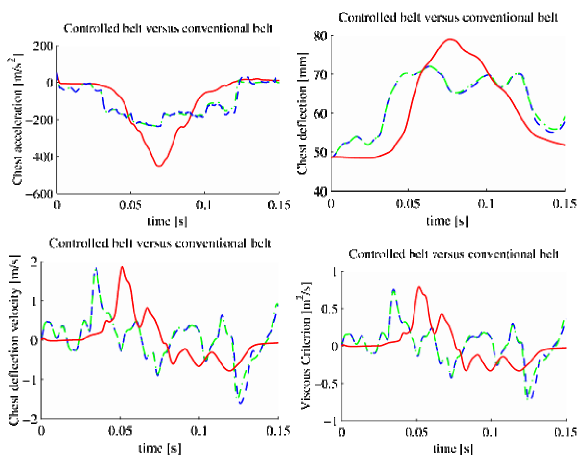

Figure 17. Results for several injury parameters for 5% dummy, non-standard crash pulse 2.

Injury Limits

Within the EURONCAP protocols (EuroNCAP, 2003), injury limits are determined for several injury criteria. Two limits are specified, i.e. a lower performance limit (limit2) and a higher performance limit (limit1). The injury criteria and limits are shown in Table 2, but only for the head, neck and chest criteria. The results for the reference system are shown in Table 3. The results for the controlled belt with realistic actuator are shown in Table 4. In these tables, three color codes are applied:

- green: the injury value is below limit1
- orange: the injury value is between limit1 and limit2
- red: the injury value is above limit2.

Table 2.
Investigated injury parameters and limits

	limit1	limit2
HIC36	650	1000
Headacc3ms	72	88
Neck shear force	1900	3100
Neck tension force	2700	3300
Neck extension moment	42	57
Chest compression	22	50
VC	0.5	1

Table 3.
Results for investigated cases: reference system

Simnr	HIC36	Headacc3ms	FX_shear	FZ_tension	NMY_ext	Chest_c	VC
1	423	54	363	1177	34	31	0.10
2	755	69	356	1302	24	31	0.10
3	776	71	1391	1779	94	50	0.24
4	218	36	288	602	16	31	0.17
5	2358	150	2604	1874	122	47	0.28
6	201	32	355	641	19	30	0.17
7	734	72	419	1072	31	30	0.09
8	420	55	364	1155	34	31	0.10
9	486	56	589	1357	46	38	0.18
10	3051	189	3390	3034	237	56	0.47
11	265	39	400	666	29	36	0.24
12	845	76	411	1800	32	34	0.15
13	491	58	620	1305	49	36	0.16
14	256	40	422	668	31	36	0.26
15	581	65	314	1339	25	31	0.15
16	450	54	361	1483	32	42	0.14
17	233	39	253	702	22	34	0.20
18	355	52	456	1099	35	34	0.14

Based on the results presented in these two tables, it can be concluded that the CRC system effectively reduces the criteria values of HIC36, Headacc3ms, neck shear force, neck tension force, and neck extension moment. The chest deflection is most of the times reduced as well, but the chest deflection velocity increases in some cases. In most cases, the VC does still not exceed limit1. Only for three cases, it slightly exceeds this limit. Overall, the CRC system improves injury mitigation in most cases.

Table 4.
Results for investigated cases:
controlled belt with realistic actuator

Simnr	HIC36	Headacc3ms	FX_shear	FZ_tension	NMY_ext	Chest_c	VC
1	177	38	523	711	29	27	0.19
2	163	35	589	553	24	32	0.52
3	161	33	611	784	29	36	0.34
4	111	32	417	542	22	32	0.35
5	191	34	526	770	26	42	0.64
6	142	42	413	585	16	33	0.34
7	142	32	727	773	38	31	0.32
8	198	39	506	706	26	27	0.18
9	272	47	451	826	34	30	0.17
10	276	40	552	1070	27	44	0.63
11	138	39	410	558	16	32	0.34
12	317	49	555	724	26	32	0.30
13	302	49	448	793	31	28	0.15
14	163	32	387	546	24	29	0.23
15	179	35	478	620	22	29	0.33
16	117	31	792	950	73	45	0.45
17	79	26	325	455	18	25	0.16
18	168	38	483	625	34	27	0.12

Previous results were obtained without the state estimator, since at the time of writing of this paper not all simulations were finished. For the 50% dummy with standard crash pulse, the results with the demonstrator including the estimator, the reference governor and a realistic actuator are shown in Figure 18 and Figure 19. The performance decrease caused by the estimator is only minor, which indicates that the estimator is quite accurate (compare Figure 16 and Figure 19).

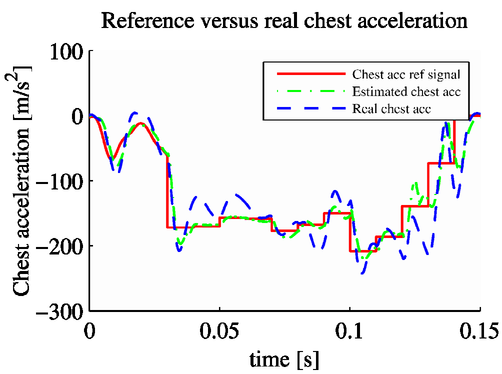

Figure 18. Estimator results for chest acceleration for 50% dummy, standard crash pulse.

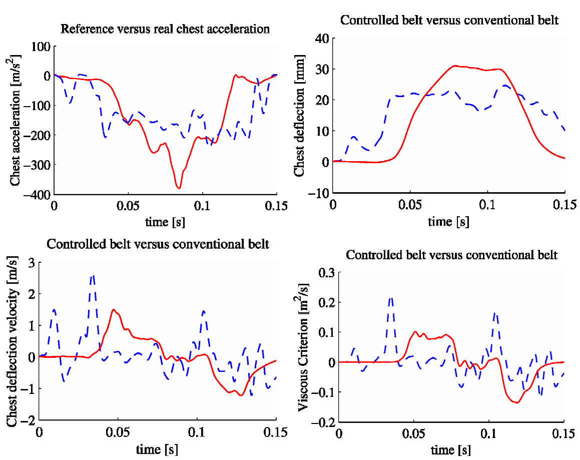

Figure 19. The red (solid) line represents the conventional restraint system, the blue (dotted) line represents the CRC with reference governor, realistic actuator and state estimator.

CONCLUSION AND OUTLOOK

In this paper, advancements are shown in the area of continuous restraint control (CRC) systems. More specifically, a system is described where the belt force is continuously manipulated as a function of measurements of the vehicle and occupant. The proposed CRC system aims at minimizing head, neck and thoracic injuries. The problems concerning the sensors, actuator and control strategy are discussed, and solutions are proposed.

Moreover, a numerical demonstrator is developed that incorporates the aforementioned CRC elements. The numerical demonstrator is based on a MADYMO model with conventional restraint systems. This model is validated with sled test experiments. Subsequently, the settings of this model are tuned to yield optimal protection for the occupant in the given scenarios, and this optimized model is referred to as the reference model.

The numerical demonstrator is tested in 18 different scenarios, including different dummy types, crash pulses, seating angles and D-ring positions. For these scenarios, the performance of the CRC system is evaluated by using performance limit values on 7 injury criteria. The resulting 126 performance values are compared to the values of the reference model for the same scenarios. Whereas the reference model has a poor performance in 9 cases and sufficient performance in 28 cases, the CRC system performs poorly in just 1 case and sufficiently in 21 cases.

Concluding, the potential for injury reduction with CRC systems has been made evident with the numerical demonstrator, in which a realistic sensor, actuator and control strategy have been implemented.

Future research will focus on evaluation of the numerical demonstrator for a larger number of crash scenarios. Furthermore, effort has to be directed in making the control and estimator algorithms run in real-time, such that they can be tested in real-world experiments.

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PROTECTION OF OVERWEIGHT CHILDREN IN CHILD RESTRAINT SYSTEMS

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ABSTRACT

According to the German road traffic regulations children up to the age of 12 or a body height below 150 cm have to use approved and appropriate child restraint systems (CRS). CRS must be approved according to UN-ECE Regulation No. 44. The regulation classifies CRS in 5 body weight categories. The upper weight group is approved for children from 22 to 36 kg.
However, studies show that already today many children weigh more than 36 kg although they have not reached a size of 150 cm. Therefore, no ECE R44 approved CRS is available for these "overweight" children. In conclusion, today's sizes and weights of children are no longer represented by the current version of the ECE R44. The heaviest used dummy (P10) weighs just 32.6 kg and has a body height of 137.9 cm.
Statistical data of German children show that already 5% of the children at a size of 137.9 cm have a body weight above 45.3 kg. Regarding children at a body height of 145 cm, the 95th percentile limit is at a weight of 53.3 kg. Based on these data 4 dummies with different heights and weights were defined and produced. Two of them are "overweight".
Up to now, there is no experience how current child restraint systems perform in a car crash if they are used by children with a body weight above 36 kg and a size smaller than 150 cm.
In the future, different child restraint systems will be tested with respect to the ECE R44 regulation using these "overweight" dummies.

INTRODUCTION

Today, child restraint systems are very popular. Investigations show that in 2007 97% of all children transported on German roads were restrained with child restraint systems [1]. Compared to 1992, the restraint rate increased by 25%. During the same period the number of seriously and fatally injured children decreased significantly. Nevertheless, the number of children restrained improperly, the so called "misuse", is still very high.

Figure 1. 10 year old boy (body size 144.2 cm, body weight 41.6 kg) in an Opel Astra (model year 2003) without child restraint system. Arrows indicate critical positions of the safety belt.

This paper deals with another problem. In Germany it is mandatory that children younger than 12 or smaller than 150 cm have to use child restraint systems. The size limit results from the fact that the standard safety belts in the cars do not fit with smaller children. The shoulder belt touches the neck and the lap belt slips from the pelvis into the abdominal region as shown in figure 1.

Using booster seats – which must be approved according to UN-ECE Regulation No. 44 – the position of children in the seat rises and belt rooting is improved. Figure 2 shows the boy from figure 1 using such a child restraint system.

Figure 2. 10 year old boy (body size 144.2 cm, body weight 41.6 kg) in an Opel Astra (model year 2003) with child restraint system.

The shoulder belt no longer touches the neck of the boy.
Unfortunately, the type approval of child restraint systems is limited to a maximum body weight of 36 kg so that the boy from figure 1 and 2 (body weight 41.6 kg) has to use booster seats which are not certified for his weight. This is not a particular case as shown in this paper and the crash performance of child restraint systems in such *overload* cases is completely unknown. Therefore, the German Federal Highway Research Institute (Bundesanstalt für Straßenwesen, BASt) initiated a project to investigate this problem. First results are presented in this paper.

Detailed results from anthropometric measurements, which are presented in the next chapter, clearly indicate that a lot of children who are shorter than 150 cm weigh more than 36 kg. Based on these data sizes and weights for new child dummies are defined. As it is impossible to develop a completely new child dummy a P10 dummy was modified. The exact definition of the modified P10 dummies and the manufacture process is described in the following chapters.

ANTROPOMETRIC DATA

Former publications [2] made evident that the median weight of children at the size of 150 cm is much higher than the 36 kg limit defined in UN-ECE Regulation No. 44. Actual data corroborate this statement. The data presented below was collected by the University of Jena in cooperation with CrescNet. Table 1 and table 2 show the weight and size of 34272 German children (girls and boys). Even the 50% percentile weight of the 11 years old children is above 36 kg. The average size of these children is 147.6 cm. An exact correlation between weight and size cannot be inferred from table 1 and 2.

Table 1.
Body weight in kg of German children for three different percentiles. The second column shows the number of measured children. [database CrestNet 2006-2008]

age [years]	N	body weight [kg]		
		5%	50%	95%
6	6703	17.3	21.6	29.7
7	5908	19.2	24.4	34.9
8	5349	21.1	27.6	40.8
9	4925	23.3	31.2	47.2
10	4288	25.7	35.2	54.1
11	3767	28.5	39.6	61.2
12	3332	31.7	44.4	68.5

Table 2.
Body size in cm of German children for three different percentiles. The second column shows the number of measured children. [database CrestNet 2006-2008]

age [years]	N	body size [cm]		
		5%	50%	95%
6	6703	109.5	117.9	126.6
7	5908	115.1	124.1	133.7
8	5349	120.4	130.2	140.5
9	4925	125.5	136.1	147.0
10	4288	130.6	141.9	153.4
11	3767	135.7	147.6	159.7
12	3332	140.8	153.3	166.0

Therefore, the data were analyzed for three different size classes. These classes are defined as follows; from 134 cm to 136 cm, from 144 cm to 146 cm and from 149 cm to 151 cm. Choosing a range of 2 cm, enough children can be evaluated. Exact data are listed in table 3 to 5. Due to the fact that not all dimensions were evaluated for all children the number of measured children differs. Table 3 points out that at least 5 % of all children in the size range 134 cm to 136 cm are heavier than 36 kg. The data in table 4 is more critical. The medium weight reaches the weight level of 37.5 kg. 5 % of all the children in the size range of 144 cm to 146 cm weigh more than 53.3 kg. Table 5 shows a similar distribution. All data indicate that the European regulation No. 44 no longer represents current children living in Germany. Based on these data new overweight dummies were defined and manufactured.

Table 3.
Different anthropometric data of German children with a body size of 134-136 cm. The second column shows the number of measured children. [database CrestNet 2006-2008]

Children body size 134-136 cm	N	percentile		
		5%	50%	95%
Age [years]	658	7	9	11
Weight [kg]	**658**	**25.5**	**29.5**	**36.0**
Torso length [cm]	475	69.5	72.1	74.4
Shoulder width [cm]	475	27.2	29.0	30.7
Pelvis width [cm]	476	19.2	21.0	22.6
Chest [cm]	583	57.5	62.0	68.4
Waist [cm]	245	51.0	55.0	62.1
Abdomen [cm]	107	54.5	60.1	69.5
Hip [cm]	109	63.7	68.6	75.9

Table 4.
Different anthropometric data of German children with a body size of 144-146 cm. The second column shows the number of measured children. [database CrestNet 2006-2008]

Children body size 144-146 cm	N	percentile		
		5%	50%	95%
Age [years]	19104	8.7	10.7	13.5
Weight [kg]	**19104**	**30.4**	**37.5**	**53.3**
Torso length [cm]	425	73.2	75.9	79.0
Shoulder width [cm]	424	28.9	31.0	33.1
Pelvis width [cm]	427	21.0	22.6	24.6
Chest [cm]	537	61.5	66.7	78.0
Waist [cm]	223	53.3	58.1	70.2
Abdomen [cm]	103	58.9	64.0	79.8
Hip [cm]	113	66.6	73.9	86.1

Table 5.
Different anthropometric data of German children with a body size of 149-151 cm. The second column shows the number of measured children. [database CrestNet 2006-2008]

Children body size 149-151 cm	N	percentile		
		5%	50%	95%
Age [years]	567	10	12	14
Weight [kg]	**564**	**33.0**	**39.5**	
Torso length [cm]	382	75.3	78.1	81.1
Shoulder width [cm]	381	30.0	32.0	34.1
Pelvis width [cm]	384	21.6	23.5	25.7
Chest [cm]	472	63.0	69.3	80.4
Waist [cm]	178	54.3	60.1	73.8
Abdomen [cm]	75	56.6	66.5	82.4
Hip [cm]	91	68.9	78.3	89.0

OVERWEIGHT DUMMIES

The objective of this study is the evaluation of child restraint systems with *overweight* crash test dummies, weighing more than 36 kg. Currently, a lot of different child crash test dummies are available. A precise overview and technical specifications for

P-series, Hybrid III-series as well as for Q-series dummies can be found in the internet [3]. Only a weighted version for the Hybrid III 6 year dummy is available (115 cm, 27.9 kg).
Although the assembly of the P-series dummies is less sophisticated than the Hybrid III dummies they are still utilized for ECE R44 compliant tests. For this reason, it was decided to modify a P10 dummy (see figure 3). The P10 (*P10 base*) has a size of 137.9 cm and weighs 32.6 kg.

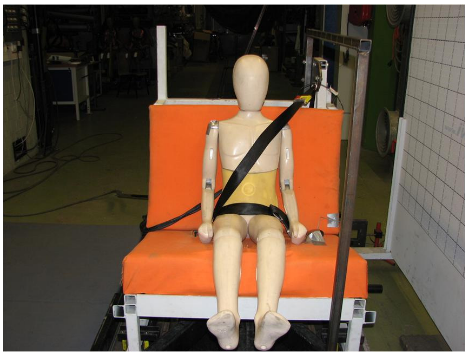

Figure 3. Standard P10 (*P10 base*) dummy belted on standard test device without child restraint system.

Three new dummies were defined (*P10 heavy*, *P10 large* and *P10 large and heavy*). Their technical data are summarized in table 6. The weights of the *P10 base* and of the *P10 large* represent the 50% percentile whereas the *P10 heavy* and the *P10 large and heavy* are 95% percentile versions (see table 4.). As children with a size of 150 cm are no longer legally obligated to use child restraint systems the *large* versions of the new dummies are restricted to a size of 145 cm.

Table 6.
Weights and heights for the P10 dummy and three modified versions.

dummy	weight [kg]	height [cm]
P10 base	32.6	137.9
P10 heavy	45.3	137.9
P10 large	37.5	145.0
P10 large and heavy	53.3	145.0

Basic dummy data

Technical data like 3d surfaces and weights of all dummy components are not commonly available, therefore the *P10 base* was scanned in detail. Using an optical 3d surface scanner the outer surfaces of all dummy parts were scanned. The skeleton of the dummy was x-rayed. Based on this data a complete 3d-Catia model of the dummy was built. Results are shown in figure 4.

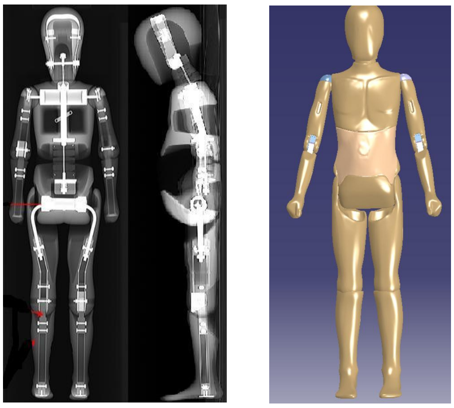

Figure 4. P10 (*P10 base*) dummy x-rayed in 2 views (left) and 3d-Catia model of the total assembly (right).

The net weights of all parts were measured necessarily. The 2 heavy versions were weighted proportionally to the reference weights. Exemplarily table 7 shows the weights of the subassembly leg.

Table 7.
Subassembly leg: weight of all parts and percentage of the total weight

#	Name	quan-tity	weight [g]	%
1	Hip ball joint	1	14,00	0,04
2	Hip joint nut/socket	1	143,90	0,44
3	Upper leg	1	3647,90	11,19
4	Lower leg	1	2566,75	7,87
5	Knee tensioner bolt	1	12,40	0,04
6	Knee tensioner nut	1	2,25	0,01
7	Friction washer	2	2,25	0,01
		total	6389,45	19,60

Overweight dummies

In order to weight the dummy torso and head additional metal plates are mounted to the rigid structure of the dummy. An additional jacket extends the girth of the torso. Shoulder and pelvis width remained unchanged. A proportional elongation of the torso height is necessary for the large versions of the new dummies. A new spine cable and additional elements for the lumbar vertebrae assembly increase the length. The foam abdominal insert is adapted respectively.

A simple modification of the extremities is not possible. Therefore, completely new arms and legs were manufactured. On the basis on the P10 extremities new parts were designed so that weight and length correspond to the new defined dummies as described in table 6. Exact data for the lower legs is given in table 8.

Table 8.
Lower leg assembly: Weights and lengths for the P10 dummy and three modified versions.

lower leg	weight [g]	length [mm]
P10 base	2567	385
P10 heavy	3566	385
P10 large	2953	404
P10 large and heavy	4197	404

The skeleton parts were scaled only in length for the large dummy versions. Therefore, the weight gain results, especially for the heavy versions, from an increased portion of the flesh. As the flesh is modeled with the original two-component polyurethane the volume of the heavy extremities was scaled up. Pictures in figure 5 and 6 show the new legs and lower arms.

OUTLOOK

Different types of child restraint systems will be inspected with the P10 and the new versions of the P10 according to UN-ECE Regulation No. 44. All selected CRS belong to ECE group II (15-25 kg) as well as to group III (22-36 kg). Some belong also to group I (9-18 kg). Figure 7 illustrates the differences between the seats. Combination seats allow children to use the same seat as they grow up.

Figure 5: Side view of four different left legs. From left to right: *P10 base, P10 heavy, P10 large* and *P10 large and heavy.*

Figure 6: Top view of four different left lower arms. From left to right: *P10 base, P10 heavy, P10 large* and *P10 large and heavy.*

Figure 7: Three typical CRS. From left to right: no-back booster seat (group II/III), high-back booster seat (group II/III) and combination seat (group I/II/III).

CONCLUSIONS

Statistical data clearly illustrate that for a lot of children not a single licensed child restraint system is obtainable. Moreover, the crash performance of child restraint systems is completely unknown if they are used by children, weighing more than 36 kg.

Based on detailed anthropometric analyses the weight of real children in Germany was identified and new overweight dummies were defined. New dummy components were built so that the crash behavior can be tested in near future.

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[3] www.ftss.com and www.radenton.com

A SAFE RIDE HEIGHT LINE FOR CHILD CAR OCCUPANTS

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ABSTRACT

Studies of child occupant safety in cars in have consistently reported that one of the biggest problems with unsafe use of child restraints is premature graduation of children into restraint systems that the intended for older children.

In 2007 our team conducted a study to identify ways of ensuring that children travel in the safest restraint for their age and size. The outcome of the review was subsequently included in revisions to Australian road rules.

During the study we identified the potential for the concept of a ‘safe ride height’ line. That is, the child restraint systems, and vehicles in which they travel, could both be clearly marked with a ‘safe ride height’ line to be used to indicate whether a child was an appropriate size for the restraint.

The ‘safe ride height’ line could be integrated prospectively and retrospectively across the full width of the seat back of the vehicle. If a child’s shoulders are below the line, the child is too small for an adult seatbelt.

In child restraints, the ‘safe ride height’ lines can be tailored for each type of restraint system. For example, in a forward facing child seat, there could be a lower ‘safe ride height’ line for a child who has just grown big enough, and an upper ‘safe ride height’ line for a child who now needs to graduate out of the restraint.

‘Safe ride height’ lines are included in the current draft for a revised Standard for child restraint systems in Australia.

What this paper offers that is new is the concept of a ‘safe ride height’ line that will provide an easy guide for carers as to the appropriate size restraint for a child and allow simple self evident enforcement of correct restraint usage rules.

INTRODUCTION

Premature graduation to booster seats and adult belts is widespread among child occupants in most developed countries [1-3], and is associated with an increased risk of injury [4-7]. Encouraging children to use the most appropriate restraint for their size is therefore a high priority in many jurisdictions.

The first step in achieving this is to clearly communicate to parents what restraint their child should be using and when their child should move to the next type of restraint. Graduation information is usually supplied to parents in terms of height and/or weight, and sometimes age. However, parents do not always know the height and/or weight of their children, particularly as their children move out of the infant and toddler stage. In a recent Australian telephone survey of parents with children aged 0-10 years, 16% reported being unsure of their child’s weight, and 34% reported being unsure of their child’s height (Brown & Bilston, unpublished data). Furthermore, without measuring heights and weights, parents often make inaccurate estimations [8]. This partly underlies the recent suggestion made by Anderson & Hutchinson [9] that restraint transition could be more easily complied with if parents and carers used age instead of weight and height.

Nevertheless, size, particularly seated height, is important in designing child restraint systems since:-

(i) there must be a good match between the restraint system and the size of child using the restraint, and
(ii) the quality of the transition from child restraint (i.e. booster) to adult seat belt requires a certain seated height and upper leg length to ensure adequate belt fit [10].

There are also some issues with weight in child restraint systems that use top tether straps as integral parts of the anchorage system as there is *theoretically* a need to stay within the design rule load requirements of tether anchorage points. Importantly however, in practice, there have been no reported failures of top tether anchorages in Australia, even in very severe real world frontal crashes up to 100km/hr in Australia since 1976. Full scale new vehicle crash barrier tests at up to 100km/h have also found no failures of top tethers or their anchorages (Griffiths & Wasiowycz, unpublished data).

The second step is the implementation of strategies to encourage parents/carers to always use the most appropriate forms of restraint for their child. This is achieved through widespread education campaigns and increasingly through mandating the appropriate size/age transitions using legislation. In countries or states with laws stipulating the use of specific types of restraint, the laws are written in terms of age or size, or a mix of both. However, it is well established that for legislation to be effective it must be accompanied by enforcement. Without realistic enforcement tools that are acceptable to enforcement officers, there is likely to be poor enforcement. Laws based on weight/height and age of child are difficult to check at the roadside. It is not realistic to expect police to carry weight scales and a tape measure, or for parents to carry a child's birth certificate with a photo ID.

Taking all of the above into account, we recently authored a discussion paper for the (Australian) National Transport Commission (NTC) reviewing child restraint legislation in Australia [11]. Previous Australian legislation required children up to 12 months of age to use a dedicated child restraint and beyond that age the legislation allowed the use of a dedicated child restraint or a seat belt. Clearly a one year old child should be in a dedicated child restraint with built-in harness rather then just an adult seat belt but the previous law has given some parents/carers the impression that a seat belt is acceptable.

The purpose of our review was to examine the possibility of extending the mandatory use of child restraints in Australia by addressing two primary issues: (i) if mandatory use of dedicated child restraints were to be extended, to what children should it be extended; and (ii) how should any legislation addressing appropriate use be written given age/size/weight issues outlined earlier. The discussion paper we prepared for the NTC formed the basis of a regulatory impact statement (RIS) [12] that initiated the formation of new Australian child restraint legislation based on child age. A copy of the legislation is included in Reference [11].

This paper presents a concept originating from that review aimed at improving the ease of communication of appropriate restraint transition sizes, and allowing for easier enforcement of legislation specifying appropriate restraint transitions. The benefits of the safe ride height concept were recognised in the RIS but were unable to be incorporated in this legislation as no vehicles were marked with these lines, and at the time the relevant Australian Federal authorities indicated they were unlikely to formulate a new Design Rule requiring ride height lines.

THE CONCEPT OF A 'SAFE RIDE HEIGHT' LINE FOR REAR SEAT OCCUPANTS

Anthropometric measurements are the best primary indicators of when good seat belt fit can be achieved [10]. Seated height and upper leg length in particular are important determinants for good seat belt fit, and these are likely to be related to overall stature, which is used by some jurisdictions to determine appropriate restraint usage. A difficulty is communicating the safety message associated which such measurements.

There are other common examples in the community where communicating a safety issue is achieved using 'safe height' indicators. For example, the Plimsoll line is a marking system at the waterline of a ship's hull to ensure the ship is not overloaded. "Safe height' indicators are also common at fairgrounds and amusement parks where a minimum height is needed to ensure safe retention of the child in the ride seat. These systems work because the regulatory 'height mark' is immediately available to both the users and enforcers. For fairgrounds, if you are not above the line, "you don't ride". The self evidence of the mark also assists parents and carers to explain to children why they are too small to ride.

We propose a similar approach for communicating the correct restraint transition size for child occupants. This would take the form of some marking on the vehicle seat trim that would indicate a minimum *seated shoulder height* for using a seat belt. The intention is that this would eventually replace the stature limit used in Europe and the USA for booster seats.

A recognised mark on the seat is clearly better than expecting parents to measure their children using a tape measure. It takes into account seat properties, such as the angle and a reclined seated height, child's seated position, and the downward compression of the seat base cushioning because of the weight of the child. It also removes the impractical need for enforcement officers to carry tape measures or other means of assessing height. Another advantage is that this allows children to see for themselves whether or not they fit the seatbelt. For example, this should assist the problem faced by parents of children who do not want to use child restraints because '*they are for babies*'.

THE 'SAFE RIDE HEIGHT' LINE LIMITS AND ASSESSMENT

The most commonly cited anthropometric transition point for child occupants moving into seat belts is a standing height of 145cm [10, 13-14]. This roughly equates to an 11.5 year old at the 50th percentile. In Europe, the recommended or legislated transition point varies from 135cm in some countries (equates approximately to the 50th percentile 9.5 year old) to 150cm in others (equates approximately to the 50th percentile 12.5 year old) [11]. These current recommendations are a useful starting point to determine what the 'safe ride height' line should be.

To include the 'safe ride height' line in a regulatory environment requires the availability of a measuring tool. There are two existing internationally accepted test dummies representing the 50th percentile 10 year olds. The overall length of these dummies falls within the 135cm to 150cm range and either dummy could be used as the reference tool, taking into account real child/test dummy seated posture differences like those described by Reed et al [18].

In our review we examined:-

- how to relate the seated 'safe ride height' line to anthropomorphic data on standing height, including the 1.35m to 1.50m guidelines

- whether the marked 'safe ride height' line should be at head height, eye height or shoulder height

Although generally overall height refers to the length between the floor and the crown of the head, accurately pinpointing the crown of a seated dummy's head can be problematic (e.g. due to chin tilt). Similar problems exist for seated eye height. Seated shoulder height appeared to be better because the child's shoulders are immediately adjacent to and normally resting on the seat back. Furthermore, seated shoulder height is a primary characteristic that is important in achieving good sash belt fit. Indeed, it could be argued that stature is a surrogate for this measurement.

Using United States data from 1997 [17] the correlation between seated shoulder height and stature among children aged four to twelve years is shown in Figure 1.

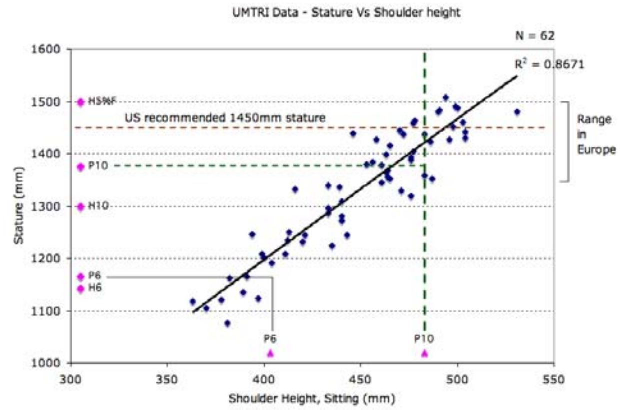

Figure 1: Shoulder height, stature, seat belt transition points and ATD anthropometry

Figure 1 also includes the relevant dimensions from a range of ATDs, where available. It is evident from this graph that the seated shoulder height of the TNO P10 ATD of 483mm (vertical dashed line) corresponds to the range of standing heights that have been suggested in Europe and the USA. That is, the P10 seated shoulder height is equivalent to a stature of about 1420mm in the US population (the actual stature of the P10 is 1376mm). This is slightly less than the 1450mm recommended by US authorities. It also spans most of the range of 1350mm to 1500mm standing height implemented in Europe.

At this point, we can not compare the seated shoulder height between the TNO P10 and the Hybrid III 10 year old, because we do not have that measurement for the Hybrid III available. However, the overall seated height of the two dummies is similar but exactly the same (72.5mm for the TNO P10 and 71.9 for the Hybrid III 10 year old) and we would expect the comparative seated shoulder height to be in the same ball park.

It is noted, that 1500mm stature is the same as that of the Hybrid III 5% adult female ATD. Basing the requirements on a seated shoulder height of 483mm, rather than 1500mm stature would exclude most small adult females from the booster rules, as intended.

Therefore we would propose the safe ride height line should be positioned close to a height of 483mm from the seat bite after allowing for some depression of the seat cushion because of the weight of the occupant. A possible alternative to using a dummy to specify this position, would be to use a simple test rig that simulates the seat cushion loading (i.e. mass and buttock shape) of the P10 dummy (i.e. something similar to a H-point machine).

As previously discussed, seated shoulder height is the primary measure for good sash belt fit. The main reason that standing height may have been used in booster rules to date is that it is perceived as more likely to be known by parents/carers (although subsequent surveys have shown that this is not the case) or that it is more readily linked to age through published growth chart data.

By introducing a 'safe ride height' line based on seated shoulder height in each vehicle seating position, the difficulties of determining child age or stature for enforcement of booster rules are eliminated.

Whilst other anthropometric measurements, such as seated eye height were considered by the authors, the seated shoulder height was clearly the most relevant and practical measurement to use for a 'safe ride height' line. For example any vehicle seat back not high enough to incorporate a shoulder height line would be unlikely to provide safe restraint for occupants whose shoulders were above the height of the seat back. Furthermore rear seat height is commonly below head and eye height (these areas being commonly protected by head restraints that occupy a small fraction of the width of the overall rear seat).

Figures 2, 3 and 4 demonstrate the 'safe ride height' line concept. The ride height line illustrated is indicative only and is 480mm above the seat bite. It is expected that using the TNO P10 ATD or some other means to measure height while depressing the cushion, would result in a slightly lower line.

Figure 2: 5 year old girl with a shoulder height clearly too small for the nominal safe ride height line.

Figure 3: 5 year old girl in booster and nominal safe ride height line

Figure 4: 13 year old boy with shoulder height greater than nominal safe ride height line.

OTHER BENEFITS

Other potentially significant benefits are that the 'safe ride height' line:-

- would be a compelling highly visible indicator of appropriate occupant height in rear seats

- as such, it would give vehicle manufacturers a stimulus to provide better sash belt geometry and provide an envelope in which they could optimise their sash belt fit.

CUSHION LENGTH, ANOTHER ISSUE

The 'safe ride height' line would effectively limit seated shoulder height for those using adult seat belts and give vehicle manufacturer's a more specific lower boundary to aim for when designing the sash geometry.

It would also address sash positioning problems associated with premature graduation to seat belts.

However, it would not have any influence on the current problem of the depth of the rear seat cushion.

Recent studies by Huang and Reed [15] and Bilston and Sagur [16] have demonstrated significant variability in rear seat cushion length and that current rear seat cushions are too deep for many occupants. Huang and Reed measured 56 vehicles in the North American fleet and found the rear seat cushion to be deeper than required for a 145cm child in all vehicles. Bilston and Sagur [16] in the 50 vehicles they measured from the Australian fleet, found all seat cushions were too deep for a child with upper leg length at the 50^{th} percentile until approximately 11.5 years, and half were too deep for a 15 year old at the 50^{th} percentile. With more attention being given to rear seat occupants it is expected that future seat cushion designs will cater for smaller occupants .

Whilst, in the authors' view, the benefits of a 'safe ride height' line are so significant that they should be quickly implemented, it is acknowledged that it would not resolve all of the problems with good seat belt fit in vehicles.

Better seat cushion length is an area that also needs attention.

EXTENDING THE CONCEPT TO CHILD RESTRAINT SYSTEMS

The 'safe ride height' line concept can easily be extended to dedicated child restraint systems and high back booster seats. The Australian/New Zealand child restraint Standards committee is currently considering a revised draft of the Standard that incorporates this concept. 'Safe ride height' lines are currently being incorporated as a more reliable way of identifying when children are too big or too small for the various classes of child restraints by using maximum and minimum 'safe ride height' lines. These match the upper and lower seated height for age limits of the various restraint types to correspond with the age based legislation being introduced into Australia (see reference 11).

PROPOSED METHOD FOR DETERMINING 'SAFE RIDE HEIGHT'

The following is suggested as one possible method for determining what the 'safe ride height' line should be in the seats of each vehicle.

1. Position the chosen anthropomorphic test device (e.g. TNO P10) in each seating position.
2. Position a "level" across both mid shoulder positions of the test dummy, so that one end of the level touches the seat back.
3. Record the positions on the seat back trim which is contacted by the level.
4. Position a tape or similar marker approximately 10 -20 mm wide (to allow for variability) to mark the 'safe ride height' line across the full width of the seat back of the seating position.

IMPLEMENTING THE CONCEPT

One way to implement the 'safe ride height' line concept would be to create an internationally harmonized vehicle regulation.

Alternatively, vehicle manufacturers could develop a voluntary set of guidelines to ensure uniformity across international markets.

Consumer strategies such as NCAP's could reward manufacturers who adopted this concept ahead of any mandatory requirements. In new vehicles it is envisioned the markings would be incorporated by manufacturers into the vehicle seat. For older vehicles there is the possibility of retro-fitting safe ride height indicators. In Australia this could be by the Government certified child restraint fitting stations. Elsewhere, organizations such as motoring service clubs could provide retro-fit services. However, since suitable child dummies are not readily available for this purpose it would be necessary for road safety authorities to arrange for each popular vehicle model to be assessed and safe ride height line locations determined. This information could then be disseminated for in-field use.

It would be feasible to develop a simple test rig that simulates the seat cushion loading (i.e. mass and buttock shape) of the P10 dummy and enables the safe ride height line to be established without the need for an expensive crash test dummy.

CONCLUDING REMARKS

In conclusion, the 'safe ride height' line concept:-

- provides a direct primary indicator of safe sash and shoulder height geometry tailored for each restraint system, in each seating position of a vehicle

- provides a simple, easy to understand, and easy to enforce tool to assist safer, more appropriate use of restraint systems

- is a minimal cost measure which could be quickly introduced for new and existing vehicles.

The content of this paper is the views of the authors only and does not reflect the views or policy of the Australian Government, Standards Australia or any other organisation.

ACKNOWLEDGEMENTS

The authors would like to acknowledge:-

- the Australian National Transport Commission (NTC) which funded the review which led to the identification of the 'safe ride height' line concept

- their co-authors in the NTC discussion paper Dr Robert Anderson and Dr Michael Henderson,

- others who provided comment particularly including Dr Lynne Bilston.

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NHTSA'S INITIAL EVALUATION OF CHILD SIDE IMPACT TEST PROCEDURES

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Paper No. 09-0539

ABSTRACT

This paper details the National Highway Traffic Safety Administration's (NHTSA) initial research to evaluate potential child side impact test procedures. Federal Motor Vehicle Safety Standard (FMVSS) No. 213, "Child Restraint Systems" currently only requires that U.S. marketed child restraints meet dynamic testing simulating a 48.3 kph (30 mph) frontal impact. NHTSA is evaluating test parameters and potential methodologies to replicate a representative side impact scenario that could potentially be developed into a future child restraint dynamic side impact test procedure. This paper will discuss (1) testing conducted using the side impact sled buck designed by TK HOLDINGS INC. (Takata), and (2) side impact moving deformable barrier (MDB) into vehicle crash tests, which were performed in an effort to refine sled buck test parameters. This study is limited to one generic sled test buck design concept and side impact tests involving small passenger vehicles. It was observed that the sled buck concept was repeatable and able to distinguish between child restraint system (CRS) models. The design of the CRSs' seat back side wing is an important element for providing side impact protection, particularly when impact angles are varied. Trends in injury response values between sled and crash tests were similar for the two CRS models used in both types of testing.

INTRODUCTION

This study looks at the use of dynamic generic sled simulations to replicate the performance observed during vehicle crash tests of a properly restrained 3-year-old child dummy. With only a side impact child dummy representative of a 3-year-old currently available, the 1- to 3-year-old age group was the primary focus for the agency's initial evaluation of child restraint systems during side impact crashes. The TNO Q3 side (Q3s) dummy and the Hybrid III 3-year-old dummy, with a side impact neck (H3Cs), were used as Anthropomorphic Test Devices (ATDs).

Children represent more than 50% of the rear seat occupants in motor vehicle crashes. Side impacts are the second most frequent collisions resulting in child occupants sustaining serious to life-threatening head, neck and chest injuries. Using NHTSA's National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) database (1995-1996, 1998-2004), it was determined that side impacts account for 27% of the crashes involving 0-12 year old occupants. For those side impacts, 42% involved children 0-3 years old, 36% involved 4-8 year olds and 22% involved 9-12 year olds. [1]

For children 1-3 years old, 9% of those with survivable injuries were unrestrained (NASS-CDS) and 46% of the fatally injured were unrestrained (FARS 1994-2003). Using unweighted values, due to the paucity of NASS-CDS data for the 1-3 years age group, side impacts with a $\Delta V \geq 30$ kph (18.7 mph) provided 28 children with 104 injuries. For this subset, it was observed that:

- The PDOF of the subject side impact crashes was approximately 30^o off lateral,
- Near-side and center occupants suffered more severe injuries (AIS2+) than far-side occupants, and
- Direct contact with the vehicle interior accounted for 45% (47) of the injuries, while 14.4% (15) were due to contact with the child restraint system (CRS). Of these 104 injuries, 57% were to the head, 21% to the torso and 6% to 9% were to the neck and the upper and lower extremities.

HYGE SLED TEST SERIES

Sled Buck Configuration

The sled buck used was a side impact buck designed by Takata, which consists of a sliding "vehicle" seat mounted to a rail system along with a "side door" structure rigidly mounted to the sled buck structure. A specific density of aluminum honeycomb is mounted below the "door" structure. The sliding "vehicle" seat is positioned sufficiently away from the "side door" to allow the sled to reach a desired velocity prior to the sliding "vehicle" seat coming into contact with the "side door" and aluminum honeycomb. The principle of this design is that the sliding "vehicle" seat and CRS impact the side "door" structure at a desired speed, at which time the aluminum honeycomb begins to crush, replicating the intrusion velocity of the "door" that the CRS would experience during an actual vehicle crash. Figure 1 shows a schematic of the Takata side impact buck configuration. A photo of the actual set-up used by NHTSA is shown in Figure 2.

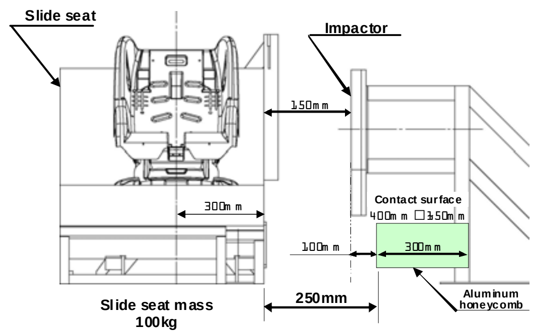

Figure 1. Takata's Side Impact Sled Buck.

Figure 2. NHTSA's Side Impact Sled Buck Set-up.

Two differences between the Takata buck and the NHTSA buck set-ups are notable. First, the ECE Regulation No. 44 seat cushion foam used by Takata was replaced with the cushion foam used in the FMVSS No. 213 seat fixture. Secondly, the initial seat to honeycomb distance was increased from 250 mm to 260 mm for the NHTSA tests. The distance was increased in order to obtain the desired impact velocity while preventing the sliding seat from bottoming out against the support structure behind the honeycomb.

Initial Sled Test Parameters Used by NHTSA

The agency chose to look at small vehicles to develop the test parameters. The vehicle models selected were previously tested in accordance with FMVSS No. 214 "Side Impact Protection" Moving Deformable Barrier (MDB) test procedure. As noted earlier, the Takata buck design is unique in that it has two moving fixtures – the sled buck itself and the seat on which the child restraint is attached. The critical factor for the sled buck is to have the "door" structure reach the desired velocity prior to its contact with the sliding "vehicle" seat. The desired door velocity and sliding seat acceleration pulse were determined in order to determine these parameters.

Determination of Sliding Seat Acceleration Pulse – The target acceleration pulse for the sliding seat was determined by evaluating the right rear sill Y-axis accelerometers in ten small vehicles that were tested per FMVSS No. 214. There was a negligible difference between the acceleration pulses obtained from use of the X-Y resultant and that from use of only the Y-axis accelerations. Therefore, only the Y-axis accelerometers were used in this analysis. Each of these vehicles had a 50th percentile adult male and/or a 5th percentile adult female dummy in the rear seat. Those vehicles* were:

- 2005 Toyota Corolla
- 2005 Toyota Corolla
- 2005 Subaru Forester
- 2005 Suzuki Forenza
- 2005 Subaru Forester
- 2003 PT Cruiser
- 2003 Mazada Protégé
- 2003 Suzuki Aerio
- 2005 Saturn Ion
- 2005 Saturn Ion

*(See Appendix for the FMVSS No. 214 Vehicle Database test numbers and dummy types)

The right rear sill values were averaged together to derive a typical acceleration level for a small sized vehicle. The dotted black line shown in Figure 3 represents this average. The upper and lower boundaries (blue lines) of sliding seat pulse were based on the maximum and minimum values of the cluster of acceleration curves when the individual curves for the ten vehicles were overlayed on one plot. The red line is representative of the actual sliding seat acceleration pulse obtained in the tests reported in this paper. The data channels were filtered with a Class 60 filter.

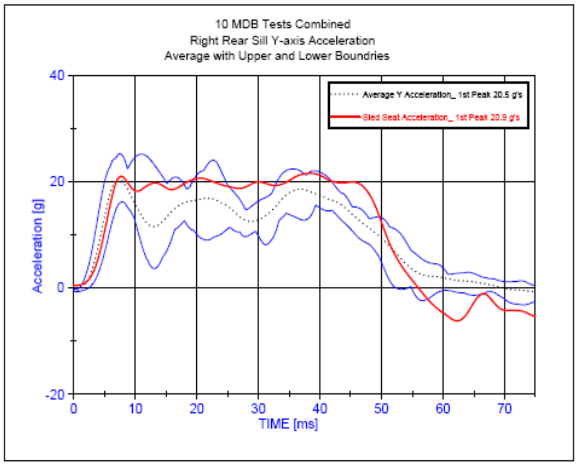

Figure 3. Sliding Seat Pulse with Boundaries.

Determination of Sliding "Vehicle" Seat Velocity – The aforementioned ten vehicles were also used to determine the desired sliding seat velocity. The accelerometers were integrated to calculate the velocity and then averaged together. The derived velocity was approximately 27 to 29 kph (17 to 18 mph).

Determination of "Door" Velocity – The determination of the door velocity was from four small vehicles tested under FMVSS No. 214. The four vehicles* used for this derivation were:

- 2005 Subaru Forester
- 2005 Toyota Corolla
- 2005 Suzuki Forenza
- 2005 Saturn Ion

*(See Appendix for the FMVSS No. 214 Vehicle Database test numbers)

The derived average velocities (Y-axis) ranged from 31.4 kph at the upper centerline of the door to 33.0 kph at the mid centerline. Therefore, 32 kph (20 mph) was selected as the target speed of the door on the sled buck. The shape of the acceleration pulse for the sled/door was not critical, but it should be at peak speed prior to the honeycomb contacting the sliding seat structure. This was achieved using a half-sine acceleration pulse for the sled/door, with a peak acceleration of about 28 G's and a duration of about 55 milliseconds.

Figure 4 shows the sled/door velocity (red line) and the sliding seat velocity (blue line) for a typical sled test. As can be seen, the actual sliding seat velocity exceeded the desired speed of 27 to 29 kph (17 to 18 mph) derived from crash tests. This is due to the mass of the sliding seat being small compared to that of the sled, as compared to in the crash tests, where the mass of the struck vehicles and the MDB were more similar. Based on engineering judgment, maintaining a door velocity of about 32 kph (20 mph) and a sliding seat acceleration pulse that matched the corridors shown in Figure 3 were deemed more critical than achieving the desired seat velocity. The large mass difference between the sliding seat and sled would require adding significant weight to the sliding seat in order to reduce the seat velocity.

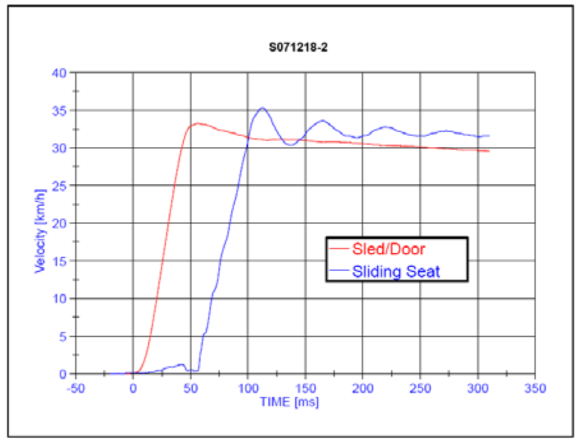

Figure 4. Typical "Door" and Seat Velocities.

Determination of Sled Buck Angle – The ten vehicles which were used to derive the test pulse boundaries and the door velocity were used to determine the impact angle of the sled buck. The right rear side sill X-axis and Y-axis accelerations were integrated to obtain the corresponding component velocities. These were then used to calculate the angle of the resultant deceleration with respect to the lateral axis of the vehicle during the crash event. The time period of interest was determined to be five to 60 milliseconds, which represents the typical time from initial motion of the struck vehicle through peak loading on the near-side occupant. A reference frame was used in which a pure left-to-right lateral impact was zero degrees and a pure frontal impact was 90 degrees. The mean angles over the time period of interest for the ten vehicles ranged from four to 15 degrees, while the angle at any specific time ranged from -8 to 22 degrees across the ten vehicles. Based on this, it was decided to consider the range from 0 to 20 degrees for the test program reported here.

Summary of Test Parameters – The following test parameters were used for the sled tests:

- Sled pulse – ½ sine, 28 G peak, 55 msec duration
- Sled velocity – 32 kph (20 mph)

- Honeycomb dimensions (2.3 PCF, 3/8" cell wall): 300 mm thick x 342 mm wide x 125 mm long
- Sliding seat initial position – 260 mm from honeycomb
- Sliding seat acceleration – matches corridors in Figure 3, 20 G peak, 55 msec duration
- Door padding - 5 cm foam thickness
- Lateral (0^o) and oblique (10^o, 15^o and 20^o) impact angles

Sled buck and test parameters, such as initial seat to door spacing, honeycomb stiffness and/or dimensions, door padding and sled speed, can be altered in order to fine-tune results.

Discussion of Side Impact Sled Test Results

CRS Models Tested – It was desirous to test models of CRS that meet FMVSS No. 213 and/or ECE Regulation No. 44 requirements. In addition to testing U.S. compliant CRS models, it was of interest to test models that meet the European restraint standard. For this initial evaluation of the test configuration, a total of five CRS models were selected:

- Graco SafeSeat Step2 Toddler
- Evenflo Triumph Advance DLX
- Safety 1st All-in-One Convertible
- Maxi-Cosi Priori (SIP)
  (meets both FMVSS No. 213 & ECE Reg. 44)
- Graco Logico M (SIP)
  (meets only ECE Reg. 44)

All of the CRS models were tested in the forward-facing mode with the 3-year-old Q3s side impact dummy. The LATCH system was used to install the seats, except for the Graco Logico M. By being compliant only with ECE Reg. 44, the Logico M does not have ISOFIX hardware. It was installed with a lap/shoulder belt restraint (no top tether).

Evaluation of Test Methodology – The first series of sled tests consisted of conducting tests with the five CRS models at a simulated 0^o impact angle. Each CRS model was tested at least twice; two of the models, the Graco SafeSeat Step2 and the Safety 1st All-in-One, were tested six and four times, respectively.

Five different dummy responses were used to evaluate the repeatability of the test procedure: HIC_{15}, upper neck tension, spine y-axis acceleration, pelvis y-axis acceleration and chest lateral displacement. Because there are currently no established injury assessment reference values (IARV) for the child side impact dummies, the test results were used solely for comparative purposes and not to ascertain "pass/fail" conditions.

Figure 5 contains the mean HIC_{15} values for each of the CRS models, while Figure 6 contains the mean neck tension values.

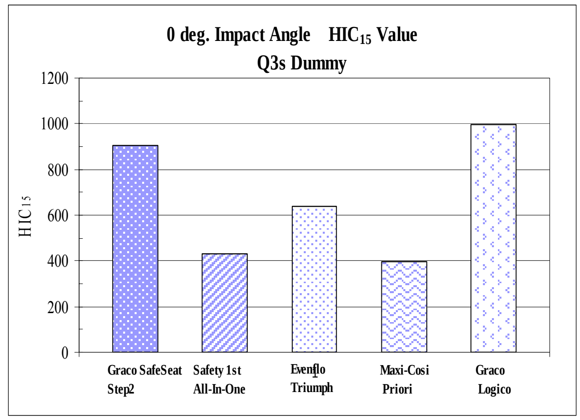

Figure 5. Mean HIC_{15} Values at 0^o Impact Angle.

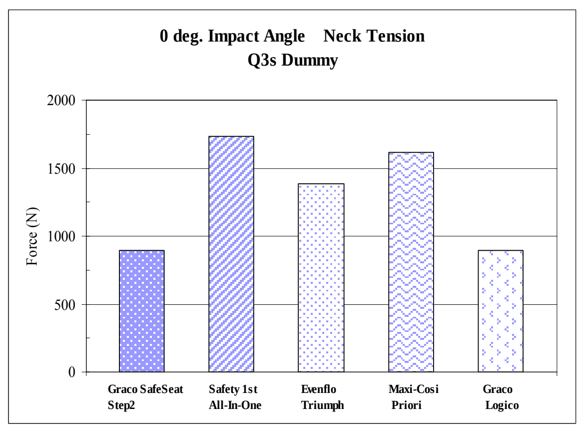

Figure 6. Mean Neck Tension at 0^o Impact Angle.

It is noted that there appears to be a trend between HIC_{15} value and neck tension; as one value increases, the other decreases. The HIC_{15} value tends to be higher when there is a more pronounced lateral component to the dummy's head motion (i.e., more direct lateral contact with CRS side wing). If the forward component of the dummy's head motion is more pronounced, the contact force on the head decreases while the inertial loading on the neck from the head increases. This tends to result in higher neck tensions and lower HIC_{15} values.

The mean values for the spine and pelvis Y-axis accelerations are shown in Figures 7 and 8, respectively, and the mean chest displacement values are shown in Figure 9 for the five CRS models tested at 0^o impact angle.

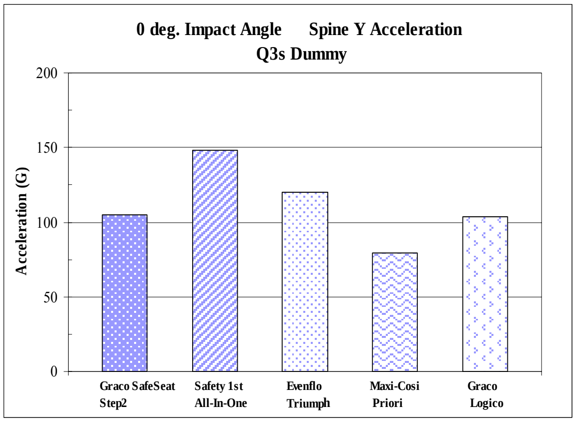

Figure 7. Mean Spine Y-axis Acceleration at 0^o Impact Angle.

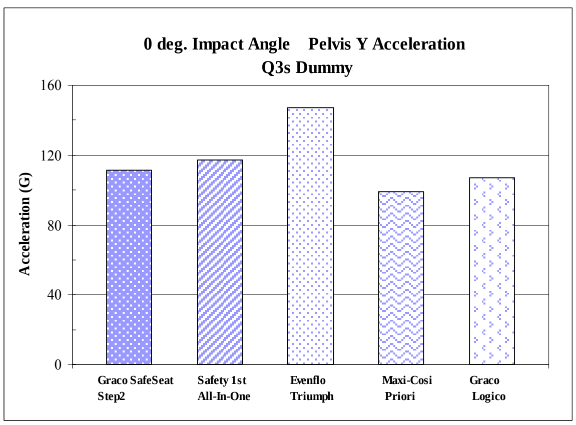

Figure 8. Mean Pelvis Y-axis Acceleration at 0^o Impact Angle.

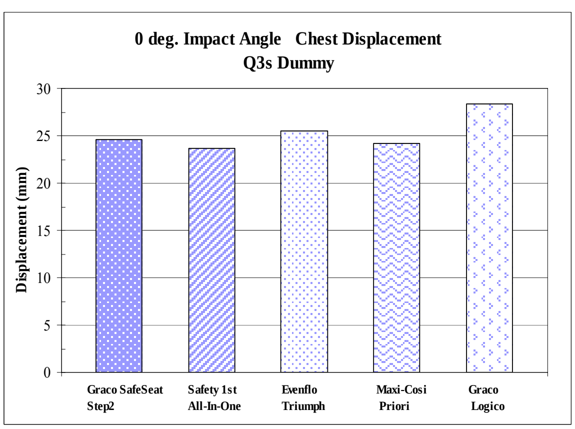

Figure 9. Mean Chest Lateral Displacement at 0^o Impact Angle.

Evaluation of Impact Angles – Subsequent to the 0^o impact angle tests, a series of tests were performed with the sled buck rotated to simulate impacts at 10^o, 15^o and 20^0. This series was conducted in an effort to evaluate the effect of the buck's impact angle on dummy kinematics. In addition to replicating dummy injury responses, it is also desirous to replicate the dummy's kinematics observed in side impact crashes.

The three CRS models tested in this series – Graco SafeSeat Step2, Evenflo Triumph and Maxi-Cosi Priori – were selected primarily because of their seat back side "wing" design. The SafeSeat Step2 and the Maxi-Cosi Priori have wings that are essentially perpendicular to the CRS seat back. The wings on the Evenflo Triumph are slightly more angled outward relative to the seat back (see Appendix for photos of CRS models). The Safety 1st All-in-One was not chosen for this series because dummy head contact with the side "door" structure had been observed when the buck was oriented at 0^o; testing at angles greater than 0^o with this CRS model would not have garnered pertinent information with regard to effect of impact angle. Also, the Graco Logico was not tested at impact angles greater than 0^o because the CRS was not available at the time of the test series.

The HIC_{15} values for the three CRS models at the four different sled buck orientations are shown in Figure 10. Two of the CRS models (SafeSeat Step2 and Maxi-Cosi Priori) exhibited a trend of decreasing HIC value with increasing impact angle, while the third CRS (Evenflo Triumph) exhibited the reverse trend – increasing HIC value with increasing impact angle. For all three CRS models, the dummy's upper torso and head increasingly rotated forward in the CRS as the impact angle increased. Although the dummy kinematics were similar for all three seats, the design of the seat back side wings appears to affect the head responses (see Figure 11 for photos of Graco SafeSeat Step2 and Evenflo Triumph CRS, respectively). The SafeSeat Step2 and Maxi-Cosi Priori's more straight forward wing design better contained the head throughout the event, allowing the head velocity to dissipate during the dummy's forward rotation. This was not the case for the Evenflo Triumph. Because the wing design for this CRS is slightly more outward relative to the seat back than the other CRS models, the dummy's head contacted the side wing and then rotated outward along the edge of the wing resulting in more pronounced head rotation and excursion than observed for the other two models.

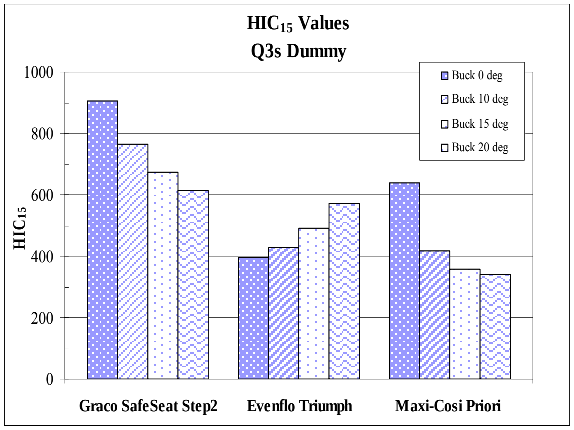

Figure 10. HIC_{15} Values for 0°, 10°, 15° and 20° Sled Impact Angles.

Figure 11. Examples of Wing Designs (Graco SafeSeat Step2 [left] and Evenflo Triumph [right]).

The dummy's peak neck tension values for the three CRS models at each impact angles are shown in Figure 12. As anticipated, neck tension generally tended to increase as the impact angle increased due to the forward rotation of the upper torso and head. Note that for the Evenflo Triumph, the neck tension significantly increased once the impact angle was greater than 0°. The CRS model's wing design appears to have an effect on the increase in tension values, as previously discussed.

Figures 13 and 14 show the spine and pelvis Y-axis accelerations, respectively, for the four sled test impact angles. The accelerations tended to be greater when tested at the 0° impact angle for the SafeSeat Step2 and Triumph, while they were virtually identical across the impact angle range for the Maxi-Cosi Priori.

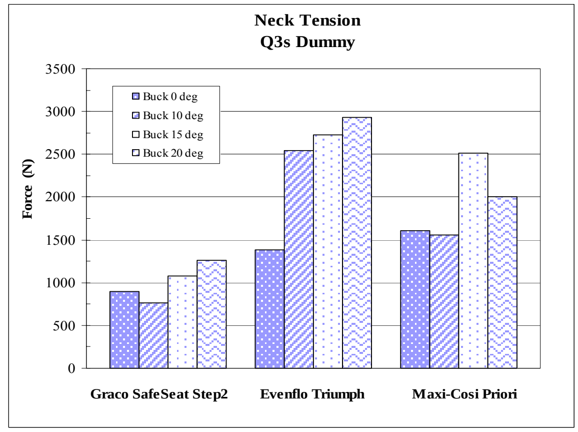

Figure 12. Neck Tension for 0°, 10°, 15° and 20° Sled Impact Angles.

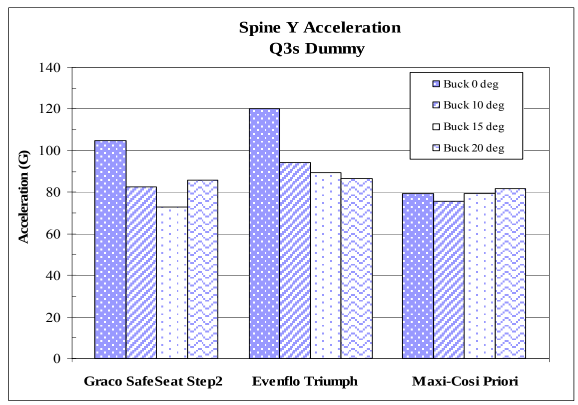

Figure 13. Spine Y-axis Acceleration for 0°, 10°, 15° and 20° Sled Impact Angles.

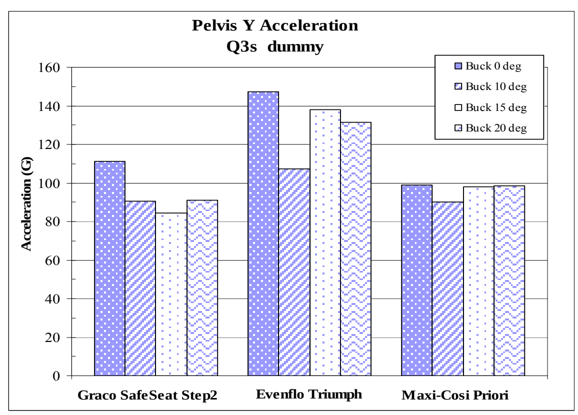

Figure 14. Pelvis Y-axis Acceleration for 0°, 10°, 15° and 20° Sled Impact Angles.

The dummy's lateral chest displacement for the four impact angles are shown in Figure 15. No specific trend appeared for the three CRS models. For the SafeSeat Step2, displacement values varied by approximately 6 mm, while displacement varied approximately 3 mm for the other two models.

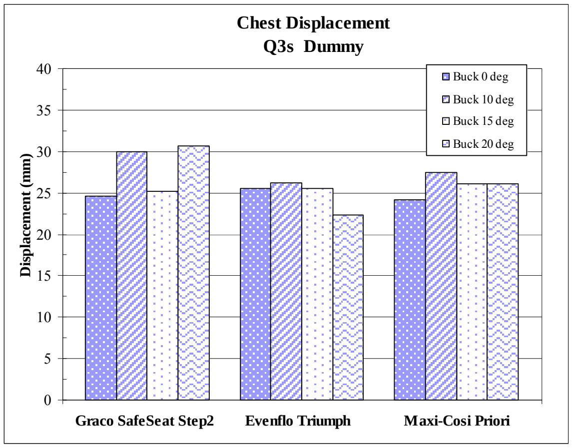

Figure 15. Chest Lateral Displacement for 0°, 10°, 15° and 20° Sled Impact Angles.

FULL-SCALE SIDE IMPACT CRASH TESTS

Subsequent to the sled testing, a series of four full-scale crash tests were conducted to better define sled parameters in an effort to more realistically replicate real-world crashes.

Two vehicles, a 2008 Nissan Sentra and 2008 Nissan Versa, were subject vehicles, and the FMVSS No. 214 standardized MDB was the striking vehicle. The targeted impact velocity was 52.8 kph (32.8 mph), with impact occurring on the left side of the vehicle. For the first test, Sentra test #v06634, the impact location was that specified in FMVSS No. 214D [2]. For the remaining three tests, the impact location on the subject vehicle was moved rearward 229 mm (9 inches) to provide for more direct contact of the MDB with the child restraint. Although both the Sentra and Versa had side curtain air bags in the rear compartment, the air bags were disconnected for the crash tests to allow for a direct comparison with the sled, which does not have a side curtain fixture.

Two ATDs representing a 3-year-old child – the Q3s and a Hybrid-III 3Cs (H3Cs) – were seated in the left and right rear passenger locations, respectively. The H3Cs dummy is the standard HIII 3-year-old dummy with a prototype neck designed for use during side impacts. Only the results of the Q3s dummy will be discussed in this paper. Each dummy was restrained in a forward-facing child restraint which had been properly installed in the vehicle using the LATCH system. The two CRS models chosen for these tests were the Graco SafeSeat Step2 and the Maxi-Cosi Priori. The matrix of crash tests is contained in Table 1.

Table 1.
CRS Side Impact Crash Test Matrix

Test No.	Vehicle	Near-side Q3s	Far-side H3Cs	Impact Location
v06634	2008 Nissan Sentra	Graco SafeSeat Step2	Graco SafeSeat Step 2	TP-214D-08
v06635	2008 Nissan Sentra	Graco SafeSeat Step2	Graco SafeSeat Step 2	228.6 mm rear of TP-214D-08
v06636	2008 Nissan Versa	Graco SafeSeat Step2	Graco SafeSeat Step 2	228.6 mm rear of TP-214D-08
v06637	2008 Nissan Versa	Maxi-Cosi Priori	Maxi-Cosi Priori	228.6 mm rear of TP-214D-08

The following sections will compare and discuss the results from the sled tests, conducted at the four impact angles, and the crash tests.

Comparison of Sled and Crash Test Results with Graco SafeSeat Step2 Child Restraint System

The HIC_{15} results from the sled tests at the four angles and the three crash tests for the dummy seated in the SafeSeat Step2 are shown in Figure 16. As noted previously for this CRS model, the HIC_{15} values decreased as impact angle increased during sled tests. For all three crash tests, the HIC_{15} values were lower than those from the sled tests. The values from the two Sentra tests were essentially identical, regardless of the fact that for test #v06635, the MDB's impact location was 229 mm (9 inches) rearward of where it was in test #v06634. Among the two vehicle models, the HIC_{15} value for the Versa test #v06636 was approximately 20% lower than those for the two Sentra tests.

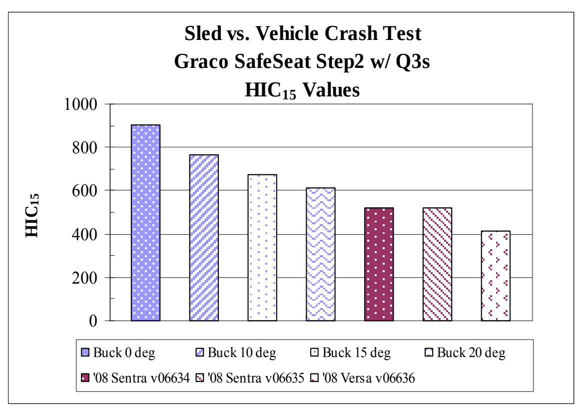

Figure 16. Comparison of HIC_{15} Values from Sled Tests at Various Side Impact Angles and Crash Tests.

Figure 17 contains the neck tension results for the sled and crash tests. The peak neck loads when the

SafeSeat Step2 was tested at 15° and 20° tended to be more comparable to those observed in the three crash tests. The 15° sled test result was consistent with the result from the Sentra test in which the MDB was positioned at the standard FMVSS No. 214 impact location. The 20° sled test result agreed with the crash test results when the MDB was moved rearward to provide for more direct contact with the CRS, regardless of vehicle model.

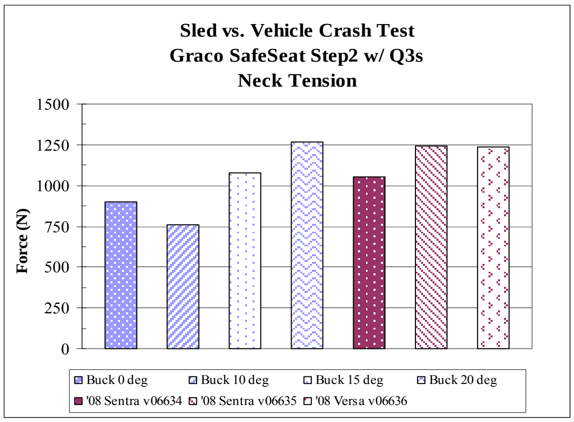

Figure 17. Comparison of Neck Tension from Sled Tests at Various Side Impact Angles and Crash Tests.

Figures 18 and 19, respectively, contain the spine and pelvis Y-axis accelerations for the sled and crash tests. As noted previously, both the spinal and pelvic accelerations were the highest during the sled tests when the impact angle was 0°. There were no definitive trends observed for the spine accelerations; the angled sled tests' and the crash tests' results were similar, ranging from 73 G's to 92 G's.

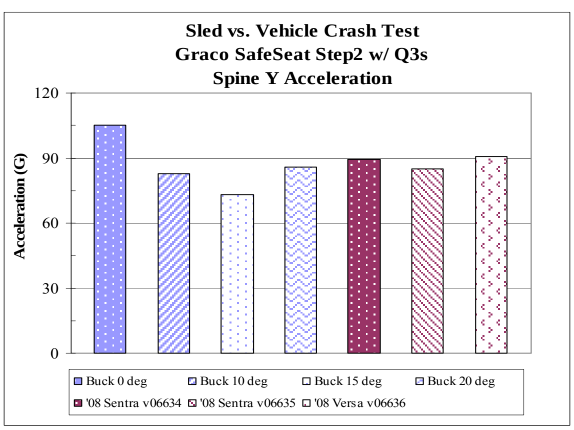

Figure 18. Comparison of Spine Y-axis Acceleration from Sled Tests at Various Side Impact Angles and Crash Tests.

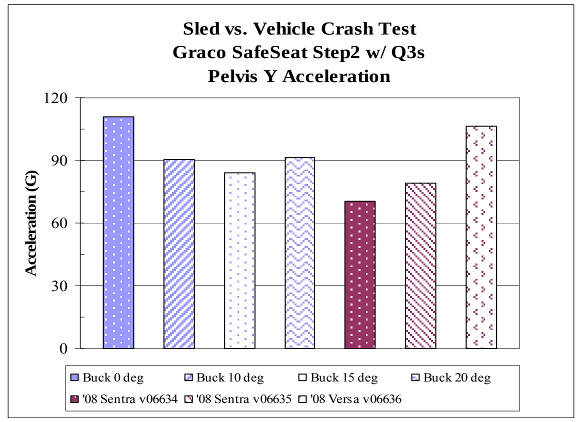

Figure 19. Comparison of Pelvis Y-axis Acceleration from Sled Tests at Various Side Impact Angles and Crash Tests.

The pelvic results for the three angled sled tests and crash tests did differ somewhat, with the results being slightly lower in the two Sentra tests. However, the pelvis response in the Versa crash test was very similar to the 0° sled test response. It was noted from the test footage that interaction with the armrest in the vehicle crash tests appeared to result in a more pronounced inboard rotation of the CRS base than was observed in the sled tests. The angular intrusion of the front edge of the door (near B-pillar) also appeared to contribute to the CRS base inboard rotation. A frame from a digital high speed imager of the near-side Q3s dummy, seated in the SafeSeat Step2 seat, at 57.5 ms into the crash event is shown in Figure 20. This typifies the more pronounced inboard rotation of the CRS base and the angular intrusion of the door observed in the crash tests.

Figure 20. Near-side Dummy (Test #v06635, Sentra); Example of CRS Base Rotation and Angular Door Intrusion.

For each of the crash tests, the following three locations on the CRS were translated to the side door structure:

- “seat bight” of the CRS’s back and cushion
- CRS base, approximately mid fore-aft of base
- front edge CRS base

These three points are designated as “4”, “3” and “2”, respectively, in Figure 21.

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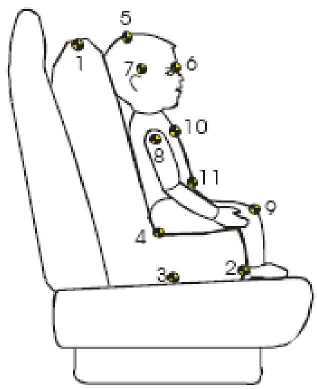

Figure 21. Measured Locations on CRS and Child Dummy.

Photographs of the struck side rear door panel, pre-test and post-test respectively, for Sentra test #v06635 are shown in Figures 22 and 23. Similar photographs for Versa test #v06636 are shown in Figures 24 and 25. For both vehicles, the armrest and, to a certain extent, the lower door panel protruded into the vehicle more than did the upper portion of the door panel, thereby resulting in the lower portion of the CRS structure being contacted earlier than the remainder of the CRS. The “door” structure used in the agency’s initial series of sled tests was essentially a flat wall configuration.

Figure 22. Sentra #v06635 Struck Side Door Panel, Pre-test.

Figure 23. Sentra #v06635 Struck Side Door Panel, Post-test.

Figure 24. Versa #v06636 Struck Side Door Panel, Pre-test.

Figure 25. Versa #v06636 Struck Side Door Panel, Post-test.

Sled versus crash tests comparison of the lateral chest displacement, when the Q3s was restrained in the SafeSeat Step2, is shown in Figure 26. Regardless of sled impact angle, the results observed in the sled tests were greater than those observed during the three crash tests. It is believed that this disparity in values is primarily due to the difference in the side door configuration and stiffness. Because the dummy’s pelvis and lower torso were engaged earlier in the crash event than was the upper torso, due to the armrest/lower door panel configuration, the thoracic displacements were not as large as those observed during the sled tests.

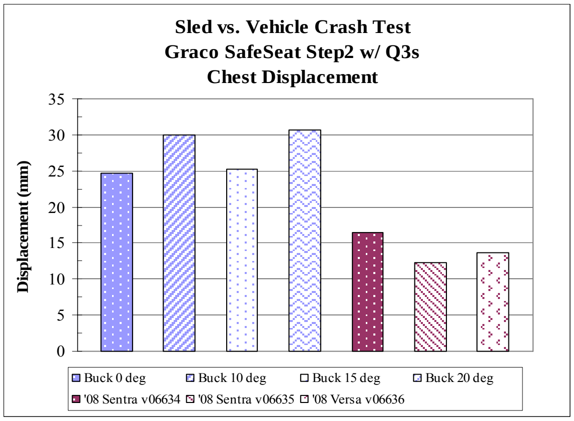

Figure 26. Comparison of Chest Lateral Displacement from Sled Tests at Various Side Impact Angles and Crash Tests.

Comparison of Sled Tests and Crash Test with Maxi-Cosi Priori Child Restraint System

Figure 27 shows the HIC_{15} results from the sled tests at the four angles and the one crash test (Versa #v06637) conducted with the dummy seated in the Maxi-Cosi Priori. This CRS model exhibited a trend of decreasing HIC_{15} values as the impact angle increased. For the one crash test conducted with this CRS model, the Q3s dummy's HIC_{15} value was approximately 50% less than the values observed for the three non-zero angled sled tests.

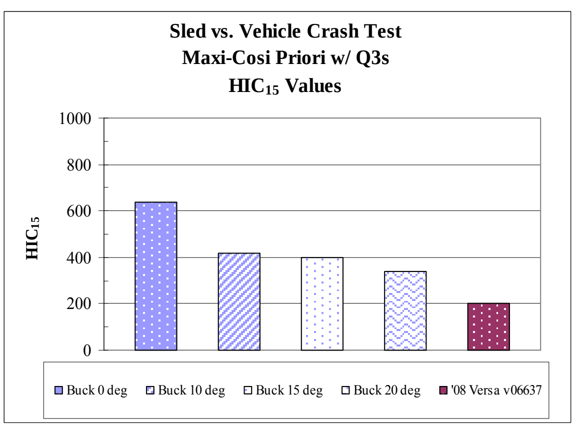

Figure 27. Comparison of HIC_{15} Values from Sled Tests at Various Side Impact Angles and Crash Test.

Comparison of the neck tension responses for the four sled angles and one crash test conducted with the Maxi-Cosi Priori are shown in Figure 28. The neck tension values observed in the crash test were comparable to the values observed during the 15° and 20° angled sled tests. This trend is similar to that observed with the SafeSeat Step2.

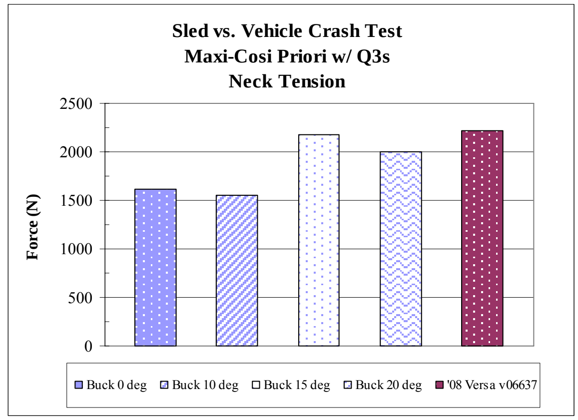

Figure 28. Comparison of Neck Tension from Sled Tests at Various Side Impact Angles and Crash Test.

Although the Q3s dummy's head rotated sufficiently around the CRS side wing to contact the side door upper panel (see Figure 29) during the crash test, the HIC_{15} and neck tension responses were less than or similar to the sled tests' responses.

Figure 29. Q3s Dummy Head Contact, Maxi-Cosi Priori in Versa #v06637.

The spine and pelvis Y-axis accelerations for the sled and crash tests are shown in Figures 30 and 31, respectively. As noted previously, spinal and pelvic accelerations observed during sled tests were essentially identical regardless of impact angle. The spine and pelvis accelerations observed during the crash were similar to those from the sled tests, although tending toward the high end of the response range.

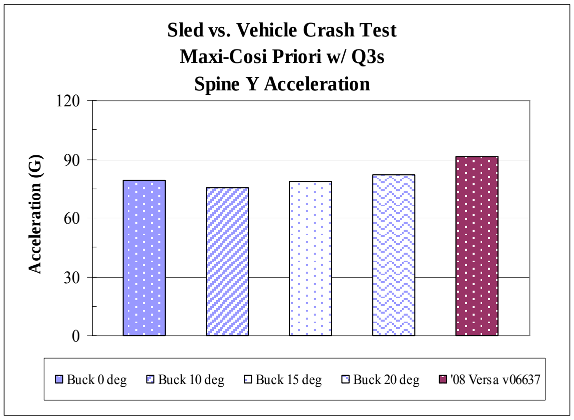

Figure 30. Comparison of Spine Y-axis Acceleration from Sled Tests at Various Side Impact Angles and Crash Test.

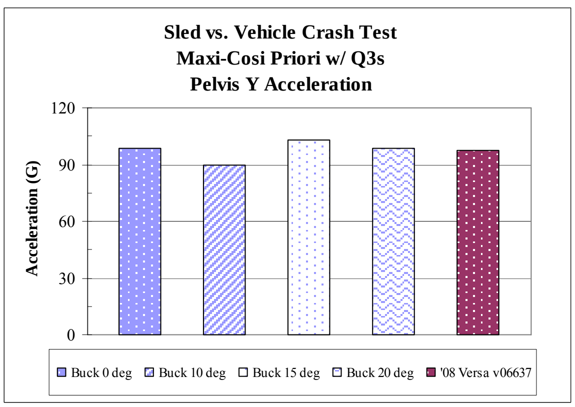

Figure 31. Comparison of Pelvis Y-axis Acceleration from Sled Tests at Various Side Impact Angles and Crash Test

As had been observed with the SafeSeat Step2, the lateral displacement of the Q3s' chest, when restrained with the Maxi-Cosi Priori during the crash test, was significantly less than the displacements observed during the sled test series (see Figure 32).

Comparison of Graco SafeSeat Step2 and Maxi-Cosi Priori Child Restraint Systems Tested in 2008 Nissan Versa Crash Tests

The last two crash tests, v06636 and v06637, enabled an indicant type of comparison of the performance of two different CRS models when crash tested in identical vehicles.

HIC_{15} and neck tension (see Figures 33 and 34, respectively) were the injury responses exhibiting the largest differences between the SafeSeat Step2 and Maxi-Cosi Priori. The spine and pelvis y-axis accelerations and the chest lateral displacements were very similar for both CRS models (see Figures 35, 36 and 37, respectively).

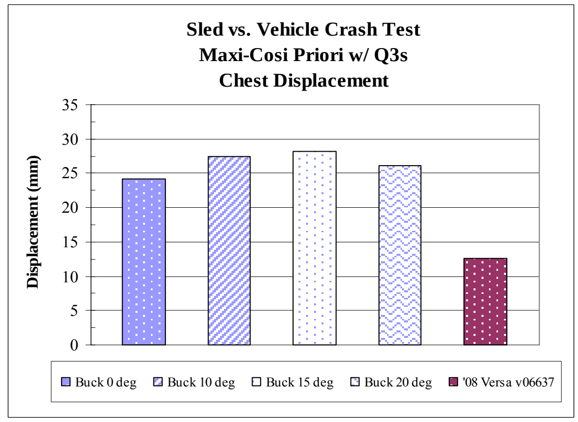

Figure 32. Comparison of Chest Lateral Displacement from Sled Tests at Various Side Impact Angles and Crash Test.

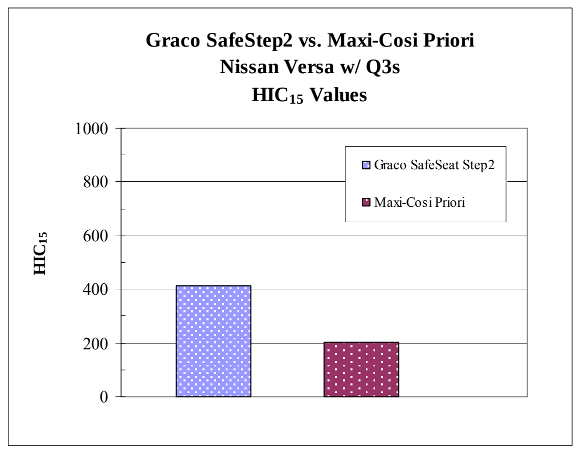

Figure 33. Comparison of HIC_{15} Values for CRS Models in Nissan Versa Crash Tests.

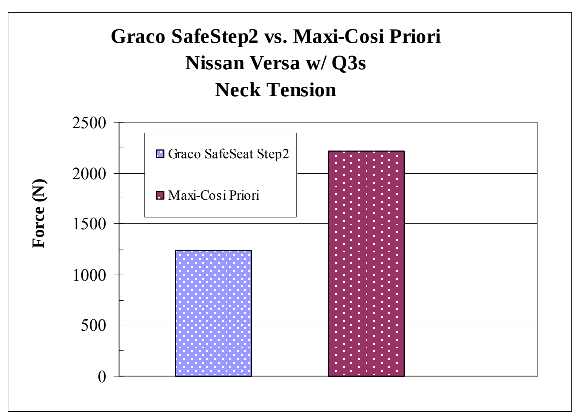

Figure 34. Comparison of Neck Tension for CRS Models in Nissan Versa Crash Tests.

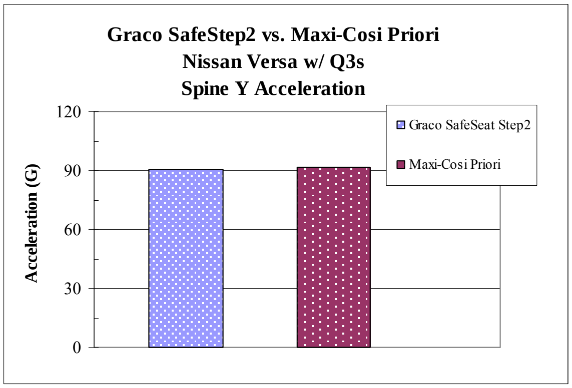

Figure 35. Comparison of Spine Y Acceleration for CRS Models in Nissan Versa Crash Tests.

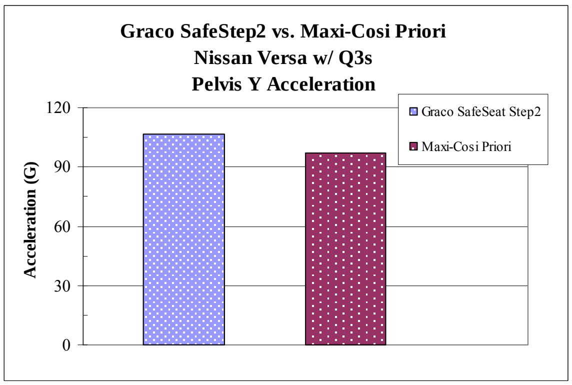

Figure 36. Comparison of Pelvis Y Acceleration for CRS Models in Nissan Versa Crash Tests.

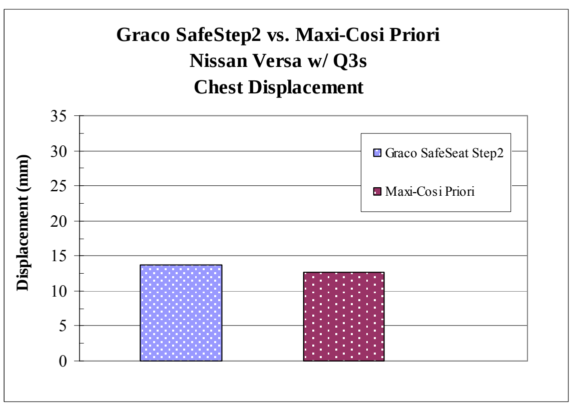

Figure 37. Comparison of Chest Lateral Displacement for CRS Models in Nissan Versa Crash Tests.

Individual test results for the sled and crash tests are available on NHTSA's Vehicle Crash Test Database (http://www-nrd.nhtsa.dot.gov/database/aspx/vehdb/querytesttable.aspx).

CONCLUSIONS

The following conclusions are based on the results from the sled and crash tests:

- The Takata sled buck concept of a sliding seat fixture on a sled appears to be a repeatable test procedure.
- Sled test results indicate that it is feasible to distinguish between child restraint models using some of the injury metrics.
- The impact angle appears to create a definite effect for certain injury metrics, while producing minimal effects for others.
- Based on the limited number of CRS models tested, the design of the CRSs' seat back side wing appears to be an important element for providing side impact protection, particularly when impact angles are varied, as noted in Evaluation of Impact Angles.
- Trends in injury response values between sled and crash tests were similar for the two CRS models used in both types of testing.
- Head and neck injury responses appeared to be more sensitive, during both sled and crash tests, to the type of CRS model used than did spinal and pelvic acceleration and chest displacement responses.

Future sled testing to refine test parameters such as door stiffness and geometry, and to further assess issues such as effect of armrest on CRS kinematics and dummy responses, is planned. Evaluation of additional CRS models within the fleet will also be conducted to validate test methodology.

REFERENCES

[1] McCray, L. et al., "Injuries To Children One to Three Years Old in Side Impact Crashes," Paper Number 07-0186, 20th ESV, June 2007.

[2] FMVSS No. 214D Test Procedure, TP-214D-08.

APPENDIX

FMVSS No. 214 compliance test vehicles used to determine sled pulse and seat velocity

- **2005 Toyota Corolla Test # 5483 ES2re**
- **2005 Toyota Corolla Test # 5491 SIDIIS**
- **2005 Subaru Forester Test # 5485 ES2re**
- **2005 Suzuki Forenza Test # 5575 SIDIIS**
- **2005 Subaru Forester Test # 5480 SIDIIS**
- **2003 PT Cruiser Test # 4614 U.S. SID**
- **2003 Mazada Protégé Test # 4575 U.S. SID**
- **2003 Suzuki Aerio Test # 4574 U.S. SID**
- **2005 Saturn Ion Test # 5460 SIDIIS**
- **2005 Saturn Ion Test # 5461 ES2re**

FMVSS No. 214 compliance test vehicles used to determine "door" velocity

- **2005 Subaru Forester Test # 5480**
- **2005 Toyota Corolla Test # 5483**
- **2005 Suzuki Forenza Test # 5575**
- **2005 Saturn Ion Test # 5460**

<u>Child Restraint System Models</u>

Graco SafeSeat Step2 Toddler

Maxi-Cosi Priori (SIP)

Evenflo Triumph Advance DLX

Graco Logico M (SIP)

Meets only ECE Reg. 44;
Does not use LATCH system

Safety 1st All-in-One Convertible

DEVELOPMENT AND IMPROVEMENT OF Q3s
– A Three Year Old Child Side Impact Dummy

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Paper Number 09-0358

ABSTRACT
The research of child restraint systems tested under side impact test conditions has been conducted extensively in the past few years. In May 2008 US Government and Industry meeting, US National Highway Traffic Safety Administration (NHTSA) presented a summary of the 3 year old child side impact dummy evaluation result with some desired improvements, including the neck biofidelity and thorax rib cage durability. With further evaluation later at Ford, Transport Canada and NHTSA Vehicle Research and Test Center (VRTC), it was observed the hip ball popped out from the cup retainer during some of the tests. The overall biofidelity of this dummy was summarized by Carlson et al, and also updated biofidelity summary was presented by Rhule [3] in 2008 Government Industry meeting. This paper summarizes the improvements that address these identified issues in the past year.

INTRODUCTION

NHTSA Traffic Safety Facts 2007[4] data shows that there were 61 million children age 14 and younger in the United States, which is about 20% of the total US population in 2007. Motor vehicle crashes are the leading cause of death for ages 3 to 6. There were total 41,059 traffic fatalities in the United States in 2007. The 14- and younger age group accounted for 4 percent (1670) of these traffic fatalities. Research has shown that lap/shoulder seat belts, when used, reduce the risk of fatal injury by 45 percent and risk of moderate-to-critical injury by 50 percent. Research on effectiveness of child safety seats has found that they reduce fatal injury by 54 percent (1 to 4 years old) for toddlers in passenger cars. Among children under age 5, an estimated 382 lives were saved in 2007 by child restraint safety seats. It is obvious that child restraint systems play a significant role in saving children's lives. However, the NHTSA data shows 165 fatalities with the use of the child seat restraint systems for age group of 1-4 years old. The 165 fatalities account for nearly 43 percent of the total fatalities. These numbers imply that improvements to child restraint systems to better protect children are needed. The child dummy has served as a good tool to assess the protection of children. A biofidelic child dummy is essential in developing safer child restraint system.

As part of the efforts to develop a safer child restraint system, the Q dummy series was developed in Europe during 1995-2004. The dummy was developed to have more human-like anthropometry and performance as the next generation of the P child dummies specified in UNECE Regulation 44. The dummy was designed to perform in both frontal and lateral test conditions. With more field accident data and biofidelity data under side impact test condition, the Q3s was introduced focusing on improving biofidelity for side impact test.

The overall bofidelity evaluation result of the Q3s dummy was published by Carlson et al in 2007[1]. The biofidelity corridor was based on the work published in 2002 by Irwin et al [2]. Also additional neck torsion biofidelity requirement was proposed by Mertz (informal communication between Dr. H. Mertz and NHTSA Vehicle Research and Test Center). These criteria serve as the basis of the dummy biofidelity evaluation.

In the 2008 presentation from Rhule [3], the Q3s dummy showed superior biofidelity in shoulder, thorax and pelvis area compared to the Hybrid III 3 year old child side impact dummy, while it also showed the neck flexion and torsion biofidelity responses required further improvement. In addition, the thorax rib cage durability became a concern from testing. One rib cage cracked after approximately 90 tests (30 sled tests and 60 pendulum tests) at 25 mm chest deflection magnitude. In spring 2008, Occupant Safety Research Consortium (OSRP) of United States Council for Automotive Research (USCAR) found the hip joint ball came out in a test. This issue was also observed later in VRTC's sled test. This paper presents a new neck design for improved biofidelity performance and also summarizes the solutions to address the durability concerns of the thorax rib cage and hip joints.

NECK DESIGN

A new neck was designed to meet the flexion, extension, lateral bending and torsion biofidelity requirements. Since each test has its own performance specification, it requires a complex structure to meet these requirements simultaneously. The neck design consists of four aluminum vertebra discs and rubber segments between the aluminum discs. The rubber segments have an oval-like shape with circumferential V-shaped groves. The V shape opening angle varies around the neck in different locations (frontal, lateral and rear) in order to govern the performance of the neck. Cuts were introduced into the front of the neck to soften it, and comply with the extension performance requirement. The molded neck is shown in Figure 1. Different rubbers were experimented with to optimize the neck performance. The test data is summarized later in this paper.

Figure 1, molded neck

Figure 2, Neck assembly with cable

A torsion cable was designed into the neck assembly to govern the torsion performance. The cable has metal sheaths crimped to both ends. At one end, the metal sheath has a key to engage with a ring underneath to control the torsion performance of the neck. During the development of the previous torsion cable, it was found that the asymmetrical torsion cable caused asymmetrical performance, which requires offset of the key position to compensate and induce earlier rotation in order to gain symmetrical neck performance. It was found a symmetrical torsion cable was desired and identified in the design to eliminate the offset of the key feature. The cable and the rings are shown in Figure 2.

NECK TESTING SETUP

The neck biofidelity test was conducted on the pendulum specified in US Regulation 49CFR Part 572 with a special headform (same design as the Q3 frontal impact dummy). The neck was tested for flexion, extension, lateral bending with this headform as shown in Figure 3.

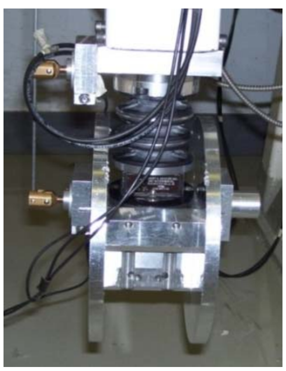

Figure 3, Headform for flexion, extension and lateral bending pendulum test

Figure 4, Headform for torsion pendulum test

The torsion was tested with a special headform designed by VRTC, shown in Figure 4. This headform has a neck load cell to measure the moment Mz of the neck and a rotary pot to measure its rotation about Z axis.

NECK TEST DATA

Neck flexion test was conducted at 5.5 m/s impact speed. Three necks with different rubber stiffness were fabricated for testing. The test results are shown in Figure 5.

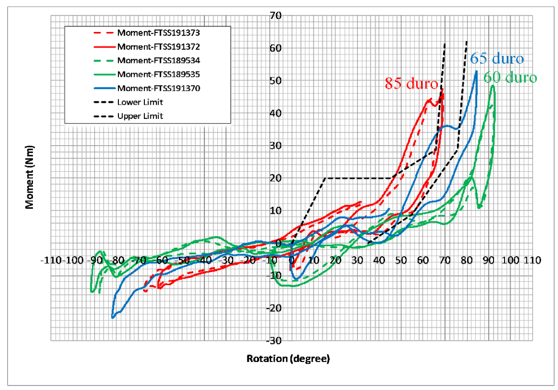

Figure 5, Flexion pendulum test, 5.5 m/s

From the test result, we can see that rubber with a stiffness range from 65 to 85 durometer shore A is close, but not well within the biofidelity specification.

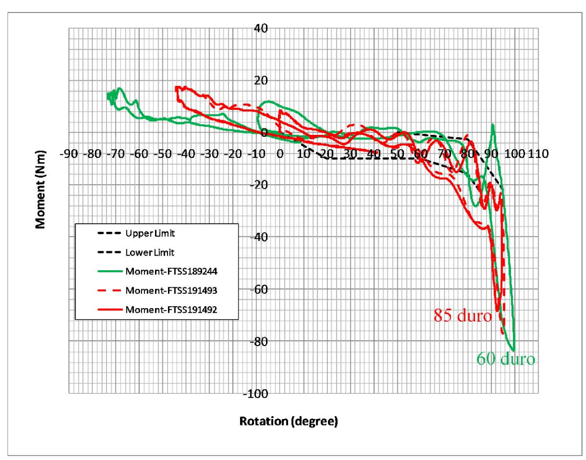

Figure 6, Neck extension pendulum test, 5.5 m/s

Neck extension test was conducted at 5.5 m/s impact velocity. The test result is shown in Figure 6.

The extension pendulum test shows close results for the neck with rubber stiffness at 65 and 85 durometer shore A. No significant performance difference was observed in the test results. During the neck extension test, the neck rotates up to a range of 90 to 100 degrees. At the maximum bending, the V groves are completely closed and bottomed out, causing the moment to increase quickly after it reaches 85 degrees.

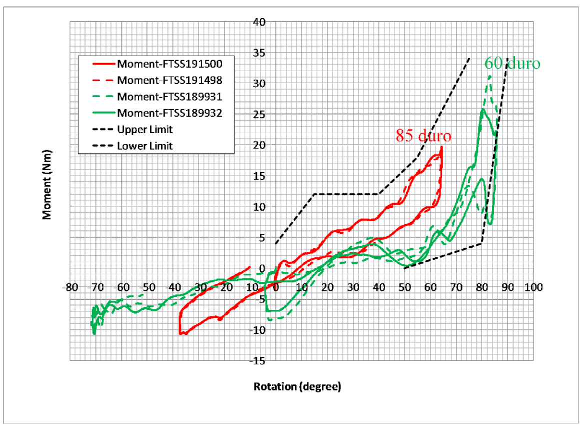

Figure 7, neck lateral bending test, 3.9 m/s

The lateral bending test was conducted at 3.9 m/s velocity. The test results are shown in Figure 7. We can see both necks with 60 and 85 durometer shore A meet the biofidelity corridor very well.

Neck torsion test was conducted with a special headform as described in the previous section. The test results are shown in Figure 8. From the test results, we can see the 85 durometer shore A rubber neck is too stiff to meet the test requirement, while 60 and 65 durometer shore A neck meet the biofidelity corridor very well. As mentioned in design section, the neck cable has an asymmetrical mechanical property, which requires offsetting the cable key to balance the rotation between the left hand and right hand rotations. At the submission of this paper, the symmetrical cable is in the fabrication process.

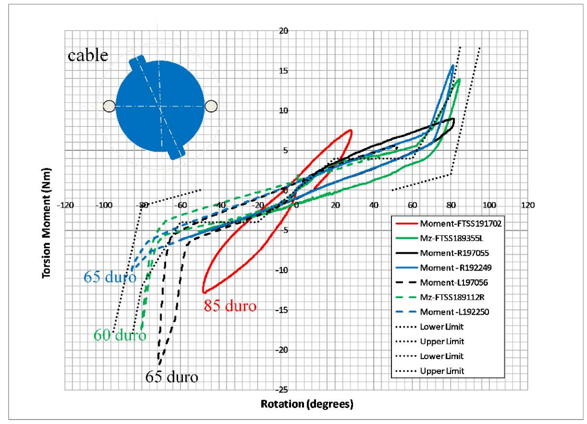

Figure 8, Neck torsion test, 3.6 m/s

From these tests, we concluded that the neck with 65 durometer rubber performs the best considering all four biofidelity requirements. However, we noticed the neck flexion performance, which is soft to meet the biofidelity requirements. After investigating the neck rubber geometry, we added some rubber material on the V grove at the front side of the dummy. This is to reduce the angle neck rotation before it bottoms out. It was also examined from CAD design that other performance would not be affected after this modification. A mockup neck was fabricated by gluing some additional rubber pieces to the corresponding area. The test results shows in Figure 9.

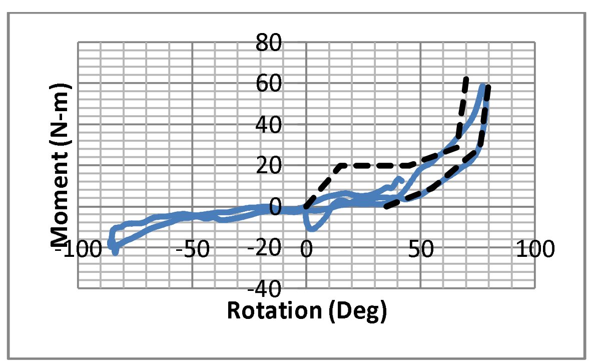

Figure 9, Neck flexion pendulum test, 5.5 m/s

The mold was updated to reflect the mockup design. At the time of submitting this paper final, the final version for neck is in the process of manufacturing.

THORAX RIB CAGE

Thorax rib cage is a critical component in the dummy design. It was observed that the rib cage was broken with a limited number of tests.

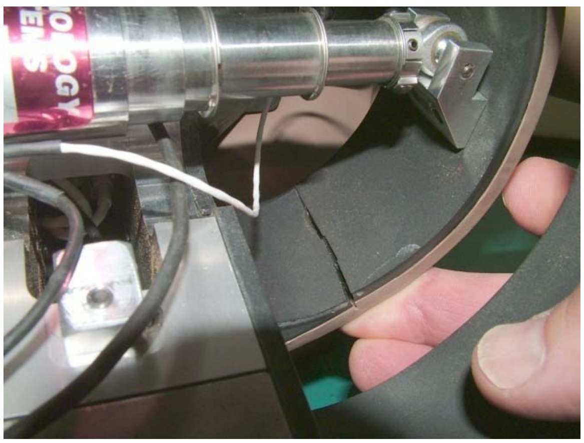

Figure 10, damage of the thorax rib cage

One rib cage was damaged after approximately 90 pendulum and sled tests combined, while another rib cage failed after 30 pendulum tests. The damage always happens toward the rear side of the rib contour as shown in Figure 10.

It was noticed some ribs have relative longer life than the others. From the analysis of the fractured surface, it has been noticed there were always defects, mainly air bubble like void on the fractured surface. These defects are typically buried inside and can't be observed visually in the quality inspection. The crack initiates from these defects and starts to propagate and become catastrophic. The rib cages that have very long life time, we believe have no such defect buried in the parts. Since it is difficult to inspect these invisible defects, quality control was a problem.

From the investigation of the damaged parts, it is clear that damage is a fatigue life issue. If we can make the design insensitive to the defects, it will elongate the life of the parts. To solve the problem, the following parameters were considered to increase the fatigue life cycles.

- Optimize the thickness of the rib to reduce the maximum stress level. If the maximum stress level was reduced, the fatigue life will increase accordingly.
- Introduce a Nitinol sheet metal insert. To maintain the same rib cage stiffness, therefore to maintain the same performance, the plastic material stiffness has to be reduced. When the plastic material stiffness is reduced, its elongation will be increased accordingly and fatigue life will increase accordingly. Also by introducing the Nitianol sheet metal insert, the plastic material thickness is as a consequence reduced. Under the same deflection level, the thinner plastic rib portion reduces the stress level as well from beam theory.

Finite element analysis was used to study the stress distribution of the fractured area, which was identified as the highest stress level in the whole rib cage. We noticed that the bending area was thickened in the early Q3 development, which was intended to address frontal failure. However, for lateral impacts, the damage shifted further forward to the thin area as it is now.

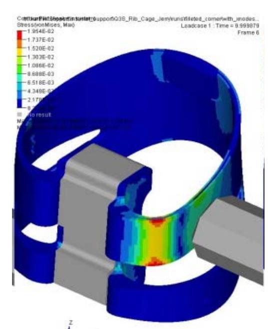

Figure 11a, FEA - the stress distribution of the rib cages (baseline – thickened contour)

We conducted analysis of the cage to compare the uniform thickness and the thickened design. It was found that rib cage with uniform thickness actually has less stress level than the thickened one that was intended to address the fracture.

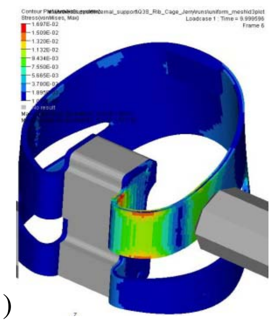

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Figure 11b, FEA – stress distribution of the rib cage (uniform thickness)

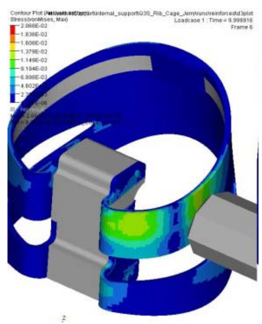

Figure 11c, FEA – stress distribution of the rib cage (uniform thickness with Nitinol sheet metal insert).

We also conducted an analysis of the rib cage with a Nitinol sheet metal insert to study the maximum stress level of the plastic material and also investigate if stiffness of the metal insert together with the plastic material is feasible to maintain the same dummy performance. The maximum stress is summarized in table 1.

From the analysis, we can see 25% stress reduction can be achieved with the Nitinol metal insert, and the proper stiffness of the rib cage can be achieved with proper combination of metal insert and plastic material stiffness.

Table 1, Max stress comparison of rib cage

Cases	Max Stress (MPa)	Reduction (%)
baseline	17.4	NA
uniform thickness	15.1	-13%
uniform thickness with insert	13.8	-25%

THORAX RIB CAGE TESTING

After the finite element analysis, prototype parts were fabricated accordingly for testing to validate the concept. The shape of the metal insert was optimized in design to address some manufacturing challenges. The final design of the rib cage with the insert is as shown in Figure 12.

Figure 12, Q3s rib cage design with metal insert

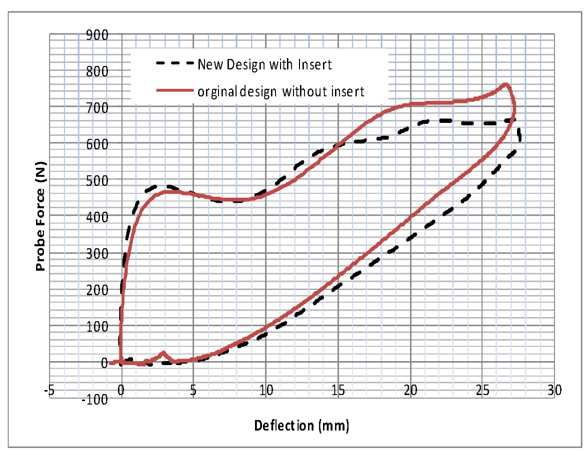

Figure 13, Pendulum impact test of the new rib cage and the old one.

The rib calibration with pendulum impact test was used to verify the rib performance. After eight iterations of refining the insert and plastic material, the performance is very similar to the existing rib cage. Further biofidelity tests will be conducted at VRTC in the near future.

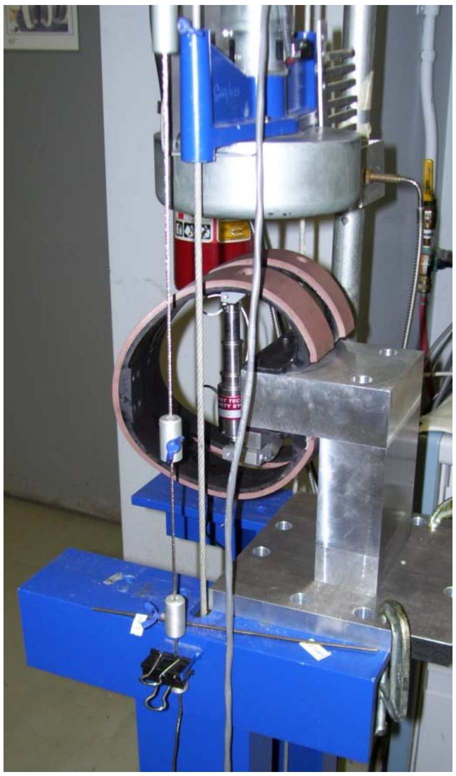

Figure 14, Rib durability drop tower test setup

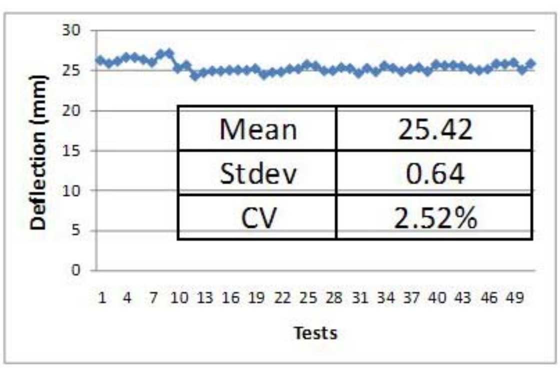

Figure 15, rib deflection under drop tower test (total 500 tests, data collected every 10 tests).

Drop tower testing was used to verify the durability of the ribs. The test setup is shown as Figure 14.

From the sled tests and pendulum tests performed previously, it was noticed the thorax was compressed to a level of 25 to 28 mm deflection. The drop tower reproduced this level of deflection for each impact. The rib cage was inspected carefully after each test.

Rib deflection data was collected every 10 tests. The deflection is plotted in Figure 15. From the data we can see the rib performance is very stable and there is no damage to the rib cage after 500 tests. The durability of the rib has improved significantly.

HIP JOINT DURABILITY

It was observed in some severe test condition, the hip ball popped out of the ball retainer, also referred as the cup.

Figure 16 Hip ball pop out from its cup

From the investigation, the cause of this problem was due to the plastic cup, not being strong enough to retain the hip joint in position. Under severe test condition, the hip cup will deform and allow the hip ball to slip out of the cup retainer. To address this problem, the deformation of the hip cup needs to be limited while the engagement between the ball and the cup needs to be improved.

To reengineer the joint, aluminum material was used to replace the plastic material for the cup, which increases the rigidity of the hip cup significantly. At the same time, the plastic hip ball and ball shaft was replaced with a hardened aluminum ball. The ball diameter was reduced from 30 mm to 25.4 mm, while the shaft diameter was reduced according to maintain the hip joint range of motion. This design change increases the engagement area between the ball and the cup and therefore strengthens the ball joint.

Figure 17, New hip joint design

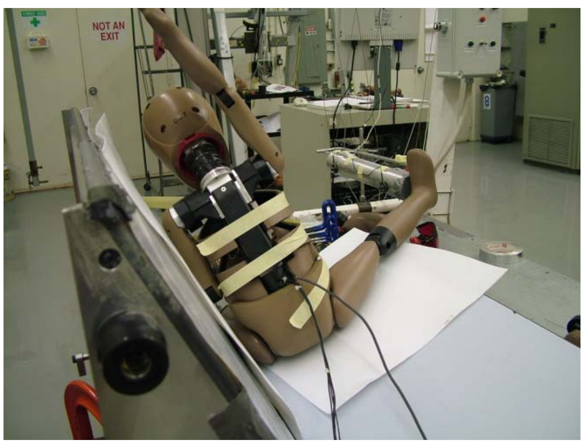

Figure 18, hip joint durability test (courtesy of VRTC)

A pendulum test was used to evaluate the new design at VRTC. The dummy was restrained in a test bench with one leg removed, and a pendulum was used to impact the other leg at the foot location from inboard. The test setup is shown in Figure 18. The plastic design hip joint ball popped out immediately, while the new design survived the test without any damage. The test was considered severe enough for the conditions that the dummy is used.

CONCLUSIONS

The few outstanding issues identified from 2008 Government Industry meeting and thereafter were addressed with new designs. The new neck design can meet the flexion, extension, lateral bending and torsion requirements. A robust rib cage design with identical geometry was validated and was shown to improve the durability significantly. A more durable hip joint design was evaluated as well. The design is very promising in a severe test condition and further evaluation will be conducted in the future. The Q3s dummy is ready as a robust tool for child restraint system development.

ACKNOWLEDGEMENT

The authors would like to thank the OSRP Q3s Task Group for the support and review of the development of the solutions, and also would like to express our appreciations to NHTSA/VRTC and Transport Canada for their contributions to the evaluation tests and instant feedback on the designs so that we can have these issues addressed in a timely manner. Also, special thanks go to Mr. Frank Laureto, who coordinated and fabricated all prototype parts.

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