

IDENTIFICATION OF HEAD INJURY MECHANISMS OF A CHILD OCCUPANT IN A CHILD RESTRAINT SYSTEM BASED ON SIDE IMPACT TESTS

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ABSTRACT

Accident data show that injury risks to children are high in side collision accidents. According to in-depth accident analyses of children seated in forward facing (FF) child restraint systems (CRSs), the head was the most frequently injured body region, and main sources of head injuries were the rear door and side window glass. There are many research studies on child occupant safety in side impacts. However, a review of previous studies of both vehicle-to-vehicle tests and sled tests found that the child head remained in the CRS shell and that the observed severe head injuries in the accident data were not reproduced in the tests. In the present study, a sport utility vehicle (SUV)-to-small car oblique side crash test and sled tests were conducted using a Q3s dummy in the FF CRS to find causes of head contacts which occur frequently in side collision accidents.

In the SUV-to-small car oblique side crash test, a Q3s dummy was seated in the FF CRS installed in the rear seat on the struck side of the small car. The CRS harness was given a slack of 75 mm beforehand. The SUV impacted the rear door of the target small car at an angle of 45 degrees so as to apply a large crash loading on the child dummy. During the crash and up to 65 ms, the vehicle velocity change in the longitudinal direction was comparable to that in the lateral direction. The velocity in the lateral direction

continued to increase due to car yaw rotation and reached a peak of 10.5 m/s. This velocity-time history affected the Q3s dummy kinematic behavior. The Q3s dummy moved in an oblique direction and then laterally, and made contact with the side window at 6.8 m/s and the resulting HIC was 702. This test result demonstrates that a forward component of vehicle velocity change and CRS harness slack are factors that may lead to the head making contact with the vehicle interior, thereby resulting in causing serious injuries.

Sled tests were conducted by using a test apparatus specially designed to reproduce the Q3s dummy kinematic behavior in the SUV-to-small car crash test. The factors which were determined to reproduce Q3s dummy kinematic behavior in SUV-to-small car side crash test included the relative location between the test seat and door, the velocity-time history of the car in the longitudinal and lateral directions, the vehicle roll angle during impact, and the contact characteristics between the door and the dummy.

From this study, the hard contact between the child head and the vehicle interior that occurs frequently in side collision accidents was reproduced in a SUV-to-small car oblique side crash test. Factors of a sled test were identified that reproduce the child occupant kinematic behavior in the SUV-to-small car side crash test. The results of this study will be useful for determining the sled test conditions of a

CRS side impact, which will be effective in reducing child head injuries.

INTRODUCTION

There are many research studies using accident data that investigated injuries to child occupants seated in a forward facing (FF) child restraint system (CRS) [1-4]. It has been shown that the injury risk is higher in side impacts than that in frontal impacts. On side impacts, it also has been shown that the injury risk for a child occupant seated at the vehicle's struck side is higher than that for the child occupant seated near the non-struck side. For child occupants seated in the FF CRS on the vehicle's struck side, the head is the most frequently occurring injured body region. It has been reported that the most frequent occurring injury sources of the head are the CRS shell, door, pillar, side window, and front seatback. From accident analysis conducted by NHTSA, it was determined that the head injury sustained when the child's head had contact with the car interior (such as door or pillar) is more severe than that when the child's head made contact with CRS [2]. There were accident cases that the child's head contacted the side interior in a forward location far from the CRS [3]. These cases indicate that the child's head traversed out of the CRS a long distance. Langwieder et al. [1] considered that a factor leading to the head making contact with the door would be the forward component of the acceleration of the struck car in the vehicle-to-vehicle side collision.

Rooij et al. investigated the child posture in the CRS [5]. In many cases, the children were seated in a standard posture. However, various child postures were observed. These include the child slouching, resting their head against the CRS side wing, and slipping their torso out from the shoulder harness. In these postures, a child's head could move in an oblique direction and make contact with side interior of the car during side collisions. However, according to the study by Arbogast et al. [3], there are accidents that child head was injured by contact with the vehicle side interior even though they were assumed to have been seated in the standard posture in the CRS. Therefore, it is necessary to understand how these head contacts occurred in side collisions even though the child was seated correctly in the CRS. In CRS usage, misuses of the CRS are frequently

observed in the field. In the survey of FF CRS usage in Canada, 42% of CRSs were observed to have had 3 inches or more slack of the shoulder harness [6]. Therefore, the slack of the CRS harness also should be considered when investigating child head contacts in side collision accidents.

Based on crash tests, child occupant responses in CRS on side impact have been investigated. Yonezawa et al. [7] carried out ECE R95-based tests with a Q3s dummy seated in a CRS installed in the rear seat on the vehicle's struck side. In the tests, though the chest deflection was comparable with the injury assessment reference value (IARV), the head was retained in the CRS shell and the resulting head injury criterion (HIC) was small. NHTSA carried out FMVSS 214-based test with a Q3s dummy seated in the rear seat on the vehicle's struck side [8]. The MDB impacted the car at an angle of 27°, and a forward component of acceleration was applied to the child dummy as a result of the crash loading. In one test, the head was retained in the shell, while in the other test a portion of the head went out of the CRS shell and then made contact with the door. In both tests, the HIC was substantially small. Accordingly, in the ECE R95-based tests and FMVSS 214-based tests, the high injury risk observed in real world accidents resulting from a child occupant head making contact with the door was not reproduced.

A sled test procedure to evaluate CRS performance in side impacts has been discussed since the 1990s. In the sled test, it is necessary to reproduce the door intrusion and the acceleration of a struck car. In an ISO proposed sled test procedure, a hinged-door panel rotates and impacts the CRS on an accelerated sled. This test method was documented as a Technical Specification (TS) [9]. Takata Corporation has proposed a sled-on-sled test procedure using an accelerating sled system [10]. A door fixed on the base sled impacts the CRS on the ECE R44 seat sled that can move in translation on the base sled. It was demonstrated that the dummy kinematic behavior was comparable with that in a full-car test. In order to reproduce the intruding door, Dorel [11] has proposed a sled test procedure in which the CRS on the test seat on the decelerating sled impacts a door that is fixed on the floor. In this test, the relative velocity between the test seat and the door is

controlled with the sled deceleration. Although there are many research studies on CRS sled tests, there has not been a discussion about contacts between the child's head and the door, a scenario which has been frequently observed in the accidents.

From the accident analysis, it has been observed that children frequently have sustained serious injuries due to head impact onto the vehicle interior such as a door. However, this head contact with a door and the risk of serious head injury were not reproduced in vehicle-to-vehicle crash tests and in sled tests. The authors have investigated and developed the CRS side impact test procedure using an accelerating sled [9]. A frame of the test method has been completed; however, some specific issues of the test procedures remain to be addressed. One of them is the introduction of a forward velocity component in the sled test procedure. In order to develop a CRS test procedure that can protect a child occupant in CRS effectively, it is necessary to include the forward velocity component in sled tests since the forward velocity component may be a significant factor in head contact of children in side collision accidents.

The purpose of this research is to understand the mechanisms that lead to a child's head making contact with the side structure of the vehicle interior in side collisions. The authors previously have conducted a vehicle-to-vehicle finite element (FE) simulation using a child FE model; and it was found that a child's head can impact the door window sill in an oblique side collision [12]. In the FE simulation, the displacement of the child occupant's head was large when the shoulder joint on the impacted side moved out beyond the CRS side wing. In this research, according to the crash configuration that resulted in the child head contacted the door in the FE simulation, an SUV-to-small car oblique side crash test was conducted with a Q3s dummy seated in the CRS on the car's struck side. A sled test method to reproduce the Q3s dummy kinematic behavior in the SUV-to-small car crash test was examined.

SUV-TO-SMALL CAR SIDE OBLIQUE TEST

Method

A crash configuration was determined such that the

head of a child dummy would contact the side interior of a car. Figure 1 shows the test vehicles. The striking vehicle was an SUV (curb mass 1309 kg, test mass 1520 kg). The target vehicle was a small car (curb mass 1100 kg, test mass 1250 kg). Figure 2 shows the crash configuration. The striking vehicle was impacted into the stationary target car at 50 km/h at an angle of 45 degrees. The vehicles were aligned such that the left front rail of the striking vehicle contacted the B-pillar of the target car. This crash configuration was comparable with the collision configuration in which a striking vehicle impacts the struck vehicle at an angle of 60 degrees with both vehicles traveling at 50 km/h, with respect to the principal direction of force.



(a) Striking vehicle (SUV)



(b) Target vehicle (small car)

Figure 1. Test vehicles

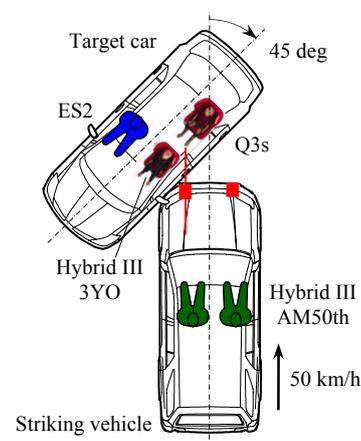


Figure 2. Test configuration

In the target car, a Q3s dummy and Hybrid III three-year-old (3YO) were seated in a CRS installed with a car seatbelt in the rear seat and front passenger seat on the car's struck side, respectively (Figure 3). The same type of FF CRS (convertible type CRS) was used for both child dummies. A slack of 75 mm was introduced in the shoulder harness for both CRSs. This amount of slack was based on the field survey in Canada that 42% of CRSs had 3 inches or more slack in the shoulder harness in the FF CRS usage [6]. The CRS was installed on the car seat according to the ECE R44 procedure, and the seatbelt was in an automatic locking retractor (ALR) mode. An ES-2 dummy was seated with a seatbelt in the front driver seat (non-struck side) in the target car. In the striking vehicle, Hybrid III AM50th dummies were seated and restrained with seatbelts in the front driver and front passenger seating positions.



Figure 3. Q3s dummy in the target car

Results

Vehicle kinematic behavior and deformation

Since the impact force was not transmitted sufficiently to the non-struck side sill in the oblique impact and the acceleration of the passenger compartment was not measured sufficiently, film analysis using the high speed video from the top view was conducted to analyze the vehicle behavior during impact. The target marks located on the roof were used for the analysis.

Figure 4 shows the trajectory of the roof of the target car. The target car moved in an oblique direction with yaw rotation since the impact force acted on the rear location away from the center of gravity (CG) of the target car. The velocity-time history in longitudinal (x) and lateral (y) direction of the car (car coordinate system) were calculated by assuming

that the car moved in translational motion with yaw rotation around the CG. This velocity-time history is significant for determining the test conditions of the sled tests.

Figure 5 shows the target marks, and the car CG and the Q3s dummy location corresponds to targets RC1 and RL3, respectively. Figure 6 shows the velocity-time history of target RL3 (Q3s dummy location). The velocity increased at 20 ms, and the velocity in x and y directions were comparable during the initial 65 ms of the crash event. The velocity in the y direction continued to increase and was higher than that in x direction due to car yaw rotation. Figure 7 shows the yaw angle, and it increased beginning at about 60 ms. The maximum delta-V of the car at RL3 (Q3s dummy location) in the x and y direction were 5.1 m/s (at 121 ms) and 10.5 m/s (at 200 ms), respectively. The roll of the target car occurred during impact (Figure 8) and the maximum roll angle was 6 degrees, which was determined from the line connecting the target marks on the rear hood (BR1 – BL1). The velocity-time histories in the x and y direction and the roll angle of the car affected the Q3s dummy kinematic behavior.

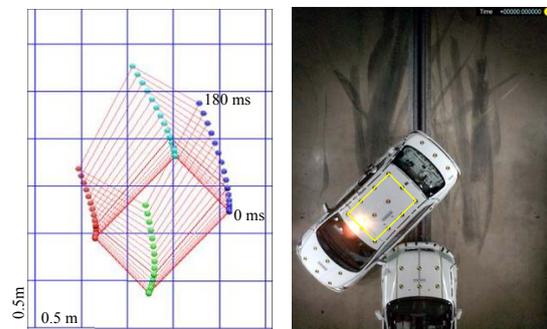


Figure 4. Trajectory of the yaw behavior of the target car



Figure 5. Target marks of the target car

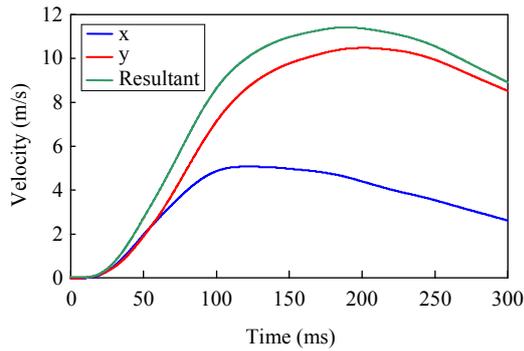


Figure 6. Car velocity at roof target point RL3 (Q3s location)

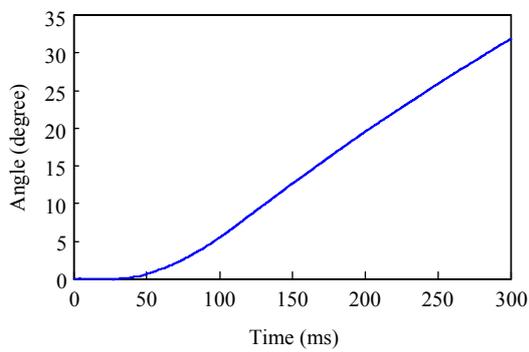


Figure 7. Yaw rotation of target car

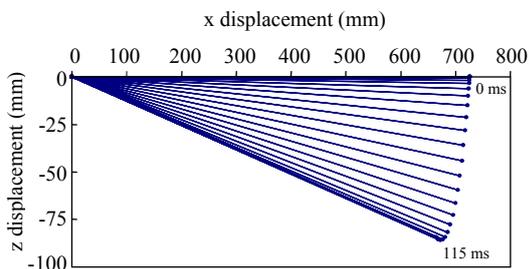


Figure 8. Rolling behavior of target car

The deformation of the target car is shown in Figure 9. The deformation was large in the area around the B-pillar. The inner panel of the rear door deformed following the B-pillar deformation and

then bent in a longitudinal direction around a vertical centerline of the rear door, and the intrusion of the rear door inner panel decreased from the front-end (180 mm) to the rear-end (16 mm). The intrusion at the armrest which contacted the front-end of the CRS shell was 70 mm. Accordingly, the intrusion of the rear door inner panel around the area where the Q3s dummy was seated was generally small.



Figure 9. Target car deformation

Q3s dummy and CRS kinematic behavior

Figure 10 shows the Q3s dummy kinematic behavior. Figure 11 shows the CRS acceleration at its base and at the upper location of the CRS seatback. The Q3s dummy acceleration, car seatbelt force, and the CRS harness force were complex because the forces are applied on the Q3s dummy from the CRS shell, the CRS harnesses, and the door during an oblique side impact.

In the initial phase (up to the first 30 ms) of the crash, though the car moved starting at 20 ms (see Figure 6), the CRS and the Q3s dummy remained in the same position with respect to the ground. Figure 12 shows the tension force of the car seatbelt (shoulder belt) and the CRS shoulder harness (non-struck side). Figure 12 shows the acceleration of the Q3s dummy. The belt force and Q3s dummy accelerations did not increase during this time. This result indicates that forces were not applied on the CRS except for

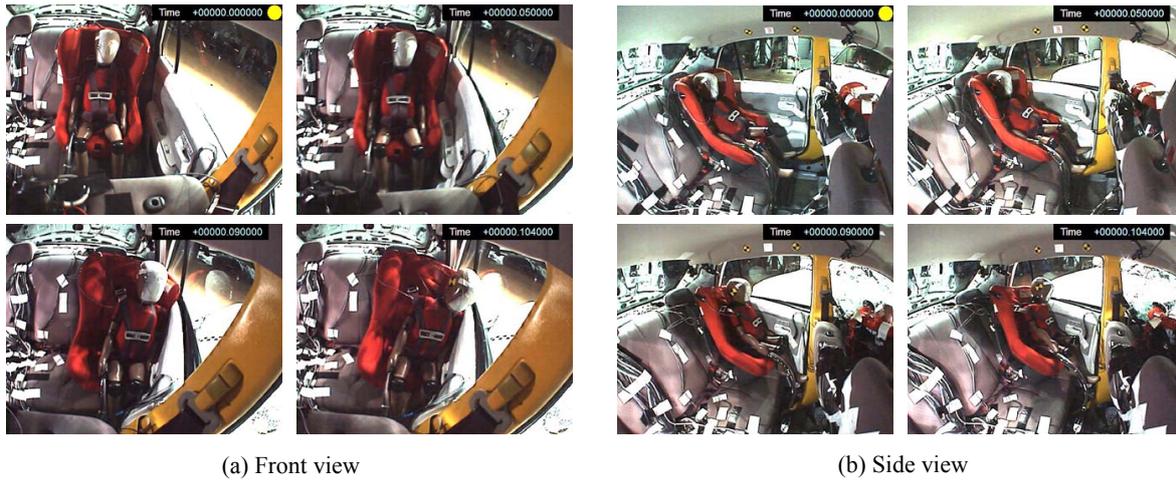


Figure 10. Q3s kinematic behavior (Head impacted the side window at 104 ms)

relatively small friction forces due to CRS contact with the car seat, and it is regarded that the CRS was in a free floating condition with respect to the ground.

From the view of the CRS motion in the passenger compartment, it was observed that after 30 ms the CRS began to move toward the door. At 50 ms, the CRS lower side wing corresponding laterally to the dummy's pelvis location started to interact with the intruding door armrest. It is probable that the CRS lateral (y) acceleration increased sharply due to this interaction. The lower side wing of the CRS overrode on the armrest which was lowered as a result of the car rolling behavior, and after 60 ms the CRS moved together with the door.

At 60 ms, the initial slack of the car seatbelt was expended because of the car's motion, and the tension force of the car seatbelt started to increase. The restraint force from the car seatbelt was applied on the CRS. However, since a large slack was added initially to the shoulder harness of CRS (75 mm), the Q3s dummy still moved in free motion during this time. After 70 ms, restraint forces were applied to the Q3s dummy from the CRS harness, and the seatbelt force and the shoulder harness force started to increase. The inertial force of the Q3s dummy was applied to the CRS harness, and the inertial forces of the CRS and the Q3s dummy were applied on the car seatbelt. However, the force levels of the car seatbelt and the CRS harness were smaller than that accounting for the CRS and the Q3s dummy

acceleration, and can be explained because the contact force of the door also was being applied on the CRS and the Q3s dummy.

The upper location of the CRS seat back started to move laterally around 45 ms, and then the upper location of the CRS side wing made contact with the door sill at 80 ms. Finally it stopped with respect to the door at 90 ms. The pelvis lateral (y) acceleration increased at 65 ms (see Figure 13(c)) when the CRS lower side wing bottomed out the door, and had a maximum value at 76 ms.

At 90 ms, the forward displacement of the dummy upper torso relative to the CRS was largest, the left shoulder joint had moved out beyond the CRS side wing, and the shoulder joint had contact with the door trim. The non-impacted shoulder belt harness had a maximum tension force at this time because the Q3s right shoulder slipped out from this shoulder harness. At 100 ms, the forward displacement of the Q3s dummy upper torso and the CRS was largest in the passenger compartment, and the car seatbelt force and the dummy chest acceleration in x and y directions also had maximum values.

The motion of the Q3s torso stopped at 90 ms relative to the CRS, and the head flexion then was initiated with respect to the torso. Since the car y-velocity was larger than x-velocity around this time (Figure 6), the Q3s head motion changed from the oblique direction to a side direction. The Q3s head made contact with the side window glass at 104 ms, and at this time the

head impact velocity in x and y direction with respect to the passenger compartment was 4.73 m/s and 6.76 m/s (as determined from video analysis), respectively. At the time of head contact (104 ms), the car velocity in the x and y direction at RL3 in the car local coordinate system was 5.39 m/s and 7.04 m/s, respectively. The maximum acceleration of the Q3s head was 1567.8 m/s² (105.7 ms) and the HIC15 was 702 (104.1 – 111.7 ms). The maximum head displacement in the x direction was 305.9 mm at 122 ms. It was observed that the side window glass was sufficiently stiff for 3-year-old child to produce such a high HIC.

During the impact, it was observed that the Q3s dummy moved upward with respect to the passenger compartment. This was because the car rolled and the struck side of the car moved downward. The Q3s dummy was in free motion and remained in the same posture in space during the initial phase due to harness slack of 75 mm, which led to this upward motion relative to the vehicle.

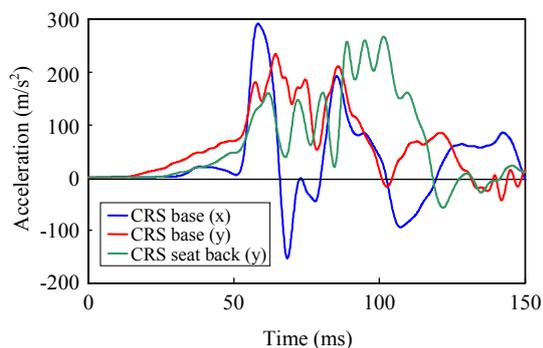


Figure 11. CRS acceleration

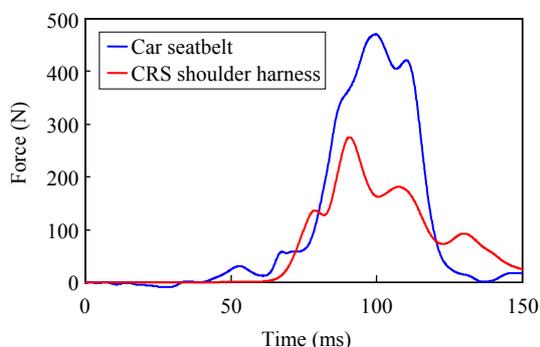
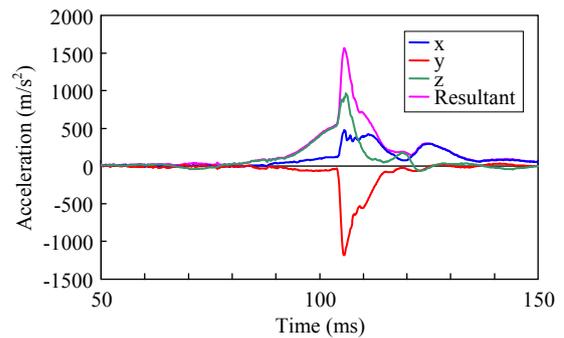
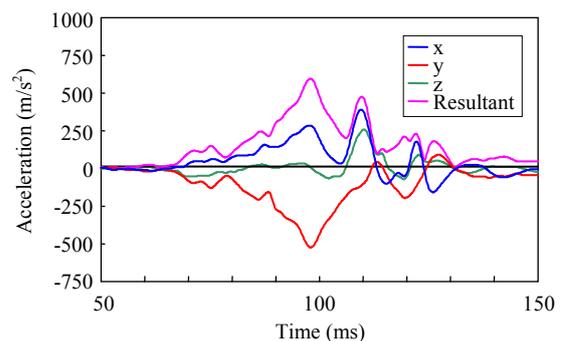


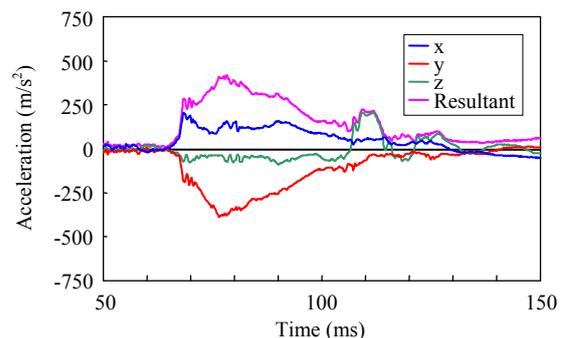
Figure 12. Tension force of car seatbelt (shoulder belt) and of CRS shoulder harness (non-struck side)



(a) Head



(b) Chest



(c) Pelvis

Figure 13. Q3s dummy acceleration

SLED TESTS

The purpose of conducting sled tests in this study was to determine a sled test methodology that reproduces the kinematic behavior of whole body, particularly for the head, of a Q3s dummy in a vehicle-to-vehicle oblique side crash. In this study, a 12 inch HYGE sled facility was used. A sled test method which reproduces the kinematic behavior of a dummy would make it possible to examine various parameters that may affect a child occupant's kinematic behavior. More than 200 sled tests were conducted while changing various test bucks, sled test devices, and test conditions so that the Q3s

dummy kinematic behavior in the sled test could be made comparable with that observed in the SUV-to-small car oblique side crash. Since the Q3s dummy's head had lateral contact with the side window in the SUV-to-small car crash, the lateral velocity (y) of the car and the dummy head were determined to be important parameters to be reproduced in the sled test to make a comparable contact phenomenon with that in the SUV-to-small car test.

Sled Test Equipment

Test buck

The test buck consists of a base plate, test seat, seatbelt with its mounting block, impact door, and leg plate (see Figure 14). In the SUV-to-small car test, the door intrusion of the target car was small in the area around the location of the CRS. Therefore, in the sled test, the test seat and the door are designed to be fixed on the base plate: the test seat does not slide on the sled. Accordingly, only an inertial force was applied on the CRS and the Q3s dummy, and the door impacted them. The test buck can be installed on the sled with several angle pitches around the vertical axis so that the ratio of the x-velocity to the y-velocity can be changed. The test seat and the impact door were slanted at an angle of 6 degrees to represent rolling of the car, which affected the Q3s dummy kinematics in the SUV-to-small car test.



Figure 14. Test buck

Test seat

The structure of the test seat was based on the ECE R44 test seat (see Figure 15). The basic shape and dimension are comparable with those of the rear seat of the target car. The seat surface angle is 5 degrees around the lateral axis based on the car rear seat

though it is specified to be 15 degrees in ECE R44 test procedure. The seat surface is flat, and polyethylene foam was the material used for the cushion of the seat bottom and seat back. The width of the test seat is 400 mm, and the gap between the test seat and the door can be adjusted.



Figure 15. Test seat

Seatbelt block

The anchor installation block of the car seatbelt was located at the left side of the test seat. The inner anchorage and the outer anchorage of the lap belt were positioned at the test set which was same as the ECE R44 since the inner and outer anchorage locations of the target car were comparable with those of ECE R44. On the other hand, the shoulder belt anchorage position was based on the target car because it was found that the position of the shoulder belt anchorage has a large effect on the CRS kinematic behavior. The seatbelt was a standard system without a pre-tensioner and a load limiter. A seatbelt for the rear seat in a car was used, and the webbing with low elongation was used. The emergency locking retractor (ELR) was set to be the ALR mode, thus the seatbelt was locked.

Impact door

The rear left door of the target car model (i.e., the undamaged and intact door) was used for the sled test impact door. The standard door such as the ISO side impact door may be preferable for future application with respect to the test methodology. However, the authors have experiences from a series of previously conducted CRS side impact tests and observed that the dummy kinematic behavior can be affected by the door. Thus, the same type of door as the target car in the SUV-to-small car test was used. Instead of using the car's side window glass, an acrylic plate with 3 mm thickness was used. A plastic plate with 10 mm thickness was attached on the acrylic plate to simulate the stiffness of glass.

Leg plate

In the SUV-to-small car test, though the intrusion of the rear door around the CRS was small, there was large intrusion at the front area of the rear door around the B-pillar. This front area of the rear door caught the left foot of the Q3s dummy, and the B-pillar caught the right foot of the Q3s dummy, which affected the kinematic behavior not only of the lower extremities but also that of the whole body as well. To reproduce the kinematic behavior of the lower extremities, the plate was installed in an area where the feet would contact (Figure 16).



Figure 16. Leg plate

Sled Test Conditions

A series of sled tests were carried out with changing parameters. As a result, the test conditions that could reproduce the Q3s kinematic behavior were determined. These test conditions are presented in Table 1.

Table 1. Test conditions

	SUV-to-small car test	Sled test
Oblique angle	45 degrees (Striking vehicle)	45 degrees (test buck)
Door/seat angle	NA	6 degrees
Side window	Glass	Acrylic plate and plastic plate
Leg plate	NA	Yes
Door-CRS center distance	350 mm	300 mm
Dummy	Q3s	Q3s
Dummy setting	R44	R44
CRS harness slack	75 mm	75 mm
Maximum resultant velocity	11.4 m/s (189 ms)	11.97 m/s (110 ms)
x direction	5.1 m/s (121 ms)	8.46 (110 ms)
y direction	10.5 m/s (200 ms)	8.46 (110 ms)

Test buck angle

The acceleration of the target car in x and y direction in the SUV-to-small car oblique side crash test changed with time. To simulate the x-accelerations and the y-accelerations in the sled test, the test buck was installed on the sled test at an oblique angle around the z axis (see Figure 17). Accordingly, the ratio of the x-acceleration to the y-acceleration was constant in the sled tests. However, in the SUV-to-small car crash, the ratio of the x-acceleration to the y-acceleration changed with time (see Figure 6). As a result of examination at several angles, the Q3s dummy was observed to have comparable kinematic behavior at 45 degrees in the sled test as that observed in the SUV-to-small car test. It was only at 45 degrees in sled tests that the left shoulder joint of the Q3s dummy moved out beyond the CRS side wing.

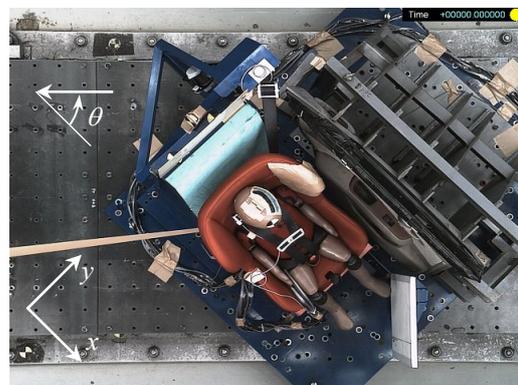


Figure 17. Angle of test buck

Slant angle of test seat

In the SUV-to-small car test, the struck side of the car lowered, moving in a right rear direction (see Figure 8). The CRS and the dummy were not completely fixed on the car; so in the initial phase of the impact, they remained at the same height due to inertial force. Then, the head of the Q3s dummy made contact with the door that lowered in the rolling target car. Therefore, in the sled tests, it was determined that the height of the CRS and the door angle should be configured so that the contact location of the head with the door in the sled test is the same as that in the SUV-to-small car test. Otherwise, the CRS lower side wing would not override the armrest in the same way that occurred in the SUV-to-small car test. The test seat and door were set at a slant angle of 6 degrees in the sled test in order to represent the roll angle of the target car in the SUV-to-small car test.

Distance between impact door and test seat

In the target car of the SUV-to-small car crash, the distance between the door trim and the center of the CRS was 350 mm. In the sled test, to less than 300 mm, the CRS and the Q3s dummy made contact at a higher location of the door than that in the SUV-to-small car test.

Setup of CRS and dummy

In the SUV-to-small car test, the rear seat of the target car became lowered due to the car's rolling behavior, and the downward displacement of the rear seat just under the non-impacted side of the CRS was estimated to be 25 mm. For the sled test setup, the roll angle of the car and the downward movement of the seat were compensated by set up of the CRS and the dummy. The setup is as follows:

1. A cushion with thickness of 25 mm is put on the test seat to represent the car downward displacement.
2. The dummy is seated on the CRS according to ECE R44.
3. The CRS centerline is aligned with the seat centerline (the distance between the door trim and the center of CRS is 300 mm).
4. The car seatbelt is passed through the belt path in the CRS.

5. The CRS is rotated through 6 degrees around the bottom corner of the non-impacted side, to set the CRS base being horizontal using gum tape before impact (see Figure 14). The test seat and the door are slanted at an angle of 6 degrees. Consequently, the CRS impact-side contacts with the slanted door at almost the same location as that in the SUV-to-small car crash.
6. The car seatbelt mode is switched from ELR to ALR.

Sled velocity-time history

A metering pin was selected for producing the desired crash pulse. Figure 18 shows the velocity-time history of the sled. The target sled velocity was set to 11.97 m/s (components in x and y directions were 8.46 m/s) at 110 ms. With this sled velocity-time history, the velocity in the x and y direction was 7.84 m/s at the time of head contact (96 ms), and a comparable head impact velocity in y direction (7.02 m/s) was obtained with that in the SUV-to-small car test (6.76 m/s). Cf: In the SUV-to-small car test, the car velocity in the x and y directions was 5.39 m/s and 7.04 m/s respectively at the time of head contact with the side window (104 ms).

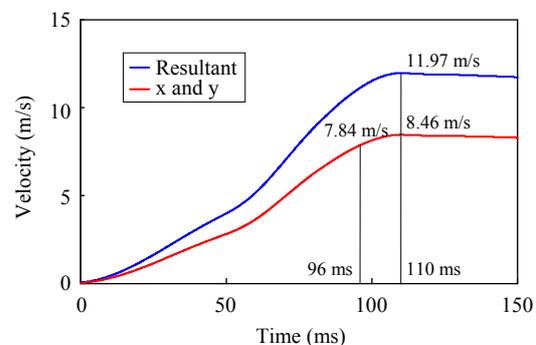


Figure 18. Sled velocity

Sled Test Results

Figure 19 shows the Q3s dummy kinematic behavior observed in the SUV-to-small car test and in the sled test. Table 2 presents the dummy injury measures in the SUV-to-small car test and the sled test. In both tests, the kinematic behavior of the Q3s dummy was comparable, and the head impacted the side window glass with similar kinematics. The time at head

contact with the side window was 104 ms in the SUV-to-small car test and 96 ms in the sled test, respectively.

One of the key points for reconstruction of a dummy's kinematic behavior on which the authors have focused is the head contact with the side window and another point was that the impacted-side shoulder joint goes out beyond the CRS side wing. The shoulder joint went out beyond the CRS side wing only in the 45 degrees sled test among all tests (including tests at larger forward angles). However, although in the SUV-to-small car test, the shoulder joint went out beyond the CRS side wing without making contact with the CRS side wing; while in the 45 degrees sled test, the shoulder joint made contact with the CRS side wing and in the final phase of the impact went out beyond the CRS side wing. There may be other factors that would affect the kinematic behavior of the dummy.

In the sled tests with the test buck configured at a forward angle of 60 degrees (i.e., the lateral velocity is larger than longitudinal velocity), although the shoulder joint remained within the confines of the CRS side wing, head contact occurred. In order that the head moves forward out of the CRS side wing and makes contact with the side window, the head should be flexed forward initially. For the forward motion of the dummy head, the delta-V in the x direction should be high sufficiently, which is dependent on the restrained condition of the dummy. In the sled test, when the forward angle of the test buck was large, the velocity in the y direction was large, whereas the velocity in the x direction was small. As a result, the dummy moved in a lateral direction; the contact force between the torso and the side wing was so large that the dummy resisted moving from the CRS side wing, and the resulting head forward displacement was small. Accordingly, it is likely that longitudinal delta-V is one of the factors which cause a child's head contact with the door or side window. The slack of the shoulder harness is also likely one of the factors that affects head contact.

The HIC and its related physical parameters were compared between the SUV-to-small car test and the sled test. In the sled test, the head made contact with the side window at 96 ms, which occurred earlier

than that in the SUV-to-small car crash test (104 ms). During this contact, the sled velocity and the head velocity in the y direction were 7.84 m/s and 7.02 m/s, respectively. The head displacement in the x direction was 264 mm on impact and 295.4 mm at maximum (114 ms), which were slightly smaller than those in the SUV-to-small car crash (271.2 mm at head impact, 305.9 mm at maximum). The maximum head acceleration was 1861.2 m/s² (97.3 ms) and HIC15 was 866 (93.8 – 107 ms), which were higher than those in SUV-to-small car crash (maximum head acceleration 1567.8 m/s², HIC15 702). At the time of head contact, the sled velocity in the y direction (7.84 m/s) was slightly higher than that in the SUV-to-small car crash (7.04 m/s). Accordingly, the head impact velocity in the y direction in the sled test (7.02 m/s) was higher than that in the SUV-to-small car test (6.76 m/s). Though the head impact severity in the sled test was slightly more severe, the authors concluded that the head impact behavior was reproduced in the sled test.

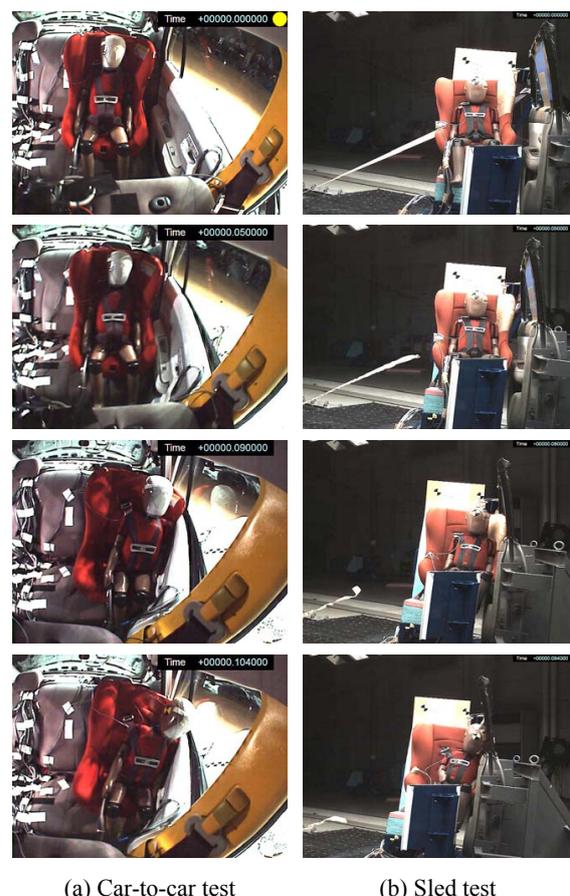


Figure 19. Q3s dummy kinematic behavior in SUV-to-small car test and sled test

It is difficult to compare the HIC directly because of the differences in mechanical properties such as the glass and plastic plate with which the head made contacted. The maximum head acceleration was 1567 m/s² and HIC was 702 in the SUV-to-small car test with a head impact velocity (y) of 6.76 m/s, while the maximum head acceleration was 1861.2 m/s² and the HIC was 866 in the sled test with a head impact velocity (y) of 7.02 m/s. The head impact velocity for the sled test was slightly higher than that for the SUV-to-small car test. If the sled velocity is controlled to be reduced or the material properties and the thickness of the plastic plate are selected to have similar relative characteristics of force-displacement to the glass, the HIC value possibly may be reproduced.

Table 2. Q3s dummy injury measures

	SUV-to-small car test	Sled test
Head		
Max. acceleration	1567.8 m/s ² (105.7 ms)	1861.2 m/s ² (97.3 ms)
HIC15	702 (104.1-111.7 ms)	866 (93.8-107 ms)
Max. velocity resultant	11.51 m/s (96 ms)	10.55 m/s (86 ms)
x direction	6.51 m/s (95 ms)	8.21 m/s (88 ms)
y direction	9.54 m/s (97 ms)	6.83 m/s (82 ms)
Max. x displacement	305.9 mm (122 ms)	295.4 mm (114 ms)
Chest		
Max. resultant acceleration	595.3 m/s ² (97.9 ms)	596.6 m/s ² (85 ms)
3 ms	529.8 m/s ²	566.1 m/s ²
Deflection	12.6 mm (133.8 ms)	6.3 mm (101.2 ms)
Pelvis		
Max. resultant acceleration	417.8 m/s ² (78.1 ms)	612.7 m/s ² (84 ms)

Sled Test without Harness Slack

The sled test was carried out on the using the same conditions for the reproduction test except for the condition without adding CRS harness slack. Table 3 presents the test results with and without harness slack. Without harness slack, the shoulder joint did not go out beyond the CRS side wing; however, the head had contact with the door side window. At the head contact time (100 ms), the head and the sled

velocity in the y direction were 6.81 m/s and 8.13 m/s, respectively. The head displacement in the x direction was 239.6 mm on impact and 241.5 mm at maximum (105 ms). The head acceleration was 1411.9 m/s² (101.7 ms) and HIC15 was 814 (94 – 109 ms).

Table 3. Q3s dummy injury measures in sled test with/without harness slack

	Sled test Harness slack 75 mm	Sled test Harness slack 0 mm
Head		
Max. acceleration	1861.2 m/s ² (97.3 ms)	1411.9 m/s ² (101.7 ms)
HIC15	866 (93.8-107 ms)	814 (94-109 ms)
Max. velocity resultant	10.55 m/s (86 ms)	9.82 m/s (83 ms)
x direction	8.21 m/s (88 ms)	6.97 m/s (81 ms)
y direction	6.83 m/s (82 ms)	6.98 m/s (85 ms)
Max. x displacement	295.4 mm (114 ms)	241.5 mm (105 ms)
Chest		
Max. resultant acceleration	596.6 m/s ² (85 ms)	703.6 m/s ² (102.7 ms)
3 ms	566.1 m/s ²	549.1 m/s ²
Deflection	6.3 mm (101.2 ms)	8.1 mm (104.2 ms)
Pelvis		
Max. resultant acceleration	612.7 m/s ² (84 ms)	502.5 m/s ² (82.2 ms)

There was a large difference in the maximum head displacement in the x direction between the tests with and without CRS slack harness. With CRS harness slack, the dummy was not restrained, and the dummy moved toward the door early. As a result, the head contact time for the test with CRS harness slack of 75 mm (96 ms) was earlier than that without harness slack (100 ms). Without CRS harness slack, the head displacement in the x direction was 239.6 mm on head impact and was 241.5 mm at maximum. For the test with a harness slack of 75 mm, they were respectively 264 mm and 295.4 mm (Note: The head displacement in the y direction was similar because the head impacted the side window). The head x displacement in the test without CRS harness slack was smaller by 24 mm than that in the test with CRS harness slack of 75 mm on head impact, and by 54 mm at maximum.

Figure 20 shows the relation of sled test and head velocity in the lateral direction (y) with and without slack harness. At the head contact time in the test without CRS harness slack (100 ms), the sled velocity in the y direction was 8.13 m/s, which was higher by 0.3 m/s than that of 7.84 m/s in the test with a CRS harness slack of 75 mm (96 ms). However, this is not consistent from the results that the head impact velocity (y) in the test without CRS harness slack (6.91 m/s) was smaller by 0.1 m/s than that in the test with CRS harness slack of 75 mm (7.02 m/s). With harness slack, the head remained almost in the same location, and the door impacted the stationary head (0.82 m/s) at a high velocity. On the other hand, without harness slack, the torso was accelerated with the sled, and the head was accelerated through the neck; then the door impacted the already accelerated head (1.22 m/s). As a result, the head impact velocity relative to the door was higher in the test with harness slack than that in the test without harness slack. Consequently, it was confirmed that the CRS slack affected not only the head displacement but also the head impact velocity.

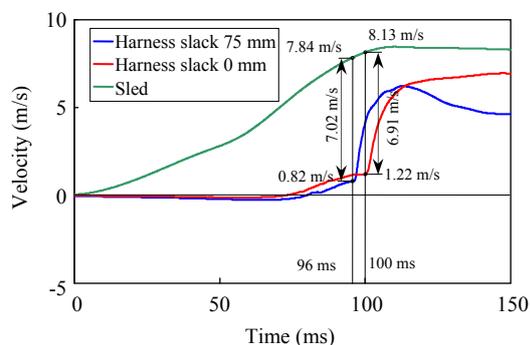


Figure 20. Sled velocity (y) and head velocity (y) for CRS slack harness of 0 and 75 mm calculated from integral of acceleration

CONCLUSION

It is considered that a CRS is effective for child occupant protection in side impact. At present, there are no official standards or regulations for specifying the protection performance of a CRS for side impact. However, accident data show that there are some cases where a child's head made contact with the vehicle interior (such as the door or door side

window) and which resulted in serious head injuries. It is still a question as to how the child head impacted a door or side window even though the child had been seated in a CRS. Moreover, to develop a CRS side impact test procedure that is effective for child protection, it is necessary to understand the mechanism of these head impacts.

In this study, an SUV-to-small car oblique side impact test was conducted in the manner such that the head would contact the door or side window. The SUV impacted the side of the target car at an angle of 45 degrees. A Q3s dummy was seated in the CRS installed on the target side of the rear seat, and during the test the dummy head contacted the side window, which led to a high HIC, even though the child was seated in the CRS in a standard posture.

A series of sled tests were carried out to reproduce the Q3s dummy kinematic behavior in the SUV-to-small car test. After many modifications, the test conditions that can highly reproduce the kinematic behavior of the Q3s whole body, particularly the head, were identified. The head impact velocity and the sled velocity in the lateral direction in the sled test were adjusted to be consistent with those in the SUV-to-small car test because the head in this test impacted the side structure laterally. The slant angle of the test buck was also included as a parameter to represent the rolling behavior of the target car. A sled test also was conducted to examine how the CRS harness slack affects on the dummy kinematic behavior. The head went out beyond the CRS side wing and impacted the door side window even when tested without slack in the CRS harness.

Through the study of reproduction in sled tests, the mechanism and factors that affects the head impacts to the door and door side window were identified. A combination of longitudinal and lateral velocity of the car affects the movement of the Q3s dummy head and torso from the CRS side wing. The rolling behavior of a car during a side impact can affect the head impact location. It was also found that the door side window is sufficiently stiff that it can cause serious head injuries to children.

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